Instrumentation

Theory and Applications

Satya Sheel

Alpha Science

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Alpha Science International Ltd.
Oxford, U.K.

Instrumentation
Theory and Applications
496 pgs. | 278 figs. | 48 tbls.

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7200 The Quorum, Oxford Business Park North
Garsington Road, Oxford OX4 2JZ, U.K.

www.alphasci.com

ISBN 978-1-84265-768-3

E-ISBN 978-1-78332-061-5

Printed in India

THIS CREATION IS DEDICATED TO
THE MEMORY OF

MY PARENTS

Preface

Instrumentation and measurement are part of all scientific and industrial activities. The theory of measurement involves sensing the phenomenon, obtaining electrical signals, their processing, and interpreting the information to make meaningful deductions about the system. The activity involves use of principles and information from several disciplines, and interestingly useful to all engineering/ scientific endeavors. The most important application of the signals is for monitoring the system/process and using this information to implement control actions. In industrial situation (and in many others) the measurement related activities are to be conducted perpetually in a pre-defined sequential manner. Such a group of activities performed with the dedicated hardware (and sometimes software too) is called an instrumentation (system). Instrumentation is an ever growing discipline with importance in all types of industries and scientific research. Its complexity has grown steadily with increasing importance of accuracy, precision, faster data acquisition & faithful transmission to ensure high product quality. This is evident from the glance at the major industries viz. Chemical units; Steel plants; Oil refineries; Cement factories; Sugar mills; Food processing & Beverages (both soft and hard) production centers; Pharmaceutical industry; Paper and pulp industry; Audio, radio, video communication; Consumer, entertainment, industrial, defense and medical electronics.

A large number of books related to various aspects of instrumentation, needs of different industries are available, but there has been shortage of a textbook which provides sound theoretical basis, followed by application and information of design/selection aspects involved, simple enough for students to understand and yet invoke minimum mathematics and electronics, so as to stress on applications, and be easily followed by practicing engineers from various disciplines and scientists. Normally to cover the necessary theory and the elements of instrumentation system architecture four to five textbooks are required. The need to reduce this problem has been felt for a long time. Also, the details required for students of different branches/groups of engineering professionals vary largely. Looking at the developments in instrumentation, it is to be noticed that mechanical, hydraulic and pneumatic instrumentation have been in use for a long period with high success rate and also have common industry standard. However, over the last 20 years the electrical and electronic instrumentation have developed so much that all earlier techniques have become outdated and might be obsolete very soon. Therefore, in this text earlier technologies have not been discussed in this text, except for cursory reference at a few places. Biomedical instrumentation is related but very specialized on its own, and not considered. However for the first course the students and fellow teachers will find useful information.

The developments in electronic instrumentation have been very rapid and wide spread, as these involve several aspects, the choice of a single text been difficult. With this in view, this text has been designed with a flexible approach, so that the main text provides the necessary theory, yet assumes little mathematical background, with necessary knowledge presented and other details are included in appendices, so that depending upon the details actually needed by the reader, the appendices and bibliography may be appropriately referred.

The book is considered useful for the following type of users:

(*i*) Students having their first course in instrumentation in any branch of engineering and needing a text complete in itself.

(*ii*) Scientists needing background of various aspects – theory, mathematical formulations and approach for development of typical need based of instrumentation systems.

(*iii*) Professors conducting course in this subject and wish to adopt a single text for one semester course at UG or at graduate level with appropriate choice of chapters compatible to the background and composition of the class of students.

(*iv*) Practicing engineers who wish to undergo self-study and update their knowledge.

The material has been organized into nine chapters and ten appendices. Author has aimed to provide concise and reliable information about the basics, technique available with emphasis on the modern ones. The principles are stressed more and applications are included as the logical use of theory, as he feels required in a first course on the subject. The details have been included considering the fact that such courses are offered at senior level in sixth or seventh semester in most universities almost, in all disciplines.

The first chapter includes the basics and scope of the subject while the second chapter on system specifications and tools provides background material for understanding analysis methods and tools. This may be omitted if the students have already undergone a course in measurements and control.

The third chapter provides background of measurement principles, errors and their analysis relevant to instrumentation systems and techniques to achieve desired quality. This may be gone through briefly for students who have undergone a course in electrical measurements. Chapter 4, 5, 6 detail the principles of sensors and transducers in detail, to be utilized for application to common physical variables later. The transducers constitute the interface between the real system and process with the electrical signal domain. Their application to common physical variables will be the subject matter of chapter 7.

Chapter 8 includes signal conditioning which is one of the most important activities responsible for improving accuracy, sensitivity, linearity and convenience of use by adding processing capability. Developments in electronics have contributed very significantly in modernizing the instrumentation systems. Selected topics from this chapter should be used depending upon the background of students *i.e.*, very little for electronics engineering to almost whole for mechanical and chemical engineering students.

Last chapter on telemetry and networked systems includes the content matter to complete the flow of information *i.e.*, from field to control room. This includes various data transmission schemes in practice along with current trend towards computer-based data transfer network systems and the standards. These topics are most often not included in the undergraduate text books and discussed only in brief to provide a complete scenario. At the end data acquisition systems (DAS) are included in brief.

It is strongly felt that data acquisition aspects should be covered in detail but if it is difficult to cover in one semester then it must be recommended for self-study as an assignment.

Also included in each chapter are solved examples to illustrates the application/computational aspects and problems for exercise are provided in all chapters with answers to selected problems included toward the end. At the end of each chapter, a list of references has been included for more detailed study by interested readers, along with a bibliography at the end. Glossary of the important terms has been provided to assist the first time reader of the subject to avoid cross referencing and make continuous reading possible without the distraction, to refer to some other book or material.

It is hoped that this text shall be able to meet the long felt need of the user community to have all aspects of industrial instrumentation from the point of view of learning the subject. The feedback for improvement and any queries are welcome at the e-mail address of the author.

I am thankful to my wife Kumud for patience and encouragement, graduate students Tarun Varshney, Omhari Gupta, Alok Kumar, Shivam Bhardwaj, Madhulika Phatak, Gunjan verma, Neha Srivastava, Honey Joshi, Mayank and Vipul Agrawal for assistance at various stages of preparation and many UG students who provided the feedback to improve upon the explanations.

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APPENDICES

CHAPTER 1

Instrumentation Systems

> "If you cannot measure it, you cannot control it.
> If you cannot control it, you cannot manage it.
> If you cannot manage it, you cannot improve it."
> Conclusion is - if you cannot measure it, you cannot improve it.
>
> *Dr. H. James Harrington International Quality Guru*

Inside the Chapter

INTRODUCTION

For any industry to be successful, quality control and scale of production at the viable economic level is a must. The quality control depends on the monitoring of vital processes and associated variables. The economy of operation is controlled by material and energy inputs into the production process/system. The monitoring of variables, the process thereby, energy and materials need instrumentation systems finally to achieve the automatic control of the given industrial process.

The integration of monitoring elements/devices and systems for each individual variable in the process is referred as data acquisition channel and a combination of all such channels is referred as Data

Acquisition System (DAS). With the integration of DAS and the process being monitored and controller the DAS acquires the level of Instrumentation system, as shown in Fig. 1.1.

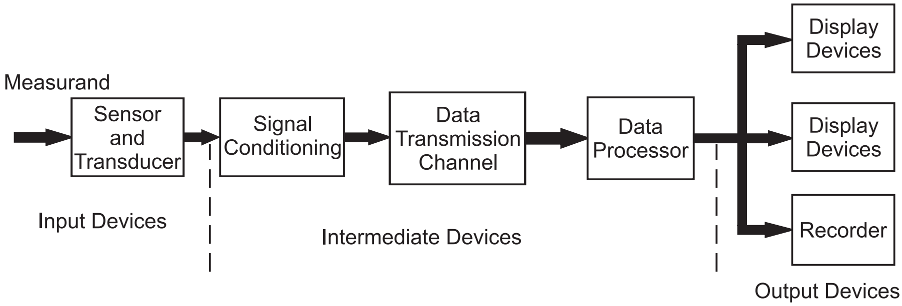


Fig. 1.1 Elements of Instrumentation System

1.1 ROLE OF INSTRUMENTATION SYSTEMS

In any industrial system, measurement of variables, provides the information about their magnitude and time of occurrence viz. The status which may be utilized for one or more of the following activities:

(*i*) Monitoring

(*ii*) Control

(*iii*) Behavioral analysis

Instrumentation professional is required to have appropriate choice of the system (or process, used synonymously) variables, measuring devices, their arrangement and method of utilization of the measurands so as to meet the desired objective(s). An arrangement satisfying the desired objective may also be called instrumentation system.

The objectives need to be defined more specifically, depending upon the type of system and the priorities associated with them. For example, the detailed objectives in the cases of oil refineries system, municipal water supply system, electric power generation system, meteorological system, aerospace vehicle system or a human physiological system have widely different objectives and therefore may lead to widely different instrumentation systems.

Objectives in general would be:

(*i*) Smooth plant operation

(*ii*) Monitoring at every stage to ensure end product quality

(*iii*) Safety of plant and community

(*iv*) Environmental protection

(*v*) Equipment protection

(*vi*) Monitoring for diagnosis, production control and profit analysis

For a set of specified objectives there are several guiding factors in the design of instrumentation such as, maximizing efficiency and speed of data acquisition, minimizing cost of devices, quality improvement of data acquired, type of display desired etc. often it is difficult to satisfy them together and one needs a good amount of skill and the complexity of the scheme is often related to the efficiency, cost and quality of the product and pollution control laws of the state.

1.2 ELEMENTS OF INSTRUMENTATION SYSTEMS

For understanding the instrumentation, their systematic organization and analysis, generalized approach is useful, as it makes possible to describe the operation and performance of the system, without referring to specific hardware.

A general instrumentation system can be categorized into two major classes - analog systems, dealing with the information available as continuous function throughout, and digital systems handling the data information in digital or discrete from. Both of these types will have three major elements as shown in Fig. 1.1. These include:

(*a*) Input devices

(*b*) Intermediate devices

(*c*) Output devices

Input quantities (also known as measurands) from the process, for the most instrumentation systems are non-electrical. Therefore for measuring, manipulation or control, it is necessary to convert them into an electrical signal. An input device performing this role is known as transducer, and may involve the use of *primary sensor*. These are discussed in detail in fourth chapter onwards.

The intermediate devices stage consists of an assortment of electronic assemblies to perform variety of useful operation such as :

(*i*) Signal conditioning of the signal obtained from the transducer is performed with the help of amplifiers, attenuators, filters, signal shapers and converters, data converters, multiplexers, transducer bridges, linearising and other processing units for suitable calibration, transfer and display etc., with avowed objective to meet the typical requirements of the system under consideration, so as to bring the signal into a format and level suitable for next stage to transmit for local/remote display, monitoring and control purposes.

(*ii*) Data transmission/telemetry is the stage of transferring the data, corresponding to physical variable being measured, already brought into the format and level suitable for sending to the control room for monitoring by display, recording and control of the process. The format and the media for telemetry are large decided on the basis of distance over which the signal is required to be sent. For example, the media could be coaxial cable for small distances with high fidelity, open telephone lines for medium distances with economy but open to noise contamination, through wireless media—the type of RF transmission analog or digital and modulation technique depending upon the distance and fidelity required but at a greater cost.

The distances can vary from very small in laboratory scale production units in case of sophisticated semiconductor device fabrication units to scattered (up to kms) in case of chemical, fertilizer, oil refinery units. Large telemetering distances are experienced in aircraft guidance and control, missile control, with very large distances traveled by signals picked up by space vehicles and satellites.

(*iii*) *Data processing* with the help of dedicated hardware or a computer, involving operations such as linearising, limit comparison, square root extraction, noise suppression, estimation of nonmeasurable/unobservable variables, signal extraction etc.

Depending upon the process type and its details one or more of above group of operations may be used.

The output devices, including visual display devices for continuous monitoring of process/system variables. These include cathode ray oscilloscope or (computer) monitor screens, alphanumeric displays, panel meters etc. Very often recorders are used to have permanent record of collected data for supervisory role, diagnostics modifications and optimization analysis, and managerial decisions. There is a wide range of paper chart type ink/non ink stylus recorders, optical recorders, galvanometric recorders, ultraviolet recorders to modern magnetic tape recorders and digital recorders and plotters available.

1.3 USE OF MONITORED INFORMATION

The purpose of instrumentation in any industrial system/process is to help in achieving desired output quality, by utilizing the values of physical variables being monitored to implement the control strategy appropriate for controlling the output variables. Here it will not be attempted to go into the details of control strategies, yet a representative control system is presented to emphasize the role of instrumentation. As shown in Fig 1.2 the main elements of a control scheme for one of the variables of the system are indicated.

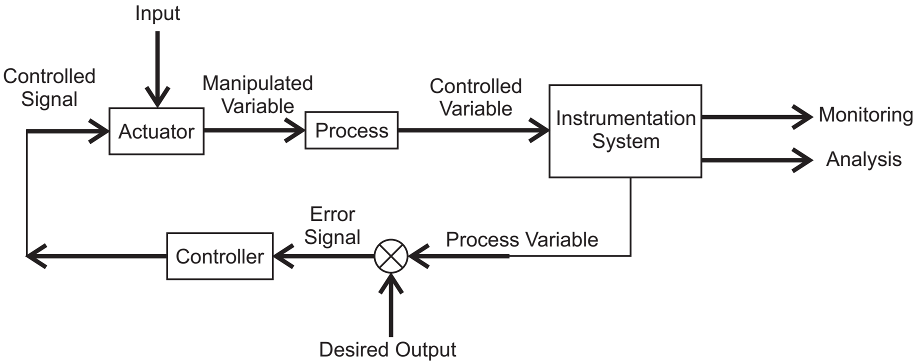


Fig. 1.2 Elements of Control System

Instrumentation system is being used to measure the process variable(s) at the output (or some inside variable) as a monitoring activity. This is compared with the desired output value of this variable in the comparator. Any difference between them is called error and needs to be corrected by the controller action(s). Error actuates the controller to produce control signal depending upon the type of error and the configuration of controller. Control signal in-turn acts upon the actuator of the system to regulate the input quantity so as to result in an output close to the desired one.

For example in a thermal system the heat inflow of the system may be controlled by actuating a valve to control the flow rate of steam or gate current of silicon controlled rectifier (SCR) to regulate the flow of current into the heater etc., to keep the temperature of the system (being monitored) close to the desired temperature (also called set point).

There may be a number of variables to be monitored and for several of them it may be possible to control independently. Depending on the degree of freedom we shall have as many closed-loops as the number of controlled variables.

1.4 TYPES OF INSTRUMENTATION SYSTEM

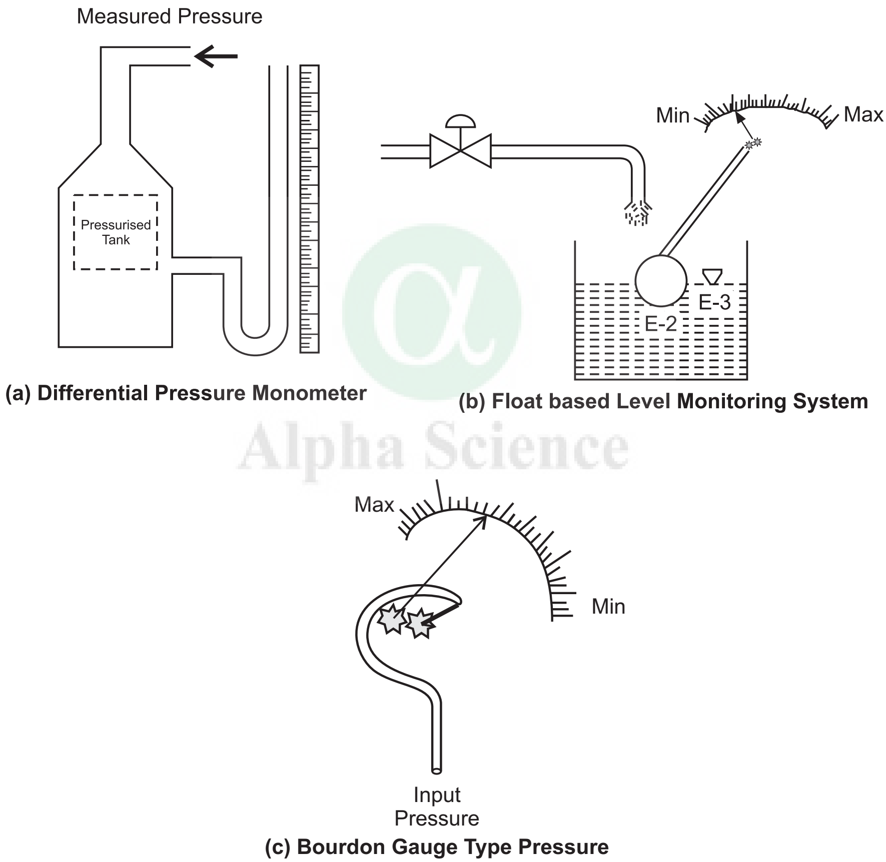
Feedback or closed-loop control systems providing automatic control have developed immensely during the last 60 years. The growth has been need base and limited by the available techniques and devices. We can broadly categorise the various instrumentation systems used with these systems into four types as:

(*i*) Mechanical, the classical one, using thermometers of various types for temperature, manometers and dial gauges for pressure etc. Some of these are quite economical, reliable and still commonly employed. Figure 1.3 shows three types of mechanical types of instruments:

(*a*) manometers for pressure measurement [Fig. 1.3(*a*)]

(*b*) a float based monitoring arrangement and [Fig. 1.3(*b*)]

(*c*) large pressure measuring arrangement using a Bourdon gauge [Fig. 1.3(*c*)] as typical example of this class.



(a) Differential Pressure Monometer

(b) Float based Level Monitoring System

(c) Bourdon Gauge Type Pressure Monitor for Large Mechanical Pressure

Fig. 1.3 Mechanical Instruments

(*ii*) Pneumatic type has been the common choice in chemical and oil industry (commonly referred to as process industry), steel plants and many a section of power industry. In this a physical measurand such as temperature, flow level etc., is converted into a pneumatic (air) pressure, in proportion to the magnitude of the input. This can be transmitted quite faithfully and have proved to be safe, efficient and clean. Developments in this have been in all aspects of process control including computing, amplifying, relaying, processing and logical decision-making.

(*iii*) Hydraulic type, claimed to be as much efficient as pneumatic but of late not popular due to various snags, mainly due to the fluid (oil) being used. It is typically used for applications involving large pressures for example in conveyors, lifts, brakes etc.

(*iv*) Electrical and electronic type: Major developments have taken place in this type during the last 20 years and a stage has been reached so that the new plants 10 years hence shall have 95% instrumentation of this type. This has been made possible due to the advances made in electronics, contribution to improvement in response time and quality of data acquisition, data display facilities, recording and reproduction, faster processing and analytical decision making to name a few. In view of the growing importance of this class of instrumentation, the present text emphasizes this with some of the widely used configurations. The first three types are not being presented, for the sake of brevity as these are becoming obsolete and within a decade shall be replaced by electronic instrumentation. However, in the present systems wherever they are in use, are being replaced slowly. Interested reader may look into bibliography.

1.5 STANDARDS IN INSTRUMENTATION DESIGN AND TELEMETRY

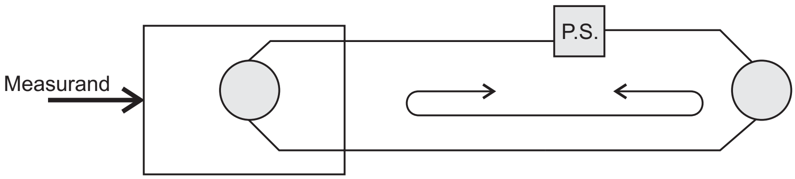
As mentioned earlier, the main objective of intermediate devices is to meet the requirements of the system. After the choice of appropriate transducer, the signal conditioning stage is needed in most cases. The selection and design of this stage and the subsequent one is simplified by using standard devices and design procedures. For this signal conditioning equipments are specified to provide standard output signal for transmission to control and display devices.

The design of instrumentation systems around an established standard provides distinct advantages in design, assembly, reconfiguration, operation and maintenance. Commonality of spares and thereby saving in cost of inventory, the reduction in training needs and avoidance of special fault diagnostic aids are other advantages that automatically follow. In a typical large process industry such as oil refinery or entertainment electronics industry the common standards offer major advantages in operation, maintenance, up gradation, training of personnel etc., according to level of modernization. This will be discussed in detail in Chapter 7.

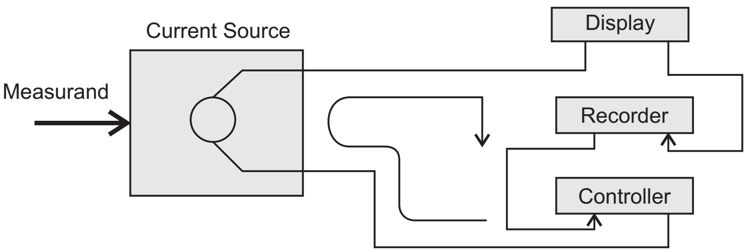
Signal transmission or telemetry is one of the most important links in data acquisition and have been standardized for universal use for the reasons of clarity of understanding, flexibility of devices connected, fidelity of signals transmission and future expansion of system.

1.5.1 Industry Standard for Analog Signal Transmission

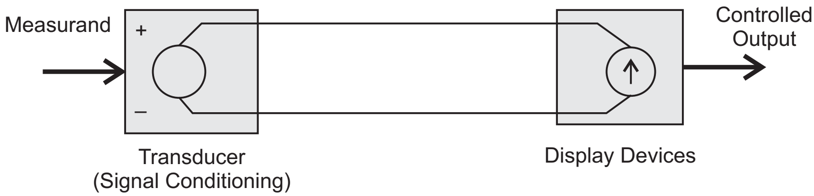
The most common 4-20 mA dc standard is based on live-zero concept, rather than the voltage. This implies that for zero value of the input measurand the current supplied is 4 mA and for the maximum (full scale) value the signal current supplied is 20 mA. Current standard provides a variable current according to the value of measurand between these limits, through the loop formed in any of the connection modes shown in Fig. 1.4., and a drop in current transmitted below 4 mA indicates malfunctioning *i.e.* usually dead connection. As can be noticed from Figs. 1.4 (*a*-*c*), current loop is totally floating from the earth and therefore provides excellent noise immunity due to the absence of common mode noise. The errors caused by different earth potentials around the plant are thus totally avoided. Also the line resistance has no disturbing effect because current, rather the voltage, is being used.



(a) Two Wire System



(b) Series Connection of Output Devices in Current Loop



(c) 4-20 mA Current Loop Principle

Fig. 1.4 Current Telemetry System

1.5.2 Current Loop Telemetry Systems

(*a*) Series connection of display/control devices with the transducer as shown in Fig. 1.4, with the total resistance limited by the consideration of the current controlling source characteristics, or several of these as in Fig. 1.4(*b*), each output device being a current sensor.

(*b*) Separately powered connection, is designed with transducer providing the current (see Fig. 1.4*c*), or, as two-wire operation with signal wires also acting as the power supplies connections.

These are generally economical as a suitable local supply can be used, to meet the demand of current for display devices too. In these systems, the transducer is required to act as a current sink and adjust a regulator to provide the correct magnitude of current in correspondence with the value of measurand.

EXAMPLE 1.1

An instrumentation arrangement for temperature monitoring produces a 4-20 mA signal with an indicator and recorder connected at the (monitoring) control room.

Show the interconnection and state assumptions.

SOLUTION:

A voltage supply of appropriate value is connected as shown in Fig. ex. 1.1. The chosen supply should be able to maintain a load independency say upto 600 Ω, so that the voltage supply needed

$$V_s = 40 \text{ mA} \times 600\ \Omega = 24 \text{ V}$$

Suppose the devices to be connected are standard device *i.e.* with definite input resistance say for indicator 200 Ω, for recorder 150 Ω. This provides a gap of 250 Ω and more devices can be connected, also the voltage may have to be reduced from 24 V so as to keep maximum line current within 40 mA.

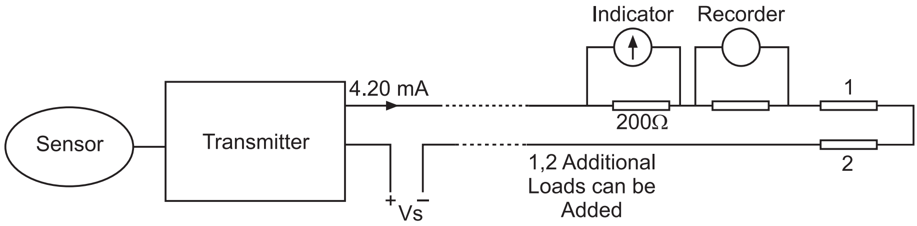
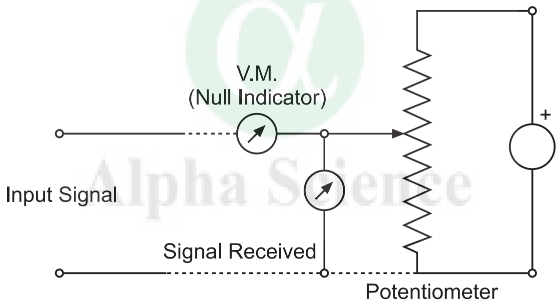


Fig. Ex. 1.1

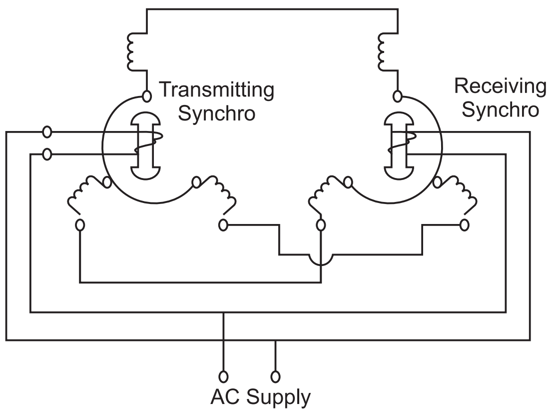
1.5.3 Other Electrical Standards

4-20 mA standard described earlier is by far the most common yet there are some others also in existence. Among these are 10-50 mA standard and 1-5 V with zero off-set.

The voltage telemetry schemes shown in Fig. 1.5, suffer from a serious disadvantage of voltage drop along the line, and this may



(a) Null Balance Type Voltage Telemetry



(b) Position Telemetry System using Synchros

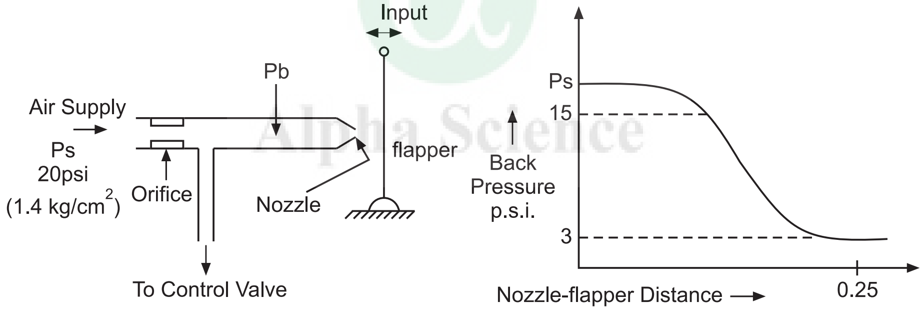
Fig. 1.5 Voltage Telemetry Schemes

necessitate the use of amplifiers/repeaters at the intermediate stations between sending and receiving ends in case of long distances. The main advantage of voltage telemetry lies in reduced power drain, almost to zero by using null deflection technique, but in dynamic situation it is difficult to achieve this as it demands faster response from the equipment.

Often depending on type of output device, there may be a need of current to voltage (I-V) or voltage to current converter (V-I), as part of signal conditioning operations.

1.5.4 Other Standards

For chemical and allied industries, pneumatic control is still the most common choice for the reasons of safety. For this class pressure standard used is 3-15 p.s.i. or 20-100 K Pascals. Response speed is improved by off-set zero. Pneumatic systems use dry, clean filtered air as a medium of flow through the tubing of rubber or steel depending upon the place of application. Pressure loss can be caused by venting to the air and has an exponential decay with time, as shown in Fig. 1.6.



(a) Schematic Diagram **(b) Characteristic Curve**

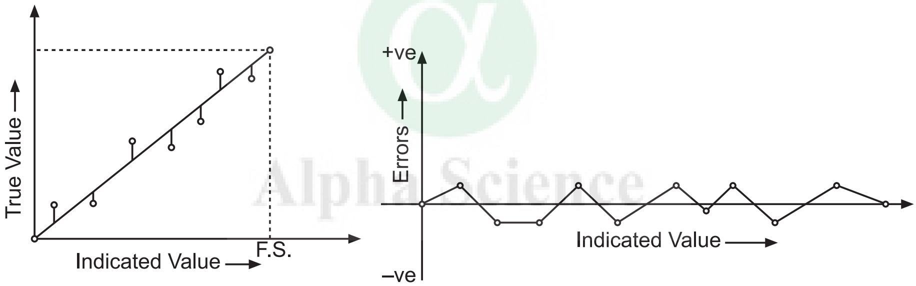
Fig. 1.6 Principle of Operation of Pneumetic Systems

The current trend is to convert the data received from the process into a digital format and make it plant wide available through a communication bus system as also to interface with computer for storage, processing and display in a chosen format with efficiency and flexibility. The details of such digital interface standards are discussed in Chapter 9.

1.6 CALIBRATION

This is one of the most important activities of an instrumentation engineer in an industry. This provides meaningful information from any system, and direct indication of the quality of instrumentation system used, in terms of the accuracy. It relates the measurand value of the variable with the (supposedly) true value or standard/reference value, and presents it through a graphical plot, called—Calibration graph. Another graph which is helpful is error versus indicated reading, relates the errors against the measurand values.

These are shown in Figs. 1.7 (*a*, *b*) for typical cases. The calibration needs to be checked from time-to-time in addition to every time repairs or modifications are made in instrument system/subsystem. There are schedules to be maintained for calibration just as these are made for maintenance. During calibration only one variable is to be changed at a time, under static conditions. Comparison is made with a reference standard, which should be traceable to standards laboratory. It should be also borne in mind that, it is being done under controlled conditions of noise and loading *i.e.* under ideal conditions and instruments might show a little different set of errors during use under actual conditions.



(a) Calibration Graph **(b) Error Graph**

Fig. 1.7 Calibration of Instruments

To identify the behavior of instrumentation system elements, we consider in the next chapter the methods of characterizing the systems and techniques available to test and verify. It will be followed by measurement and analysis aspects.

1.7 RECENT TRENDS

Currently the emphasis is on miniaturization of transducer and related units, (to be discussed in detail) all packaged into one, using VLSI technology is called smart transducer. Needless to say that, the accuracy norms and portability criteria have created the need for digital specifications. The data sharing has become prevalent and supports digital data format. Plant wide networking is a common strategy to meet the demands of resource optimization at higher level, distributed and hierarchical control. The network bus architectures topologies shall be the future. In order to facilitate the data transfer efficiently, sharing of buses compatibility of devices is important and is taken care through the use of standards. IEEE standards are the established ones and a brief introduction is included in this text.

SUGGESTED READINGS

1. Doeblin, E.O. - Measurement systems (MGH).
2. Fribance, A.E. - Industrial instrumentation fundamentals (MGH).
3. Holzbock, W.G. - Instruments for measurements and control (East-West Press).
4. Eckman, D.P. - Industrial instrumentation (Wiley eastern).

REVIEW PROBLEMS

1.1 What is the role of instrumentation engineers in industry?

1.2 What are the building blocks of the instrumentation channel?

1.3 What is a legacy instrumentation system?

1.4 What is the difference between measurement and monitoring?

1.5 What are the objectives of monitoring?

1.6 Identify the major inputs in any industry? Explain their role with example.

1.7 What can be the advantages of off-line behavioral analysis?

1.8 Explain the live-zero concept and its importance in current telemetry.

1.9 Why is current telemetry preferred over voltage telemetry in industry?

1.10 Explain the operation of synchro transmitter-receiver pair operation for position telemetry.

1.11 What are the other devices available in synchro family? Explain their application in instrumentation and control.

1.12 Where are the national test house located in your country for primary calibration of instrumentation?

PROBLEMS FOR EXERCISE

1.13 Draw the control loop for control of liquid level in a reservoir (tank) and identify all instrumentation, control components.

1.14 Identify the variables and the monitoring instruments in a four-wheeler with role and range of each.

1.15 Draw a possible control loop to maintain the temperature in a room at a desired value, lower than outside (ambient) in summers and higher in winters. Explain the control action and identify the component blocks needed.

1.16 From the appendix E note the standard symbols for various instruments and controllers and use them for problems 1.13 and 1.15 above to draw the process instrumentation diagram.

CHAPTER 2

System Specifications and Tools for Analysis

INTRODUCTION

Inside the Chapter

- Performance Characteristics
- Static Characteristics
- Dynamic Inputs
- Dynamic Systems
- Analytical Techniques for Dynamic Systems
- Stability of Systems
- System Representation and Variables
- Review Problems
- Problems for Exercise

The behavior of an instrument, a complex system or a component can be specified by a set of characteristics. These are obtained by actual experimentation on the device in the appropriate domain – time or frequency. Usually the time-domain has better tuning with mental thought process but the frequency response techniques provide better insight into the behavior typically from design point of view. The approaches are interrelated, though in a complex manner.

Both the technique has been presented in this chapter only from application view point. For rigorous definitions and more details the references may be pursued.

In order to have understanding of the methods of analysis and correlate theory with the practice, the representation of systems via mathematical models is included. Some other mathematical procedures and concepts such as stability also have been included briefly.

2.1 PERFORMANCE CHARACTERISTICS

Considering the generalized input-output system or the black box approach, it can be characterized by three properties:

(*a*) Input characteristics

(*b*) Transfer characteristics

(*c*) Output characteristics

Input and output characteristics are considered for a functional unit within the system *e.g.* range, linearity, impedance etc., and have an important bearing on their interconnection with other unit in the system. Transfer characteristics show a relation between input and output variables.

Another approach for specifying the qualitative behavior of the devices is to consider the characteristics as static, if the measurement conditions are stationary in time, and dynamic if the measurements are having time variable properties.

2.2 STATIC CHARACTERISTICS

These are specified by the following measures:

(*a*) Accuracy and Error: Accuracy of an instrument or a system is the measure of the closeness between measured value and the actual value of the process variable being measured. A precise term to express the accuracy is error. This can be expressed in a number of ways. A common approach is to express the maximum difference between the actual value and the measured value as % of full-scale deflection (FSD) of the measuring device, or as a % of actual value of process variable (PV). Yet another method of expression of the error is absolute indication of error, *e.g.* ± 1°C for temperature instrumentation irrespective of the value. Figure 2.1 shows the relation between the actual and indicated values in a chemical process. The error expressed as per the above approaches would be, (15/65 × 100)% of actual value and absolute error at 65°C.

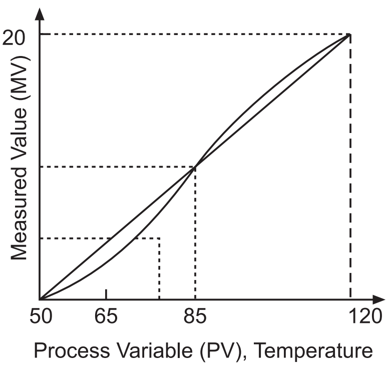


Fig. 2.1 Accuracy and Error Calculation

(*b*) **Repeatability and Hysteresis:** These terms are measure of consistency of the measurements, and at times may be more important than accuracy. Also referred as precision, to which the same output will be obtained if the given input is applied again and again over a period of time. The difference in readings can be attributed to several reasons such as—hysteresis, internal noise, temperature change or drift.

Hysteresis: is said to exist if the reading obtained for same measuring point, in the different (increasing and decreasing) directions are not same. A common source of mechanical hysteresis is slippage in mechanical linkage such as gears, as shown in Fig. 2.2. Stiction or static friction is also a common cause of hysteresis in mechanical systems in the form of force or torque necessary to initiate the motion of body from rest.

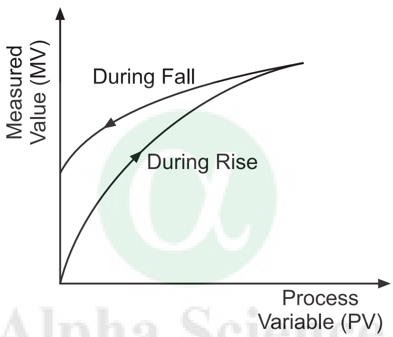
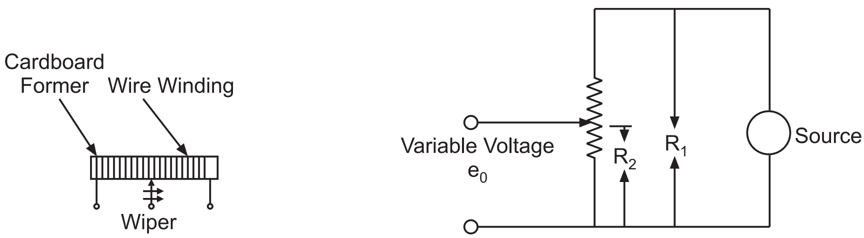


Fig. 2.2 Hysteresis Effect

(*c*) **Resolution:** represents the smallest increment of the measurand which can be detected with certainty. It also defines the steps in which a reading can be sensibly made. A wire wound resistance for example, shown in Fig. 2.3 having a movable wiper, can be used to provide an output voltage corresponding to the position of wiper. This potentiometric arrangement has an inherent output voltage step size depending on the gauge of the wire and number of turns of wire used per unit of length.



(*a*) Physical Arrangement (*b*) Electrical Connection

Fig. 2.3 Wire would Potentiometer

(*d*) Range and Span: The range of a variable is specified by its maximum and minimum values obtainable/observable. For example, a temperature sensing device may have an input range Pa_{ving} to PV_{max} of 30°C to 200°C and an output range of 6-20 mA.

Span is the difference between maximum and minimum values. For example, in the earlier case, the input span is 170°C and the output span is 14 mA as indicated in Fig. 2.4.

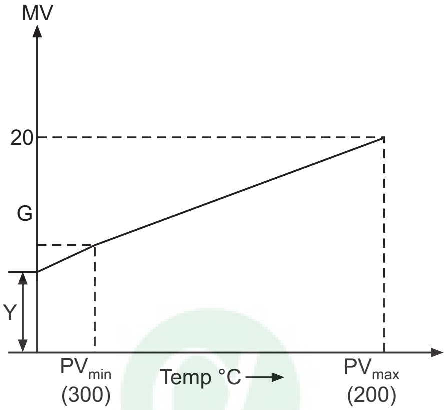


Fig. 2.4 Transfer Characteristics of a Temperature Sensor

(*e*) Sensitivity: This is defined as the ratio of the change in magnitude of instrument output to a corresponding change in magnitude of measurand, also called gain or amplification factor, referring to Fig. 2.4,

$$K = (MV_{max} - MV_{min})/(PV_{max} - PV_{min}) \qquad ...(2.1)$$

where *MV* and *PV* are measured value of process variable (electrical signal) and the actual value of the physical variable (*e.g.* temperature).

EXAMPLE 2.1

For a temperature to voltage transducer, the range of measurement is 30°C to 280°C, resulting in output variation from 0V to 10 V. Calculate the sensitivity of this transducer.

SOLUTION:

Sensitivity K for the given data shall be $K = (10 - 0)/(280 - 30)$

$$= 40 \text{ mV/°C}.$$

The sensitivity being too small for low temperatures if the device is used for the whole range. In situations where monitored information is being used for controlling the temperature at (say) about

233°C ±5° a span adjustment for 200 to 250°C to give a full-scale output is beneficial providing a larger sensitivity

$$K = 10/(250 - 200) = 200 \text{ mV/°C}$$

This will result in less error for the actual range of measurement needed.

(*f*) Linearity: This is a desirable property of all instruments and implies constant sensitivity, *i.e.* the plot of process variable (PV) and the measured variable (*MV*) is expected to be a straight line, defined by:

$$MV = K \times PV + Y \qquad \text{...(2.2)}$$

Figure 2.4 shows such a relationship for such a transducer and the ideal expected response, the off-set *Y* can be positive, negative and zero. The various types of linearity are shown in Fig. 2.5. In each of these, the maximum deviation from the ideal linear response expressed as percentage of full-scale deflection is an indication of the extent of nonlinearity in the measurements.

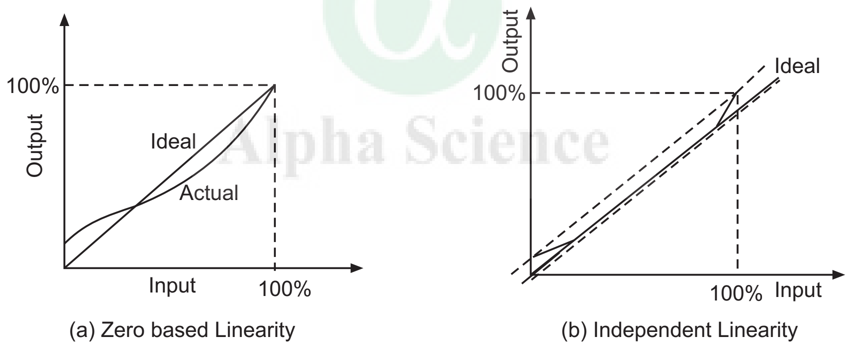


Fig. 2.5 Types of Linearity

Nonlinearity = (Actual output Y_i – Linear output $X_i)_{\max}$/(Full-scale output)

where i = 1, 2,………………….. represent the successive inputs applied over the full range producing corresponding outputs.

Though linearity is a desirable property, it is difficult to obtain for some devices, as in the case of a thermocouple type of temperature sensors. A typical response for such a device is shown in Fig. 2.6. This cannot be approximated by a linear equation yet a quadratic relation of the type,

$$MV = A + B \times PV + C \times PV^2 \qquad \text{...(2.3)}$$

will be able to provide a reasonably close approximation for modeling the response. For linearising the characteristics of such devices, hardware as well as software procedures are available so as to obtain acceptable results in the range of interest. Whereas, for some devices the nonlinearity is of such a magnitude that it cannot be and need not be linearised, for example, orifice meters used for flow measurements in pipes, without complex signal processing techniques, as the governing relationship is:

$$MV = A \times PV^2$$

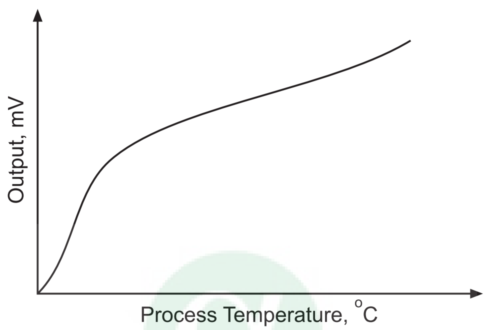
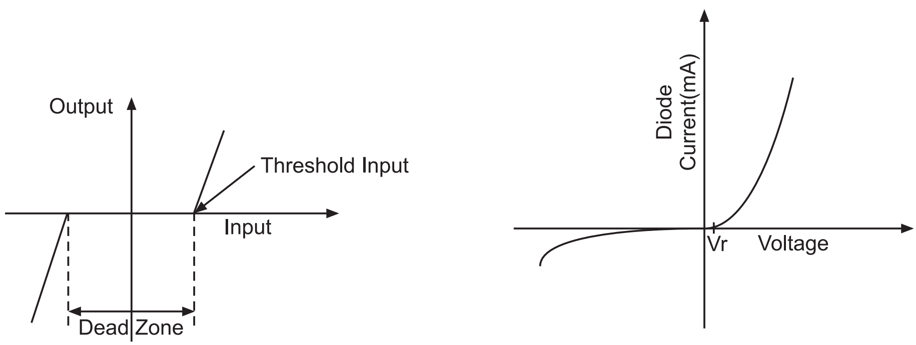


Fig. 2.6 A Typical Thermocouple Characteristic

(*g*) **Dead-zone/dead-band characteristics:** This is a nonlinear effect observed in many mechanical, electrical and hydraulic devices. Dead zone is observed if no response occurs for small inputs and only after a critical or threshold value is exceeded, the response shows up as indicated in Fig. 2.7 (*a*). In mechanical systems it can be attributed to friction or free play between the gears, in electronic devices – the cut-in voltage in the forward characteristic of PN junction diode, Fig. 2.7 (*b*).



(a) Dead Zone Representation

(b) p-n Junction Diode Charcteristics

Fig. 2.7 Dead-zone Characteristic

(*h*) Saturation Characteristic: If input-output (I/O) characteristic is such that, beyond a certain value of input there is no corresponding change in output, *i.e.* the sensitivity drops to very low or zero value, as shown in Fig. 2.8, the device said to have saturation characteristics. This may be observed in both the directions *i.e.* increasing and decreasing.

Some causes for saturation are : magnetic saturation of the core, valves opening to maximum, amplifiers providing a maximum collector current, prime movers having an upper limit of speed due to physical limitations etc.

It must be noted that, many of the properties can be simultaneously observed in a system. The desired properties are to be emphasized and used judiciously, whereas the undesirable ones are required to be suppressed/eliminated by a suitable modification, processing technique or limiting the range of operation to an acceptable one.

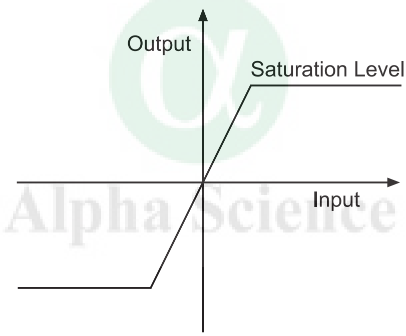


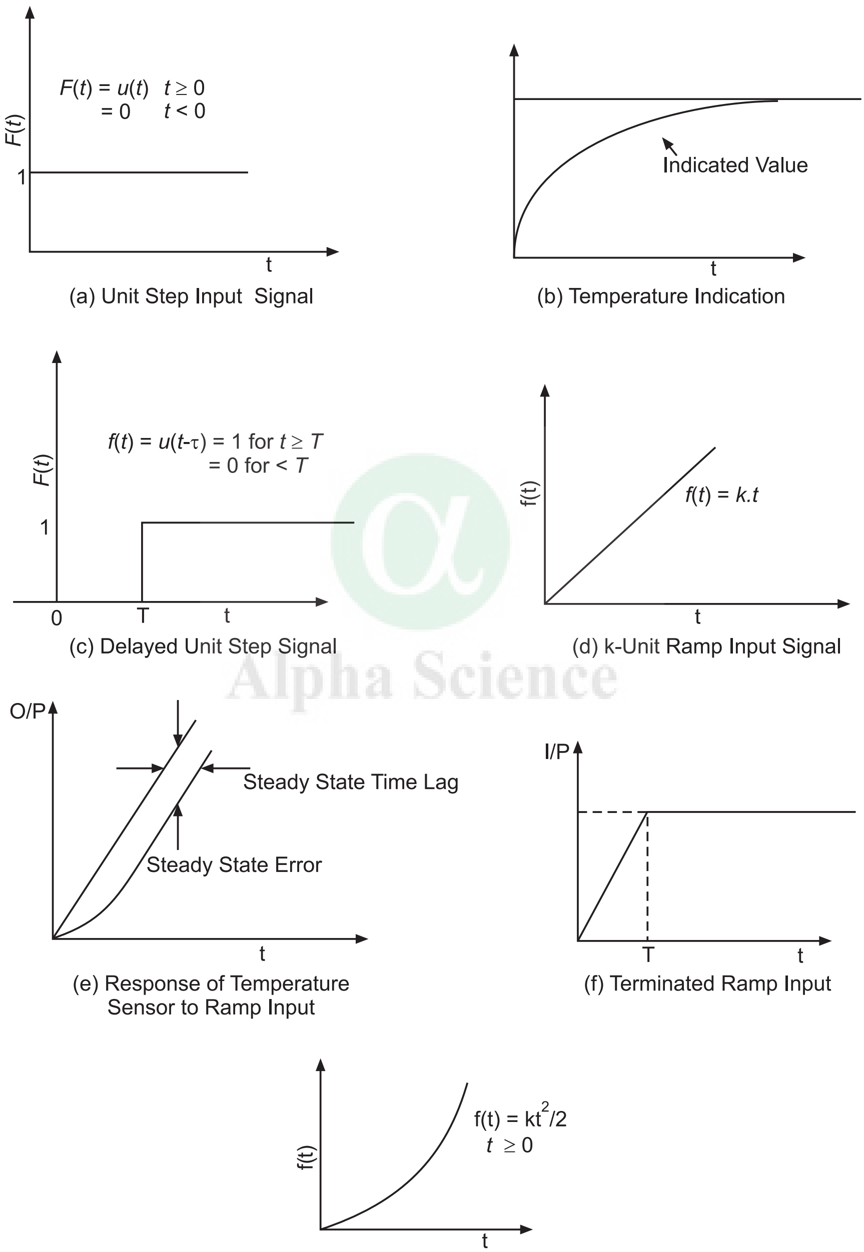
Fig. 2.8 Saturation Characteristic

2.3 DYNAMIC INPUTS

The system having response varying with time, for a given set of conditions, is referred as dynamic systems. The various factors responsible for time dependent behavior are the types or configuration of the system and the parameters, character of the signal applied at the input and the initial conditions of the system. Since a system behaves differently to different type of signals, the types of input signal is considered first.

2.3.1 Types of Input

Since the inputs from the system or into it, may even be arbitrary in real life, the behavioral study and testing cannot be made for all of these. Therefore, standard signals (inputs) are selected to tests the response under various extreme situations possible. Some of these standard test inputs are as shown in Fig. 2.9, are discussed next.



(a) Unit Step Input Signal
(b) Temperature Indication
(c) Delayed Unit Step Signal
(d) k-Unit Ramp Input Signal
(e) Response of Temperature Sensor to Ramp Input
(f) Terminated Ramp Input
(g) k-Unit Parabolic Input Signal

Fig. 2.9 Common Test Input Signals

2.3.2 Step or Position Input

This presents the worst type of input *i.e.* temperature sensor suddenly put into the liquid bath and expected to indicate the temperature of bath correct to a reasonable degree of closeness to true value within the shortest possible time. Response of a typical temperature sensor is indicated in Fig. 2.9 (*a*); Pressure gauge being used to monitor pressure in a gas tank is suddenly applied the full pressure; etc. Such inputs are mathematically presented as:

$$f(t) = K\,u(t)$$

and $f(t) = K\,u(t - T)$, is called a delayed step signal where T is the delay, see Fig. 2.9(*b*).

2.3.3 Ramp or Velocity Input

This represents an input which is increasing slowly with time according to a linear relationship as shown in Fig. 2.9 (*c*). For a temperature sensor when subjected to such an input, the response is as shown in Fig. 2.9 (*d*). This input physically presents the most desirable type of inputs, for example the load on the beam applied in a gradually increasing manner so that the stresses are changing slowly and monitored more easily within the safe (ultimate) limits for the material of the beam. Quite often it may be possible that the structure may fail under the step input but may be able to bear the same or sometimes even larger load under the ramp input conditions. Also, the response of the system, if acceptable for step input, will surely be acceptable with ramp input.

It can mathematically be represented as:

$$f(t) = K\,t, \quad \text{for} \quad 0 < t$$

If $K = 1$, it is referred as unit-ramp input. A practical ramp input would be a modified/terminated ramp input as shown in Fig. 2.9 (*e*), wherein magnitude of input is constrained to be constant after a certain value instead of monotonically increasing and reaching a dangerous values causing a certain failure of the system.

2.3.4 Parabolic or Acceleration Input

This represents a signal which is rather sluggish in the early period but rises at a faster rate as the time progresses, as shown in Fig. 2.9(*f*). Such signals are encountered in speed instrumentation systems, for example a motor starting under large load (inertia) starts slowly and pick up high speed later as also in the case of a passenger aircraft or freight carrier. The peak response to this class of signals is always within the limits of worst case *e.g.* step-input.

2.3.5 Sinusoidal Input

These are the ideal class of inputs subject of limits of amplitude and frequency, compatible to the system under test. The practical load disturbance signals are quite often of this type and there are standard techniques available for analysis based on sinusoidal signals. These are amenable to use for systems running under normal operating conditions and are quite often used for identification of designed systems' parameters and performance rather than design tests.

2.3.6 Impulse Input

These are not for testing the physical systems may be used for further analysis only and details can be found in any text on control engineering.

2.3.7 General Effects

The final steady state errors due to step, ramp and parabolic inputs are referred as position, velocity and acceleration errors respectively. These are relevant to the type of input being monitored and their values are dependent on the configuration of the system. In general the steady state error is required to be minimum but during implementation, the other specifications may be more important are discussed later in Sec. 2.5.5.

2.4 DYNAMIC SYSTEMS

2.4.1 Definition

Dynamics of a system is specified in terms of the rate of change of the variables involved when subjected to specified inputs (which may also have dynamics) and the observation is made over a reasonable period of time.

For example a general dynamic system as shown in Fig. 2.10 can be presented by a mathematical model, by the equation:

$$a_n \frac{d^n c(t)}{dt^n} + a_{n-1} \frac{d^{n-1} c(t)}{dt^{n-1}} + a_{n-2} \frac{d^{n-2} c(t)}{dt^{n-2}} + \dots + a_1 \frac{dc(t)}{dt} + a_0 c(t)$$

$$= b_m \frac{d^m r(t)}{dt(m)} + b_{m-1} \frac{d^{m-1} r(t)}{dt^{m-1}} + b_{m-2} \frac{d^{m-2} r(t)}{dt^{m-2}} + \ldots\ldots + b_1 \frac{dr(t)}{dt} + b_0 r(t) \quad \ldots(2.5)$$

or, $\sum_{i=0}^{n} a_i c^i(t) = \sum_{j=0}^{m} b_i r^j(t)$

where, $c(t)$ is the output and $r(t)$ is the input. The coefficients a_0, a_1, a_2, ... a_n depend on system characteristics; b_0, b_1, ... b_m depend on the dynamics of the signal. These coefficients may be time variant/ invariant. The system has the dynamics of order n and for almost all practical systems $n > m$. The analysis is simplified if the coefficients are assumed to be constants.

Since the instrumentation devices-transducers, amplifiers, filters etc., are generally limited to second order the above equation simplifies to:

$$a_2 \frac{d^2 c(t)}{dt^2} + a_1 \frac{dc(t)}{dt} + a_0 c(t) = b_0 r(t) \quad \ldots(2.6)$$

For a simple input of any of the types discussed earlier. We shall consider later the various possibilities to identify the dynamical model representations for instrumentation systems, devices described by hardware configuration, and evaluate their performance for the type of expected inputs.

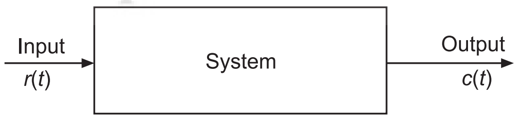


Fig. 2.10 Block Diagram of a SISO System

2.4.2 Comments

The most common technique for analysis of the assembly if instruments along with the system devices, is the transfer function modeling and simulation. It has been possible to model the systems such as: boilers, reactors, heat exchangers, water tanks etc., instruments *viz.* analog indicating instruments, devices *viz.* sensors for temperatures, pressure, flow, level, speed etc., and controllers of the analog type–pneumatic, hydraulic or electrical....

There are other approaches to modeling *i.e.* state variable model, time series model etc. but they have not found much application in instrumentation, except for complex systems and then too, these are limited to representation of process system only.

Simulation is the standard approach whenever analytical solution is difficult. With the availability of computers now, it is possible to think ahead and consider the eventualities, well before the actual commissioning of the system and study of experimental results. For more details, references cited at the end may be looked into.

2.4.3 Transfer Function Approach to Modeling

The approach is most helpful in determining the output response of a system or network for any given input, under relaxed conditions.

As an extension of our discussion earlier in Sec. 2.4.1 for dynamical systems represented by Eqn. (2.5), with $c(t)$ as output and $r(t)$ as input, $a's$ and $b's$ as real constants is considered again. By taking Laplace transform of equation, neglecting the effect of initial conditions it is possible to rearrange as :

$$a_n s^n C(s) + a_{n-1} s^{n-1} C(s) + \ldots\ldots\ldots\ldots\ a_1 s C(s) + a_0 C(s)$$
$$= b_m s^m R(s) + b_{m-1} s^{m-1} R(s) + \ldots\ldots\ldots\ldots + b_1 s R(s) + b_0 R(s)$$

or $$\frac{C(s)}{R(s)} = \frac{b_m s^m + b_{m-1} s^{m-1} + \ldots\ldots\ldots\ldots\ldots\ldots + b_1 s + b_0}{a_m s^n + a_{n-1} s^{n-1} + \ldots\ldots\ldots\ldots\ldots\ldots + a_1 s + a_0} = G(s) \qquad \ldots(2.7)$$

For a second order system it would reduce to

$$\frac{C(s)}{R(s)} = \frac{b_2 s^2 + b_1 s + b_0}{a_2 s^2 + a_1 s + a_0}$$

This relation in s domain is defined as transfer function and is a frequency domain representation.

2.4.4 Use of Transfer Function

From the last equation we have

$$C(s) = G(s) \cdot R(s) \qquad \ldots(2.8)$$

and the frequency response of the system with T.F. $G(s)$ can be obtained by setting $s = j\omega$, and evaluating the amplitude and phase function values.

The time response of the system is evaluated using inverse Laplace transform technique, so that:

$$C(t) = L^{-1}\{G(s) \cdot R(s)\} \qquad \ldots(2.9)$$

It has to be remembered that, since the Laplace transform of unit impulse response of any network or system is the T.F., provided all initial conditions are zero.

For those readers, who are having reasonable background of Laplace transforms are advised to see any standard textbook in control engineering for more details (see bibliography).

2.4.5 Properties of Transfer Function

According to the configuration of transfer function the information about the poles and zeros, the likely response can be guessed without going for the complete solution. In many cases it is possible to rearrange the Eqn. 2.7 in factorized form:

$$G(s) = \frac{K(s+z_1)(s+z_2).................}{s^m(s+p_1)(s+p_2).................} \qquad ...(2.10)$$

then, $s = -z_1, -z_2,...$ etc., represent the poles in the s-plane at which $G(s) = 0$. All such points are referred as zeros of $G(s)$ function. Conversely the points, $s = -p_1, -p_2, ...$ etc., at which the value of $G(s)$ become infinite are called poles. Also, m indicates the number of poles at the origin and K is called steady state or dc gain. A general map is shown in Fig. 2.11.

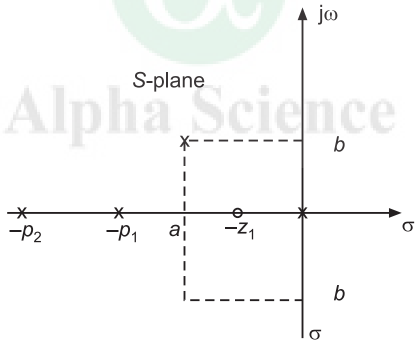


Fig. 2.11 *s*-plane Mapping of Poles and Zeros

If there exists a factor in T.F. of the type $\{(s + a)2 + b2\}1/2$, then complex poles or zeros are to be found. Depending upon the value of a the complex zeros/poles would be at origin or some other location but will always be at origin or some other location but will always be present in pair. Some typical responses are indicated in Fig. 2.12 corresponding to typical pole/zero mappings.

$$G(s) = \frac{K(s+z)}{s(s+p_1)(s+p_2)\{s-(a+jb)\}\{s-(a-jb)\}}$$

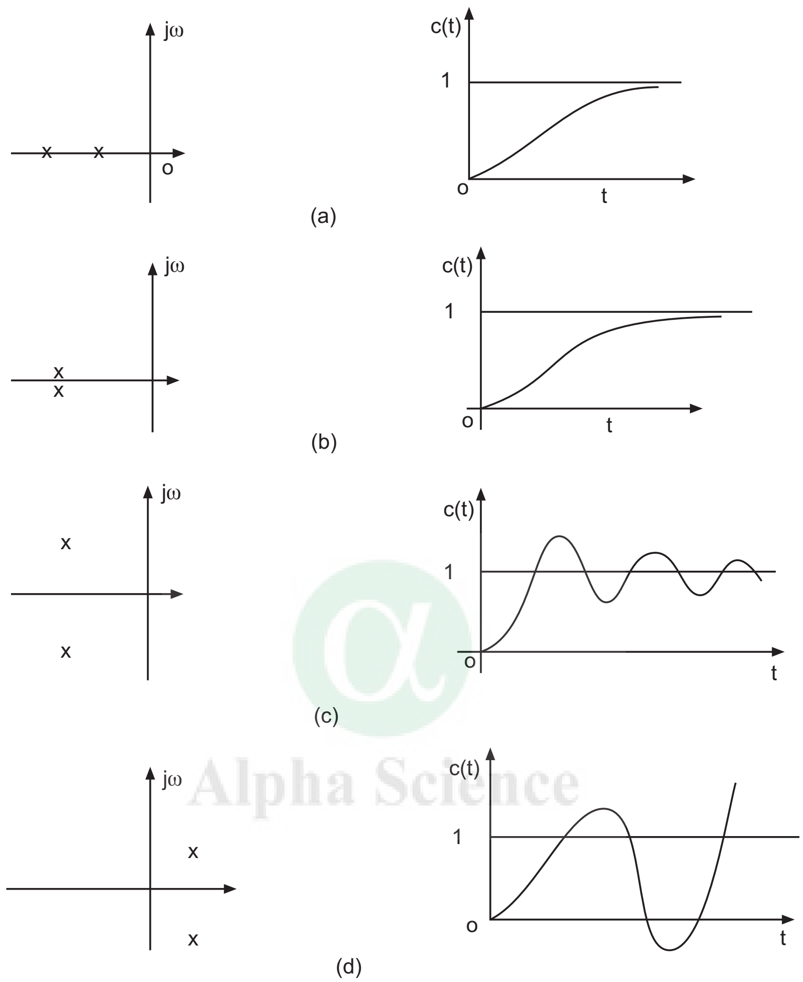


Fig. 2.12 Effect of Pole Location on Response

2.5 ANALYTICAL TECHNIQUES FOR DYNAMICAL SYSTEMS

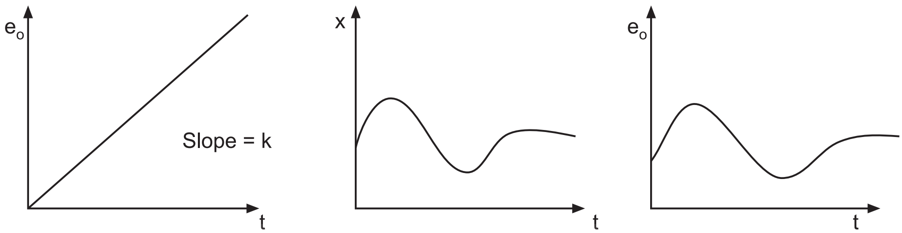
In this section we shall be considering some examples from industrial systems with different orders of dynamics to correlate the material of the previous section with the characteristics observed.

2.5.1 Zeroth Order Systems

If the device or the process is such that, on applying an input the output appears immediately without any delay, storage or phase change the it is said to be of zeroth order. For example, a potentiometer shown in Fig. 2.3 used as a position transducer is a zeroth order element with scalar relation between the input (mechanical displacement of wiper) and output (voltage at the output terminals).

$$e_0 = \left(\frac{R_2}{R_1}\right)V_t = \frac{R.V_i}{R_1}.x = K_1.x \qquad ...(2.11)$$

Transfer characteristic, typical input and corresponding response are shown in Figs. (2.13*a*, *b* & *c*).

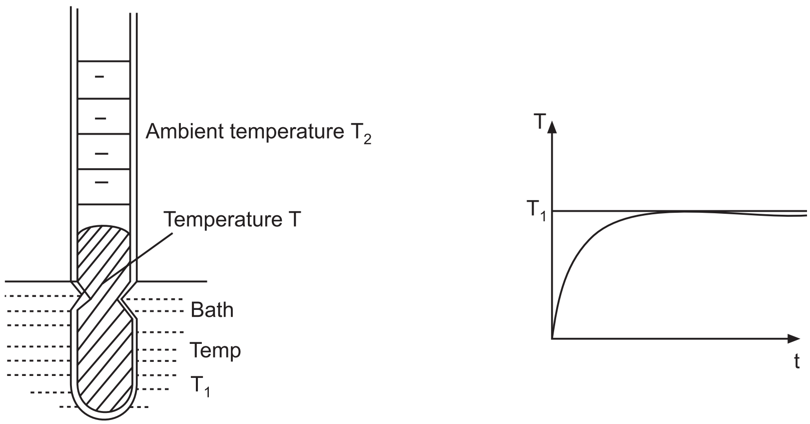


(a) Transfer (b) Input Behaviour (c) Output Behaviour

Fig. 2.13 Response of Zeroth Order Device

2.5.2 First Order Systems

Systems characterized by first order rate of change of output variable are called first order systems and they show a lag in the response. Examples include temperature sensors *i.e.* thermometers, which take a finite time to reach steady value (or close to it), depending upon the properties of thermometer and the conditions of the surroundings. Figure 2.14 shows a typical mercury thermometer as a first order



(a) Mercury Bulb Thermometer (b) Temperature Indication

Fig. 2.14 A Typical First Order Device and its Characteristic device and the indication of temperature when subjected to a sudden change in the input conditions (step input) *i.e.* thermometer being suddenly dipped into a heated bath.

The heat transfer involved in such a case over a small period dt can be related as:

$$MC_p \frac{dT}{dt} = UA\,(T_1 - T_2) \qquad \text{...(2.12)}$$

where,

M = mass of mercury in thermometer bulb

C_p = thermal capacity of thermometer bulb

A = area of the surface through which heat transfer takes place from bath liquid to thermometer bulb

On rearrangement,

$$\frac{MC_p}{UA}\frac{dT}{dt} + T_2 = T_1 \qquad \text{...(2.13)}$$

or,

$$\tau \frac{dT}{dt} + T_2 = T_1 \qquad \text{...(2.14)}$$

where,

$$\tau = \frac{MC_p}{UA}$$

T being the temperature of the thermometer bulb at any instant of time and is called time constant of this first order system. 1/UA is referred to as resistance and MCp as the capacity. It can also be considered analogous to capacity in electrical circuit.

The time response of the thermometer to step input *i.e.* sudden immersion in the liquid bath can be obtained by procedure outlined earlier to finally yield:

$$T' = T_2 + T$$

and,

$$T = (T_1 - T_2)\left\{1 - \exp\left(\frac{t}{\tau}\right)\right\}. \qquad \text{...(2.15)}$$

Therefore the rate of change of temperature indicated by the thermometer would depend on τ, as shown in Fig. 2.15 for various values of τ.

It is to be noticed that only 63.2% of the final steady state value is reached in time τ, 86% in 2τ, 95% in 3τ, 98% in 4τ and it takes practically infinite time for reaching final steady state value.

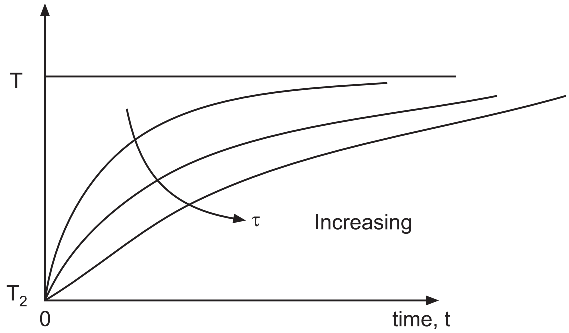


Fig. 2.15 Effect of Changing Time-constant on Response

Settling time is defined as the time to reach and stay within a permissible tolerance around final steady value, is important and a smaller settling-time indicates a faster response. In practical temperature sensors it is an important parameter and choice depends on the objectives of the typical application situation.

EXAMPLE 2.2

Obtain the time response of the resistance temperature detector measuring device, initially at ambient temperature of 25°C, when suddenly dipped into the liquid bath being maintained at 115°C. Assume effective time constant for the sensor to be 2 seconds. In how much time sensor indication will settle within 2% of final steady temperature.

SOLUTION:

Dipping the sensors suddenly into the bath amounts to the step input of (115 – 25 = 90°C). The sensor is known to be a first order system with unity gain.

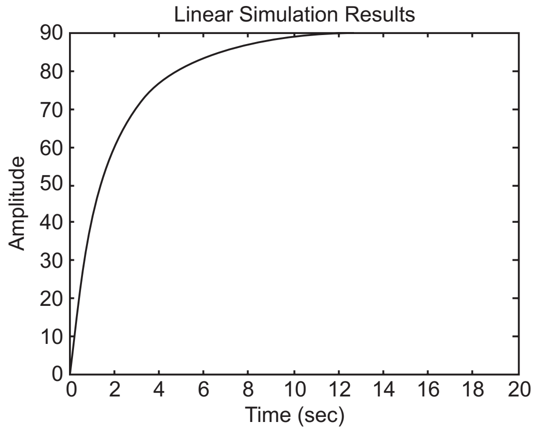
So, the temperature of the sensor shall change according as:

$$\frac{T(s)}{U(s)} = \frac{1}{1+s\tau}; \text{ where } \tau \text{ is the time constant}$$

Therefore,

$$T(t) = 90\,(1 - e^{-t/\tau})$$

The response plot of $T(t)$ is shown below:



The 2% settling time is 7.82 seconds.

Another aspect to consider is the response of such systems to inputs other than sudden (or step) *e.g.* ramp or velocity, parabolic or acceleration input etc. For ramp-input the response would be obtained as:

$$T = Q_1 (e^{\frac{t}{\tau}} + t - \tau) \qquad \text{...(2.16)}$$

where, $Q_i - K\,t = Q_1$

The typical response will be as shown earlier in Fig. 2.16. The derivation is left to the reader as an exercise.

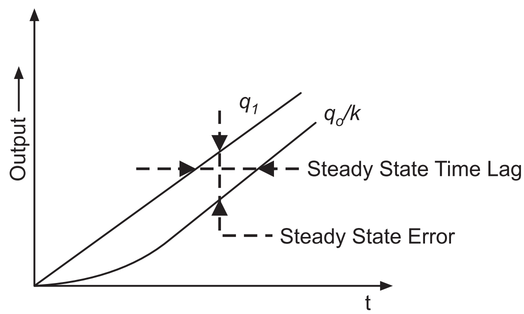


Fig. 2.16 Response of a Temperature Sensor to Ramp Input

The two terms in the response equation represent important time behavior of systems. Referring to the Eqns. (2.15) and (2.16), it may be noticed that, the outputs have a time-variable term responsible for steady-state response and becomes the dominant one as time elapses after application of input. The other time variant term called transient, should have value reducing to zero as time increases for any stable system *i.e.* useful in practical sense. This implies that, the response of any system should finally have a steady value only, of finite magnitude and in a definite relation with input magnitude. The ratio of steady output to the constant input amplitude is called steady-state gain.

Time response evaluation is the most commonly identified technique for analysis but not simple or easily implementable one. Also the considerations of design, strategic choice of other possibilities and assuring frequency response and impulse response technique may be important.

EXAMPLE 2.3

Write the dynamical equation for a liquid level tank being used for maintaining the inventory of a feed-stock of an important ingredient in a chemical manufacturing unit. Controlled input is allowed into the tank such that a balance with the outflow is maintained and level in the tank (stock) is maintained constant at H meters. Tank may be considered circular with cross-sectional area ofA-m^2.

Obtain the transfer function and indicate the nature of response (change in level) for a sudden change in the inflow to the tank.

SOLUTION :

Dynamic relation is derived from the material balance equation:

Input – Output = Storage

If left hand side is positive the stock (level) in tank will rise, if negative level will fall and if zero the level shall maintain the original level, *H*.

$$Q_i - Q_0 = 0$$

where Qs are the flow rates in M^3/sec Initially, inflow is maintained equal to outflow and R.H.S. is zero and is referred as steady state. Now if there is a disturbance in inflow rate, the balance is disturbed and dynamic state is represented by

$$Q_1 - Q_0 = A\frac{dh}{dt}$$

where h indicates the change in level due to unbalance.

Q_0 is dependent on the level in the tank and can be approximated = H/k steady under initial steady condition. Suppose Q_i changes by ΔQ_i resulting in a change in level to $(H + \Delta h)$. Rise in the level to $H + \Delta h$ will cause the outflow Q_0 to riseby say ΔQ_0 and the dynamic relation becomes:

$$(Q_i + \Delta Q_i) - (Q_0 + \Delta Q_0) = A\frac{d(H+\Delta h)}{dt}$$

$$(Q_i + \Delta Q_i) - \left(\frac{H+\Delta h}{k}\right) = A\frac{d(H+\Delta h)}{dt}$$

Using the steady state relation and remembering that H is constant,

$$\Delta Q_i - \frac{\Delta h}{k} = A\frac{d\Delta h}{dt}$$

By uniformly dropping the Δs in the relation, we obtain

$$Q_i - h = A\frac{dh}{dt}$$

and by taking Laplace transform of the relation

$$Q_i(s) - \frac{H(s)}{k} = A\ s\ H\ (\mathrm{s})$$

$$\frac{H(s)}{Q_i(s)} = \frac{1}{As + \frac{1}{k}}$$

$$= \frac{k}{1+sT}$$

where time-constant, $T = A.k$

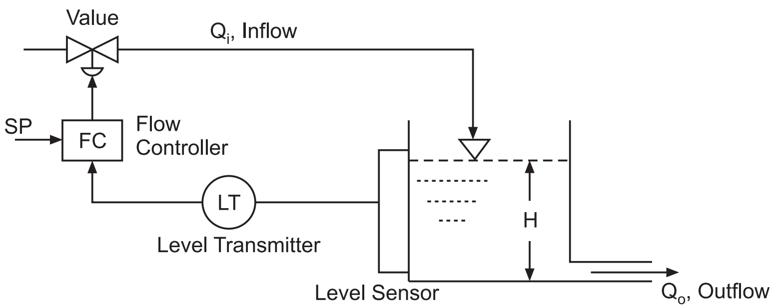


Fig. Ex. 2.3 Liquid Level Control in Tank

The response of the system here implies the change in height for a sudden change in the opening of input valve increasing the inflow. Since the output also tends to increase (or decrease) with increase (or decrease) in inflow and thereby the height, there is a self regulation experienced and such systems are also called 'self-regulated systems'.

The nature of response will be same as for any First order system to step input, as shown in Fig. 2.14(*b*).

2.5.3 Frequency Response Technique

This provides useful information about the behavior of systems. Applied to first order system/instruments, for sinusoidal inputs, it is expressed in transfer function (T.F.) form as:

$$G(s) = \frac{e_0(s)}{e_i(s)} = \frac{K}{1+s\tau} \qquad \text{...(2.17)}$$

This form is also known as prototype first order T.F.

By substituting $s = j\omega$ we have

$$G(s) = \frac{K}{(1 = \omega^2\tau^2)^{1/2}} \angle -\tan^{-1}(\omega\tau) \qquad \text{...(2.18)}$$

where $\dfrac{K}{(1+\omega^2\tau^2)^{\frac{1}{2}}}$ is gain/amplitude and $\phi = \angle -\tan^{-1}(\omega\tau)$ is the phase angle.

The gain and phase plots for typical first order instrument are shown in Fig. 2.17. It may be noted that for zero order system, similar plots are available but of lesser consequences as:

$$\frac{e_o(j\omega)}{e_i(j\omega)} = K \angle 0° \qquad \text{...(2.19)}$$

i.e. gain is independent of frequency and phase is identically zero.

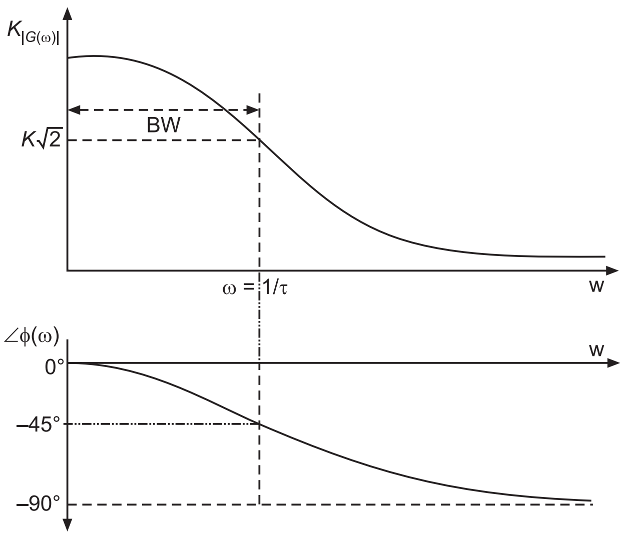


Fig. 2.17 Frequency Response of a First Order System

2.5.4 Second Order Systems/Instruments

This class of systems/instruments involve two energy storage elements formed singly or in combination of elements such as mass, damper, capacity, inductance, resistance etc., and involve two rates of changes in the dynamical representation of this class of systems.

In Fig. 2.18 are shown two examples of this class. For these devices Equn. 2.6 holds and this can be rearranged as:

$$\frac{d^2x}{dt^2} + 2\xi\omega_n \frac{dx}{dt} + \omega_n^2 = b_o r \qquad \text{...(2.19)}$$

After taking Laplace transform and rearranging:

$$\frac{X(s)}{R(s)} = \frac{K\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2} \cdots \qquad \text{...(2.20)}$$

This form is also known as second order prototype T.F. where ξ is called damping factor and ω_n is the natural frequency of oscillation of the system. The responses of this class of instruments for unit-step input for various values of ξ are noted as follows:

For input $r(t) = 1,\ 0 < t < \infty$

(*i*) Under-damped case ($\xi < 1$):

$$x(t) = K\left(1 - \frac{e^{-\xi\omega_n t}}{(1-\xi^2)^{\frac{1}{2}}} \sin\left\{[1-\xi^2]^{\frac{1}{2}}\omega_n t + \phi\right\}\right) \qquad \text{...(2.21}a\text{)}$$

where $\sin\phi = ([1-\xi^2)]^{\frac{1}{2}}$

(*ii*) Critically damped case ($\xi = 1$):

$$x(t) = K\,(1 - (1+\omega_n t)\, e^{-\omega_n t}) \qquad \text{...(2.21}b\text{)}$$

(*iii*) Over damped case ($\xi > 1$):

$$x(t) = K\left(1 + \frac{\xi - (\xi^2-1)^{\frac{1}{2}}}{2(\xi^2-1)^{\frac{1}{2}}} e^{\{(-\xi-(\xi^2-1)^{\frac{1}{2}}).\omega_n t\}} - \frac{\xi + (\xi^2-1)^{\frac{1}{2}}}{2(\xi^2-1)^{\frac{1}{2}}} e^{\{-\xi+(\xi^2-1)^{\frac{1}{2}}.\omega_n t\}}\right) \qquad \text{...(2.21}c\text{)}$$

The general nature of the time response would be computed from the Eqns. (2.21) (*a*),(*b*),(*c*) is shown in Fig. 2.19. For details of the characteristics and the effects of parameter thereferences are cited at the end.

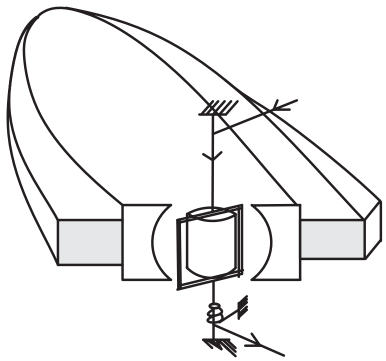


Fig. 2.18 Configuration of a PMMC Deflection Meter

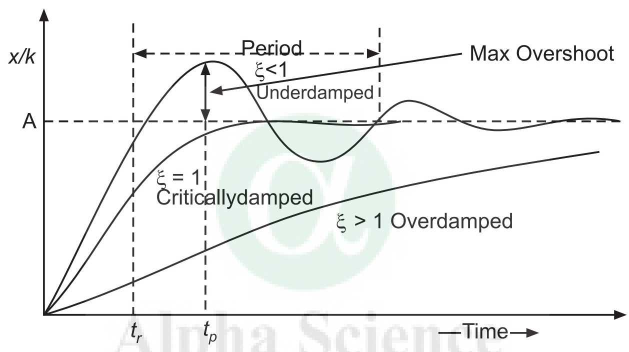


Fig. 2.19 Time Response of a Second Order System to Unit Step Input

EXAMPLE 2.4

For a second order instrument system with transfer function as given below, obtain the time response, if the input has experienced a sudden change of on step that remains.

$$G(s) = 4/(s^2 + 1.2s + 4)$$

SOLUTION:

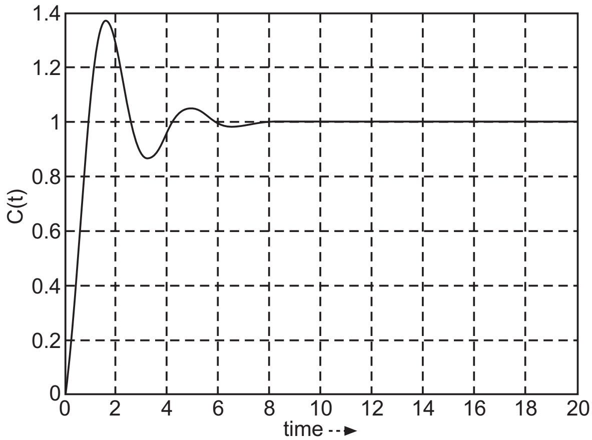
By comparing with the standard form:

$$G(s) = \omega_n^2/(s^2 + 2\xi\omega_n s + \omega_n^2)$$

We have $\omega_n = 2$ rad/sec; $4\xi = 1.2$; $\xi = 0.3$ *i.e.* under damped system

Response for the unit step input shall be given by Eqn. (2.21)(*a*).

It is shown in the figure below:



The various parameters of the response are noted as:

Rise time = 1 sec — Delay time = 0.8 sec

Overshoot = 37% — Peak time = 1.8 sec.

EXAMPLE 2.5

In a mechanical system consisting of a mass, spring and damper connected as shown in figure below, obtain the transfer function in standard form. If the stiffness K = 0.5; B = 0.1, and M = 2 (in appropriate units),find the likely time response and overshoot to the unit step force applied?

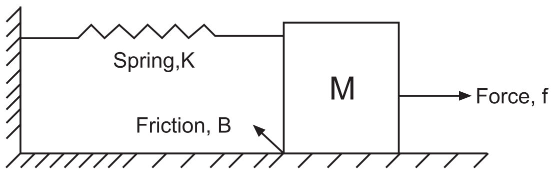


Fig. Ex. 2.5 Second Order Mechanical System

SOLUTION:

The force-balance equation can be written as:

$$M\ddot{x} + B\ddot{x} + Kx = f$$

by taking the laplace transform

$$Ms^2X(s) + BsX(s) + KX(S) = F(s)$$

$$\frac{X(s)}{F(s)} = \frac{1}{MS^2 + Bs + K}$$

$$= \frac{\frac{K}{M}}{s^2 + \frac{B}{M}s + \frac{K}{M}} = \frac{\omega^2 n}{s^2 + 2\xi\omega_n + \omega_n^2}$$

From the characteristic equation of the system we have:

$$\omega_n = \sqrt{\frac{0.5}{2}} = 0.5 \text{ rad/sec}$$

$$\xi = \frac{\frac{0.1}{0.5}}{2 \times 0.5} = 0.2$$

$$\text{O.S.} = \frac{e^{(-\pi\xi)}}{\sqrt{1-\xi^2}} \times 100 = 54.45\% .$$

The response of second order instruments is considered next for ramp input and more practical terminated-ramp inputs. These provide useful information for sensitive, undamped devices like piezoelectric type used for pressure sensors, accelerometers etc., more often subjected to such input. Such devices would be rejected on the basis of step response, but are in fact useful in practical situations.

The response of second order system described by the Eqn. (2.20) subjected to a terminated ramp can be evaluated from:

$$\frac{X_0}{K} = \frac{t}{T} - \frac{2}{\omega_n T} + \frac{1}{\omega_n T\left([1-\xi^2]\right)^{\frac{1}{2}}} e^{-\omega_n t} \sin\left[[1-\xi^2]^{\frac{1}{2}} \omega_n t + \phi\right] \qquad ...(2.22(a))$$

for $0 \le t \le T$

$$= \frac{t}{T} - \frac{2}{\omega_n T} + \frac{1}{\omega_n T\left([1-\xi^2]\right)^{\frac{1}{2}}} e^{-\omega_n t \sin} \left[\left([1-\xi^2]\right)^{\frac{1}{2}} \omega_n t + \phi\right]$$

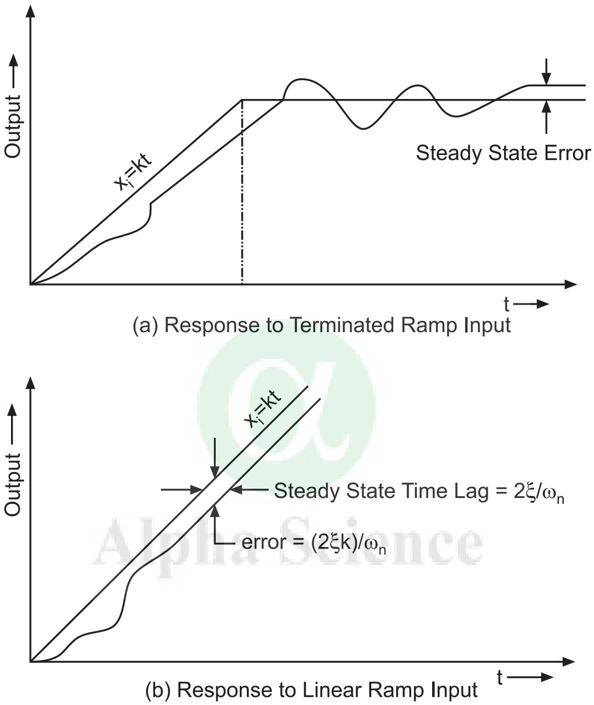
$$= -\left(\frac{t}{T} - 1 - \frac{2}{\omega_n T} + \frac{1}{\omega_n T\left([1-\xi^2]\right)^{\frac{1}{2}}} e^{[-\xi\omega_n (t-T)]}\right) \qquad ...(2.22(b))$$

For $T \le t \le \infty$

where, $\phi = 2\tan^{-1} \frac{([1-\xi^2])^{\frac{1}{2}}}{\xi}$

The nature of time response is shown in Fig. 2.20(*a*) and for terminated ramp and linear ramp input in Fig. 2.20(*b*). It is to be noted that for terminated ramp the steady state error (e_{ss}) is $\dfrac{2\xi}{\omega_n T}$ and transient state error is limited to:

$$\frac{1}{\omega_n T\,[1-\xi^2]^{\frac{1}{2}}}$$



(a) Response to Terminated Ramp Input

(b) Response to Linear Ramp Input

Fig. 2.20 Response of a Second Order System

Thus in design it should be possible to reduce e_{ss} by making small (more sensitive also) and selecting $\omega_n >> 1/T$ (increases the band-width of the instrument).

The ramp response can be evaluated for the system represented by:

$$a_2 \frac{d^2x_0}{dt^2} + a_1 \frac{dx}{dt} + a_0 x_0 \;=\; b_0 x_i \qquad \text{...(2.23)}$$

or, $$\left(\frac{a^2}{a_0}s^2 + \frac{a_1}{a_0}s + 1\right)x_0 \;=\; \frac{b_0}{a_0}x_i$$

or, $$\left(\frac{s^2}{\omega_n^2} + \frac{2\xi}{\omega_n}s + 1\right)x_0 \;=\; kx_i$$

$$\therefore \qquad \frac{x_0}{x_i}(s) = \frac{K\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2}$$

(same as Eqn. 2.20)

where, $x_i = \dot{x}_i t = kt$; $k = 1$ for unit ramp

(*i*) For $\xi > 1$, over damped case

$$\frac{x_0}{K} = t - \frac{2\xi}{\omega_n}\left[1 + \frac{2\xi^2 - 1 - 2\xi\sqrt{\xi^2 - 1}}{4\xi\sqrt{\xi^2 - 1}} e^{(-\xi + \sqrt{\xi^2 - 1})\omega_n t} + \frac{-2\xi^2 + 1 - 2\xi\sqrt{\xi^2 - 1}}{4\xi\sqrt{\xi^2 - 1}} e^{(-\xi - \sqrt{\xi^2 - 1})\omega_n t}\right] \quad \text{...(2.24}(a))$$

(*ii*) For $\xi = 1$, critically damped case

$$\frac{x_0}{K} = t - \frac{2}{\omega_n}\left[1 - e^{\xi\omega_n t}\left(1 + \frac{\omega_n t}{2}\right)\right] \quad \text{...(2.24}(b))$$

(*iii*) For $\xi < 1$, under-damped case

$$\frac{x_0}{K} = t - \frac{2\xi}{\omega_n}\left[1 - \frac{e - \xi\omega_n t}{2\xi\sqrt{1 - \xi^2}}\sin\left(\sqrt{1 - \xi^2}\,\omega_n t + \phi\right)\right] \quad \text{...(2.24}(c))$$

where, $\phi = \tan^{-1}\left(\dfrac{2\xi\sqrt{1 - \xi^2}}{2\xi^2 - 1}\right)$

Referring to Fig. 2.20 and the above equations, steady state error shall be $\dfrac{2\xi}{\omega_n}$ and therefore controllable by ξ and ω_n. Steady-state time lag is $\dfrac{2\xi}{\omega_n}$.

2.5.5 Frequency Response Behavior of Second Order Systems

Earlier in Sec. 2.5.3, frequency response of first order systems has been discussed. Extending it to second order systems, the standard transfer function of prototype second order system is (Eqn. (2.20))

$$M(s) = \frac{C(s)}{R(s)} = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2}$$

The T.F. at sinusoidal steady state is obtained by substituting $s = j\omega$, so that

$$M(j\omega) = \frac{C(j\omega)}{R(j\omega)} = \frac{\omega_n^2}{(j\omega)^2 + 2\xi\omega_n(j\omega) + \omega_n^2}$$

It can be simplified by defining, $u = \dfrac{\omega}{\omega_n}$

Then $$M(ju) = \frac{1}{1 + j2u\xi - u^2} \quad \text{...(2.25)}$$

Magnitude, $$|M(u)| = \frac{1}{\sqrt{(1-u^2)^2 + (2\xi u)^2}} \quad \text{...(2.26)}$$

and, phase, $$\angle M(ju) = \phi_m(u) = -\tan^{-1}\frac{2\xi u}{1-u^2} \quad \text{...(2.27)}$$

The frequency at which peak of magnitude occurs is called peak response, M_p and the corresponding frequency is referred resonant frequency ω_p.

The resonant frequency can be determined as:

$$\frac{d|M(u)|}{du} = -\frac{1}{2}[(1-u^2)^2 + (2\xi u)^2]^{(-3/2)}(4u^3 - 4u + 8u^2\xi) = 0$$

$$\therefore \quad 4u^3 - 4u + 8u\xi^2 = 0 \quad \text{...(2.28)}$$

and, the roots of equation (2.28) are

$$u_p = 0,\ u_p = \sqrt{1-2\xi^2}$$

$u_p = 0$ is trivial and the resonant frequency shall be:

$$\omega_p = \omega_n\sqrt{1-2\xi^2} \quad \text{...(2.29)}$$

Since frequency is real entity, Equn. 2.29 is valid only for $2\xi^2 \le 1$ or $\xi \le 0.707$.

Therefore, for all, $\xi = 0.707$, $\omega_p = 0$ and $M_p = 1$. By substituting ω_p in equation for $|M(Ju)|$, we can obtain

$$M_p = \frac{1}{2\xi\sqrt{1-\xi^2}} \quad \text{...(2.30)}$$

It is to be noted that, for proto type second order systems M_p is a function of damping ratio ξ and ω_n, for higher order systems the approach as above is complicated, therefore computational approach is used. Plot of magnitude and phase for different values of ξ are shown in Fig. 2.21.

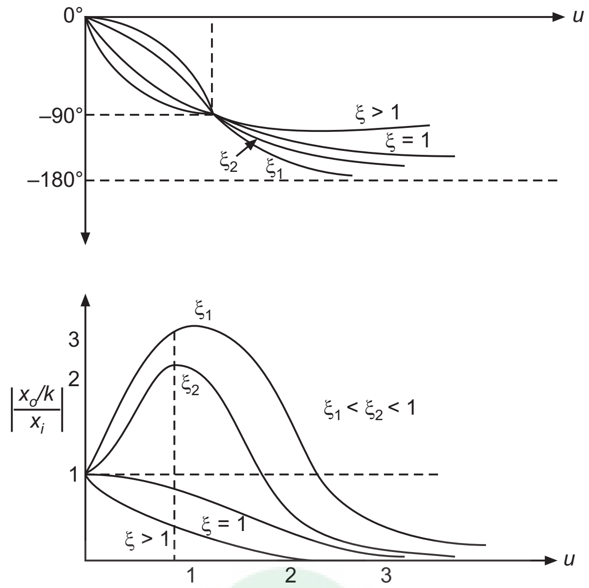


Fig. 2.21 Frequency Response of a Typical Second Order System

In addition to the above two specifications, bandwidth is another measure of frequency domain specifications. Bandwidth is the frequency at which $|M(u)|$ drops to 70.7% of (or 3dB down from), its zero frequency value.

It can be obtained from

$$|M(ju)| = \frac{1}{\sqrt{\left[(1-u^2)^2 + (2\xi u)^2\right]}} = 0.707$$

$\therefore\ (1 - u^2)^2 + (2\xi u)^2 = 1.414$

or, $$u^2 = 1 - 2\xi^2 \pm \sqrt{4\xi^4 - 4\xi^2 + 2} \qquad ...(2.31)$$

u must be positive real, therefore solution with negative sign is non admissible,

$$\therefore \qquad BW = \omega_n \sqrt{(1-2\xi^2) + \sqrt{4\xi^4 - 4\xi^2 + 2}} \qquad ...(2.32)$$

It is seen from the above relation that bandwidth is proportional to ω_n and for a fixed ω_n, as ξ decreases from unity (maximum BW), the bandwidth increases and M_p also increases.

2.5.6 Time Response Specifications of the Systems

For linear systems, the time response specifications are defined for the transient response obtained with unit step input called unit step response. These are indicated in Fig. 2.19 and defined as follows:

(*a*) Maximum overshoot: If $C(t)$ is the unit-step time response, let C_{max} is the maximum value of $C(t)$ and C_{ss} be the final steady-state value. It would be observed for under damped system that $C_{max} \geq C_{ss}$. The maximum overshoot is defined as

Maximum overshoot = $C_{max} - C_{ss}$

It is often expressed as percentage of the final value of response *i.e.*

$$\% \text{ maximum overshoot} = \frac{\text{maximum overshoot}}{C_{ss}} \times 100\% \qquad ...(2.33)$$

A mathematical expression for % overshoot can be derived from the response Eqn. (2.21(c)), by evaluating the time elapsed before reaching the peak and then substituting this in the equn for output. This yields the

$$\% \text{ overshoot} = \exp\left(\frac{-\pi\xi}{\sqrt{1-\xi^2}}\right) \qquad ...(2.34)$$

A system with large overshoot is undesirable and for instruments it is generally limited to 10% for indicating instruments and much smaller in most others. The overshoot is recognized as the first peak and for all stable systems the successive peaks will be gradually smaller.

(*b*) Rise Time (t_r): It is defined as the time required for the step response to rise from 10% to 90% of its final value. It may also be expressed as inverse of the slope of step response at instant where response is 50% of final value. In instrumentation systems it may vary from a few seconds to milli seconds.

(*c*) Delay Time (t_d): The delay time is defined as the time in which the response reaches 50% of the final value.

(*d*) Settling Time (t_s): It is defined as time required for the response to decrease to and stay within a specified percentage (generally 5%) of final value. It is desired to be as low as possible.

(*e*) Steady state error (e_{ss}): It is defined as the error between the desired value of the output and the final steady value of output. For a system given by Eqn. (2.20) subjected to unit step input shall have final steady value can be evaluated from Eqn. (2.21) for $t = \infty$, as $x(\infty)$, and the expected value of the system is also k (due to dc gain k) *i.e.* the time response will settle to or final steady value without error.

2.5.7 Relation between Time Domain and Frequency–domain Specifications

There are only approximate relations between them:

(*a*) $t_d = \dfrac{1+0.7\xi}{\omega_n};\ 0<\xi<1.0$ ...(2.35)

or, for fixed ω_n delay time increases with ξ.

(*b*) $t_r = \dfrac{1-0.4167\xi+2.917\xi^2}{\omega_n};\ 0<\xi<1.0$ ...(2.36)

or, for fixed ω_n, rise time increases with ξ.

(*c*) $t_s = \dfrac{3.2}{\xi\omega_n};\ 0<\xi<0.69$ ...(2.37)

or, settling-time decreases with increase in ξ *i.e.* system tends to become slow with increase in damping.

Therefore, for system response to be fast *i.e.* low rise time, ξ should be small resulting in lower delay time, larger settling time with increase in bandwidth but larger overshoot.

Thus, choice is not straight forward and designers' dilemma is to compromise the specifications for obtaining most acceptable response, keeping in mind that most control, instrumentation systems do not need large bandwidth to keep the noise entering into the system, at the minimum level.

2.6 STABILITY OF SYSTEMS

During the study of the systems it is important to note that for any change in the input, it takes a while to reach steady output, depending on the dynamical characteristics of the system and the type of input.

Before the steady state is reached, the transient or time varying state is important and characterizes the stability of system. A system is said to be stable if its impulse response approaches zero, as time approaches to infinity and in an unstable system output increases unboundedly for even a small finite input. A critically stable system would be one, having sustained oscillation of fixed amplitude. For instrumentation and real life control systems both unstable and critically stable system are not acceptable.

A detailed discussion on this topic is not possible here but the following points must be noted:

(*a*) The poles of given T.F. must be in the left half of *s*-plane about the *jw* axis, for the system to be stable. Farther they are in the left-half of the *s*-plane, more stable is the system.

(*b*) For a closed-loop system as shown in Fig. 2.22 the overall T.F. modifies to:

$$\frac{C(s)}{R(s)} = \frac{G(s)}{1 + G(s)\,H'(s)} \qquad \text{...(2.38)}$$

and it is possible that the closed loop system is stable even though open loop system is unstable. In practice it is desirable to have both open-loop and closed-loop systems to be stable. The feedback element represents the instrumentation channel and usually adjusted to have unity gain.

(*c*) In the Eqn. (2.38) above, the denominator when substituted equal to zero, yields characteristic equation of the system. The various methods of determining stability are based on determining conditions for:

$$|G(s)\,H(s)| = 1, \text{ and } \Phi = -180^\circ.$$

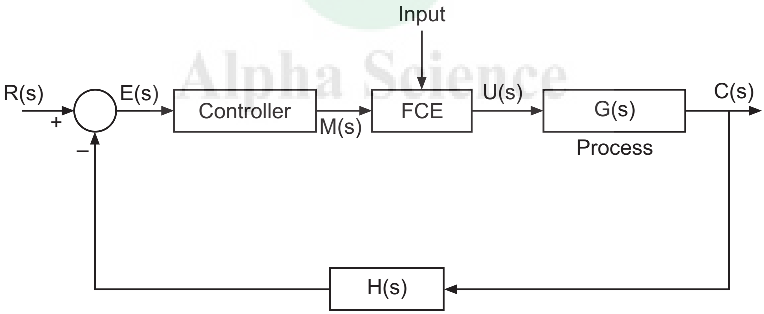


Fig. 2.22 Representation of a Closed-Loop System

For a detailed discussion on stability, references are listed at the end, but it is to be noted the total lag in the loop should be made as far-off-as-possible from –180°. Since the process is not adjustable, the instrumentation engineer must strive to ensure that the phase delay introduced due to monitoring/feedback path should be as small as possible *i.e.* delays with each element are to be minimized.

2.7 SYSTEM REPRESENTATION AND VARIABLES

The transfer function concept introduced earlier is valid only for systems with single input-single output (SISO) systems, yet there are real systems which are having multiple inputs and multiple outputs (MIMO), and need to be treated differently. In this section we are going to see, how in a close to real situation the various elements and variables are identified in general terms.

2.7.1 Single Input – Single Output Systems

As shown in Fig. 2.22, with the important blocks of the controlled system the variables are identified as:

$R(s)$ = set input/reference for the process output required to be achieved.

$E(s)$ = error *i.e.* the difference between the desired output value and the actual value at any point of time.

$G_c(s)$ = transfer function of the controller being used to control the input to system as a function of error.

$M(s)$ = manipulated variable, the signal produced by the controller

FCE = final control element *i.e.* valve for the control of liquid/steam inflow providing output according as the input signal m, depending on its transfer function with dc gain between 0.4 – 0.8, first order lag and desirably a small time-constant.

$U(s)$ = controlled input variable actually entering into the process-heat, mass flow etc.

$G(s)$ = process transfer function, representing system dynamics depending upon typical configuration.

$C(s)$ = output of process, required to be monitored (and controlled).

$H(s)$ = transfer function of instrumentation channel, simplified to include various elements, normally adjusted by calibration to have unity gain.

The set of notations can be extended to multi input-multi-output system with minor modifications in the representation, as shown next.

2.7.2 Multivariable Systems

Industrial systems such as process systems are commonly multivariable wherein the number inputs and outputs both may be more than one and may be unequal. There is always a possibility of their mutual interaction among the controlling inputs and outputs adding to complexity and it is not possible to identify independent pairs of input-output from each other. One controlling input may affect more than one output and an output may be affected by more than one input. The controller is required to be fast, sophisticated and accurate. The overall performance of the controller in addition to its configuration, implementation aspects and quality also depends on the quality of measurements made available through the instrumentation channel. A representation of such systems is indicated in Fig. 2.23 along with the control scheme. Here the system transfer function is a transfer matrix, final control elements (FCE) could be many, controller shall also be having a matrix format, and feedback path shall be consisting of as many channels as the number of outputs being feedback.

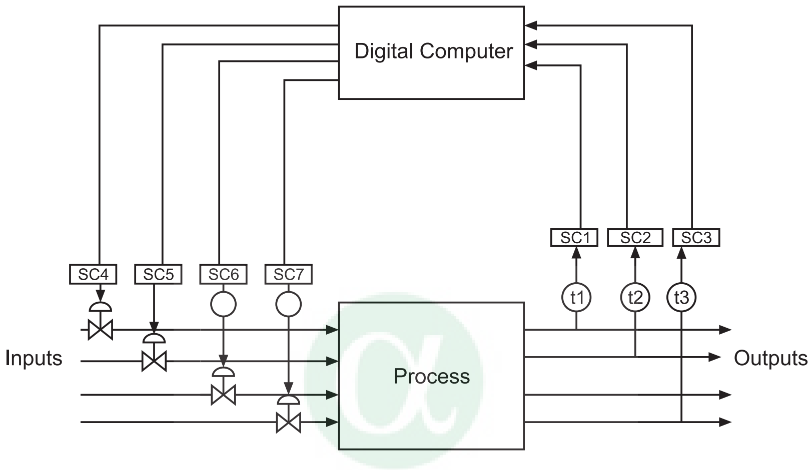


Fig. 2.23 Representation of Direct Digital Control of Multivariable System

In modern industry with large number of variables involved the implementation of many interactive loops is highly complex and intriguing beyond human comprehension in fast changing processes.A computer is very often required for monitoring, data acquisition and control *e.g.* in chemical industry, petroleum refinery. A scheme is shown in Fig. 2.24 to represent the situation. The role of computer embedded in the system is highly advantageous with multifunctions such as:

(*a*) to receive the output data

(*b*) process it with number of operations involved

(*c*) provide the role of comparator by comparing with the corresponding reference/desired value to

(*d*) generate error vector, and

(*e*) making it available to the controller for producing the proper manipulated signal

The control aspects need detailed exposition and are beyond the scope of present text. For more details bibliography may be referred to.

Comments

In this chapter the basic concepts of systems have been explained with basic properties of static and dynamic characterization relevant to instrumentation systems and components, types of inputs and essential tools and techniques of testing and specifying design criteria for meaningful realization.

In the next chapter the basics of statistical data analysis, characterization and techniques of minimization shall be discussed as these forms the basis for evaluation of any instrumentation systems and strategy of control essential for achieving the objectives of industrial activity undertaken.

SUGGESTED READINGS

1. For complex variables: Advanced Engineering Mathematics – E. Kreyszig (Wiley)
2. For time response, frequency response and stability of systems:
   (*a*) Automatic Control Systems – B.C. Kuo (Prentice Hall Inc.)
   (*b*) Modern Control Engineering – K. Ogata (Prentice Hall)
   (*c*) Control Systems Engineering – I.J. Nagrath, Madan Gopal (New Age)
   (*d*) Control Systems Engineering – N.S. Nise (Wiley)
3. Handbook of Control – J.G.Truxal (McGraw Hill)

REVIEW PROBLEMS

2.1 What are performance specifications of a first order system?
What information is conveyed by these?

2.2 What is the nature of dead-zone and saturation characteristics combined?
Name such devices that show such a characteristic.

2.3 How the response is related to real and complex poles in second order systems?

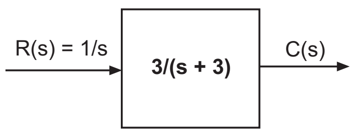
2.4 What is the difference between natural frequency and damped frequency of oscillation in second order under damped systems?

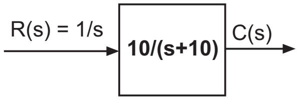
2.5 How is time domain response practically helpful?

PROBLEMS FOR EXERCISE

2.6 Evaluate the time response $c(t)$ of the following systems. Also find rise time and time constant from the response plots.

(*a*)



(*b*) 

2.7 For the second order systems given below, find ω_n, location of poles, the nature of response, and % overshoot. Write the numerical expression of response without involving inverse Laplace transform:

(*a*) $M(s) = \dfrac{1}{s^2 + 0.4s + 1}$; (*b*) $M(s) = \dfrac{4}{s^2 + 0.8s + 4}$;

(*c*) $M(s) = \dfrac{10}{s^2 + 6s + 144}$; (*d*) $M(s) = \dfrac{2}{(s+1)(s+5)}$.

2.8 Evaluate the value of % overshoot for different values of ξ, by using equn. 2.34, starting from 0.1 to 0.7 in steps of 0.1 and plot the graph ξ vs.% overshoot.

2.9 Obtain and plot the response of a mercury bulb thermometer to be used for monitoring temperature in a bath, heated from 25°C to 90°C.

Data available is mass M = 5 gms, specific heat of mercury C_p = 0.2, rate of heat transfer for the bulb glass U = 0.6, area of cross-section of bulb A = 0.5 cm^2 with negligible thickness and thermometer may be assumed to be suddenly dipped in the bath.

2.10 The response of a second order system to unit step shows a response such that the magnitude of first peak is four times that of the second positive peak. What is the damping factor of this system?

READING ASSIGNMENT

2.11 For each of the systems listed below consult the relevant hand books, list the major equipment used and prepare a table to show the each major variable to be monitored :

A. Power generation plant

B. Pulp and paper industry

C. Blast furnace in a steel plant

D. Aircraft

2.12 From appendix-E observe the methodology adopted for symbols of various instruments used in industries and try to understand the process instrumentation diagram shown.

2.13 Visit the website of the Instruments Society of America (ISA) and search for more standard symbols for representing various equipments, instrumentation devices with a process & instrumentation diagram (P&ID). (This will be helpful in understanding and preparing P&I diagram at a later stage.)

2.14 Simulate the systems given in problems 2.6 and 2.7 above, on MATLAB and study the response to unit step and unit ramp signals. (This will be helpful in selection of transducers at a later stage).

CHAPTER 3

Measurement Principles

> I have no special talents, I am only passionately curious.
>
> — *A. Einstein*

INTRODUCTION

It is to be emphasized that the accuracy of the control of a process cannot be better than the accuracy of the measurements available, as the control strategy works on the data available. In turn the quality of measurements depends on the quality of the instrumentation used, the techniques and principles appropriate for the particular situation and the interpretation of the data available.

Inside the Chapter

The purpose of this chapter is to introduce the most commonly employed principles and techniques used, assessment of quality of measurement by analysis and the practical calibration procedures to account for the errors. The discussion starts with the consideration of the general techniques.

3.1 DEFLECTION METHODS

These have been the most common approach over the ages and still being used for the display of variables for common use in daily life, laboratory and industrial applications.

3.1.1 Principle

These are the most commonly employed method for the measurement of various devices for monitoring various physical variables, in various measurement activities for common electrical and physical variables of different types. Some common measuring devices being used are ammeters, voltmeters, pressure gauges, thermometers, flow meters, level indicators, force indicators, etc. wherein the input quantity/measurand causes a direct (desirably proportional) indication of output in terms of a mechanical movement of an indicator needle along a calibrated scale.

For example, to measure the common electrical quantities *e.g.* current, voltage, power, frequency, energy etc. are converted into mechanical movement and final steady indication is obtained with the help of a controlling force provided by a spring acting in opposite direction, until a dynamic balance is reached. The magnitude of measurand is obtained as a function of deflection. The model of the technique is shown in Fig. 3.1.

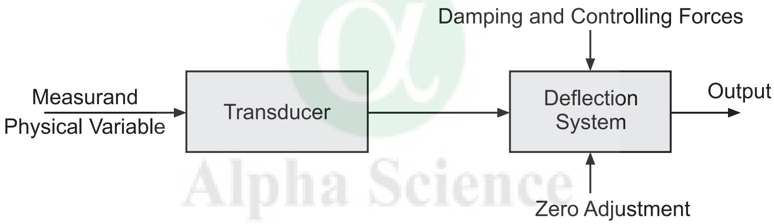


Fig. 3.1 Model for Deflection Method of Measurement

3.1.2 Electrical Instruments

As shown in Fig 3.2 for a permanent magnet moving coil (PMMC) type of instrument used for precise measurement of DC currents or voltages, flow of current, I amperes (measurand) through the coil causes a deflection due to the torque is produced as:

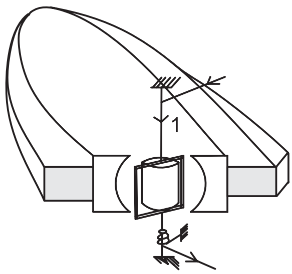


Fig. 3.2 Configuration of a PMMC meter

$$T_d = B \times I \times N \times (l \times b) = K_1 \times I \qquad ...(3.1)$$

where, B is the strength of magnetic field in Wb/m^2; N is the number of turns of coil; l and b are active length and breadth of coil respectively.

The movement is opposed by the spring which wounds in the opposite direction by an angle θ, and this controlling torque is given by

$$T_c = \frac{Ebt^3\theta}{12l} = K_2\theta \qquad ...(3.2)$$

where b, t and l are the breadth, thickness and the length of the metallic strip used to form the spring respectively. E is the Young's modulus of elasticity of the material of spring.

Steady value of θ shall be obtained when the two terms become equal *i.e.*

$$T_d = T_c$$

i.e. $$K_1 \cdot I = K_2 \cdot \theta;$$

or, $$\theta = K \times I \qquad ...(3.3)$$

the indication proportional to the measurand is the commonly employed approach for ammeters, voltmeters and other such instruments. Zero adjustment, full scale adjustment and range extension are standard facilities made available in these instruments.

3.1.3 Advantages and Limitations of Deflectional Methods

These methods are simple and easy to understand, reliable, easy to calibrate and replace, rugged and less complex to use. What one would be noticing in the above example is that for fluctuating input there is no steady position and hence no final deflection. The indicator tries to track the change in the measurand value and these small changes do not get reflected against the steady component of the reading about which the change takes place and during the process of settling to the final steady value, there is loss of time, drain of curent and energy. At times it is desirable to track the changes and act accordingly for control of process. In a system with hundreds of variables this would involve a considerable amount of energy loss!

This situation is avoidable by using null deflection methods discussed next.

3.2 NULL DEFLECTION METHODS

In this measurement technique, the measuring system is in a balanced or null condition initially. Corresponding to a change or disturbance in the measurand an unbalance occurs. So long the change exists the amount of unbalance/deviation from initial steady value, is an indication of the change in measurand. The calibration of the change in most cases provides a direct measurement of the measurand.

For a change in input (measurand), balance is tried to be obtained again by effecting a balancing adjustment required and these balancing efforts are calibrated to serve as an indication of the change in the measurand. If the change in input becomes constant the balance is obtained again. The various techniques used include bridge balance and potentiometric balance principles. The model of null techniques is shown in Fig. 3.3.

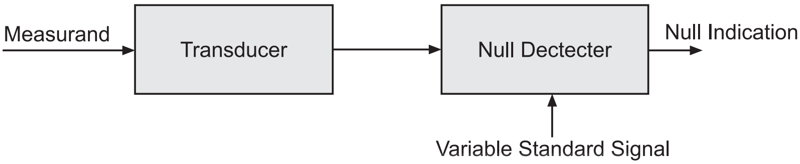


Fig. 3.3 Model of Null-deflection Measurement

3.2.1 Bridge Balance Principle

As shown in Fig. 3.4, in a Wheatstone bridge with pure resistive elements and the values indicated, the bridge can be under steady state balanced condition, indicated by a null in the output meter. At this stage

$$R_1 \times R_3 = R_2 \times R_4 \qquad \text{...(3.4)}$$

If the parameters of any arms undergo a change, say R_3 (supposedly a resistive sensor) by an amount ΔR due to some associated property, the bridge becomes unbalanced. The output meter will show this condition with a voltage appearing in it. Manual or automatic change needs to be made in the other arm R_4, by an

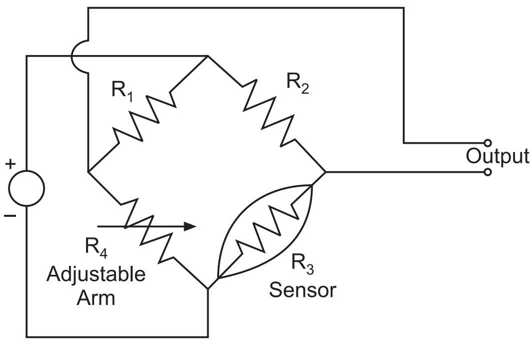
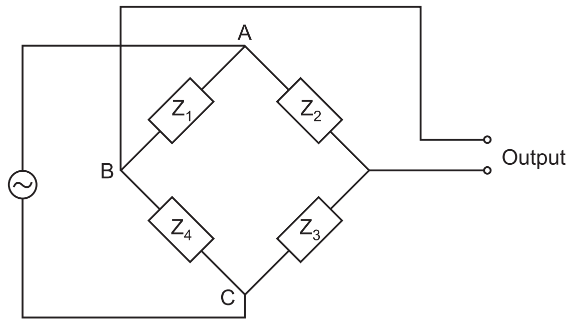
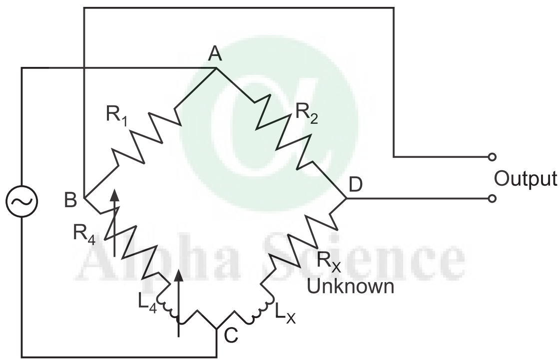


Fig. 3.4 Wheatstone Bridge

amount depending on the ratio R_1/R_2, so as to nullify the unbalance and bring back the null indication in the output meter. Change required to be made in R_4 is calibrated for changes taking place in R_3-say due to temperature, pressure etc.



(a) General Configuration



(b) Maxwell Bridge for Measuring unknown L_X and R_X

Fig. 3.5 AC Bridge Configuration

The method is extendable to AC bridges for inductive and capacitive elements in the measuring arms of the bridge arms with ratio arms R_1 & R_2 remaining resistive.

With the use of AC source as in Fig. 3.5, the balance condition is replaced by:

$$Z_1 \times Z_3 = Z_2 \times Z_4 \quad ...(3.5)$$

i.e.

$$|Z_1| \cdot |Z_3| = |Z_2| \cdot |Z_4| \quad ...(3.6)$$

and,

$$\angle(Z_1 + Z_3) = \angle(Z_2 + Z_4) \quad ...(3.7)$$

Under the measuring state a change occurring in the magnitude of Z_3 will cause an unbalance of the bridge and a voltage will appear at the output terminals *B* & *D*, which will be a function of change in Z_3. A galvanometer connected at output terminals will draw a current until the bridge is balanced again by making a suitable change in Z_4. The change so made will be a direct measure of Z_3 and can be calibrated to the cause (change in measured value from the previous balance) which made the change in Z_3.

EXAMPLE 3.1

For a resistive 4 arm bridge, as shown in fig. Ex. 3.1, with one of the arms R_3 composed of a temperature sensitive resistance, with values R_1, $R_4 = 500\Omega$; R_2, $R_3 = 2\ K\Omega$. If the bridge is initially balanced calculate

(a) The output voltage V_0 for a 10% change in R_3, if the internal resistance of source is neglected.

(b) Voltage indicated at the output by a voltmeter of resistance 5 KΩ is connected between points B and D.

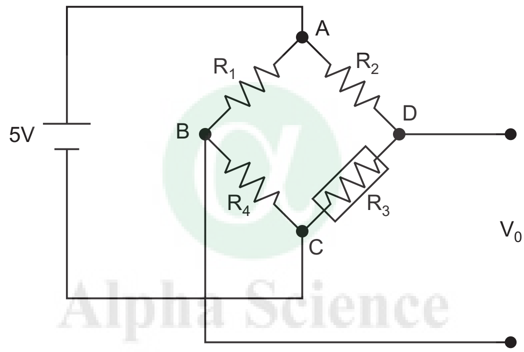


Fig. Ex. 3.1

SOLUTION :

Resistance R_3 changes by 10% to 2 KΩ + 10% = 2200 Ω.

(*a*) Current through the path ADCA =

$$I_{ADC} = 5/(500 + 2000)\ \text{V}$$

Potential at point *D*,

$$V_D = 5 - V_{AD} = 5 - I_{ADC} \cdot R_1$$
$$= 5\ [1 - 500/2500] = 4\ \text{V}$$

Similarly potential $V_B = 5\ [1 - 2000/4200] = 2.619$ V

$$V_{BD} = 1.38\ \text{V}.$$

(*b*) Voltage V_{BD} can be assumed Thevenin's source voltage.

Thevenin's resistance of the bridge network looked into from the terminals B, D will be:

$$R_{Th} = R_1 \| R_4 + R_2 \| R_3$$

$$\frac{500}{2} + \frac{(2000 \times 2200)}{4200} = 1297.619\ \Omega.$$

$$\text{Current in voltmeter} = \frac{E_{th}}{R_0 + R_{\tau h}} = \frac{1.38}{5000 + 1297.619} = 0.219 \text{ m Amp}$$

Voltage indicated by voltmeter = **1.095 volts**.

3.2.2 Current Balance Bridge

The balance of Wheatstone bridge is obtained by tedious process of choosing appropriate values of resistances. This can be avoided by having a slightly different configuration as shown in Fig. 3.6 for current balance bridge, wherein a current from an external (current) source through R_5, so as to compensate for the potential V_{BD} thus providing a self-nulling facility,

For, $R_3 >> R_5$ and $(R_2 + R_3) >> R_5$

$$V_{BD} = \left(\frac{E_i}{R_1 + R_4}\right) R_4 - \left(\frac{E_i}{R_2 + R_3 + R_5}\right) (R_3 + R_5) - IR_5$$

Bridge balance can be easily obtained by adjusting direction and magnitude of I and the complexity of self balancing potentiometer type electro mechanical device can be avoided.

Starting from an initially balanced bridge for any arms changing its resistance due to environmental reasons *i.e.* due to effect of measurand can be brought back to null condition again by external current source and this current required *I*, can be calibrated for instrumenting the physical variable causing change of resistance.

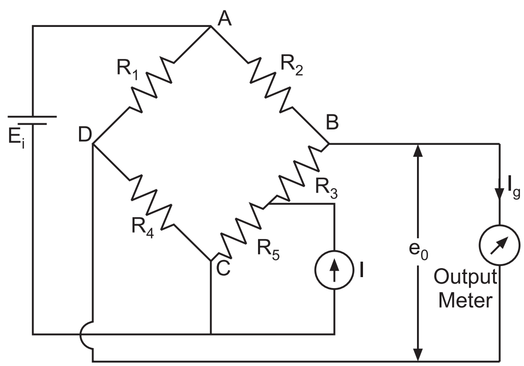


Fig. 3.6 Current Balance Bridge

3.2.3 Potentiometric Principle

Potentiometric technique of measurement involves the principle of balancing the e.m.f.s in a local circuit so that the net voltage is zero and no current is drawn throw the output meter and the measurement of voltage is under open circuit condition.

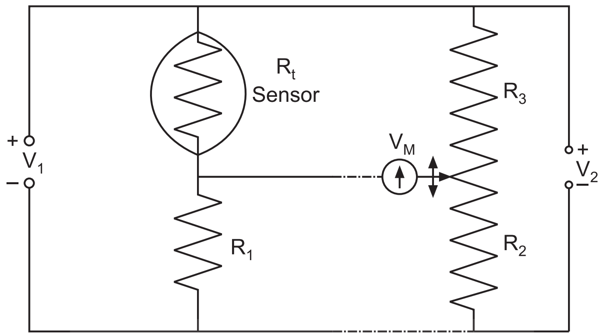


Fig. 3.7 Potentiometric Principle

The principle of dc potentiometer as may be applicable to measurements of variable temperature using a change of resistance is shown in Fig. 3.7. A change in measuring element R_t due to temperature causes a change in current throw the fixed resistance R and thereby a potential across it.

The meter initially shows a null in steady state with the resistive sensor for temperature Rt in series with the source V_1 and constant resistance R_1 (with negligible temperature coefficient). Sensor resistance R_t undergoes a change, due to change in temperature being measured and it is sought to achieve the null again by adjustment of potentiometer at the other end, excited by a voltage V_2. The adjustment of potentiometer wiper can be manual (in this case) or automatic using a self-balancing potentiometer discussed next.

It can be easily concluded that for the ratio

$$\frac{R_2}{R_2 + R_3} = \frac{V_1}{V_2}\left(\frac{R_1}{R_t + R_1}\right)$$

Null shall be reached and indicated by the voltmeter.

3.2.4 Self-balancing Potentiometers

These potentiometers are commonly employed in industrial situations, typically in process and power industry for tracking deviation and achieving null condition dynamically using automatic wiper movement control.

In this a motorized potentiometer as shown in Fig. 3.8, is set to provide a voltage, equal to the voltage developed by temperature sensor at the desired temperature for the process in the steady state *i.e.* null condition. The servo-motor will be having movement only when the process temperature is away from the steady state, the deviation is indicated on the chart and the motor feedback link adjusts the reference potentiometer to obtain a null again, thus avoid the need for any very accurate calibration of detector as would be required in deflection method.

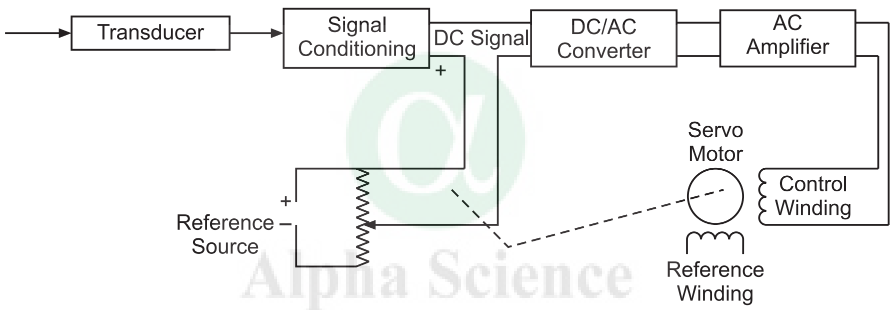


Fig. 3.8 Self-balancing Potentiometer

This class of arrangement reduces the continuous drain on the source and wear and tear of mechanical parts. These are ideally suited for accurate measurements with high sensitivity, continuously for long periods. But they have limitations for dynamic measurements (low bandwidth) and have small measurement range in operations, therefore mostly used for instrumenting deviation of chosen variable from its normal/steady operating value and not for whole value measurement. These are also known as servo type indicators/ instruments and the principle is used in many other situations such as servo stabilizers.

3.3 SPECIAL METHODS

In addition to the basic principles described in the last section, there are two schemes commonly used in industrial situation and recognized by the following names:

3.3.1 Differential Measurements

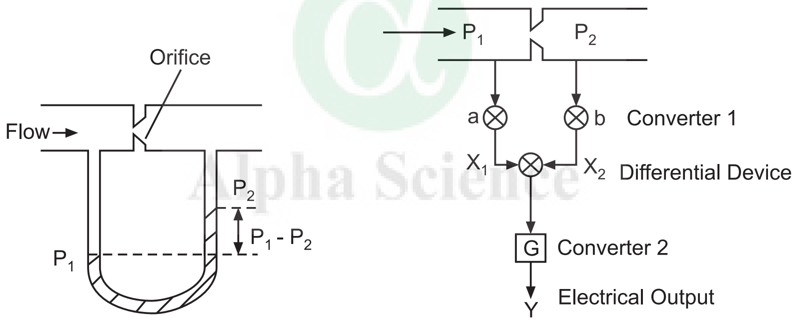
Used for measuring difference between two like quantities. This is a variation of null balance method. Differential manometers and differential pressure cells are commonly used for flow measurements, as shown in Fig. 3.9. In both the examples, pressure drops across the orifice is a function of flow and therefore after proper calibration the pressure difference directly indicates the flow rate within the pipe. With transfer functions '*a*' and '*b*' for pressure to displacement converters-1 and T.F. G for the converter at the Stage-2, mathematical relationship can be described as:

$$Y = G\,(X_1 - X_2) \qquad \text{...(3.8)}$$

$$= G\,(a\,p_1 - b\,p_2) \qquad \text{...(3.9)}$$

Our interest is in the differential pressure: $(p_1 - p_2)$.

If the gains '*a*' and '*b*' are not identical, and for no flow or null case *i.e.* $p_1 = p_2$, the output may still be finite instead of zero. Therefore an approximation is made to understand the effect of noise.



(a) Differential Manometer (b) Differential Pressure Cell

Fig. 3.9 Differential Measurement Devices

Let $B_{av} = \dfrac{(a+b)}{2}$ and $P_{av} = \dfrac{p_1 + p_2}{2}$

So that, $$Y = G\left[B_{av}(p_1 - p_2) + (a-b)\,P_{av}\right] \qquad \text{...(3.10)}$$

is obtained by a simple arrangement.

Of the two components, Ist term: $G\,B_{av}\,(p_1 - p_2) = Y_d$ is the desired signal and, IInd term: $G\,(a - b)\,P_{av} = Y_c$ is unwanted signal or noise in electronic parleyance. The above equation can be rearranged as:

$$Y = Y_d + Y_c$$

$$= Y_d\left(1+\frac{Y_c}{Y_d}\right) \quad ...(3.11)$$

$$= \text{desired signal}\left(1+\frac{\text{noise}}{\text{desired signal}}\right)$$

$$= G\cdot B_{av}\cdot(p_1-p_2)\left[1+\frac{(a-b)\,P_{av}}{B_{av}(p_1-p_2)}\right]$$

$$= G\cdot B_{av}\cdot(p_1-p_2)\left[1+\frac{(a-b)\,(p_1+p_2)}{(a+b)\,(p_1-p_2)}\right] \quad ...(3.12)$$

To reduce the effect of noise '*a*' and '*b*' are usually chosen large and close, so that the end result is implementable by Eqn. (3.9) in a simplified scheme.

3.3.2 Inferential Measurements

This approach is applicable for variables which cannot be measured directly but can be inferred from other related measurements available. For example, at times due to logistical difficulties it is not possible to place the sensor in a particular difficult position, or no direct sensor is available, then the inferred value of measurement is the only possible solution and economical. It is experienced in case of specific gravity measurements of liquids; pressure measurement in a gas pipe line through strain gauge sensing, composition of manufactured chemicals for real time control of process, temperature of generator windings etc. In all such cases inferential measurement technique is very useful. The physical laws are required to relate the variable whose value is to be determined to the measurable input and output values to make the inference about the specified variable. All measurements are being inferred mathematically by computing.

3.3.3 Comparison of the Measurement Techniques

Its meaningful only if the measurement environment and conditions are identical. Comparative measurements from tests are usually part of test reports, considered before the acceptance of the equipment. The process of measurement under standardized conditions is simple but interpretation of test results correctly may be a complex process *e.g.* results available for static tests can not be extended for dynamic conditions, prediction of behavior for a pressure to current converter at 50°C cannot be made directly on the basis of the test results at 27°C since extrapolation may be complex. A general comparison of the two basic approaches is presented in Table 3.1.

TABLE 3.1 : Comparison of Measurement Techniques

Property	Null balance	Deflection
1. Sensitivity	High near null, nonlinear for large deflections	Less; linear is expensive
2. Accuracy	More	Less
3. Loading Effect	Minimum	Prohibitive for continuous operation
4. Complexity	More	Less
5. Response Speed	Less	Varies
6. Typical Applications	Static/low frequency measurements	Usually for dynamic measurements
7. Cost	Very high	Less expensive

Thus it may be noted that, the role of each technique is quite different and a correct choice is very important.

3.4 ERRORS IN MEASUREMENTS

These are classified as of two basic types:

- Systematic errors and
- Random errors.

3.4.1 Systematic Errors

These errors are identified as those which can be associated with known causes and are predictable in nature *i.e.* errors due to:

- Nonlinearity,
- Dead-band,
- Friction,
- Backlash and hysteresis,
- Temperature effect
- Human error in measurement

It is usual to quantify these errors and provide for necessary corrections in the measured value to obtain the true value of the measurand. Systems involving only this class of errors are also known as deterministic systems.

3.4.2 Random Errors

Random errors are those which may not be quantified exactly as in the case systematic errors. These may be due to noise in system or due to nonlinearity *i.e.* principle of superposition not holding ideally, resulting in arbitrary combination of errors, mentioned earlier and therefore exact quantification may not be possible. Only maximum and minimum limits may be specified or the particular measurement can be said to be equal to the corrected value, only with a certain degree of confidence, depending on the number of measurements lying with in a particular band of error tolerance.

Another cause of random error is contribution of unpredictable or not fully understood reasons *i.e.* electromagnetic and electrostatic interference, cross talk (coupling) between signals, shot noise in devices and unknown causes. A few of the known causes identified include:

(*a*) Schottky's noise due to random nature of electrons crossing the potential barrier.

(*b*) Johnson's noise/thermal noise/resistance noise due to the random thermal vibration produced by the flow of electrons in a conductor.

(*c*) Contact noise, due to flow of current across a junction of dissimilar metals.

(*d*) Burst noise, due to defects in production stage, causing abrupt noises.

(*e*) Flicker noise, due to imperfections in depletion layers of semiconductors, leakage from surface etc.

The effective contribution of these is purely random and non repetitive in nature. These can expressed only in terms of statistical parameters. The measurements involving such errors are called noise measurements.

3.5 STATISTICAL CONSIDERATION OF ERRORS

The purpose of analysis is to validate the measurements and eliminate the unacceptable ones. Random quantities are characterized only by a number of statistical parameters and random signals generated by the same source or obtained from the repetition of same experiment performed under the same conditions will not match in time domain representation yet their overall effect may be same. Conversely the two random sequences can be considered same provided their statistical parameters are same.

3.5.1 Statistical Parameters

For a measurement set available from a system:

$$x_k \in X; k = 1, 2, 3, \ldots\ldots\ldots\ldots N \qquad \ldots(3.13)$$

(*a*) **Mean** value of N measurements of the measurement set X is given by:

$$\bar{x} = \frac{1}{N}\sum_{k=1}^{N} x_k \qquad \text{...(3.14)}$$

and tends to be equal to the true value as N tends to infinity for systems with only random errors.

(*b*) Deviation and **Standard Deviation**:

These are defined about the mean value $\bar{x}$ as:

Deviation, $d_k = x_k - \bar{x}$ and

$$\text{Standard deviation (S.D)} = \sqrt{\frac{1}{N}\sum_{k=1}^{N} d_k^2} \qquad \text{...(3.15)}$$

$$= (\text{Variance})^{1/2}$$

S.D. is an important measure of accuracy and higher accuracy is indicated for a smaller value of S.D, also it can be evaluated by a shorter method for computing as:

$$\alpha^2 = \frac{1}{N}\sum_{k=1}^{N}(x_k - \bar{x})^2$$

$$= \frac{1}{N}\sum_{k=1}^{N} x_k^2 - \frac{2}{N}\bar{x}\sum_{k=1}^{N} x_k + (\bar{x})^2$$

$$= \overline{x^2} - (\bar{x})^2 \qquad \text{...(3.16)}$$

(*c*) **Uncertainty:** Error uncertainty U_k in a trial, over N observations will contribute an error e, given by:

$$e^2 = \sum_{k=1}^{N}\left(\frac{dx}{dx_k}U_k\right)^2 = \sum_{k=1}^{N}\left(\frac{1}{N}\right)^2 U_k^2$$

$$= \frac{1}{N}\left(\frac{1}{N}\sum U^k\right) = \frac{\alpha^2}{N}$$

$$\therefore \qquad e = \pm\frac{\alpha}{\sqrt{N}} \qquad \text{...(3.17)}$$

This is an important and quick indicator of confidence in the results obtained. For example if the errors lie within an uncertainty error limit of ±5%, we have 95% confidence in the accuracy of the result obtained etc.

(*d*) **Histogram, frequency and distributions:** For N observations X_k, k = 1, 2, ...N quantized into regions of width Δx, frequency f of occurrence that the result X_k lying within a region, gives the number of times that X_k falls in that region. If relative frequency f/N is plotted as a function of x, it is referred as a histogram (see Fig. 3.10) shown for a small value of N. A graph joining all top centers of histogram is called frequency-distribution curve. For very large N, as $\Delta x \to 0$, histogram becomes a continuous plot, called amplitude probability density distributions of the functions of x.

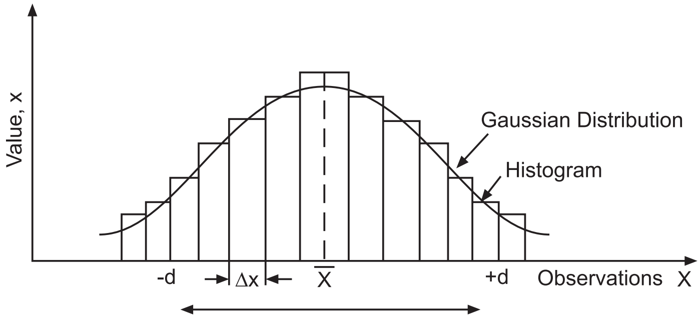


Fig. 3.10 Histogram

3.5.2 Distributions and Probability of Errors

Almost all engineering systems have random errors, which can be described as Gaussian or Normal distribution and corresponding probability density distribution is given by:

$$p(x) = \frac{h}{\sqrt{\pi}} e^{-h^2 x^2}; \; h > 0 \qquad \text{...(3.18)}$$

$p(x)\delta x$ will be the probability that $x(\cdot)$ lies between x and $x + \delta x$ and can be measured. The total area under p.d.f. is always unity, *i.e.*

$$p(x)\ \delta x = 1.0$$

where, h represents a geometric spread of curve *i.e.* a measure of precision and equals $1/\sqrt{2}\alpha$. A plot of $p(x)$ for different values of x shows a bell shaped curve (Fig. 3.11).

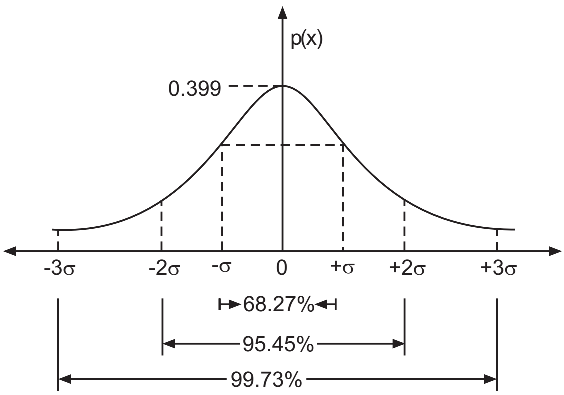


Fig. 3.11 Gaussian (or normal) Distribution Curve

It is to be noted that:

(*a*) For high values of *h* (or low s.d.), distribution curve is more peaky *i.e.* more precise observations about the true value.

(*b*) For Gaussian distribution

$$\alpha = \frac{1}{h\sqrt{2}};\ \bar{x} = \frac{1}{h\sqrt{\pi}};\ \frac{\alpha}{\bar{x}} = \sqrt{\frac{\pi}{2}}$$

Observations and the probability of their occurrence within the stipulated error range is related as shown in Table 3.2.

TABLE 3.2 Probability of Occurrence of Errors

Deviation considered from mean value of x	*% of Observations lying within this deviation*
± 0.675 α	50%
± 1.0 α	68.27%
± 2.0 α	95.45%
± 3.0 α	99.73%

Since Gaussian distribution assumes the mean value to be the true value the number of observations should be infinite which is practically never feasible. It will be a finite number and should be greater than 30. It is always preferred to have sharp normal distributions curve so that the readings are close to $\bar{x}$.

There may be situations where for large number of groups of observations each of *N* data points, the mean values X_1, X_2,................ are distributed in Gaussian manner with standard error of mean = $\alpha/\sqrt{N}$, about the true mean.

This indicates that, precision may not always be increased by having more observations.

3.5.3 Validation of Distribution

(*a*) Verification of Gaussian Error Distribution

To ensure that the errors are corresponding to normal distribution as assumed, there are several test procedures available. Statistical estimation theory provides a basis for expressing confidence level for the parameter estimates from a sample.

Let μs and σs the mean and s.d. of the data sample *S* considered. If the sampling distribution of *S* is normal (which usually is for $N > 30$) it can be expected to find the true value.

Sample statistic lying in the interval $\mu s - \sigma s$ to $\mu s + \sigma s$, $\mu s - 2\sigma s$ to $\mu s + 2\sigma s$, $\mu s - 3\sigma s$ to $\mu s + 3\sigma s$ are about 68.27%, 95.45% and 99.73% of the time respectively.

Equivalently we can confident to find μs in the interval $S - \sigma s$ to $S + \sigma s$, $S - 2\sigma s$ to $S + 2\sigma s$ or $S - 3\sigma s$ to $S + 3\sigma s$ about 68.27%, 95.45% and 99.73% respectively. Due to this, the respective intervals 68.27%, 95.45% and 99.73% are confidence intervals. Similarly $S \pm 1.96\sigma s$ and $S \pm 2.58\sigma s$ are 95% and 99% confidence limits for S; % is also referred as confidence level. More generally the confidence limits are given by $\bar{X} \pm Z_c \sigma_{\bar{x}}$ where Z_c depends on the level of confidence desired and is read from Table 3.3.

Thus, the confidence limits for sample mean are given by:

$$\bar{x} \pm Z_c \sigma / \sqrt{N}$$

TABLE 3.3 Measure of Confidence Level

Confidence level	***99.73%***	***99%***	***96%***	***95.45%***	***95%***	***90%***	***80%***
Z_c	3.00	2.58	2.05	2.00	1.96	1.645	1.28

(*b*) Chi-square test: It is used as a goodness of fit test.

The procedure is to find:

$$x^2 = \sum_{j=1}^{k} \frac{\left|Y_{oj} - \hat{Y}_j\right|^2}{\hat{Y}_{oj}} \quad \text{...(3.19)}$$

where Y_o are observations, is expected value and k is number of observations.

The value of x^2 is a number of mismatches of distributions of observed data series from the normal. The result is interpreted in terms of the degrees of freedom, $F = k - m$, where m is the number of imposed conditions on the distribution expected. Chi-squared tables relaste probability with degree of freedom.

Yet another approach is the least square method. This involves fitting the best curve of a predetermined form through a series of experimental points based on minimization of squares of errors, hence the name. It is applicable to any order of curve fitting, to estimate a mathematical model for the experimental graph obtained. Very often it is necessary for calibration of instruments between input u and output y. It is being presented for a linear fit as an example.

If a linear relationship with constant slope/sensitivity m is expected of the form:

$$y = m\,u + z \qquad \text{...(3.20)}$$

z being the intercept on the output axis (see Fig. 3.12), also called zero drift.

The best fit straight line of the above type, can be obtained for the set of observations x, y for N-pairs by minimization of the sum-of-the-error squared S for all N-data pairs available.

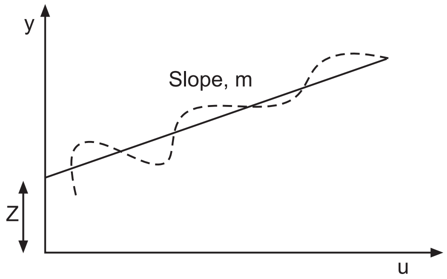


Fig. 3.12 Linear Least Square Fit

Define error for k^{th} data set: y_k and u_k,

$$e_k = y_k - (mu_k + z)$$

Optimizing function, $S = \sum\{y_k - (mu_k + z)\}^2$

By obtaining $\frac{\partial s}{\partial m}, \frac{\partial s}{\partial z}$ and equating to zero, linear equations are obtained:

$$\sum y_k u_k = m\sum u_k^2 + z\sum u_k \qquad \text{...(3.21)}$$

and $$\sum y_k = m\sum u_k + zN \qquad \text{...(3.22)}$$

By solving these, m and z are computed as:

$$m = \frac{N\sum y - \left(\sum u\right)\left(\sum y\right)}{N\sum u^2 - \left(\sum u\right)^2} \qquad \text{...(3.23)}$$

$$z = \frac{\left(\sum y\right)\left(\sum u^2\right) - \left(\sum uy\right)\left(\sum u\right)}{N\sum u^2 - \left(\sum u\right)^2} \qquad \text{...(3.24)}$$

It is also possible to compute standard deviation of output y, sensitivity m and that of zero-drift z, as s.d. of output

$$\alpha_y = \pm\left[\frac{1}{N}\sum\left(mu_j + z - y_j\right)^2\right] \qquad \text{...(3.25)}$$

s.d. of sensitivity, $\alpha_m = \pm\sqrt{\dfrac{N\alpha_y^2}{N\sum u^2 - \left(\sum u\right)^2}}$ ...(3.26)

s.d of intercept or zero drift,

$$\alpha_z = \pm\sqrt{\frac{\alpha_y^2\left(\sum u^2\right)}{N\left(\sum u^2\right) - \left(\sum u\right)^2}} \quad ...(3.27)$$

s.d in measurement or lack of precision shall be:

$$\alpha_y = \pm\sqrt{\left[\frac{1}{N}\sum\frac{(y-z)}{m} - u\right]} \quad ...(3.28)$$

$$\alpha_y = \pm\frac{\alpha_y}{m} \quad ...(3.29)$$

Thus from these relations it is possible to have a measure of the various quantitative measures in the presence of noise in the data and arrive at the conclusions about the behavior of system/instrument.

3.6 COMBINATION OF ERRORS

It has been considered to calculate the mean and standard deviation. The set of variates can be completely expressed in the form of $\bar{x} \pm \sigma$. The mean is taken to be the best estimate of the measurement and for a normal error distribution about 68% of all measurement are within ± σ of the mean.

However, it is necessary to evaluate the uncertainty in the estimate of mean itself, and the estimated uncertainty to be expected in a quantity computed from other sets of similar experiment having specified errors.

3.6.1 Preposition-1

Sum of two independent sets of variables has mean equal to sum of mean of each set.

Suppose two sets of measurement are $v_1, v_2, \ldots v_n$ and $w_1, w_2 \ldots w_k$ be independent sets where k and n may be unequal.

Means would be

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} v_i;\ i = 1, 2, \ldots.\ n \quad ...(3.30)$$

and $$\bar{w} = \frac{1}{k}\sum_{i=1}^{k} w_i;\ k = 1, 2, \dots k \qquad \text{...(3.31)}$$

sum of two variates,

$$s_{ij} = \sum(v_i + w_j);\ i = 1, 2, \dots n,$$

$$j = 1, 2, \dots n \qquad \text{...(3.32)}$$

thus, there will be nk different variates in the sum set for all possible combinations.

Therefore, Mean of sum set

$$\bar{s} = \frac{1}{nk}\sum(v_i + w_j)$$

$$= \frac{1}{nk}\sum v_i + \frac{1}{nk}\sum w_j \qquad \text{...(3.33)}$$

Since $$\sum_{ij} v_i = k\sum_{i=1}^{n} v_i = kn\bar{v}$$

and $$\sum_{ij} w_j = n\sum_{j=1}^{k} w_j = nk\bar{w}$$

therefore $$\bar{s} = \bar{v} + \bar{w} \qquad \text{...(3.34)}$$

3.6.2 Preposition-2

Variance of the sum set $s_{ij} = v_i + w_j$ is almost equal to sum of the individual set variances.

For the first set of measurements

$$\sigma_v^2 = \frac{1}{n-1}\sum_{i=1}^{n-1}(v_i - \bar{v})^2$$

and for second set

$$\sigma_w^2 = \frac{1}{k-1}\sum_{j=1}^{k}(w_j - \bar{w})^2$$

Variance of the sum set

$$\sigma_s^2 = \frac{1}{nk}\sum(s_{ij} - \bar{s})^2 = \frac{1}{nk}\sum_{ij}(v_i + w_j - \bar{v} - \bar{w})^2 \qquad \text{...(3.35)}$$

By considering a long expansion of right hand side and arranging

$$\sum_{ij}(v_i - \bar{v})^2 = k(n-1)\,\sigma_v^2 \cong kn\sigma_v^2$$

$$\sum_{ij}(w_i - \overline{w})^2 = n(k-1)\,\sigma_w^2 \cong nk\sigma_w^2$$

and $\sum_{ij}(v_i - \overline{v})(w_i - \overline{w}) = 0$ ...(3.36)

$$\sigma_s^2 \cong \sigma_v^2 + \sigma_w^2 .$$

3.6.3 Preposition-3

The result for the variance of the sum of two sets can be extended to the difference of two sets. If w_j is replaced by $-w_j$, then difference

$$d_{ij} = v_i - w_j \quad \text{...(3.37)}$$

Then, mean of the difference of 2 sets is equal to the difference of means of the two sets *i.e.*

$$\overline{d} = \overline{v} - \overline{w} \quad \text{...(3.38)}$$

and, the variance of the difference

$$\sigma_d^2 = \sigma_v^2 + \sigma_w^2 \quad \text{...(3.39)}$$

These results can also be extended to more than two sets, say for p sets,

$$\sigma_s^2 = \sigma_1^2 + \sigma_2^2 + \ldots \sigma_p^2 \quad \text{...(3.40)}$$

This leads to inference that, if one element is selected at random from each of the *p*-sets, then probability that the random sum lies within + σ_s of the mean of combined is 0.68, if the distribution is normal.

3.6.4 Preposition-4

Standard deviation of a set of data '*a*' times as larger than the original set, is '*a*' times the standard deviation of original set.

If for original set

$$\sigma_v = \left[\frac{1}{n-1}\sum_{i=1}^{n} n(v_i - \overline{v})^2\right]^{\frac{1}{2}} \quad \text{...(3.41)}$$

Now, if each v_i is multiplied by a, then mean of new set would be $a\overline{v}$ and standard deviation for new set, would be:

$$\sigma_{\text{new}} = \left[\frac{1}{n-1}\sum(av_i - a\overline{v})^2\right] = a\sigma_v \quad \text{...(3.42)}$$

Extending this to a combination of *p*-sets,

$$\sigma_s^2 = (a_1\sigma_1)^2 + (a_2\sigma_2)^2 \ldots + (a_p\sigma_p)^2 \quad \text{...(3.43)}$$

3.6.5 Preposition–5

Standard deviation of mean:

If measurements are carried over p-sets each of n samples with their individual mean calculated for each, then it is possible to determine the standard deviation of the mean from the mean of the group of means over *p*-sets, providing more accurate measure of the quantity.

It may be considered that, each of *n* variates of a given sets as selected at random from a large group (also called population) of standard deviation σ. The mean of sets of *n* elements is

$$\bar{v} = \frac{1}{n}\sum_{i=1}^{n} v_i = \frac{v_1}{n} + \frac{v_z}{n} \ldots + \frac{v_n}{n} \; (p = n) \qquad \ldots(3.44)$$

each set is multiplied by same constant *i.e.* $1/n$ before summing.

Variance of the sum set, of which is a typical member, is equal to sum of variance, given by

$$\sigma_s^2 = \left(\frac{\sigma}{n}\right)^2 + \left(\frac{\sigma}{n}\right)^2 \ldots + \left(\frac{\sigma}{n}\right)^2 = n\left(\frac{\sigma}{n}\right)^2 \qquad \ldots(3.45)$$

Therefore, $\sigma_s = \pm\frac{\sigma}{\sqrt{n}}$ is the variance of mean $\bar{v}$

It is to be noted that standard deviation of mean decreases as *n* increases, though slowly with increase in *n*, *i.e.* a 100 fold increase in *n* reduce uncertainty in the mean by only 10 times !

EXAMPLE 3.3

Suppose, the standard deviation of a set of 100 measurements is 1.0 and the mean is 6.0, then 68% of the measurement lie between 5.0 and 7.0 and the standard deviation of mean is $\frac{1}{\sqrt{100}} = 0.1.$ *Thus, the probability of any measurement chosen at random (from among the 100) to lie between 5.0 and 7.0 is 0.68.*

Also, for another 100 new measurements from same population have probability of 0.68 to have mean lying between 5.9 and 7.1 (standard deviation of mean being 0.1).

EXAMPLE 3.4

Two currents are measured $I_1 = 100 \pm 1$ *A and* $I_2 = 200 \pm 4$ *A, determine the error in the sum* $I = I_1 + I_2$.

Case (*a*)

Assuming indicated uncertainty to be limits of error,

$$(I_1 + I_2)_{max} = 101 + 204 = 305 \text{ A}$$

and, $$(I_1 + I_2)_{min} = 99 + 196 = 295 \text{ A}$$

$$I_1 + I_2 = 300 \pm 5 \text{ A}.$$

Case (*b*)

Assuming the limits of error to be ±1% and ±2%, limit of error would be ±1.66%.

Case (*c*)

Assuming the limits of error to be standard deviations, σ then standard deviation of sum current, I

$$\sigma_I = \sqrt{1^2 + 4^2} = \sqrt{17} = 4.1231 \text{ A}$$

and $$I = 300 \pm 4.1231 \text{ A}.$$

The use of standard deviations rather than limits offers more optimistic results and logical because the probability of both I_1 and I_2 being far from their mean values is rather small.

3.6.6 Approximate Standard Deviation of Computed Results

For functional relationships the evaluation of error and the probability of overall error, the consideration of the error of various variables may not be so straight forward, as in the earlier cases.

Suppose z is a function of two variables x, y as

$$z = f(x, y)$$

for $x = x_o$ and $y = y_o$ as the measured values, computed value can be given by

$$z = z_0 = f(x_o, y_o)$$

For any change in z due to very small changes in x and y,

Let $\Delta x = x - x_o$, $\Delta y = y - y_o$, it can be expressed in terms of differentials as

$$\Delta z = \Delta x + \Delta y = \left(\frac{\partial x}{\partial z}\right)_{x_0, y_0} + \left(\frac{\partial y}{\partial z}\right)_{x_0, y_0} \quad \text{...(3.46)}$$

With partial derivatives evaluated at $x = x_0$, $y = y_0$. The deviations Δx and Δy have been considered from x_0 and y_0. Now, if we assume x_0, y_0 be the mean values and Δx, Δy be deviations from their respective means. Relation will hold for small deviations without the need for including higher order terms in Taylor series approximation.

If it is assumed that Δx, Δy are independent sets of variables, each multiplied by a constant, *w* can write for variance of Δz,

$$\sigma_{\Delta z}^2 \simeq \left[\left(\frac{\partial x}{\partial z}\right)_{x_0, y_0} \sigma_{\Delta x}\right]^2 + \left[\left(\frac{\partial y}{\partial z}\right)_{x_0, y_0} \sigma_{\Delta y}\right]^2 \qquad \text{...(3.47)}$$

where each term on right hand side can be considered sum of two variables *i.e.* $x_o + \Delta x$ with x_0 being mean with zero variance and Δx with variance. Similarly it holds for second term. Therefore, differentials $\frac{\partial x}{\partial z}$ and $\frac{\partial y}{\partial z}$ are considered to, act as weights

$$\therefore \qquad \sigma_{\Delta z}^2 = \sigma_{\Delta x}^2 + \sigma_{\Delta y}^2. \qquad \text{...(3.48)}$$

EXAMPLE 3.5

For determining resistance applied measured voltage across it and measurement of current flowing through is very common, with functional relationship as

$$R = \frac{V}{I} = R(V, I).$$

SOLUTION:

We have, $$\sigma_R^2 = \left[\left(\frac{\partial R}{\partial V}\right)_{V_0, I_0} \sigma_V\right]^2 + \left[\left(\frac{\partial R}{\partial I}\right)_{V_0, I_0} \sigma_I\right]^2$$

Suppose, V_0 = 10 Volts, I_0 = 2A, $\sigma_V = 2V$, σ_1 = 0.25 A

Then, $$R_0 = \frac{V_0}{I_0} = 5\,\Omega,$$

$$\therefore \qquad \sigma_R^2 = \left[\frac{1}{I}\sigma_v\right]^2 + \left[\frac{-V}{I^2}\sigma_I\right]^2$$

$$\therefore \qquad = [0.5 \times 2]^2 + [-2.5 \times 0.25]^2$$

$$\therefore \qquad \sigma_R = 1.27$$

$$\therefore \qquad R = 5 \pm 2.69\ \Omega.$$

It can be verified that a deviation of 20% in voltage and 12.5% in current would give a larger deviation in the value of resistance *R*.

Also, the weights in bracketed terms provide an identification of the terms, as to which variable contribute more to the error and guides towards the improvement to be made. The result is extendable to functions of more variables also.

3.6.7 Standard Deviation of Special Function Forms

(*i*) Sum and difference

Let $$z = x \pm y$$

Then $$\frac{\partial z}{\partial x} = 1, \frac{\partial z}{\partial x} = \pm 1$$

By substitution $$\sigma_z^2 \cong \sigma_x^2 + \sigma_y^2$$

and it is extendable to more variables.

(*ii*) Simple product

Let $$z = x\,y$$

Then $$\frac{\partial z}{\partial x} = y, \frac{\partial z}{\partial y} = x$$

$$\therefore \quad \sigma_z^2 = y^2\sigma_x^2 + x^2\sigma_y^2 \qquad \text{...(3.49)}$$

$$\therefore \quad \frac{\partial z}{z} = \sqrt{\left(\frac{\partial x}{x}\right)^2 + \left(\frac{\partial y}{y}\right)^2} \qquad \text{...(3.50)}$$

(*iii*) Simple divisors

Let $$Z = \frac{x}{y}$$

Then $$\frac{\partial z}{\partial x} = \frac{1}{y};\ \frac{\partial z}{\partial y} = -\frac{x}{y^2}$$

$$\therefore \quad \sigma_z^2 \cong \frac{1}{y^2}\sigma_x^2 + \frac{x^2}{y^4}\sigma_y^2 \qquad \text{...(3.51)}$$

$$= \frac{x^2}{y^2}\left[\frac{\sigma_x^2}{x^2} + \frac{\sigma_y^2}{y^2}\right]$$

$$\frac{\partial z}{z} = \sqrt{\left[\left(\frac{\partial x}{x}\right)^2 + \left(\frac{\partial y}{y}\right)^2\right]}$$

: Same as for simple product.

(*iv*) Simple power of variable

Let $z = x^{\alpha}$; where α is an integer constant

Then $\frac{\partial z}{\partial x} = \alpha x^{n-1}$

$$\therefore \sigma_z^2 \cong \alpha^2 x^{2(\alpha-1)} \sigma_x^2 = x^{2\alpha} \alpha^2 \frac{\sigma_x^2}{x^2} \quad ...(3.52)$$

$$\therefore \quad \frac{\partial z}{z} = \alpha \frac{\sigma_x}{x}.$$

EXAMPLE 3.6

The two resistors of values R_1 =100 ± 2Ω and R_2 = 200 ± 3Ω are connected in (i) series, (ii) parallel, where errors are the standard deviation of the mean values. Find the approximate standard deviation of the combinations.

(*i*) $$R_{\text{series}} = R_1 + R_2$$

$$\sigma_{\text{Rseries}} \cong \sqrt{2^2 + 3^2} = 3.60\ \Omega$$

$$R_{\text{series}} = 300 \pm 3.60\ \Omega.$$

(*ii*) $$R_{\text{parallel}} = \frac{R_1 R_2}{R_1 + R_2}.$$

SOLUTION:

Here numerator and denominator are not independent and the case does not come under any of the cases discussed earlier. Therefore, consider it as function of two variables

$$\frac{\partial R_{\text{Parallel}}}{\partial R_1} = \left(\frac{R_2}{R_1 + R_2}\right)^2$$

$$\therefore \quad \left(\frac{\partial R_{\text{parallel}}}{\partial R_1}\right)_{\text{mean}} = \left(\frac{200}{300}\right)^2 = 0.44$$

$$\frac{\partial R_{\text{Parallel}}}{\partial R_2} = \left(\frac{R_1}{R_1 + R_2}\right)^2$$

$$\therefore \quad \left(\frac{\partial R_{\text{parallel}}}{\partial R_2}\right)_{\text{mean}} = \left(\frac{100}{300}\right)^2 = 0.11$$

By substitution in Eqn. (3.51)

$$\sigma^2_{R\text{parallel}} = [0.44 \times 2]^2 + [0.11 \times 3]^2 = 0.8824$$

Therefore, $R_{parallel} = 66.66 \pm 0.94\ \Omega$

The calculation of s.d. for functions is applicable in many situations in instrumentation (See Q. 3.7 also).

Comments

The choice of proper technique of measurement is very important so as not to disturb the conditions of system and this makes the null-balance methods the preferred choice. Accuracy determines the quality of measurements and the quality of production, subject to right choice of process, equipment before operation commences. Instrumentation engineer ensures the quality by minimizing the errors and then by accounting for the errors with their correct evaluation in dynamic mode, by providing and maintaining the high standards of calibration. Errors and their analysis play an important role not only in calibration but also in statistical process control.

In the next chapter, the discussion shall be about the devices to be used for monitoring the system variables, the features required of them and primary interface needed for some of the cases.

SUGGESTED READINGS

(*i*) E.Frank – Measurement Analysis (McGraw Hill)

(*ii*) E.O. Doeblin – Measurement Systems (McGraw Hill)

(*iii*) Spiegel, M.R. – Statistics (McGraw Hill)

(*iv*) Stout,M.B. – Basic electrical measurements (PHI)

(*v*) Box, G.P. and Jenkins, G.M. – Time series analysis-forecasting and control (Holden-day)

(*vi*) R.E. Walpole, R.H. Meyers, S.L. Meyers, K. Ye – Probability & Statistics for Engineers & Scientists (Pearson)

REVIEW PROBLEMS

(*i*) Compare deflection and null-deflection methods.

(*ii*) How do you compare dc and dc/ac indicating instruments in terms of performance?

(*iii*) In case of nonlinear indicating scale of meters what care is required to be taken in the selection of range of the instrument?

(*iv*) In the operation of bridges, what is the effect of source resistance on the balance of bridge?

(*v*) How is the sensitivity of the bridge adjusted?

(*vi*) What is the advantage of current balance bridge over the conventional bridge?

(*vii*) What is understood by the term ‘customising the self-balance-potentiometer’?

(*viii*) What are inferential measurements? When does the need arise for these?

(*ix*) What are bridges with differential arrangement? Why are they also referred as 'push-pull' arrangement?

(*x*) Differentiate between systematic and random errors, and list the errors that come in each category.

(*xi*) How are random errors characterized?

(*xii*) Why the error distribution is assumed to be Gaussian in most of the systems you deal with?

(*xiii*) What are the various methods of linear curve fitting for a set of input-output data?

(*xiv*) Explain the situation in which the 'linear least squares' method of linear curve fitting is used.

(*xv*) What is understood by the term 'confidence level'? Explain with example.

(*xvi*) What are 'auto' and 'cross' correlations, and how they are evaluated?

PROBLEMS FOR EXERCISE

3.1 A nonlinear resistance X is known to follow the law $X = A + CI$, where A is the zero current value of X, I is the current through X and C is constant. The Wheatstone bridge as shown in Fig. Q3.1, below with $R_1 = 200\Omega$, $E = 10$ volts and $R_b = 0$, is used to determine A and C. With $R_3 = 100\ \Omega$, a value of $R_2 = 100\ \Omega$ is required for balance. With $R_3 = 200\ \Omega$, R_2 required for balance is 60 Ω. Compute A and C.

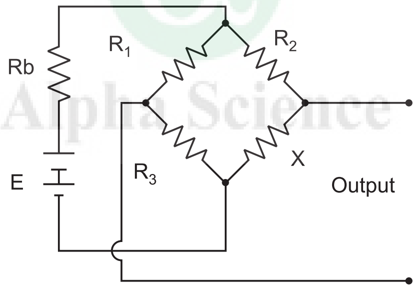


Fig. Q 3.1

3.2 In a Wheatstone bridge arrangement as shown in Fig. Q3.2, a voltage controlled by setting k of the pot ($0 \le k \le 1$) is applied to point A-B. Specify the range of setting in terms of k, for which bridge balance is not possible by variation of R_1.

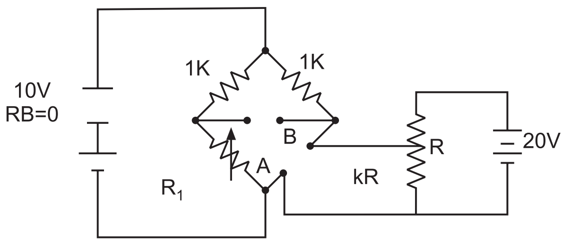


Fig. Q 3.2

3.3 Find the best linear fitting estimate of parameters and a quadratic (fit) model parameters, with the experimental data obtained from a gas turbine driven generator, steady state power delivered as a function of flow rate.

Fuel flow rate, Ui (input)	***Power generated, Yi (output)***
1.0	2.0
2.3	4.4
2.9	5.4
4.0	7.5
4.9	9.1
5.8	10.8
6.5	12.3
7.7	14.3
8.4	15.8
9.0	16.8

3.4 Consider the first nine integers 1 to 9 to be a set of integers.

(*a*) Compute the mean.

(*b*) Demonstrate that the sum of deviations from the mean is zero.

(*c*) Compute the sum of squares of the deviations from the mean.

(*d*) Demonstrate that the sum of square of the deviations after the input 4, exceeds the result in part(c)

3.5 In measuring emf with a potentiometer, 5 independent reading were obtained in volts as: 1.485, 1.478, 1.480, and 1.483.

Assuming all reading to have equal weight, find the best value to be chosen as most correct for the emf and calculate % deviation.

3.6 For a batch of 1000 resistors, the value of resistance was specified as $R = 92.2 \pm 0.1\Omega$. How many of them can be estimated to be in the range $R = 92.2 \pm 0.15\Omega$? Assume normal distribution.

3.7 Two resistors, $R_1 = 200 \pm 5\ \Omega$ and $R_2 = 300 \pm 4\ \Omega$ are connected in parallel. What is the resistance of combination and its standard deviation? Assume errors to be in terms of standard deviation.

3.8 The resistances have the following ratings considering the probability of error: $R_1 = 30\Omega \pm 5\%$; $R_2 = 75\ \Omega \pm 5\%$.

Calculate

(*a*) The magnitude of error in each resistor.

(*b*) The limiting error in Ωs and percentage when resistor are connected in (*i*) series (*ii*) parallel.

3.9 A temperature sensing device working on the principle of change in resistance obeys the law: $R = R_0[1 + \alpha(T - 25)]$ where $R_1 = 200 \pm 0.3\%\ \Omega$ at 25°C, $\alpha = 0.004/\Omega C \pm 1\%$, and $T = 60 \pm 1°C$ is the actual temperature of the sensing element placed in both whose temperature is being monitored with this device. Find the resistance of sensor with limits of error at 60°C.

3.10 A voltage divider is to provide an output equal to 10% of its input. The standard deviation of the ratio of output to input is required to be 0.1% or less. A 100 Ω precision resistance potentiometer with standard deviation of 0.01% is available. What is the maximum allowable s.d. of the 900 Ω resistor?

3.11 The resistance of an unknown resistor is determined by using Wheatstone bridge using relation $R_x = R_1 R_2/R_3$.

If the balance was obtained with $R_1 = 520\ \Omega \pm 1\%$; $R_2 = 610\ \Omega \pm 1\%$; $R_3 = 100\ \Omega \pm 0.5\%$.

Calculate (*a*) the nominal value of unknown resistor. (*b*) Limiting error in the calculated value of unknown.

PROJECT EXERCISE

1. How the principle of servo-balance potentiometers is utilized in servo stabilizers? What are the other types of stabilizers available and list the advantages of this over other types.
2. How can a sinusoidal variable voltage signal be obtained from potentiometer?

CHAPTER 4

Sensors and Transducers

Inside the Chapter

INTRODUCTION

The various variables in the engineering and non-engineering systems are being measured monitored and recorded since ages. Many of these offer very accurate and sophisticated techniques. The recent trend of the interaction of electrical engineering has been able to provide a new dimension to the science and art of measurement in the last few decades.

It is now possible to convert a physical variable such as temperature, pressure, displacement, velocity, acceleration, vibration, flowrate of liquids and gases, level in reservoirs etc., in electrical signal. The electrical signal developed is a function ofthe input measurand quantity and can be calibrated, so that the current or voltage at the output of this transfer device provides a measure of mechanical, thermal, chemical, metallurgical and physical or biological activity associated with the variable being considered.

4.1 TRANSDUCER ELEMENT

The words sensors and transducer are widely used in measurement systems, often interchanged. The word sensor is more popular in U.S. whereas transducer in Europe and Asia for many years. The dictionary meaning of sensor is a device that detects a change in physical stimulus and turns it into a signal, which can be measured or recorded.

Transducer is defined as a device that accepts an input energy and produces output energy in some other form, with a known, fixed relationship between input and output. Thus transducer contains a sensor and may be a little more, and most sensors will be transducers. Electrical transducers provide an electrical output corresponding to physical input variable (also called measurand).

It may be considered as an energy modulating device or converting device and accordingly is the classification as passive and active types.

The conversion into electrical form leads to many advantages compared to conventional methods *i.e.* manometer and dial type gauges for pressure, venturimeters for flows, mechanical hand held tachometers for speed etc., in terms of capabilities added for manipulation, transmission, recording and analysis etc.

4.1.1 Definitions and Types of Transducers

The electrical transducers have the property to provide an electrical output for input physical variables such as temperature, pressure, load, flowrate, level, radiation, illumination, force, torque, speed, acceleration, vibration, frequency, humidity, thickness, displacement, magnetic flux, phase etc.

In mechanical systems, to transfer the variables into electrical signal, at times, it is not possible to convert directly and we have to use primary sensing elements which make possible to convert the variables pressure, load,torque etc into speed or change of position - an intermediate variable, which then can be transduced into an electrical signal by the transducer. Various types of primary sensors used to link the mechanical system with transducer are also discussed in this chapter.

Similarly, in liquid level and flow systems the rate of flow has to be converted in to a pressure difference and the level in storage tank into an equivalent load/pressure, with the help of primary sensors before transducers are used.

In electrical systems, variables such as frequency and its deviation, magnetic field & flux, phase, phase difference, heat and light radiation need primary sensors in some of the techniques used.

4.1.2 Types of transducers

Transducersare categorized into three types as:

(*a*) **Passive transducers** are those which can cause a change in value of some parameter of an electrical element but can not provide an electrical output (voltage or current) signal with out the use of an energizing source. For this reason, they are also called energy modulating type.

For example, an input variable say temperature, a change in which can cause a change in resistance placed in close vicinity. The change in resistance though an electrical parameter can not produce a signal but if this resistance is part of an electrical circuit like Wheatstone bridge or a potentiometer arrangement, excited by a constant energy source, then the change in resistance (from the initial null-balance condition) will cause an unbalance of the bridge to produce a voltage output.

Similarly changes are possible in value of resistance (due to other variables), inductance or capacitance, which again shall be part of a circuit will produce an electrical output due to this change, from initial steady or null-balance condition. Thus the change in variable is modulating the output.

(*b*) **Active transducers** are those which experience a change in some electrical characteristics of chosen device and generate an output. This output is generated without any energy source provided and hence the name ACTIVE. These are basically self-generating types may and act on any of the principles such as:

- Electromagnetic
- Thermoelectric
- Piezoelectric
- Photovoltaic
- Electrochemical effect
- Magnetostriction
- Ionization

Examples of this class include tacho-generators for speed, thermocouples for temperature, photovoltaic cells for illumination etc. The detailed description and principles of operation is the subject matter of Chapter 6.

(*c*) **Digital transducers** are those which directly produce digital output, with out any external data conversion device being used.

The examples include encoders for speed instrumentation, event-counting type for nuclear system measurements.

4.2 ADVANTAGES OF ELECTRICAL TRANSDUCERS

Compared to conventional techniques of instrumentation, the instrumentation with transducers offers several advantages of improving efficiency, accuracy, flexibility, remote sensing etc and can be listed as:

(1) The electrical signals can be amplified by any amount of finite gain, to improve sensitivity of basic transducer arrangement.

(2) The noise contained in the signals can be reduced/eliminated by using electrical filters to improve accuracy of measurements.

(3) The signal conversion and processing become simpler and easy to implement. These also take care of some of the hardware difficulties such as nonlinearities and calibration.

Availability of electronic techniques has provided additional impetus and these have facilitated analog and digital displays as well as recording in a user friendly manner.

(4) Electrical signals are eminently suitable for transmission over any distance with accuracy, speed and efficiency, using standard electronic communication technology by use of suitable format and protocols.

(5) With the above facilities and the availability of electronic design technology in modular forms, design of instrumentation systems has been realized, which is in most cases is comparable and even better than conventional mechanical, hydraulic and pneumatic systems.

(6) It is possible to integrate computers in the data acquisition process. This has increased the capability to deal with large number of transducer signals simultaneously with high degree of accuracy, flexibility in terms of display, storage, retrieval, alarm annunciation, at high speed of response, flexibility and reliability of operations.

4.3 PRIMARY SENSORS

Primary sensors are different from transducers, that, for some physical variables it may not be possible to directly convert in to electrical form. Therefore, we use these to convert the physical variable into an intermediate non-electrical variable form which may now be the input to transducer so as to obtain electrical signal as shown in Fig. 4.1. This electrical signal can be related to the primary sensor output and there from to the physical variable.

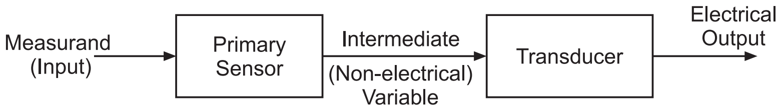


Fig. 4.1 Role of Primary Sensor in Instrumentation

One such example is pressure variable which is converted into another form say, displacement by using a primary sensor (discussed in next section in detail).The displacement is next used as input to transducer to obtain an electrical input. The Table 4.1 provides a list of such variables and types of primary sensors being used. The Table lists the primary sensing elements and their applications.

It is to be noted that, in instrumentation of physical variables, there are always several possible solution strategies. In some strategies it may be possible to have direct conversion to electrical signal and at times more than one primary sensor may have to be used. In the next section we discuss the various primary sensors are discussed in detail.

TABLE 4.1 Primary Sensing Elements

Variable	*Primary sensing element*	*Output variable*
Pressure	Diaphragm, capsule & bellow, Bourdon tube, membranes	Displacement
Flow rate	Orifice plate, Venturi tube, Pitot tube, Turbine, Rota meter float	Differential pressure Speed Displacement, Position
Temperature	Bimetallic strip	Closing of contact
Acceleration	Seismic mass	Linear motion
Force, stress	Spring, cantilever, columns	Change of length
Speed	Gyroscope	Dynamic position of equilibrium
	Tachometer	Optical pulses
Liquid level	Float, diaphragm	Change in position
Torque	Torsion bar, flat spiral spring, gyroscope.	Displacement, strain Displacement.

4.3.1 Primary Sensors for Mechanical Variables

For the instrumentation of variables such as gaseous pressure, mechanical pressure due to load, stress and differential pressure elastic primary sensors are commonly used. The configuration of 03 common types' diaphragms, bellows and Bourdons are presented next.

4.3.2 Diaphragms

These are usable for both gas and liquid pressures. The three types of these are shown in Fig. 4.2. They are characterized by wide range, high accuracy, and good dynamic properties-suitable for rapidly varying pressures. Diaphragms are made as thin circular plate fastened (generally) rigidly at the support along periphery.

Pressure on diaphragm plate causes displacement of central point as a function of the input pressure as in Fig. 4.2. The material of the diaphragm is chosen so as to have high sensitivity, mechanical strength, stability and low nonlinearity. With these criteria, the materials that qualify for diaphragm are phosphor-bronze, stainless steel and alloys such as beryllium–copper, monel, inconel-x, nickel-span-C etc. The Table 4.2 presents a comparison of various materials used for diaphragms.

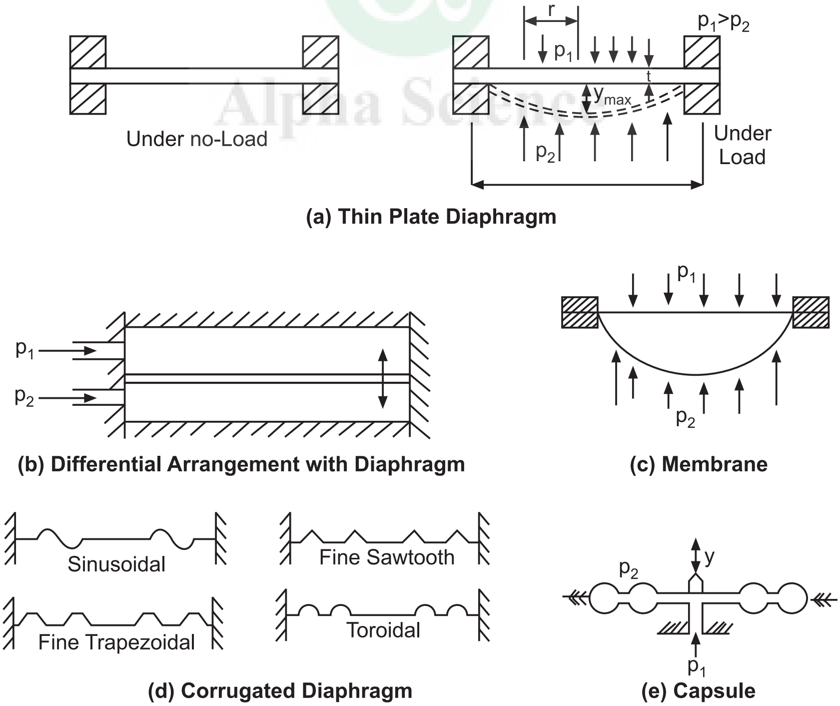


Fig. 4.2 Various Types of Diaphragms

TABLE 4.2 Properties Materials used for Diaphragms

S. No.	***Property***	***Phosphor Bronze***	***Berylleum Copper (Alloy 25)***	***Monel (400)***	***Inconel-x***	***Nickel Span-C(1902)***
1.	Composition %	Cu 90.5-92.8		Ni & Co 63-70	Ni $\geq$ 72	Ni 41-43
		Fe $\leq$ 0.1	Be 1.8	C $\leq$ 0.3	Cr 14.1	Cr 4.9-5.8
		P 0.03-0.35	Cu 98.2	Fe $\leq$ 2.5	Fe 6.10	Fe 48
		Pb $\leq$ 0.05		Mn $\leq$ 2.0	Ti 2.2-2.7	Ti 2.2-2.8
		Sn 7.9		Si 0.5	Al 0.41	
		Zn $\leq$ 0.2		S $\leq$ 0.024	Mn $\leq$ 1	
				Cu 28-34	Si $\leq$ 0.5	
					S $\leq$ 0.5	
					Co $\leq$ 0.5	
2.	Sp. gravity (kg/m^3)	8800	8250	8830	8470	8050
	Hardness (Rockwell B)	85	30	60	310	450
3.	Tenstile strength yield (MPA)	450	1200	550	6875	645
	Modulus of elasticity GPa	110	124	178	175	<200
	Poission Ratio	0.35	0.285	0.32	0.29	0.33
	Resistivity (Ω-cm)	1.33×10^{-5}	$4.6\text{-}8.6 \times 10^{-5}$	5.47×10^{-6}	Na	5.0×10^{-5}
4.	Thermal Conductivity W/m-k	62	130	21.8	Na	NA
	Melting point, °C	880-1025	110	1300	1413	1480
	Annealing Temp. °C	475-675	420-470	NA	NA	650
5.	Remark	Good resistance to corrosion, cold workability to drawing, forming, bending, shearing	Ductile weldable, Good for abrasive wear, Good strength, durability, electrical conductivity	High resistance against corrosion useful in acidic environment.	Useful for precision springs, diaphragms High strength even at high temp	Useful for heated atmosphere, Thermo elastic

The relation between input pressure and output displacement of diaphragm-centre for different types vary according as the type of diaphragm and represents the sensitivity. These are discussed further.

(*a*) Thin plate diaphragm, is the most commonly used type of primary sensor. It is a pressure sensitive elastic circular plate made of alloy. Thickness of plate '*t*' and diameter '*d*' are chosen according to the range of pressure to be measured. The choice of *d*/*t* ratio varies from 25 to 100, with thickness ranging from 0.1 to 5.0 mm.The plate is rigidly clamped at the circumference as shown in Fig. 4.2(*a*) to experience the deflection (maximum) at the center or the displacement or to have differential operation as shown in Fig. 4.2(*b*) Diaphragms can also takes the form of more flexible membrane (c) or more length (for larger pressure) corrugated shape (*d*). Capsule, Fig. 4.2(*c*) is a combination of two diaphragms sealed together. To understandthe relation between impressed pressure and deflection caused consider Fig. 4.2(*a*).

A diaphragm of radius R, thickness *t* is subjected to a test pressure p_2 where as p_1 is the ambient (or reference) pressure. The small displacement due to deformation is sensed and measured by a transducer providing electrical output. Such diaphragms are suitable for dynamic measurements up to 10 kHz and can be made quite insensitive to temperature changes. These are stable and rugged with minimum effect of clamping achieved by precision machining of thicker plates.

The maximum deflection under bending at the center for applied pressure p_2 is given by:

$$p_1 - p_2 = p = \frac{16Et^4}{3R^4(1-\mu^2)}\left\{\frac{y_m}{t} + 0.488\left(\frac{y_m}{t}\right)^3\right\} \qquad ...(4.1)$$

where p = differential pressure in N/m^2

E = Young's modulus of elasticity of the material of diaphragm in N/m^2

t = thickness of the diaphragm in *m*

R = radius of the diaphragm in *m*

μ = Poisson ratio of diaphragm material

Equation (4.1) can be approximated by a linear relation for $\frac{y_m}{t} \le 0.3$ by

$$p_1 - p_2 = p = \frac{16Et^4}{3R^4(1-\mu^2)}\left\{\frac{y_m}{t}\right\} \quad ...(4.2)$$

or,
$$y_m = \frac{3R^4(1-\mu^2)}{16Et^3}p \quad ...(4.3)$$

The deflection y at any radius $r < R$ is given by

$$y = \frac{3(1-\mu^2)}{16Et^3}p(R^2 - r^2)^2 \quad ...(4.4)$$

and
$$y_{max} = \frac{3}{16}p\frac{R^4(1-\mu^2)}{Et^3}. \quad ...(4.5)$$

(*b*) Membranes

These are very thin diaphragms made of non metallic materials such as Teflon, leather, neoprene, backed by soft metallic springs or polythene coated with gold. Membranes are in radial tension under pressure and the surface tends to become hemispherical under pressure Fig. 4.2(*c*) the deflection of member at centre is given by

$$y_{max} = \frac{R^2}{4T}(p_1 - p_2) \quad ...(4.6)$$

where T is the radial tension in N/m.

These are used for low pressure and high sensitivity applications.

(*c*) Corrugated diaphragms and capsules

The corrugations or folds on the diaphragm increase the mechanical strength, flexibility and sensitivity to measurand pressure variations: Different profiles of corrugated diaphragms are shown in Fig. 4.2(*d*).

The deflection is related to input pressure by a non-linear relation,

$$p_1 - p_2 = A \times y_m + B \times y_m^3 \quad ...(4.7)$$

$$= \left(\frac{Et^3}{R^4}a\right)y_m + \left(\frac{Et^3}{R^4}b\right)y_m^3 \quad ...(4.8)$$

where a, b depend on corrugations size and type, and material of diaphragm respectively.

Capsules, are made by soldering, brazing, or weld jointing (depending on material) of identical corrugated diaphragms as shown in Fig. 4.2(*e*). Often these are made of metallic foils to have high strength, flexibility and have high sensitivity. They find common application in pneumatic instrumentation as also for converting gas pressures into displacement.

4.3.3 Bellows

The bellow is a thin walled, single piece structure with a number of folds on cylindrical surface along the axis as shown in Fig. 4.3. The folds also called corrugations or convolutions, helps to generate much larger displacement of tip.

These are made of beryllium-copper (Be-Cu), phosphor-bronze or stainless steel of about 0.1 mm wall thickness for precision and higher pressures (than diaphragms). These can be made from plastic and rubber for use at low pressures but without precision.

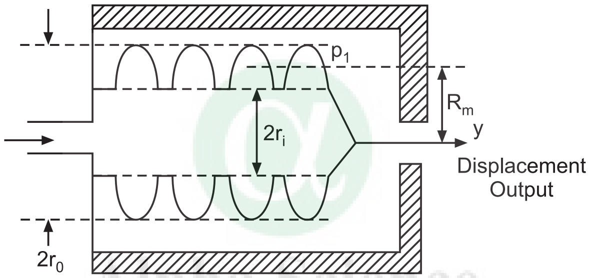


Fig. 4.3 Below as Primary Sensor

Bellows are also used in control applications where pneumatic instrumentation and control is preferred such as in chemical and oil industry. Be-Cu provides good dynamic response while steel is corrosion resistant.

These are available in various sizes from 5 mm to 100 mm and wall thickness from 80 to 300 microns. Their major advantage lies in low spring stiffness, linear relation between input differential pressure and displacement output and is given by:

$$y_m = \pi R_m^2 \left(\frac{1-\mu^2}{E.t}\right) \left(\frac{n}{a_0 + b_0\left(\frac{t}{r_i}\right)^2}\right) \Delta p \qquad \text{...(4.9)}$$

where, n is number of convolutions

R_m is mean radius in meters

Δp is $p_2 - p_1$

a_0, b_0 are functions of internal and external radii, radius of curvature and have to be specified by manufacturer.

4.3.4 Bourdons

These are used as primary sensors for high pressure range upto 100,000 p.s.i. or about $10^4 - 10^8$ Pascals. As shown in Fig. 4.4 the Bourdons are available in various shapes working on similar principle. Suitable arrangement has to be provided to measure the displacement of bourdon tip, caused due to input air/gas pressure applied and has to be converted in to an electrical signal by using another device *i.e.* transducer.

Consider the C-shaped bourdon made from a hallow tube in this shape (and hence the name) with other end closed. On applying a pressure the bourdon tries to straighten up resulting in tip moment. The sensitivity is defined as

$$S = \frac{\frac{\partial\phi}{\phi}}{\Delta p} = \frac{0.05\alpha}{E\beta^{\frac{1}{3}}}\frac{R^{\frac{1}{5}}}{t^{\frac{3}{5}}} \qquad \text{...(4.10)}$$

where $\frac{\partial\phi}{\phi}$ represents the fractional rotation of the tip of the tube, ϕ being the total angle of bourdon, t is thickness of wall of tube/helix, E is the Young's modulus of elasticity and R is the radius of the C-formed, all in S.I units.

These are made of same material as that of diaphragms.

The sensitivity of the helical Bourdon is given by

$$S_H = \frac{\frac{\partial\phi}{\phi}}{\Delta p} = \frac{1.16r^2}{t.y.b} \qquad \text{...(4.11)}$$

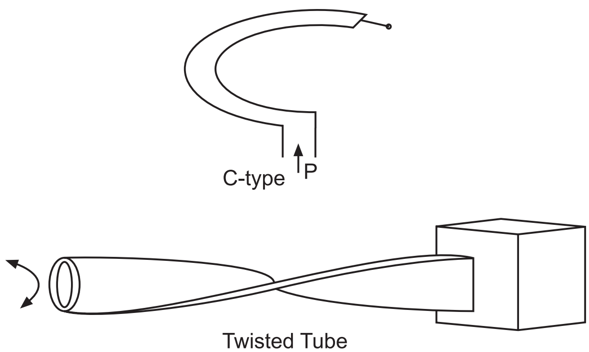


Fig. 4.4 Bourdons as Primary Sensor

These can be made of fused silica quartz with very low hysteresis, creep etc., and offer high sensitivity but are limited to static measurements.

With each of the above primary sensor, a transducer shall have to be associated so as to transduce the sensor output into electrical signal. In the next two chapters the principle of operation of the various transducers are discussed in the 3 categories as passive transducers (Chapter 5), active and digital transducers (Chapter 6).

4.4 PRIMARY SENSORS FOR FLOW

The various such devices have already been listed in Table-4.1. These are very useful in chemical and process industries, water and gas pipelines for utilities and power generating stations of both thermal and hydroelectric types.

Before entering into the description of primary sensors for flow instrumentation it is relevant to the mechanics of fluid flow in brief.

4.4.1 Dynamics of Fluid Flow

Fluid flow is important phenomenon in the operation of industry, sustaining human life and responsible for cycle of nature as well. Depending upon the specific case the devices to monitor the parameters and properties of fluid material may vary but the basics of flow remain common. Once the rate of flow is known, the pressure distribution and hence the force acting upon can be determined.

Types of fluid flow

The flows can be classified on different basis such as

1. Steady and unsteady flow: wherein the velocity, pressure and density etc., do not change with time.
2. Uniform and non-uniform flow: according as the change in velocity with occurring or not.
3. Laminar and turbulent flow: according as the fluid particles move in a straight line path or zig-zag.
4. Compressible and non-compressible flow: according as the density is constant or not.
5. Rotational and non-rotational flow: according as the laminar flow particles rotate about their axis.
6. One, two and three dimensional flow: according as the flow is a function of time and 1, 2 or 3 space coordinates.

4.4.2 Rate of Flow and Continuity Equation

This basic relation is based on the conservation of mass or material balance principle. Rate of flow through a pipe, Q, is dependent upon the velocity and the area of cross section as: Q = A.V (V in m^3/sec for liquid and in Kgf/sec for gases).

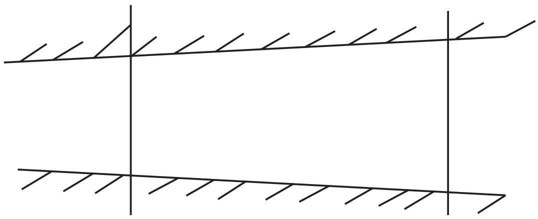


Fig. 4.5 Section of a Pipeline

Considering the Fig. 4.5 for the fluid flowing through a pipe with area of cross section, volume and density at any two arbitrary chosen points A and B to be A_1, V_1, ρ_1 and A_2, V_2, ρ_2 respectively then

Rate of flow at section $A = \rho_1 A_1 V_1$

Rate of flow at section $B = \rho_2 A_2 V_2$

According to material balance principle

$$\rho_1 A_1 V_1 = \rho_2 A_2 V_2 \qquad \text{...(4.12)}$$

and for incompressible fluids : $\rho_1 = \rho_2$

so that $A_1 V_1 = A_2 V_2$

4.4.3 Equation of Fluid Motion

Considering the force that cause motion assuming fluid to be incompressible and Non-viscous, the motion is defined by Euler's and Bernoulli's equation.

According to Newton's second law, the force F acting on a fluid is given by

$F_x = m\, a_x$ along the X-axis

= gravity force + pressure force + viscosity Force (negligible) + Turbulence force + Compressibility force (negligible)

With the assumption considered,

$$F_x = (F_g)_x + (F_p)_x + (F_v)_x \text{ : Navier-Stokes Equation} \qquad \text{...(4.13)}$$

For ideal fluids

$((F_v)_x = 0)$ then $F_x = (F_g)_x + (F_p)_x$: Euler's Equation. ...(4.14)

Euler's equation of motion considers the motion of fluids under the force of gravity and the pressure. This can be derived by considering a fluid element along a streamline by considering an cylindrical fluid element of length ds and area of cross section dA. The force acting on the element shall be (please see Fig. 4.6)

(*a*) Pressure flow in direction of flow = p.dA

(*b*) Pressure flow opposite to direction of flow due to pressure difference = $\left(p+\frac{\partial p}{\partial s}ds\right)dA$

(*c*) Weight of fluid element = ρ $g\ dA.dS$

If the angle between direction of flow and direction of action of weight is θ,

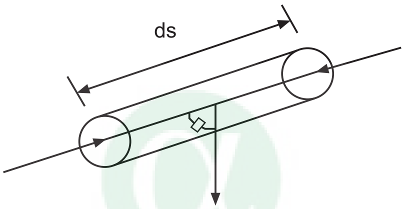


Fig. 4.6 Forces on a Fluid Element

the resultant force on the element shall be its weight multiplied by acceleration as

$$= \rho dA\ dS\ x\ a_s$$

$$= \rho dA - \left(\left(p+\frac{\partial p}{\partial s}ds\right)dA\right) - \rho g\, dA dS \cos\theta \qquad ...(4.15)$$

Acceleration along direction S, $a_s = \frac{\partial V}{\partial t}$

Velocity being function of S and t = $\frac{\partial V}{\partial S}\frac{\partial s}{\partial t}+\frac{\partial V}{\partial t}$

$$= \frac{\partial V}{\partial S}V+\frac{\partial V}{\partial t}$$

And, for steady flow $\left(\text{with } \frac{\partial V}{\partial t}=0\right)$ = $V.\frac{\partial V}{\partial S}$

By substituting the value of a_s in Eqn. 4.15 and simplifying

$$-\frac{\partial P}{\partial S}dA - \rho g dA \cdot dS Cos\theta = \rho dA dS V\frac{\partial V}{\partial S}$$

Divide by ρ dS dA throughout we get

$$\frac{1}{\rho}\frac{\partial p}{\partial S}+g\cos\theta+V\frac{\partial V}{\partial S}=0$$

Or $$\frac{1}{\rho}\frac{\partial p}{\partial S}+g\frac{dz}{dS}+V\frac{\partial v}{\partial S}=0.$$

as $\left(\cos\theta=\frac{dz}{dS}\right)$

Or $$\frac{dp}{\rho}+g\frac{dz}{ds}+VdV = 0 \qquad ...(4.16)$$

Equation (4.16) is known as Euler's equation of fluid motion.

Bernoulli's equation is obtained by integrating the Euler's equation of motion, as

$$\int\frac{dp}{\rho}+\int gdz+\int V\,dV=0$$

ρ is constant for incompressible fluids,

$$\frac{p}{\rho}+gz+\frac{V^2}{2} = \text{constant}$$

Or $$\frac{p}{\rho g}+\frac{V^2}{2g}+z = \text{constant} \qquad ...(4.17)$$

Equation (4.17) is known as Bernoulli's equation with

$\frac{p}{\rho g}$ = pressure energy p.u. weight of fluid or pressure head

$\frac{V^2}{2g}$ = Kinetic energy p.u.weight/kiead head

z = potential energy p.u. weight/potential head

Assumptions made are:

(*i*) The fluid is ideal. *i.e.* zero viscosity.

(*ii*) The flow is steady.

(*iii*) The fluid is non-compressive.

(*iv*) The flow is non-rotational.

In case of real fluids, the assumptions may not be held true and result in loss of head. The Bernoulli's equation in modified form will be :

$$\frac{p_1}{\rho g} + \frac{V_1^2}{2g} + z_1 = \frac{p_2}{\rho g} + \frac{V_2^2}{2g} + z_2 + h_L \qquad \text{...(4.18)}$$

where h_L is the head loss.

Also, the flow velocity can be deduced from the above equations as by using Eqn. 4.17 applied at any two sections along the flow:

$$V_1 = \frac{2}{\rho}\sqrt{\frac{1}{\left(\frac{A_1}{A_2}\right)^2 - 1}} \cdot \sqrt{\Delta p} \qquad \text{...(4.19)}$$

$$= K_1\sqrt{\Delta p} \qquad \text{...(4.20)}$$

provides the measure of fluid velocity.

and, flow rate $\quad Q_v = A_1 V_1$

$$= \sqrt{\frac{2}{p\left(\frac{1}{A_2{}^2} - \frac{1}{A_1{}^2}\right)}} \cdot \sqrt{\Delta p} \qquad \text{...(4.21)}$$

$$= K_2\sqrt{\Delta p} \qquad \text{...(4.22)}$$

Thus measurand differential pressure depends on fluid density which is a function of temperature and pressure, ratio of A_1 and A_2 and flow velocity.

Simplified Bernoulli's equation would be

$$\frac{\rho}{2}V_1^2\left[\frac{A_1^2}{A_2^2} - 1\right] = p_1 - p_2 = \Delta p \qquad \text{...(4.23)}$$

Ratio of A_1 and A_2 depends on tap locations, Reynolds number and location of vena-contracta.

Thus the fluid velocity and flow rate can be measured using the differential pressure (Δp) developed across the orifice, using relationships of Eqns. (4.20) and (4.23).

Similar type of square root relationship exists for other differential pressure (dp) type flowmeters (also called dp cell). Flow nozzles are in common use with steam and have high capacity. Elbows are low cost, low accuracy devices.

Due to squareroot relationship as observed, a common approach for output processing is to use an accurate squareroot extractor as signal conditioning/linearising devices.

4.4.4 Venturi Flowmeters

Venturi Flowmeters are useful in applications where low pressure drops are needed. The cross sectional area is reduced gradually to generate a differential pressure, as show in Fig. 4.7. These can be designed for range between 10:1 offering same accuracy over a wide range and applications *e.g.* volumetric flow rate of dirty fluid, slurries, air flows, steam flows etc.

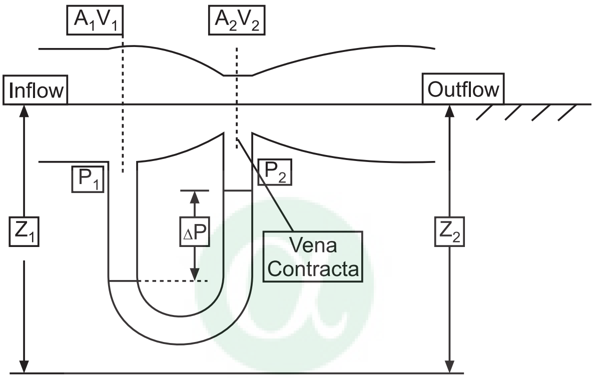


Fig. 4.7 Venturimeter for Flow Monitoring

In the newer types, the venture is used as a primary sensor to convert the pressure difference due to flow, and electrical transducer converts the pressure difference into electrical signal.

EXAMPLE 4.1

The dimension of a pipe at the section (1) and (2) are 20cm and 30cms respectively. Find the velocity of flow at location (2)and the discharge through the pipe if the velocity of flow at section(1) is 2m/s.

SOLUTION:

$$d_1 = 20 \text{ cms} \therefore A_1 = \frac{\pi}{4}(20)^2 = 100\pi \text{ cm}^2$$

$$v_1 = 2\text{m/sec}$$

$$d_2 = 20 \text{ cms} \therefore A_2 = \frac{\pi}{4}(30)^2 = 225\pi \text{ cm}^2$$

Velocity of flow at Section (2),

$$v_2 = Q/A_2 = v_1A_1/A_2 = 2 \times 100\pi/225\pi = 0.88\text{m/sec}$$

and the discharge $Q = v_1A_1 = 2 \times 0.01\ \pi = 0.0628 \text{ m}^3/\text{sec}$

EXAMPLE 4.2

A jet of water drop of 20 mm nozzle is directed to remain circular and the loss of energy assumed negligible. Calculate the velocity with which the jet will strike an object at a distance of 2 meters. Assume the velocity of jet at the nozzle to be 10 m/sec. Also, calculate the area that will be impacted by jet.

SOLUTION:

Diameter of nozzle $d_1 = 0.020$ m

Velocity of jet at nozzle $V_1 = 10$ m/sec

Let the velocity 2 meters above (the nozzle) to be V_2

We know that......

$$(V_2)^2 - (V_1)^2 = 2g\,h$$

$$V_2^2 = (10)^2 + 2 \times 9.8 \times 2 = 139.2$$

and $$V_2 = 11.7983 \text{ m/sec}$$

By using continuity equation

$$V_1 A_1 = V_2 A_2$$

So $A_2 = V_1 A_1 / V_2$ on solving it and putting the value of A_2, we get the desired value of

$$(d_2)^2 = A_2 / \frac{\pi}{4} = 3.3903 \times 10^{-4}$$

$$d_2 = 18.41 \text{ mm.}$$

EXAMPLE 4.3

A fluid with specific gravity 0.8 brought to a plant through a pipe at the rate of 40 litres/sec. A venturi is being used to monitor the flow rate in an inclined section with the diameter of 2 Sections (1) and (2) as 20 cms and 10 cms respectively, along the direction of flow Section 1 and 2 are 4m and 3m above the reference. If the pressure p_1 is 40 N/cm^2, find the pressure p_2.

SOLUTION:

$$d_1 = 0.\ 2\text{m} \quad \therefore\ A_1 = \frac{\pi}{4}(0.2)^2 = 0.0314 \text{ m}^2$$

$$d_2 = 0.\ 1 \text{ m} \quad \therefore\ A_2 = \frac{\pi}{4}(0.1)^2 = 0.007853 \text{ m}^2$$

$$p_1 = 40 \times 10^4 \text{ N/m}^2$$

z_1 = 4m, z_2 = 3 m

Q = 40 litre/sec = 0.04m^3/sec

= $V_1A_1 = V_2A_2$

∴ $V_1 = Q/A_1$= 1.273 m/s

∴ $V_2 = Q/A_2$ = 5.1282 m/s

By application of Bernoulli' sequation, assuming liquid chemical to be non compressive with ρ = 800.

On substituting the values, we get $p_2 = 33.04 \times 10^4$ N/m^2.

EXAMPLE 4.4

Find the volume and mass flow rates of water through a pipe of 0.1 m diameter if the flow velocity is 0.8 m/Sec.

SOLUTION:

Volume flow rate, Q = V.A

where, $$A = \frac{\pi d^2}{4} = \frac{\pi \times 0.01}{4} = 7.854 \times 10^{-3}\ \text{m}^2$$

∴ $Q = 0.8 \times 7.854 \times 10^{-3} = 6.28 \times 10^{-3}$ m^3/Sec

and, mass flow rate, $W = P.Q$

∵ Relative density for water = 1000 kg/m^3

∴ $W = 1000 \times 6.28 \times 10^{-3}$ = 6.2831 kg/Sec.

In Chapter 7 it will be seen that using ventury, orifice plate or flow nozzle to covert the flow rate into pressure difference can be further transformed into an electrical parameter, which in turn converts to an electrical signal with the appropriate signal conditioning.

4.4.5 Orifice plate

This is the most common primary sensing device for monitoring the flow rate of liquids and gases based on differential pressure and cause the minimum drop in head among the various devices. It offers an obstruction to the flow by putting a plate having an orifice/hole, perpendicular to flow axis. This creates a loss of head due to constriction and a pressure difference appears on the two sides of orifice. As shown in Fig. 4.8, the liquid upstream at a steady flow rate, approaches the orifice B, the pressure increases and liquid experiences a minimum size of stream little beyond the orifice at *vena contracta*. There after the stream tends to expand and the pressure too, slowly becoming steady (say) p_C though a little less than the upstream steady pressure. The differential pressure $p_A - p_B$ provides a measure of the velocity of flow as derived later. Upstream and downstream pressure taps are carefully placed to achieve accuracy up to 0.5%. Length of the orifice plate unit is required to be 15 times the diameter of pipe for laminar flows and β factor (ratio of internal diameter of orifice to internal diameter of pipe) of about 0.1, to limit the head loss to 0.5 $(p_A - p_B)$.

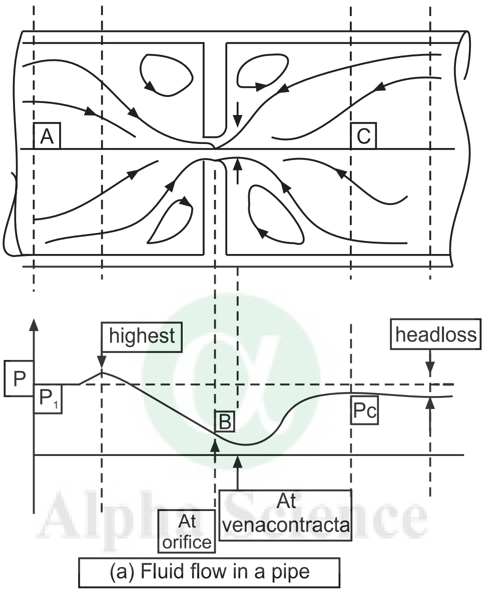


Fig. 4.8 Fluid Flow in a Pipe

If at point '*A*' upstream we assume pressure p_A, velocity v_A, area of cross section A_A respectively and similarly the quantities at point B *i.e.* at the orifice are p_B, v_B, A_B, and σ is the specific gravity of the liquid.

Energy balance equation at the two points A and B for laminar flow provides

$$p_A + \frac{V_A^2}{2\rho} = P_B + \frac{V_B^2}{2\rho} \tag{4.24}$$

and flow $\qquad Q = V_A A_A = V_B A_B$

$\therefore \qquad V_b = (V_A A_A)/A_B$

$\therefore$ Eqn. (4.24) can be written as

$$2\rho\,(p_A - p_B) = v_b^2 - v_a^2$$

$$\therefore \qquad v_A^2 = v_b^2 - 2\rho(p_A - p_B)$$

$$= \frac{v_A^2 A_B^2}{A_B^2} - 2\rho(p_A - p_B)$$

$$\therefore \qquad v_A^2\left[1-\left(\frac{A_A}{A_B}\right)^2\right] = 2\rho\ (p_B - p_A)$$

$$\therefore \qquad V_A = \sqrt{\frac{2\rho(p_B - p_A)}{1-\left(\frac{A_A}{A_B}\right)^2}} \qquad \text{...(4.25)}$$

$$\therefore \qquad Q = V_A\, A_A = A_A.\sqrt{\frac{2\rho}{1-\left(\frac{A_A}{A_B}\right)^2}}\sqrt{(p_B - pa)}$$

$$= K\sqrt{(p_B - p_A)} = K\sqrt{\Delta P} \qquad \text{...(4.26)}$$

The Eqn. 4.26 needs to be modified to account for non laminar flow, viscosity and temperature variation effects, any imperfections by including an empirical coefficient, C_d the coefficient of discharge, so that

$$Q = C_d K\sqrt{\Delta P} \qquad \text{...(4.27)}$$

EXAMPLE 4.5

In a measurement with orifice plate, with incompressible fluid, a pressure drop of 0.25M (of water column) was caused. Calculate the flow rate measured by orifice meter if the flow coefficient is 0.52.

SOLUTION :

From Eqn. (4.27)

Liquid flow velocity, $V = C_d\sqrt{2gH}$

$\therefore$ $Cd = 0.52$; $g = 9.8$ m/Sec^2; $H = 0.25$ m

$$\therefore \qquad V = 0.52\sqrt{2 \times 9.8 \times 0.25} = 1.151 \text{ m/sec}$$

Orifices are available for gas flow monitoring also and the velocity, volume and mass flow rate are obtained indirectly by some processing. It is possible to have linear output for pressure by root extraction through signal processing (signal conditioning) of the electrical signal obtained for the differential pressure as shown in Fig. 4.9.

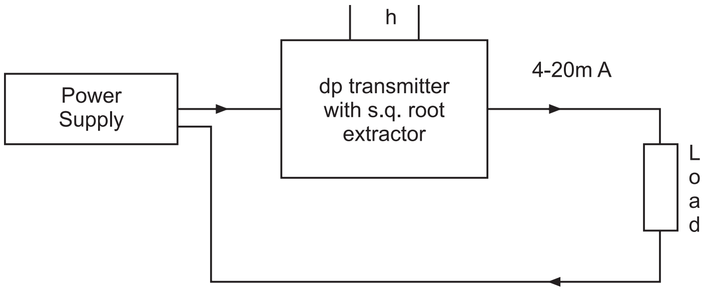


Fig. 4.9 dp Transmitter with Square Root Extractor

Flow Nozzles

These are preferred in many applications as it is able to have an optimum advantage of the simplicity of orifice plate and low pressure drop feature of venturi. It approximates a venture tube with gradually reducing area of cross section, as shown in Fig. 4.10, so that the discharge is parallel to the axis of downstream pipe. The downstream end approximates a short tube with diameter of vena-contracta, of an orifice of equal capacity *i.e.* large flow coefficient.

These are suitable for fluids with suspended solid particles, for high pressure and high temperature stream-flows.

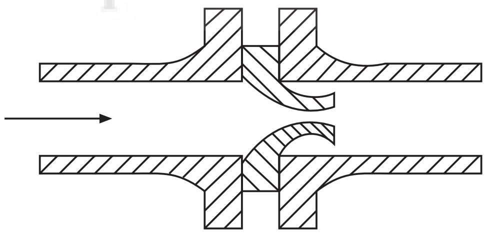


Fig. 4.10 Flange Type Flow Nozzle

4.5 SELECTION OF TRANSDUCERS

The general properties of instruments and systems-static and dynamic, have been discussed in Chapter 2 and earlier in this chapter. In the light of this information, the various factors to consider in the selection of transducers and the choice available is presented as :

Output	:	4-20 mA/0 – 5 Volts/frequency
Accuracy	:	±% of nominal range/full-scale value
Linearity	:	±% of full-scale

Repeatability	:	10,000 times or more, without the difference from previous set.
Hysteresis	:	% difference admissible between ascending and descending values of output for same input.
Proof value :		A test value for calibration *e.g.* 7.25 p.s.i. for pressure for which the output can be checked without any special device.

Comment

In this chapter sensor and transducers have been introduced which are the interface of instrumentation system with the real/physical world, that we are trying to observe closely or monitor. Primary sensors play an important role to convert the physical/non-electrical variable into an intermediate variable which is again non-electrical and interfaces with the transducer, that converts the intermediate variable into an electrical parameter or signal as may be possible, depending on the choice of transducer. Primary sensors typically find use with pressure and flow monitoring applications.

The problems are included to exert, search and devise the solution for some real-world problems that are being solved with the application of such devices.

This is an important technical activity and learnt over a period of time by experience. In this text at several occasions, choice tables shall be introduced for avid reader to develop an insight into the application mode (Chapter 7).

SUGGESTED READINGS

1. Patranabis, D – Industrial instrumentation (TMH)
2. Jones, B.E. – Instrumentation, measurement and feedback (TMH)

REVIEW PROBLEMS

4.1 What are the advantages of electrical transducers?

4.2 What are different methods of specifying linearity in device input-output Characteristics?

4.3 What is the principle of

(*i*) Bimetallic strip as a primary sensor for temperature

(*ii*) Gyros for sensing speedas displacement

(*iii*) Float for sensing level as displacement (*iv*) Spring for sensing force as displacement

4.4 What are the possible common application situations of: floats, springs?

4.5 What are primary sensors? Explain with examples.

4.6 How diaphragms can be used for transmission of sound signals?

4.7 What are different types of diaphragms and identify the typical application range of each?

4.8 How diaphragms can be used for converting pressure difference across any two points in a pipe line due to liquid flow, into an electrical parameter?

4.9 How gas pressures can be instrumented with the help of diaphragms of high sensitivity?

4.10 How helical Bourdon can be used to monitor the high pressure due to liquid?

4.11 Identify the situations in a car garage (workshop) for high pressure being used, how these shall be monitored and controlled?

4.12 What is mechanical hysteresis and how it affects the performance? Explain with example and figures.

4.13 What is the effect of defining the linearity in different ways?

4.14 What is the principle of flapper-nozzle assembly and how it is useful in pneumatic control and pneumatic instruments?

4.15 Search, identify and list with figures different pneumatic instrumentation and control components?

PROBLEMS FOR EXERCISE

4.16 List the various operations needed for ticket vending system to go through before the commuter is able to get his ticket and the cash balance. What are the sensor types to be provided to make the processing accurate and fast.

4.17 Repeat the above problem for checking the ticket of people entering the metro station and allowing only those who have valid tickets for the day.

4.18 In an automatic car parking lot, the vehicles are to be charged according to the time for which the vehicles have been parked, and to be allowed only after payment.

List the sensors and processing operations need to be implemented.

CHAPTER 5

Passive Transducers

Inside the Chapter

INTRODUCTION

Most of the transducers being used, for whatever application they may be used, fall in this category. In this chapter emphasis is on principles employed and their main features, so that with a reasonable understanding of these, the choice is wide and open for a typical application. The passive transducers can be of the following types:

(*a*) **Resistive type**-based on the change of resistance or conductance of an element/device according as the change in measurand variable.

(*b*) **Inductive type**-based on the change of inductance (self or mutual) or reluctance of an element/device according as the change in measurand/variable.

(*c*) **Capacitive type**-based on the change of capacitance of an element/device in accordance with the changes occurring in the input measurand/variable.

(*d*) **Frequency modulating type**-based on the change of frequency of an oscillator according as the changes in the input measurand.

As can be noticed, in passive transducers, a voltage or current signal is not produced but only a change occurs in an electrical parameter which is used to modulate or condition the voltage (or current) from an external source, so as to obtain an electrical signal. In effect the electrical parameter is used to modulate a voltage source output to result in a modulated electrical signal and the change having a functional relationship with the magnitude of input measurand quantity.

5.1 RESISTIVE TRANSDUCERS

These transducers utilize the basic property of metallic conductors (in general) for which the resistance is given by:

$$R = \left(\frac{\rho l}{A}\right) \Omega \quad \text{...(5.1)}$$

where, ρ is the resistivity of conductor material in ohm-meter

l is the length in meters,

A is area of cross-section in meter square.

If a change can be made to occur in any of these parameters ρ, l, A due to measurand, we get a basis for the design of transducer. The major types of resitive transducers are discussed next.

5.1.1 Resistive Potentiometers

These work as a transducer to convert a mechanical position into a proportional voltage, depending on the fraction of total potentiometer resistance being used, with a movable wiper arm. Position of wiper varies according as the position input being monitored and required to be converted into a voltage signal. These can be worked with ac or dc but usually dc. The input motion may be linear, rotational or a combination of the two. Simple configurations to illustrate the principle are shown in Figs. 5.1(*a*), (*b*). Variable output voltage is function of input displacement X_i or θ_i and the desirable linear characteristicis shown in Fig. 5.2. This ideal characteristic is difficult to realize in practice as it stipulates that, no current is being drawn on the output side by the meter or recorder connected to measure. Invariably a loading error results, due to the current being drawn by the output meter connected, to measure the voltage. This voltage varies according as the magnitude of the resistance R_V of measuring device, relative to the resistance of potentiometer R_t. A smaller value of ratio $r = \frac{R_t}{R_v}$ ensures smaller loading error.

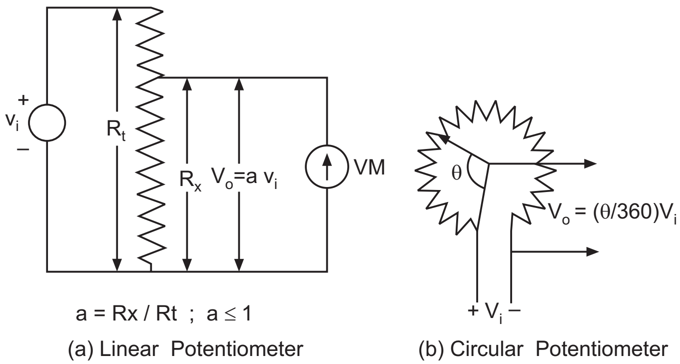


Fig. 5.1 Applications of Potentiometer as Displacement Transducer

For $a = \left(\dfrac{R_x}{R_t}\right)$ assumed to be the fraction of the total resistance of potentiometer being tapped and coming in parallel with the output measuring device (say voltmeter) of resistance R_v, the observed value V_0 of the voltage tapped across wiper arm would be:

$$v_0 = \left(\frac{A R_t R_v}{a R_t + R_v}\right)\frac{V_s}{\left(\dfrac{a R_t R_v}{a R_t + R_v}\right) + (1-a)R_t}$$

$$= \left(\frac{a R_t}{ar+1}\right)\frac{ar+1}{aR_t + (1-a)(1+ar)R_t}V_s$$

$$= \frac{a}{1+(1-a)ar}V_s \quad \text{...(5.2)}$$

Thus, it is evident that, if the resistance is pure (inspite of single or multi-turn winding), output for any position is a function of r and a. A typical set of characteristics is shown in Fig. 5.2 along with the ideal characteristic x_i vs. v_0.

The ideal or desirable output relation shall be:

$$V_0 = a \cdot V_s \quad \text{...(5.3)}$$

Therefore, loading error, $e = a \cdot V_s - v_0$ ...(5.4)

$$= \frac{a^2 r(1-a)}{1+(1-a)ar}V_s \quad \text{...(5.5)}$$

There are various types of potentiometers available. Commonly, either wire wound or conductive strip types are used, the later offering better resolution and more continuous, step-less resistance variation as the wiper travels along the turns. These are formed by depositing a conductive plastic coating or carbon film on a cardboard or on a non conductive former. For a potentiometer,

$$\text{Resolution} = \frac{1}{(\text{Total no. of turns})} \times 100\% \qquad \text{...(5.6)}$$

Typically, a single turn 360 degree (card type/wire wound pot.) with diameter of about 8 cm has a resolution of 0.04% at 10 K Ohm. A larger diameter potentiometer would normally result in still better resolution. For further improvement of resolution, the card is bent into a helix allowing more turns of resistance which also improves linearity.

In yet another improved type of pot, wiper is always in contact with the resistance wire, by having a spring loaded contact mechanism such that the contact of wiper with the previous turn is broken only after the contact is made with the next turn, as shown in Fig. 5.3. The resistance element is shaped in a spiral of about 1000 turns. This is an improved form, with the advantages of very high resolution, low capacitive and inductive effects, and excellent zero based linearity. These are available up to 25 KΩ with linearity up to 0.025%. The cost and manufacturing difficulties over 50 KΩ are main limitations. These are constructed by mounting within a steel, aluminum or plastic case. The shaft bearings are precision ball bearings and do not need lubrication.

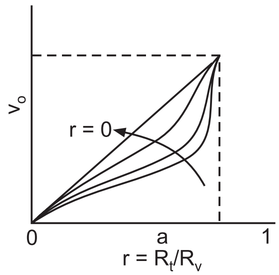


Fig. 5.2 Desirable Characteristic of Potentiometer

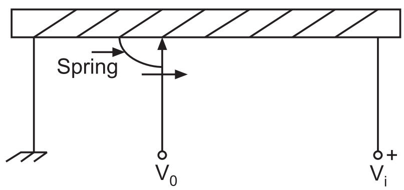
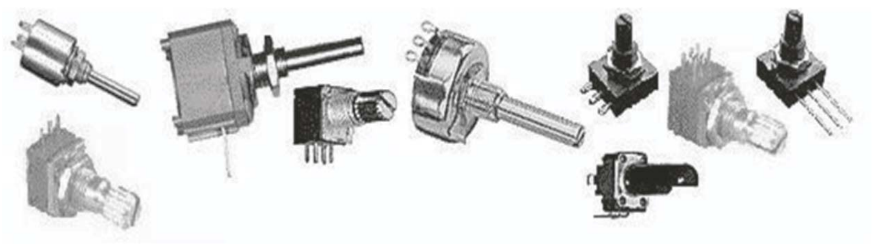


Fig. 5.3 Continuity Arrangement in Potentiometer

These can withstand acceleration up to 100 times that of gravity. Multi-turn models of pot are provided with mechanical stoppers at each end of resistance wire. Torque requirement for standard models with ball bearing, for starting is 1 Oz-in and for low torque models about 0.25 Oz-in. With jewel bearings it can be brought further down to 0.003 Oz-in. Running torque will be about ½ of starting torque. For lightweight construction for 7 cms dia pots, moment of inertia (M.I.) shall be about 0.05 Oz-in^2 and for those with body dia less than 2.5 cms can be assumed to have M.I of 0.005 Oz-n^2.

It is possible to have the output voltage from the pot as a particular function of the mechanical input, if required *e.g.* for synthesizing an optimum switching function in a relay control system or scheduling control for textile looms, *e.g.* sinθ, cosθ, etc. Of the various methods available for the purpose, one is to shape the former card to provide required function at great difficulty. Second is, by using linear resistors with tapings every few degrees (say 10°) and installing padding resistors across the taps, to have overall output characteristics as a piece wise linear segments approaching the desired function. Third approach uses voltages of suitable magnitude placed across the taps at regular steps of shaft movement.

Wire wound pots offer wide range, high output, low noise and better linearity but poorer resolution which is related to total resistance and size. For more details refer to text cited at the end. Noise in potentiometers is due to both electrical and mechanical reasons *viz.* motion of wiper over the turns of wire and bouncing of contact, when it is above a threshold speed causes drift and wear at the contacts, finite contact resistance and its variation during movement of wiper, friction at the wiper contact, resistance change with temperature, shock, vibration, humidity etc. These are available in the ranges up to 100 mm in dia., linearity up to 0.25% of full-scale, temperature ranges from –10°C to 75°C, resolution up to 10 microns and frequency bandwidth up to 10 Hz. Clearly these are suited for static measurements of displacement, pressure, force. A few common types of potentiometers are shown below:



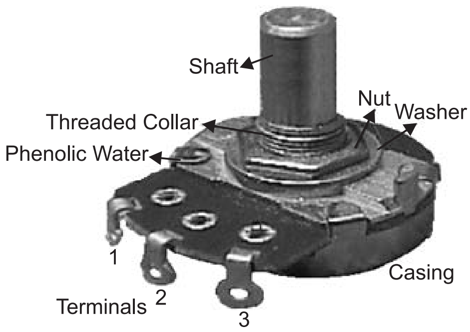


Fig. 5.4 Typical Wire Wound Potentiometers

Note that these are not to scale, although the relative sizes are passably close. Apart from the different body shapes and sizes, there are also many "standard" mounting hole and shaft sizes.

EXAMPLE 5.1

For a resistive potentiometer of total resistance 5 KΩ connected across a dc source of 10 volts. Find (a) the reading of voltmeter of resistance 1000Ω connected at the midpoint and the error in measurement. (b) Repeat for a voltmeter of resistance 10 KΩ.

SOLUTION:

From Eqn. (5.2) $V_0 = \dfrac{a}{1+(1-a)ar} \times V_s$

(*a*)

$$a = R_x/R_t = 0.5$$
$$r = R_t/R_V = 5\text{ K}\Omega/1\text{ K}\Omega = 5$$
$$V_s = 10\ v$$

$$\therefore \quad V_0 = \frac{0.5}{1+(1-0.5)\times 0.5\times 5} \times 10 = \frac{0.5}{1+0.25} \times 10 = 2.22 \text{ Volts}$$

True value with the ideal voltmeter should indicate 5v for midpoint connection.

Loading error = 5 – 2.22 = 2.78 v !! large.

From the Eqn. (5.5) Loading error,

$$e = \frac{a^2 r(1-a)}{1+(1-a)ar} V_s = \frac{0.25\times 5\times 0.5}{2.25} \times 10 = 2.777 \text{ volts}$$

and % loading error $\dfrac{2.22}{5.0} \times 100 = 44.4\%$

(*b*) $a = 0.5,\ r = 0.5$

$$V_0 = \frac{a}{1+(1-a)ar} \times V_s = \frac{0.5}{1+(1-0.5)0.5 \times 0.5} \times 10 = 4.444 \text{ volts}$$

$$\text{and, Loading error} = \frac{0.25 \times 5 \times 0.5}{1+(1-0.5) \times 0.5 \times 0.5} \times 10 = 0.0555 \text{ volts}$$

and % loading error

$$= \frac{0.0555 \times 100}{5} = 1.11\%.$$

If the voltmeter has still higher (input) resistance, say of the order of 1 MΩ and more the error will be further cut down! You may check.

Thus the loading error is greatly reduced with voltmeters having higher resistance being used. It will be further lower with voltmeter resistance still higher. Therefore, in all practical measurements this practice must be followed as far as possible.

5.1.2 Resistance Strain Gauge

These work on an entirely different approach, based on the change in resistance value due to mechanical forces applied on the resistance element itself. According to the laws of mechanics, the force causes stress in the resistance element and change in length *i.e.* the strain. This mechanical input – strain results in a change in resistance value. The increase or decrease will depend on the nature of strain *i.e.* force applied. A relation between input (strain) and the output (change in resistance) can be derived as follows:

Under pressure or force on a resistance wire element, all the three parameter ρ, ℓ and A undergo a change. Using partial differentiation we can write

$$\delta R = \frac{\rho}{A}\delta\ell + \frac{\ell}{A}\delta p - \frac{\rho\ell}{A^2}\delta A \qquad \text{...(5.7)}$$

or

$$\frac{\delta R}{R} = \frac{\delta\ell}{\ell} + \frac{\delta\rho}{\rho} - \frac{\delta A}{A}$$

For small changes it is possible to assume,

$$\frac{dR}{R} = \frac{d\ell}{\ell} + \frac{\delta\rho}{\rho} - \frac{dA}{A} \qquad \text{...(5.8)}$$

For resistance wires with circular cross-section and diameter D,

$$\frac{dA}{A} = 2\frac{dD}{D}; \text{ where } A = \frac{\pi}{4} \times D^2$$

Using Poission ratio $\mu = -\dfrac{\frac{dD}{D}}{\frac{d\ell}{\ell}}$ the Eqn. (5.8) can be arranged as:

$$\frac{\frac{dR}{R}}{\frac{d\ell}{\ell}} = 1 + 2\mu + \frac{\frac{d\rho}{\rho}}{\frac{d\ell}{\ell}} \qquad ...(5.9)$$

the last term $\dfrac{d\rho}{\rho} \Big/ \dfrac{d\ell}{\ell} = \psi E$ represents the change in resistivity due to mechanical stress (or, strain), is called piezo-resistivity and ψ is called Bridgeman constant. Its value depends on the material and chosen in such a way that it is small enough to be neglected without any appreciable error. With this approximation,

$$\frac{dR}{R} \Big/ \frac{d\ell}{\ell} = 1 + 2\mu = G \qquad (5.10)$$

and G is referred to Gauge Factor (G.F.)

Therefore, $dR = G\, \varepsilon\, R$, where $\varepsilon = \dfrac{d\ell}{\ell}$ is the strain.

The measurement of strain ε in terms of the change of resistanced R is the principle of strain gauge. By making strain gauge resistance part of an electrical circuit, it will be possible to have an electrical output which changes according as the change in strain, which in turn is due to the pressure or the force impressed upon is the measurand in the system.

By using the relation for Young's modulus of elasticity, E = stress/ strain

$$dR = \left(\frac{GR}{E}\right) \times \text{stress} \qquad ...(5.11)$$

In order to have high sensitivity, gauge factors should be as large as possible. For the assumption of linearity to be true, the specimen ought to be as small as possible and the effect of temperature should be minimal. Table 5.1 shows the properties of few materials suitable for making gauges and Fig. 5.5 illustrates the various configurations of strain gauges.

Constructional Features of Strain Gauges

These were developed by E.E. Simmons and A.C. Ruge in 1939 and are commonly available as metallic gauges or semiconductor gauges. Metallic gauges can be wire wound flat grid type or wrap around type as shown in Figs. 5.5(*c, d*) and foil type as shown in Fig. 5.5(*a*).

Flat grid type is wound as shown and firmly bonded to a backing material which may be paper, epoxy or bakelite using adhesive *e.g.* nitro cellulose cement.

Wrap around or helical grid type has the conductor wire wound on a flattened paper tube or a card and again firmly bonded on to the backing.

Foil type metallic gauges are formed by deposition of metal by printing and etching process on the backing of plastic base of low thickness to provide large contact surface for better transfer of strain from the specimen surface to gauge. The thickness of the foil is of the order of 4 micron with base of 25 micron, whereas the wire wound type gauges have wire dia. of about 25 micron. The overall size of gauge ranges from 5 cm to 0.04 cm.

The resistance of individual gauge ranges from 40 Ω to 2 KΩ but the values 120, 350 and 1000Ω are most commonly used. When properly cemented or fastened to the surface in which the strain is to be measured the gauge material also undergoes the same strain whether under tension or compression. Strains up to 20 – 50 microns can be measured with suitable signal conditioning.

5.1.5 Piezoresistive Sensors as Semiconductor Strain Gauges

It has been noted that the change in resistance in semiconductors under the influence of mechanical stress is one or two orders of magnitude greater than in metals.

This fact opened up the possibility of improving the strain gauge techniques. Piezoresistive sensors measure pressure by means of a resistance bridge diffused in silicon. The sensors excited with constant current are passive sensors. These are ideally suited for instrumenting static pressure.

They have been successfully used in offshore engineering for measuring depth and wave pressure, in technology for measuring and monitoring oil pressure in large bearings. Hydraulic systems, railway brakes, in rocketry for pressure measurement in fuel tanks, in automobile for diesel injection pressure measurements.

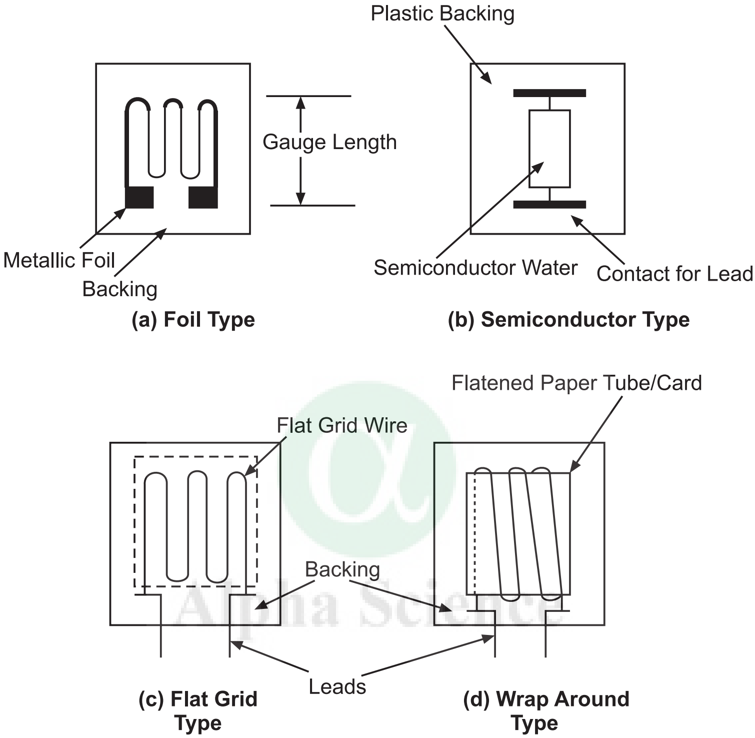


Fig. 5.5 Strain Gauges of Various Types

TABLE 5.1 Properties of Materials used for Gauges

Materials & Compositions	***Gage factor***	***Temp. co.eff.***	***Temp. range***	***Remark***
Nichrome Ni 80% Cr 20%	2.2-2.5	1	18-350°C	for dynamic cases; commonly used
Advance Ni 45% Cu 55%	2–2.2	2×10^{-3}	0-300°C	Poor temp stability low sensitivity
Isoelastic Ni 50%Cr 8% Mo 0.5% Fe 55.5%	3.5	1.75	-195 to 205°C	Ideal for dynamic strains; High sensitivity to temp. Only for dynamic strains

Materials & Compositions	***Gauge factor***	***Temp. co.eff.***	***Temp. range***	***Remark***
Karma Ni 74%Cr 20% Fe 3%Cu 3%	2.1	$2{\times}10^{-3}$	-45 to 200°C	Good fatigue feature; High stability; Self compensation possible
Semiconductor Wafer	100-150	high	up to 315°C	Very sensitive; fragile for static measurements; chemically inert; free from hysteresis and creep effects
Thin films	500-700		-200-400°C	High strain sensitivity/ High resistance; Rugged; Low power consumption

They are usable for both static (low frequency) and dynamic (high frequency) signals. Significant improvements have been obtained in sensitivity with simpler signal conditioning. These are able to meet the demands of high pressure up to 2000 bar level to meet the need for high efficiency and low carbon emission.

Piezoelectric crystal when desired to be used as semiconductor type strain gauges there are two modes of use. One is by using silicon wafer as shown in Fig. 5.5(*b*). In these the strain sensitivity is mainly due to resistivity changes in the semiconductor material (being used) *i.e.* Piezoresistivity effect is dominant. Semiconductor wafer to be used is obtained by slicing the growth crystal, cleaning and then slicing to filament of thickness 100 – 150 microns. The electrodes are made by vapor deposition technique and electrical contacts are made of gold wires. The resistance value can be made by electrolytic etching. The semiconductor elements are embedded in a base of Bakelite or fiber glass. The temperature coefficient is highly dependent on type – P or N and the amount of doping. Consequently the gage factors are observed to be highly variant with temperature *i.e.* negative for P-type silicon and decrease with increasing amount of doping.

Another approach is to have piezoresistive pressure measuring element/cell as shown in Fig. 5.6 undergoing change of resistance due to pressure (static or dynamic) via the elastic deformation of a diaphragm made of mono crystalline silicon. Silicon measuring cell is the basic unit of piezoresistive (PRT) transducers. Pressure is exerted from one side on a diaphragm made of mono crystalline silicon. A Wheatstone bridge comprising of semiconductor resistors is diffused into the surface of diaphragm. The bridge circuit is unbalanced proportionally by the applied pressure to produce an output voltage as a measure of pressure exerted.

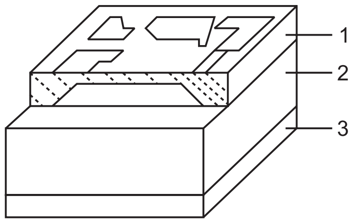


Fig. 5.6 Silicon Measuring Cell with Resistors Diffuse into its Surface

Constructional features are shown in Fig. 5.6. The cell consists of

(1) Anisotropic etched diaphragm on silicon,

(2) Glass spacer,

(3) Silicon base plate

The PRTs are sensitive to temperature and need compensation for frequencies other than at which it is calibrated. The cavity behind the diaphragm can be evacuated or ventilated. Special bonding techniques provide highly stable and hermetically sealed connections between glass and silicon. Measuring element is retained free of strain in transducer.

Thin film gauges are formed by vaporization and deposition of desired material in vacuum to form a desirable pattern. The substrate of materials such as gold, nickel, aluminum, palladium, cobalt, platinum can be used. Here again the piezoresistivity plays the dominant role. The deposited film has thickness of the order of 50 nanometer offering high resistance. Gauge factor varies nonlinearly with the resistivity of the material deposited and can be realized up to 700-800.

For resistive strain gauges the equation has been derived earlier as (5.9), wherein,

$$\text{G.F.} = 1 + 2\mu + \frac{\partial \frac{\rho}{\rho}}{\varepsilon} \qquad \text{...(5.12)}$$

$$= 1 + 2\mu + K\psi \qquad \text{...(5.13)}$$

For the semiconductor strain gauges the last component is much larger than the first two and given by:

$$\text{G.F.} = (1 + 2\mu) + \frac{\partial \frac{\rho}{\rho}}{\varepsilon} = GF + \psi E \simeq \frac{\frac{dR}{R}}{\varepsilon}$$

where ψ is Bridgeman constant and E is the modulus of elasticity and therefore

$$\Delta R = \psi\, E.\varepsilon.R \qquad ...(5.14)$$

Due to piezoresistive effect gauge factor increases to very large values, say 100 to 150.

For typical doped Silicon filament of thickness 150 μm with crystal orientation 111/100, the gauge factor can be calculated as

$$GF \equiv \frac{dR/R}{\varepsilon} = G_1 + G_2\alpha + G_3\,\alpha^2 + \ldots\ldots\ldots\ldots$$

whereas at 20°C $\quad \alpha \leq 10^{-4}$

Therefore, $\quad GF = 175 + 72625\,\alpha$ (for light doping)

$= 119 + 4000\,\alpha$ (for heavy doping).

EXAMPLE 5.2

For a metallic strain gauge of G.F. of 3, poission ratio μ of 0.6, modulus of elasticity E of 1.8 × 10^{16} kg/m² determine the value of Bridgeman constant.

SOLUTION:

Since, $G.F. = 1 + 2\mu + \psi E$

Therefore with $G.F. = 3$; $\mu = 0.6$; $E = 1.8 \times 10^{16}$ kg/m²

$\psi = (G.F. - 1 - 2\mu)/E = (3 - 1 - 1.2)/1.8 \times 10^{16} = 4.44 \times 10^{-12}$ m²/kg

This is reasonably small, so that for metallic strain gauges the peizoresistive effect is really negligible. For semiconductor strain gauges the value of ψ shall be much larger.

Bonding of Gauges

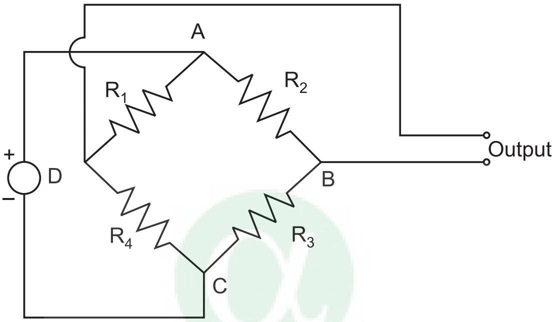
To facilitate perfect bonding of strain gages with the structure in which the strain/stress is being monitored, typical nitrocellulose cement adhesives are used. The gauge can not be removed from the surface without destroying it.

Nitrocellulose cement are synthetic compounds in paste or gel form and provide perfect adhesion of gauge with the surface of structure or machinery under test in which the stresses/strain are being measured.

5.1.3 Measurement with Strain Gauges

It is difficult to measure the change in resistance quickly and accurately particularly for changing loads. A simple technique of converting this change of resistance into a proportional change in voltage removes this difficulty. To achieve this, the gauge rigidly fixed to the body in which the stress/strain is to be monitored is made one of the arms (electrically) of the 4-arm resistive Wheatstone bridge, as shown in Fig. 5.7. The bridge is arranged, usually equal arm, such that, initially with the gauge unstressed is, balanced and the output voltage v_0 measured across points B and D is zero. As the strain gauge undergoes strain, due to loading (or stress) coming on the member, to whom it is attached, it experiences a change in resistance from the nominal value R, becomes $R \pm \Delta R$.

The sign of change depends on the stress condition *i.e.* tension or compression.



R_1 is S.G. under stress R_2, R_3, R_4 are Dummy Resistances

Fig. 5.7 Wheatstone Bridge as Measuring Device with Strain Gauge

Under the (initial) zero stress/strain bridge condition:

$$V_0 = E_{AD} - E_{AB}$$

$$= E\left[\frac{R_1}{R_1 + R_4} - \frac{R_2}{R_2 + R_3}\right] \quad \text{...(5.15)}$$

$$= E\left[\frac{R_1 R_3 - R_2 R_4}{(R_1 + R_4)(R_2 + R_3)}\right] \quad \text{...(5.16)}$$

The condition $R_1\,R_3 = R_2\,R_4$ is realized by adjusting the resistances to obtain null output. A common approach is to form an equal arm bridge *i.e.* choosing values of R_2, R_3, R_4 resistances equal to R_1 and still better to choose these three also to be strain gauges from the same lot as R_1.

Now consider that, the strain gauge R_1 undergoes stress resulting in strain ε and thereby a change in resistance $\Delta R_1 \Omega$. The bridge is no more balanced and the resulting output voltage of the bridge can be evaluated as

$$V_0 = E\left[\frac{(R_1 + \Delta R_1)\,R_3 - R_2 R_4}{(R_1 + \Delta R_1 + R_4)(R_2 + R_3)}\right] \quad \text{...(5.17)}$$

$$= E\left[\frac{\Delta R_1 R_3}{(R_1 + \Delta R_1 + R_4)(R_2 + R_3)}\right] \qquad \text{...(5.18)}$$

Chosing the values such that $R_1 = R_2 = R_3 = R_4 = \text{R}$ (say) and $\Delta R_1 = \Delta R$,

The Eqn. (5.18) simplifies to:

$$V_0 = E\left[\frac{\Delta R}{2(2R + \Delta R)}\right]$$

$$= E\left[\frac{\Delta R}{4R\left(1 + \frac{\Delta R}{2R}\right)}\right] \qquad \text{...(5.19)}$$

If the strain is limited to 1% then $\Delta R << R$ can be assumed and Eqn. (5.18) can be approximated to:

$$V_0 \approx \frac{E\,\Delta R}{4R} \qquad \text{...(5.20)}$$

Equation (5.19) is commonly referred as output equation for strain bridge in quarter bridge mode *i.e.* only one arm being active. The equation is nonlinear and its approximant Eqn. (5.20) is used more commonly, assuming ΔR to be much smaller than 2R.

For a tensile strain the change is considered positive and for compressive force the corresponding strain is taken to be negative *i.e.* the change in resistance as $-\Delta R$.

General form of Strain bridge

To make the bridge more effective, consider a situation when two opposite arms are active gauges with changes of opposite nature/ signs occurring *i.e.* $\Delta R_1 = -\Delta R_3 = |\Delta R|$, R_1 is under tension and R_3 under compression. Other assumptions remaining the same, R_2, R_4 referred as dummy gauges, the output can be derived to be:

$$V_0 \approx \frac{E\,\Delta R}{2R} \qquad \text{(5.21)}$$

Such a bridge with two equal arms is called **half bridge mode of operation**.

A further extension of this approach is to have the bridge with all four arms in active mode, such that $\Delta R_1 = \Delta R_3 = \Delta \text{R}$, $-\Delta R_2 = -\Delta R_4 = -\Delta R$.

General expression for output voltage under measuring condition can be written as:

$$V_0 = E\left[\frac{(R_1 + \Delta R_1)}{(R_1 + \Delta R_1 + R_4 - \Delta R_4)} - \frac{(R_2 - \Delta R_2)}{(R_2 - \Delta R_2 + R_3 + \Delta R_3)}\right]$$

$$\approx \frac{E\,\Delta R}{R} \tag{5.22}$$

A bridge with all four arms composed of active strain gauges is in **full-bridge mode of operation**. Later in Chapter 8 on signal conditioning, we shall consider the limitations of the output equations of strain bridges, of Wheatstone bridge and discuss an improved technique.

EXAMPLE 5.3

For a strain gauge having nominal resistance of 400 Ω and GF of 2.1, calculate the change in resistance of gauge if it is subjected to a strain of 1% under (a) tension (b) compression.

SOLUTION:

The change in resistance from Eqn. (5.9) is given by

$$dR = G\ E\ R$$

$$= 2.1 \times \frac{0.1}{100} \times 400 = 0.88\ \Omega$$

Under compression the change will be in opposite direction and the resistance of gauge will be reduced by 0.88Ω to 399.12Ω.

EXAMPLE 5.4

A strain gage of 120 Ω forms an arm R_1 of a Wheatstone bridge as in Fig. 5.6, with other arms of fixed resistances each of 120 Ω, and excited by a dc source of 5V. If strain gauge arm undergoes tensile stress resulting in strain of 0.1%, determine the output voltage V_0.

SOLUTION:

Change in resistance due to strain,

$$\Delta R = \text{G.F.} \times R \times V_0 = 2.0 \times 120 \times 0.001 = 0.24\ \Omega$$

$$\therefore \quad R_1 = 120 + 0.24 = 120.24\ \Omega$$

$$\therefore \quad V_0 = 5\ [\ (120.4/240) - (120/240)]$$

$$= (5 \times 0.24)/240$$

$$= 5\ \text{mV}.$$

EXAMPLE 5.5

A 4-equal-arm Wheatstone bridge as shown in Fig. 5.6 is used for monitoring strain. The gauge has G.F. of 2.0 and resistance 200 Ω, excitation voltage E is

5.0 V with negligible internal resistance and the output detector has resistance of 100 Ω. Calculate the output current in detector if, the bridge is being used in quarter bridge mode of operation with gauge forming arm R_1 and strained by 0.1%.

SOLUTION:

ΔR = GF. E.R. = $2 \times \frac{0.1}{100} \times 200$ = 0.4 Ω

$$V_0 = \frac{E\Delta R}{4R} = \frac{5 \times 0.4}{4 \times 200} = 2.5 \text{ mV}$$

To evaluate the current that will flow in the detector connected at the terminals *B*, *D* the bridge network can be considered a Thevenin's network with $V_0 = V_{TH}$ and R_{TH} to be determined.

Thevenin's resistance is calculated as

$$R_{TH} = 200 \,||\, 200 + 200 \,||\, 200.4\ \Omega.$$
$$= 100 + 100.099 = 200.099\ \Omega$$

∴ Current through detector $I_d = \frac{2.5}{200.099 + 100}$ mA = 8.33 mA

If the detector is considered to be a sensitive galvanometer, say with a sensitivity of 12 mm/mA, the deflection output mechanical (or optical) can be determined.

For the present arrangement, deflection in galvanometer shall be

12 × 8.33 = 99.96 mm = **9.996 cms**.

EXAMPLE 5.6

For a 120 Ω strain gauge with G.F. of 2.0 made from wire with temperature coefficient of resistance α of 4 × 10^{-3}/°C at 25°C. Find the maximum current that can be allowed through the gauge so that the error due to self heating is limited to 1000 μ-strain units. Heat dissipation from the gauge assembly is known to be 20 mW/°C.

SOLUTION :

Heat generated = $I^2(R + \Delta R) < 20 \times 10^{-3}$

Change in resistance for the gauge corresponding to strain of 1000 μ-strain units is

$$\Delta R = \text{G.F.} \times \text{strain} \times \text{Resistance of gauge}$$
$$= 2 \times 1000 \times 10^{-6} \times 120 = 0.24\ \Omega$$

New resistance due to rise in temperature = 120 × (1 + $\alpha\Delta T$) = 120.24 Ω.

$$I^2 < \frac{(20 \times 10^{-3})}{(120 + 0.24)}$$

$$\therefore \quad I = 0.407 \text{ mA.}$$

5.1.4 Resistance Temperature Detectors (RTDs)

These are used for measurement of temperature, and work on the basis, that some materials particularly metals have good temperature-resistance sensitivity. By characterizing the temperature behavior *i.e.* the change in resistance value between two temperatures one of them a specified reference (usually ambient), temperature can be calibrated from the change of resistance noted for the resistance transducer element being used. The change in resistance or a signal produced there from can be calibrated, to provide the measure of temperature difference. The actual temperature at any point of time during monitoring can be deduced by adding reference temperature and displayed.

(A) Metallic resistance thermometer

Also known as PTC (positive temperature coefficient) thermometer has metallic resistance element, whose resistance changes with change in temperature around it, according to the following equation:

$$R_T = R_0 (1 + \alpha\,\Delta T + \beta\,\Delta T^2 + \gamma\,\Delta T^3 + \ldots.) \quad \ldots(5.23)$$

where, R_T and R_0 are the resistances at temperatures T°C and at reference temperature T_0 and $\Delta T = (T - T_0)$.α, β, γ etc., are the temperature coefficients of resistance and their values depends upon the properties of the metal being used. In general over a limited range β, γ etc., are small and can be considered to be relatively small compared to α. Suitable choice of the metal provides α to be positive and hence the name. The approximation leads to:

$$R_T \cong R_0 (1 + \alpha\,\Delta T) \quad \ldots(5.24)$$

Figure 5.8 shows the resistance-temperature relationship for some of the metals commonly used for RTDs. Characteristics shown in this figure together with Table 5.2 provides the information base for selection of suitable RTD in a given application situation.

The factors which govern the choice of RTD material are:

- Sensitivity
- Linearity with temperature

- Range of operation
- Resistivity
- Repeatability
- Reliability
- Accuracy
- Stability – mechanical and thermal
- Cost

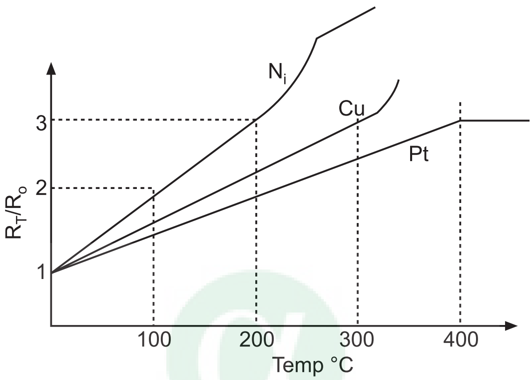


Fig. 5.8 Resistance Temperature Relationship

The calibration of temperature in terms of resistance can be obtained by using Callender's equation:

$$T = \frac{R_t - R_0}{R_{100} - R_0} \times 100 + \delta\left(\frac{t}{100} - 1\right) \times \frac{t}{100} + \beta\left(\frac{t}{100} - 1\right)\left(\frac{t}{100}\right)^3 \qquad \ldots(5.25)$$

R_0, R_{100} are the resistance values at ice point and steam point. δ is characteristic constant and β is the coefficient for higher order term of the thermometers, usually of small magnitude.

Platinum RTD are the most commonly acceptable temperature sensor all over the world, being most reliable for measuring and comparing temperature information. They provide long term stability and repeatability for use as a primary standard. The wide useful temperature range makes it ideal for laboratory and industrial applications.

In Fig. 5.9 is shown an advanced design of a platinum RTD for surface probes. For this class it is necessary to bring the greatest amount of object surface heat in direct contact with the sensor for effective heat transfer. Sensor is made by carefully winding a fine diameter wire into a circular coil and then bonding to a platinum base plate of low thermal resistance which contacts with the specimen surface. Platinum base is bonded directly to thin stainless steel bell shaped housing of low mass. Heat loss is impeded by the housing, being poor conductor of heat and the coil spring, when used, also has high thermal resistance. Spring articulated surface probe provide automatic articulation of the tip for conformity and uniform contact with the mesurand surface.

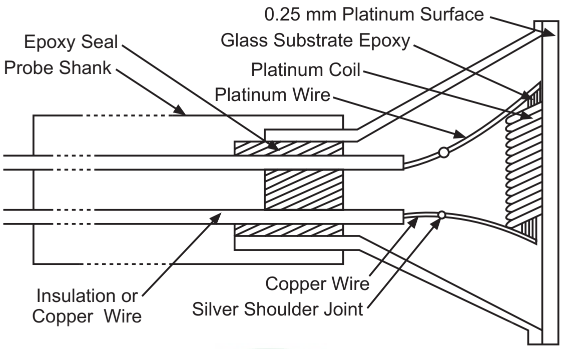


Fig. 5.9 Advanced RTD Probe Construction Details

TABLE 5.2 Properties of Materials Commonly used for RTD

Material	α Ω/Ω/°K	*Resistivity (μΩ-cm)*	*Temperature range (°C)*	*M.P. (°C)*	*Comments*
Copper	0.0043	1.56	-200 to 250	1083	Cheap; big size
Nickel	0.0067	6.38	-100 to 350	1455	High sensitivity; good reliability & repeatability
Platinum	0.0039	9.83	-250 to 700	1755	Wide range, accurate, costly

RTD probes vary in their design and construction according as the application as shown in Fig. 5.10.

Immersion types of probe (*a*) with sensing element typically 1.5 mm in dia and 9.5 mm long. The platinum element is protected by a 3/16″ stainless steel sheath in immersion probes to resist the corrosive atmosphere and provide longer life. The sheath has a thin wall section at the tip to provide good heat transfer to the resistance element for fast response. These are characterised by temperatures up to 480°C and time constant as low as 1.4 seconds. For corrosive solutions, probe is Teflon coated to avoid contamination.These are used for liquids, semi-liquids, granular materials, food and candy, plating baths, brewing vats etc.

Penetration probes (Fig. 5.10(*b*)) have conical pointed tips to penetrate foods, vegetable, meat, candy or other soft materials *viz*. Plastic melts, rubber, asphalt with time-constant of about 2 seconds for temperatures up to 230°C and 3.7 seconds up to 480°C.

Figure 5.10(*c*) represents platinum RTD thermo-well probe with spring loading. This provides fast response and positive contact at the bottom of thermo-well. These have time constants of about 2s and measures to 99% of final steady value in less than 15 secs.

Figure 5.10(*d*) shows air probes. These have high sensitivity and designed for temperature measurements with gas and air flows. The sensor is shielded by a perforated steel tube to induce good velocity and prevent radiation error. These have very thin dia of about 1.25 mm, and are useful for industrial ovens, stack and duct temperatures, gas and air measurements in high voltage ac applications.

Figure 5.10 (*e, f, g*) shows different types of surface probes.

These include 45° angled ultra-fast spring articulated type with tip having broad surface for efficient heat transfer and usable up to 480°C with response time of 2 sec.; Self-adhesive surface probe with sensor encapsulated in a polymer material and pressure sensitive adhesive used mainly for environmental tests, curing cycles and oven monitoring; Bolt on probe for temporary fixing on a surface and usable up to 500°C with time constant of 2 seconds.

The comparative features of various types of RTDs including those discussed above are summarised in Table 5.3, which includes the characteristics–temperature range and response time.

EXAMPLE 5.7

An RTD is used to measure the temperature over the range 25°C to 700°C. It is known to have the temperature coefficient of resistance of 0.0039/°K with nominal resistance of 100Ω at ambient temperature of 25°C. Calculate the resistance at 250°C and at the maximum of range.

SOLUTION:

As we know, $R_T = R_{25}(1 + \alpha\,\Delta T)$

There is no need to convert α to per °C as the difference is being taken,

$$\therefore \quad R_{250°C} = 100\,[1 + 0.0039\,(250 - 25)] = 187.75\ \Omega$$

$$\text{and} \quad R_{700°C} = 100\,[1 + 0.0039\,(700 - 25)] = 343.75\ \Omega.$$

For a large range to be covered with some RTD and a large change occurring in resistance, it is necessary that the variation of resistance with temperature should be as linear as possible. Therefore a suitable transducer must be chosen to meet this requirement.

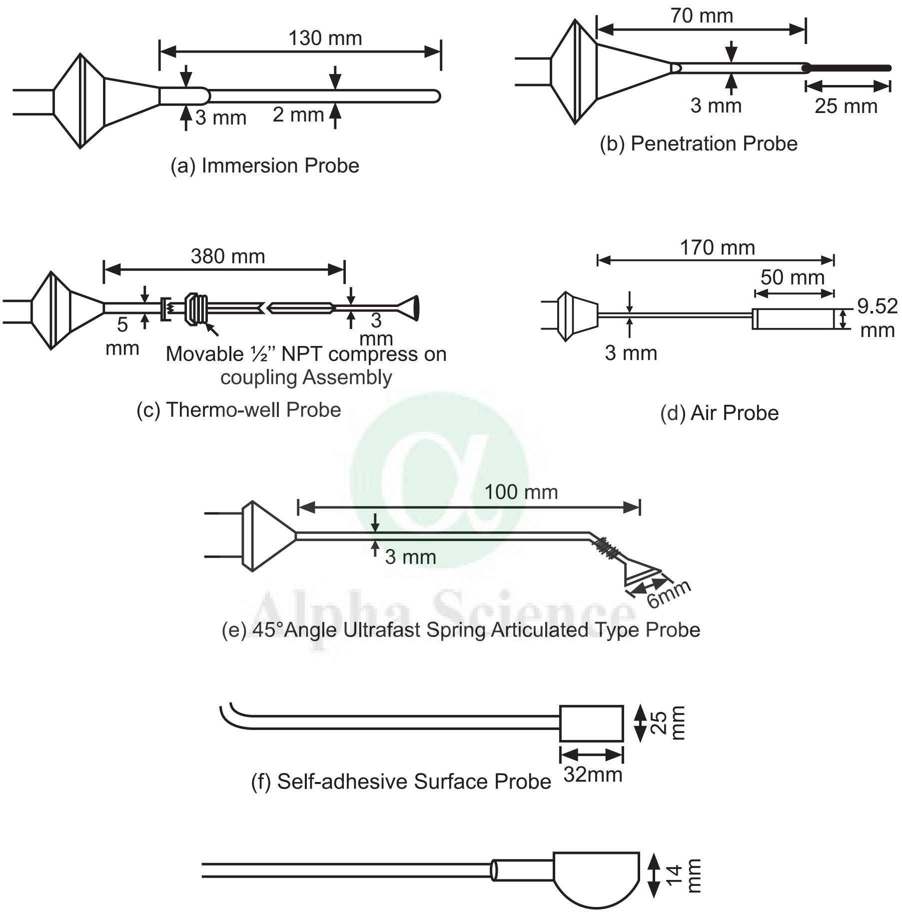


Fig. 5.10 Various Types of RTD Probes

EXAMPLE 5.8

An RTD with resistance of 400Ω at 30°C and temperature coefficient of resistance $\alpha = 0.004/°C$ is used in a dc bridge circuit. R_1 and R_2 arms are of fixed resistance 400Ω and R_3 is a variable resistance to balance bridge. The RTD has a heat dissipation rate of 20mW/°C measured at 30°C. If the RTD is placed in a bath at 40°C, what is the value of R_3 to have null output?

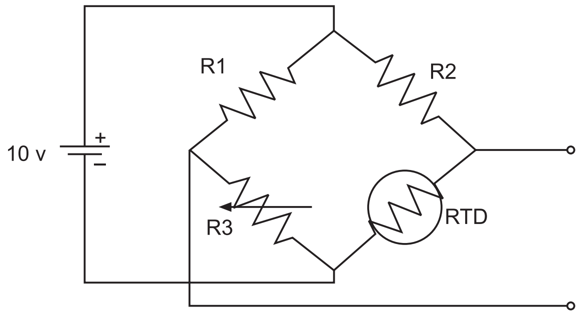


Fig. Ex. 5.8

SOLUTION:

By neglecting the effect of self-heating

Resistance of RTD at 40°C = 400 [1 + 0.004 × (40 – 30)]
= 400 × 1.04 = 416Ω

Current through the RTD = 10/(400 + 416) = 10/816 = 12.254 mA

∴ Heat produced due to self-heating in RTD = $I^2 R$
= $(10/816)^2 \times 416$
= 0.0624 W

Temperature rise of RTD = 0.0624 W/20 mW/°C = 3.12 °C

Therefore, RTD is actually at 30 + 3.12 = 33.12 °C

And, RTD's actual resistance = 400 [1 + 0.004 (40 – 33.12)]
= 411 Ω = R_3 for balance.

TABLE 5.3 Characteristics of Platinum RTD Surface Probes

Types of surface probe	***Features***	***Use***	***Characteristics***
(*a*) 45° angle ultrafast articulated with: straight probe, long reach or right angled	Contact certainty Miniature tip	Moulds, dies, bearings	480°C, 2 secs
(*b*) Self-adhesive patch type Bolt on type	Pressure sensitive, adhesive. Sensor encapsulated Sensor in fiber glass	Environmental tests, Automobile Engine, reactor monitoring	175°C, 1 sec 250°C, 2 sec 500°C, 2 sec
(*c*) Immersion type	Fast, low mass sensor in stainless steel casing	Liquids, semi liquids granular material, food, ice cream; For corrosive solution	480°C, 2 sec

Types surface probe	Features	Use	Characteristics
Teflon coated long probe heavy duty	300 mm long dia 3 mm length 310, 460, 610 mms	Solder bath, gases	230°C, 2 secs 480°C, 2 secs
(*d*) Penetration probe	Conical pointed tip	Food	230°C, 2 secs
(*e*) Air probe	Sensor shielded by perforated steel tube	Gas & air, in ovens, stacks, ducts	540°C, 6 secs
(*f*) Thermowell probes	Fast, + ive contact 75 – 305 mms		480°C, 2 secs

EXAMPLE 5.9

The lead wire resistance of an RTD connection to measuring station is 2Ω per lead. If no compensation scheme is used, determine the effect of load resistance on temperature reading and the percentage error for actual temperature of 400°C. Assume temperature coefficient of resistance for RTD = 0.4 Ω/°C.

SOLUTION:

The load resistance appears as additional resistance to the measuring device, to the change experienced by RTD. The additional resistance to load wire = 4Ω. Additional resistance corresponds to additional change in temperature

$$= \frac{\text{Additional resistance}}{\text{Temperature coeff of resistance}} = \frac{40}{0.4} = 10°\text{C}$$

$\therefore$ Temperature indicated = 400 + 10 = 410°C

$$\therefore \ \% \text{ error } = \frac{410 - 300}{400} \times 100 = \frac{10}{400} \times 100 = 2.5\%.$$

(B) NTC Thermometers

Contrary to the behavior of RTDs discussed earlier having reasonable sensitivity and almost linear characteristic, a group of semiconductor materials exhibit a large sensitivity but highly nonlinear resistance-temperature characteristic (NTC) with negative slope. Typical characteristic of a thermistor element is shown in Fig. 5.12(*i*), characterised by high sensitivity and exponential variation. The behavior can be modeled by the equation:

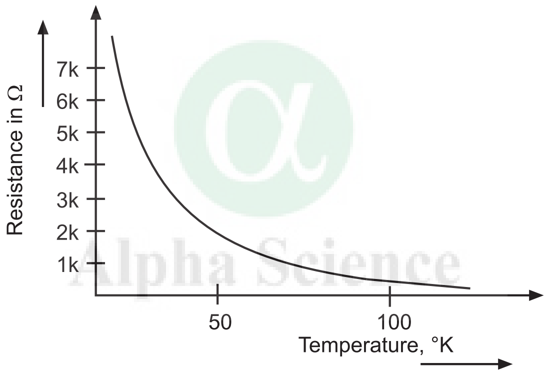
$$R = \alpha e^{\frac{\beta}{T}} \qquad \text{...(5.26)}$$

where α and β are constants for the given thermistor element; T is the temperature in degree Kelvin. As this equation is not always convenient to use, a practical form relating resistance values R_1 and R_2 for the same element at two different temperature T_1 and T_2 in °K can be expressed as follows:

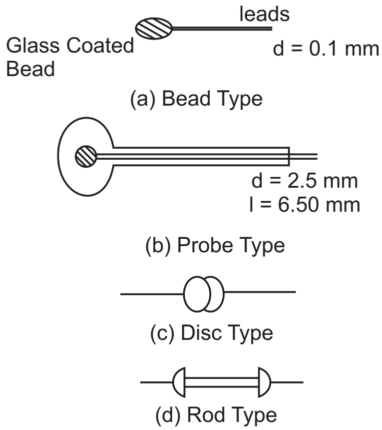
$$R_2 = R_1 e^{\beta\left(\frac{1}{T_2}-\frac{1}{T_1}\right)} \qquad \text{...(5.27)}$$

β is referred as characteristics temperature, whose value is specified by the manufacturer.

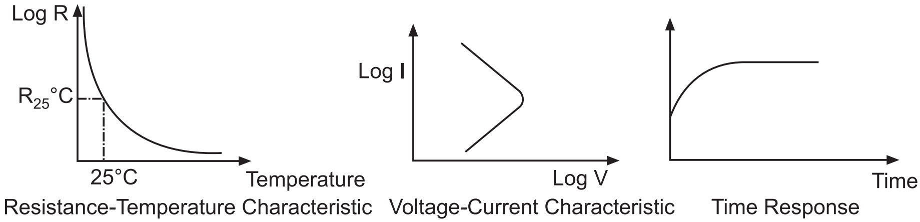
Thermistors are available in various shapes and sizes. The various forms are shown in Fig. 5.11(*ii*). As these are much smaller than RTDs of metallic type, these have faster response due to smaller mass. These



(*i*) Variation with Temperature For a Typical NTC Thermistor



(*ii*) Types of Thermistors



(*iii*) Dynamic Response

Fig. 5.11 NTC Thermistor (Mn - Ni + X Ceramics) characteristics

are constructed from sintered mixtures of the compounds of the oxides of iron, manganese, cobalt, copper etc. and sold under trade name, composition being proprietary. The nominal values of the thermistor bead are specified at a reference temperature and required characteristic graphs are available in manufacturers' data sheets. A set of typical resistance against temperature, voltage against current and current versus time characteristics is shown in Fig. 5.11.

The constants α and β need be specified by the supplier or else can be experimentally determined, using the relations for the thermistor resistance R_1 and R_2 at temperatures T_1 and T_2°K respectively, as:

$$R_1 = \alpha e^{\frac{\beta}{T_1}} \text{ and } R_2 = \alpha e^{\frac{\beta}{T_2}}$$

$$\frac{R_1}{R_2} = e^{\beta\left(\frac{1}{T_1}-\frac{1}{T_2}\right)} \qquad \text{...(5.28)}$$

$$\ln\frac{R_1}{R_2} = \beta\left(\frac{1}{T_1}-\frac{1}{T_2}\right)$$

$$\beta = \ln\frac{R_1}{R_2}\times\frac{T_1T_2}{T_2-T_1} \qquad \text{...(5.29)}$$

and

$$\alpha = R_1/\exp\left(\frac{\beta}{T_1}\right)$$

$$= \frac{R_1}{e^{\left\{T_2\ln\left(\frac{\left(\frac{R_1}{R_2}\right)}{(T_1-T_2)}\right)\right\}}} \qquad \text{...(5.30)}$$

Thermistors are useful in the temperature range of—60° to 150°C only with the accuracy of $\pm$0.1% at 100°C. Beyond this range the problems of self-heating or thermal runaway(or instability) may arise. For special applications, like those in process industry and convenience of handling, these are commercially available with enclosures. The use of enclosing shield provides mechanical strength, protection against chemicals and longer life, but they make the response somewhat slower.

This class of sensors referred as NTC (Negative Temperature Coefficient) sensors is ideally suited for temperature alarm circuits, where nonlinearity is of little importance.

EXAMPLE 5.10

A thermistor is observed to have resistance measurement data as:

(1) 5.2 K Ω at 90°C (2) 480Ω at 150°C

Determine the constant α and β for the thermistor and resistance at an intermediate value 120°C.

SOLUTION:

From Eqn. (5.29)

$$\beta = \left(\ln\frac{R_1}{R_2}\right)\left(\frac{T_1 T_2}{T_2 - T_1}\right)$$

$$= \left(\ln\frac{2500}{480}\right)\left(\frac{(90+273.15)(150+273.15)}{150-90}\right)$$

$$= 2.382 \times 2563.58 = 6106.6°\text{C}$$

and α, can be evaluated from Eqn. (5.30) as

$$\alpha = \frac{R_1}{\exp\left(\frac{\beta}{T_1}\right)} = \frac{5200}{\exp\left(\frac{6106}{363.15}\right)} = \frac{5200}{20054993}$$

$$= 2.592 \times 10^{-4}\ \Omega/°\text{C}$$

$$R_{120} = R_2 \exp\left(\beta\left(\frac{1}{120+273.15} - \frac{1}{T_2}\right)\right)$$

$$= 480 \exp\left(6106\left(\frac{1}{120+273.15} - \frac{1}{150+273.15}\right)\right)$$

$$= 1443.58\ \Omega$$

As can be noticed from the table of results below that:

Temperature	***Resistance***
90°C	5200 Ω
120°C	1443.58 Ω
150°C	480 Ω

The resistance at midpoint between 90°C and 150°C is far below the mid point value on a linear scale. This is not unexpected in case of nonlinear behavior *i.e.* in this case, exponential decay of resistance with rise in temperature. The fall in resistance is very fast in the beginning compared to later part, finally asymptotic or very-very slow and therefore not usable for higher temperatures.

Of late, it has been possible to prepare PTC thermistors showing nonlinear increase of resistance with temperature, as shown in Fig. 5.12. The sudden nonlinear increase in temperature about the reference temperature makes them unsuitable for temperature measurement but they find wide application in temperature and fire alarm devices.

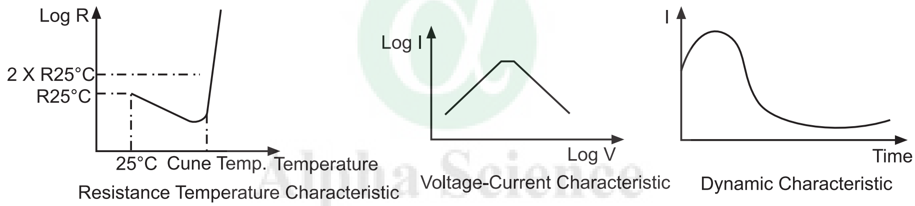


Fig. 5.12 PTC Thermistor ("POSISTOR") $BaTiO_3$ Ceramics

Sensitivity of a thermistor is defined as the rate of change of resistance with temperature, evaluated as:

$$\frac{\frac{dR_T}{dT}}{R_T} = \alpha\left(\frac{\exp \beta\left(\frac{1}{T}\right)\left(-\frac{\beta}{T^2}\right)}{R_T}\right) = \frac{-\beta}{T^2} \tag{5.31}$$

Value of α is defined over the range low temperature, (say) between 0°C to 50°C and typical value could be 0.06 at 25°C and will correspond to 66Ω/°C change in temperature for a thermistor having a value of 1 KΩ at 25°C, which is very high compared to any metallic RTD available (see Table 5.2).

5.2 INDUCTIVE TRANSDUCERS

This class of transducers is based on the principle that a change in the inductance (self/mutual) can be effected by changing its parameters due to variation in some external physical variable, so that the physical variable can be monitored by relating it to the change in inductance.

The self-inductance of a coil can be expressed as $L = \frac{N^2}{R}$, where N is number of turns of the coil then the reluctance of coil can be given by

$$R = \frac{M}{\phi} = \frac{\ell}{\mu A}$$

$$\therefore \qquad L = \frac{\mu A N^2}{\ell} \qquad (5.32)$$

Looking carefully at the Eqn. (5.32), it can be observed that the variation in inductance of a coil can be thus perceived as a function of change in a physical variable which causes a change in:

- Reluctance of the circuit about coil
- Permeability associated with the coil
- Flux linkage between two closely placed coils *i.e.* causing a change in mutual inductance.

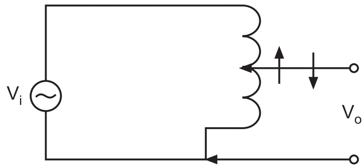
For this class of transducers there is no common theory of operation and there are hundreds of variations being used. Only a few of these are described here:

5.2.1 Inductive Type Transducers based on Change in Reluctance

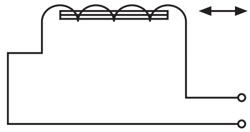
Inductive type transducers based on change in reluctance are far less common for industrial applications. The change can be affected as shown in Fig. 5.13 *a*, *b*, *c*, and *d*. These can be made with high sensitivity,linearity as good as 0.5% to 1% for very small displacements. A change in inductance is related as:

$$\frac{\Delta L}{L} = \pm\frac{\Delta X}{X} \qquad ...(5.33)$$

The use of this type is found in proximity sensors with non-contact property providing mechanical and electrical isolation typically for displacement and speed.

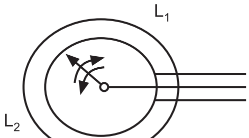


(Change in Position of Wiper)
(a) Inductive Potentiometer



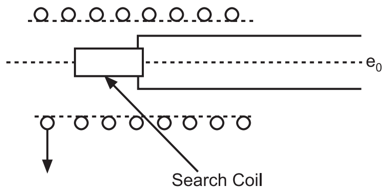
(Change in Permeability of coil)

(b) Plunger and Core

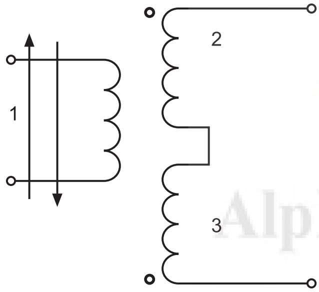


$L_1 = L_0 \pm \Delta L$
$L_2 = L_0 \pm \Delta L$

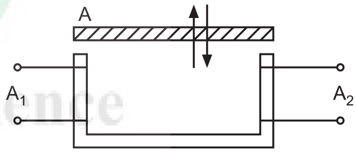
(c) Differential Arrangement (L_1 and L_2 in Opposition)



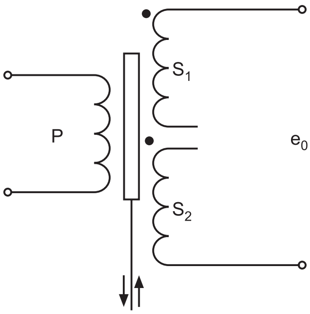
(d) Change in Mutual Inductance due to Geometric Position of Search Coil



(e) Change in Mutual Inductance due to Geometric position of Coil producing Differential Output



(f) Change in Mutual Inductance with Variation of Reluctance due to Position of Plate A



(g) Change in Mutual Inductance between Primary and Secondary due to Position of core, Resulting in Differential Output

Fig. 5.13 Change of Inductance Techniques for Inductive Transducer

5.2.2 Inductive Type Transducers based on Change of Mutual Inductance

Inductive type transducers based on change of mutual inductance have been used for a long time and a few possibilities are indicated in Fig. 5.13(*e, f, g*). In Fig. 5.13(*g*) is shown a Linear Variable Differential Transformer (LVDT) as a typical example, used as a displacement transducer. The unit consists of a transformer with two identical secondary windings and a movable core, schematically shown in Fig. 5.14. Electrical equivalent representation is shown in Fig. 5.15. With the core positioned centrally as shown in figure, the voltage induced in the two secondary windings are equal and the net output in the differential connection mode shall be zero. With the movement of core in either direction due to input displacement, a resultant output – voltage will be available, as a function of displacement, shown in Fig. 5.16 also known as Input-output characteristics for this device.

Amplitude of output voltage is a measure of the magnitude of the displacement after calibration and the phase of signal indicates the direction of motion. Input-output characteristics for this device.

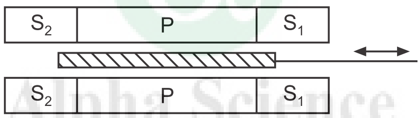


Fig. 5.14 Schematic Arrangement of LVDT

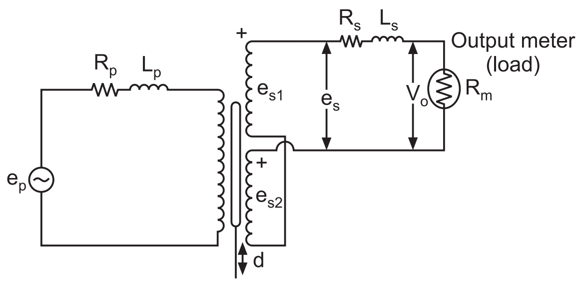


Fig. 5.15 Electrical Equivalent of LVDT

This device offers electrical isolation between the primary and two secondary windings and with a careful design can be made very sensitive to offer extremely good mechanical properties, compared to potentiometers. These have long life and wide range of applications *e.g.* under water up to 150 mm range and corrosive environment in the range of 0.1 to 500 mms.

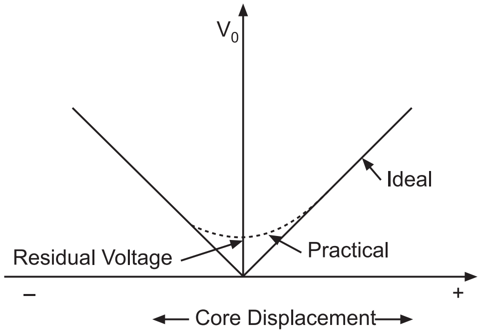


Fig. 5.16 Input-Output Characteristics of LVDT

5.2.3 Analysis of LinearVariable Differential Transformer (LVDT)

For the primary circuit by KVL,

$$e_p = i_p R_p + L_p \frac{di_p}{dt} \quad \text{...(5.34)}$$

and for the two secondary windings the emf induced due to mutual inductance, shall be

$$e_{s_1} = M_1 \frac{di_p}{dt} \quad \text{...(5.35)}$$

$$e_{s_2} = M_2 \frac{di_p}{dt} \quad \text{...(5.36)}$$

By connecting the two secondary windings differentially,

$$e_s = e_{s_1} - e_{s_2} = (M_1 - M_2)\frac{di_p}{dt} \quad \text{...(5.37)}$$

and $M_1 - M_2 = k\,d$ is assured from design considerations.

For the secondary circuit closed with the out meter with resistance R_m connected as shown in the Fig. 5.15.

$$e_s = i_s R_s + L_s \frac{di_s}{dt} + i_s R_m \quad \text{...(5.38)}$$

$$= i_s (R_s + R_m) + L_s \frac{di_s}{dt}$$

Taking Laplace transform of Eqns. (5.34), (5.37), (5.38) and equating the last two, it is possible to obtain:

$$I_p(s) = \frac{E_p(s)}{(R_p + sL_p)}$$

and $I_s[(R_s + R_m) + sL_s] = s.k.d(s).I_p(s)$

$$= s.k.d(s).\frac{E_p(s)}{R_p + sL_p}$$

and, by substituting, $V_0(s) = R_m I_s(s)$, we have

$$\frac{V_0}{R_m}\left[(R_s + R_m) + sL_s\right] = s.k.d(s).\frac{V_p(s)}{R_p sL_p}$$

$$\therefore \qquad \frac{\dfrac{V_0(s)}{E_p(s)}}{d(s)} = \frac{s.k.R_m}{(R_p + sL_p)(R_s + R_m + sL_s)} \qquad \text{...(5.39)}$$

$$= \frac{s.k.R_m}{R_p(R_s + R_m)(1 + s\tau_p)(1 + s\tau_s)} \qquad \text{...(5.40)}$$

The term on the left hand side is referred as transfer function whereas $\frac{V_o(s)}{E_p(s)}$ is electrical T.F. The frequency response can be estimated by rewriting Eqn. (5.40) as,

$$\frac{\dfrac{V_o(\omega)}{E_p(\omega)}}{d(\omega)} = \left|\frac{\omega.k.R_m}{R_p(R_s + R_m)(1 + j\omega\tau_p)(1 + j\omega\tau_s)}\right| \qquad \text{...(5.41)}$$

where $\phi = 90° - \tan^{-1}\omega\tau_p - \tan^{-1}\omega\tau_s$

The magnitude plot would be as shown in the Fig. 5.17.

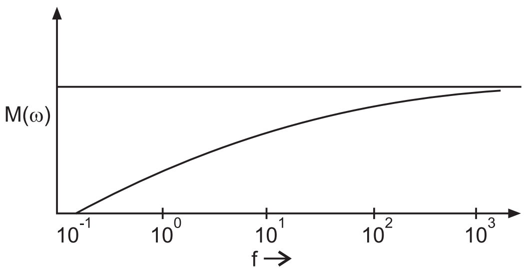


Fig. 5.17 Magnitude Response of LVDT

It must be noted that magnitude of output is a function of load (or meter) resistance and varies with ω directly. The effect is shown in the Fig. 5.18.

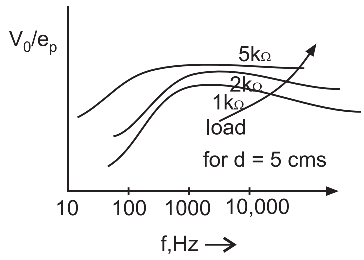


Fig. 5.18 Effect of LVDT Loading on Electrical Characteristics

The LVDTs are commonly operated at frequency larger than 1 KHz to improve sensitivity and this also helps to reduce the phase lag *i.e.* closer to zero.

EXAMPLE 5.11

For a ± 10 mm LVDT, calculate the output voltage available for a displacement of 5.6 mm from the null position. The available data is:

Primary winding resistance = 70 Ω

Primary winding inductance = 0.3 mH

Primary excitation = 2 Volts at 2 kHz

Each secondary winding resistance = 20 Ω

Each secondary winding inductance = 0.01 mH

Displacement constant, $k = (M_1 - M_2)/d = 0.001$

Voltmeter resistance =1 KΩ.

SOLUTION:

From Eqn. (5.28) for LVDT,

$$V_0(s)/E_p(s)/d(s) = \frac{skR_m}{r_p(r_s + R_m)(1+s\tau_p)(1+s\tau_s)}$$

$$V_0 = \frac{2\pi \times 2000 \times 0.001 \times 1000}{70(20+1000\left(1+2\pi \times 2000 \times 0.3 \times \frac{10^{-3}}{70}\right)\left(1+2\pi \times 2000 \times 0.01 \times \frac{10^{-3}}{1000+20}\right)}$$

$$\frac{1256 \times 10^3}{70 \times 1020 \times 1015 \times 1} V/m = 17.314 \text{ V/m}$$

$\therefore$ Output for 5.6 mm displacement = 96.958 mV.

5.3 CAPACITIVE TRANSDUCERS

In this class of transducers, the capacitance of a condenser is made to change in value, according as the changes in magnitude of input variable (being measured). Based on the theory of parallel plate capacitors with solids (or liquid) dielectric, the capacitance is determined as:

$$C = \frac{k \varepsilon A}{x} \qquad \text{...(5.42)}$$

The value of capacitance can be variable depending on the change in ε the permittivity of dielectric constant between the plates, A the area common between the plates or x the distance between the plates. These possibilities are shown in Fig. 5.19. The above three options are based on displacement and therefore can be used for instrumenting it. Among these the choice of any particular one depends on the acceptable sensitivity provided, as noted in the following:

Starting from the basic relation for parallel plate capacitor

$$C = k\,A/x$$

where k is a constant based on the geometry of the plates, A the area of plates and x the distance between them.

$$\therefore \qquad \frac{dC}{d\varepsilon} = \frac{kA}{x} \qquad \therefore \frac{dC}{C} = \frac{d\varepsilon}{\varepsilon} \qquad \text{...(5.43)}$$

$$\text{and } \therefore \qquad \frac{dC}{dA} = \frac{k\varepsilon}{x} \qquad \therefore \frac{dC}{C} = \frac{dA}{A} \qquad \text{...(5.44)}$$

$$\text{and } \therefore \qquad \frac{dC}{dx} = -\frac{k \varepsilon A}{x^2} \quad \therefore \frac{dC}{C} = -\frac{dx}{x}. \qquad \text{...(5.45)}$$

5.3.1 Capacitive Transducer based on Change in Gap between Plates

It is to be noted that, for small changes in gap between the plates, provides the maximum sensitivity but the variation of capacitance is nonlinear. It is therefore desirable to linearise the characteristics, which may otherwise pose problems in case of large displacements.

A simplified approach to obtain linear response is by using a differential arrangement as shown in Fig. 5.20. In Fig. 5.20(*a*) a movable central plate is introduced between the two fixed plates, to form a set of two capacitances in series, across the supply terminals. If initial gap for each of the 02 capacitors so formed, is assumed d and the displacement provided to the central vane is x, then we have

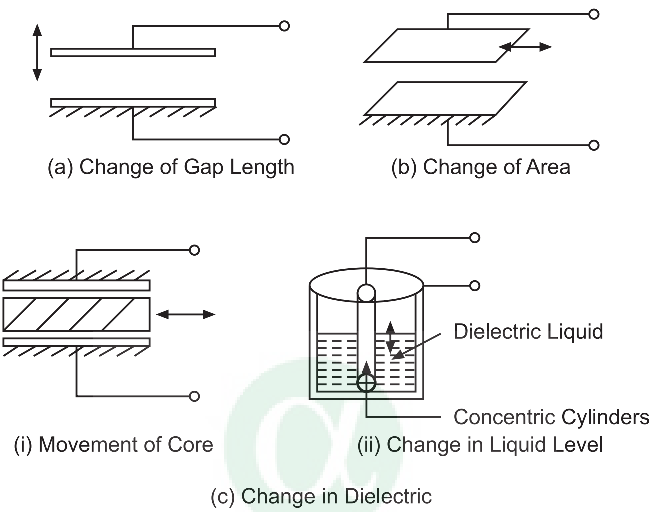


Fig. 5.19 Techniques for Change in Capacitance

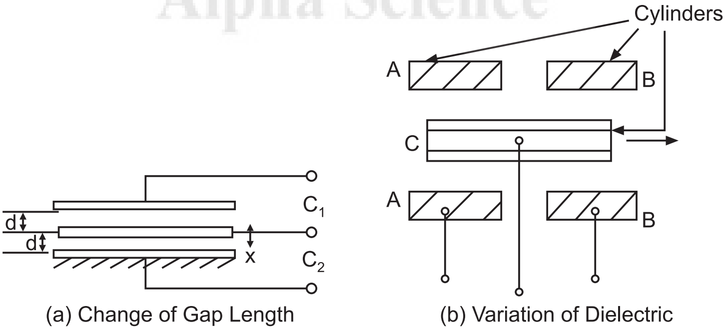


Fig. 5.20 Differential Capacitor Arrangement

Initially, $$C_1 = C_2 = \frac{k\varepsilon A}{d} \qquad \text{...(5.46)}$$

and, later with displacement x of the central vane upwards, the new values:

$$C_1 = \frac{k\varepsilon A}{d-x} \text{ and, } C_2 = \frac{k\varepsilon A}{d+x}$$

The voltage E applied across the 02 external plates *i.e.* the capacitor combination will be distributed over the two capacitances as,

$$E_1 = \frac{EC_2}{(C_1 + C_2)} \text{ and, } E_2 = \frac{EC_1}{(C_1 + C_2)}$$

By using an arrangement to measure the difference of the two voltages, as shown in Fig. 5.21,

$$E_d = E_2 - E_1 = \frac{Ex}{d} \qquad \ldots(5.47)$$

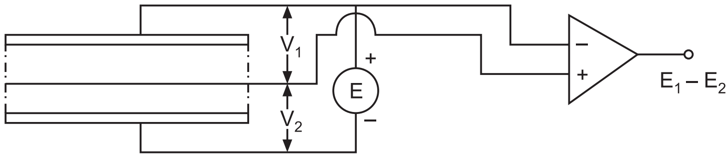


Fig. 5.21 Voltage pick-up for differential capacitive transducer

Thus, a linear relationship is obtained between the output voltage and the displacement of central vane. Such a differential arrangement with capacitive device offers a wide range of transducers, for process instrumentation applications.

In Fig. 5.20(*b*), a cylindrical movable core is used, for similar result.

EXAMPLE 5.12

A differential capacitive transducer arrangement is used for monitoring differential gas pressure, as shown in Fig. 5.21. The gap between plates on either side of central vane before use is 0.1 cm and the area of plates is 2 cm^2. If on introducing a differential gas pressure in the system, the central vane moves by 0.02 cm, calculate the change in each capacitance and the differential voltage available, for a source of 5 V, 1 kHz connected across the fixed plates.

If the differential pressure introduced is 100P_a (1P_a = 70 kg/cm^2), gas permittivity assumed to be 1.4, find the sensitivity of transducer.

SOLUTION:

Initially $C_1 = C_2 = \dfrac{\varepsilon A}{d}$

After the pressure have been introduced,

$$C_1 \to C_1 + \Delta C \; ; \; C_2 \to C_2 - \Delta C$$

$$C_1 = C_2 = \frac{1.4 \times 8.854 \times 10^{-12} \times 2 \times 10^{-4}}{10^{-3}} = 2.17912 \text{ pF}$$

and $$C_1 + \Delta C_1 = \frac{1.4 \times 8.854 \times 10^{-12} \times 2 \times 10^{-4}}{1.04 \times 10^{-3}} = 2.383769 \text{ pF}$$

$\therefore$ Change in capacitance $C_1 - (C_1 + \Delta C_1) = 0.0953$ pF
and, differential voltage developed shall be,

From Eqn. (5.35) $E_d = E_2 - E_1 = \dfrac{Ex}{d}$

$$= \frac{2 \times 0.04 \times 10^{-3}}{0.10 \times 10^{-3}} = 0.8 \text{ Volts}$$

Therefore, the sensitivity of the differential capacitive transducer for the gas pressure being measured can be evaluated from,

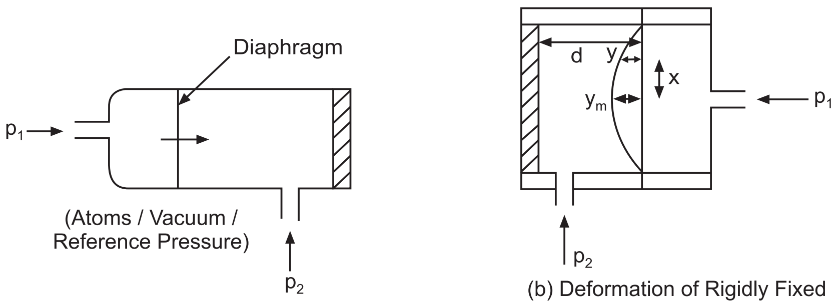
$$s = \frac{\text{Output voltage produced}}{\text{p.u. gas pressure introduced}} = \frac{0.8}{100} = 8m \text{ Volts/Pa.}$$

5.3.2 Realization of a Capacitive Pressure Transducer

Based on the principle of diaphragm deflection under pressure discussed in Sec. 4.32 and the principle of differential capacitor resulting in linear result discussed in previous section, it is possible to realize a pressure transducer which can be used for monitoring differential pressure, gauge pressure, atmospheric pressure etc., by making appropriate choice of p_2 which may be:

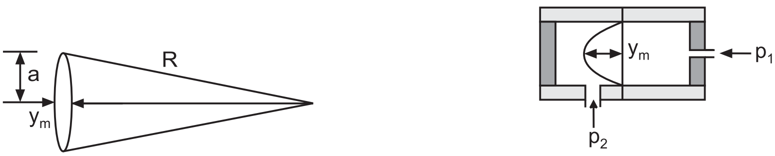
p_2	For
Vented to open	Gauge pressure measurement
Connected to vacuum	Absolute pressure
Connected to reference pressure	Differential pressure measurement

The realization of configuration may be as shown in Fig. 5.22. Next we consider the relationship between the input pressure of any of the above types and the change in capacitance.



(a) Arrangement

(b) Deformation of Rigidly Fixed thin Plate Diaphragm



(c) Catenry Form of Diaphragm

(d) Deformation of a Stretched Membrane

Fig. 5.22 Capacitance Pressure Transducer

5.3.3 Primary Pressure Sensors for Capacitive Transducer

Consider the thin metallic diagram as shown earlier in Fig. 4.2(*a*), subjected to a pressure p_1 due to gas flowin a pipe or acoustic pressure of speech. A differential pressure will be impressed on the diaphragm against the reference p_2 due to pressure in the other side. The diaphragm hinged on periphery will be uniformly stretched as shown in Fig. 5.23.

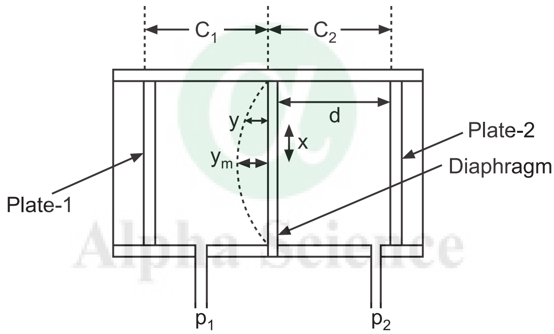


Fig. 5.23 Differential Capacitance Base Pressure Transducer using Thin plate Diaphragm as Primary

Consider an elemental annular ring at distance r from the centre, expressing a deflection y due to pressure $p_1 - p_2$. Due to change in the gap between fixed plate and the diaphragm the capacitance of the annular ring shall be,

$$dC = \varepsilon_0 \varepsilon_r \frac{2\pi r dr}{d-y} = \varepsilon_0\, \varepsilon_r 2\pi \left(\frac{1}{d-y}\right) rdr \qquad \text{...(5.48)}$$

where,

$$\frac{1}{d-y} = \frac{1}{d}\left(\frac{1}{1-\frac{y}{d}}\right) = \frac{1}{d}\left(1-\frac{y}{d}\right)^{-1} \cong \frac{1}{d}\left(1+\frac{y}{d}\right) \qquad \text{...(5.49)}$$

$$\because \qquad \frac{y}{d} << 1, \frac{y_m}{d} \cong 0.01$$

Therefore due to this change in capacitance over the initial state, the new value of capacitance can be expressed as:

$$C_0 + \Delta C = C = \frac{2\pi\varepsilon_0\varepsilon_r}{d}\int_0^R \left(1+\frac{y}{d}\right) r\,dr \qquad ...(5.50)$$

From Eqn. (4.4), where,

$$y = \frac{3}{16}p(R^2 - r^2)^2 \frac{(1-\mu^2)}{Et^3} = K.P.\ (R^2 - r^2)^2$$

By substitution and integration

$$C_0 + \Delta C = \frac{\pi\varepsilon_0\varepsilon_r R^2}{d}\left[1+\frac{K.p.R^4}{d}\right] \qquad ...(5.51)$$

$$\therefore \qquad C_0 = \frac{\pi\varepsilon_0\varepsilon_r R^2}{d} \qquad ...(5.52)$$

$$\frac{\Delta C}{C_0} = \frac{3}{16}p\frac{(1-\mu^2)R^4}{Et^3 d}. \qquad ...(5.53)$$

Thus an incremental change in capacitance is directly proportional to the pressure with the other parameters being constant, contribute towards sensitivity of the arrangement.

Very often soft diaphragms are used for higher sensitivity, which take a shape more like a stretched membrane as shown in Fig. 5.22(*d*) for which the approximations valid for a catenary hold:

(*a*) $2R = y_m + \dfrac{a^2}{y_m}$ (*see* Fig. 5.22 (*c*))

(*b*) $(y_m - y)\left[2R - (y_m - y)\right] = r^2$

Therefore by eliminating R, we can obtain

$$\frac{y}{y_m} = 1 - \frac{r^2}{a^2} + \frac{y_m^2}{a^2}\left(\frac{y}{y_m} - \frac{y^2}{y_m^2}\right) \qquad ...(5.54)$$

$$\cong \left(1 - \frac{r^2}{a^2}\right); \text{ as } \frac{y_m^2}{a^2} << 1 \qquad ...(5.55)$$

Also, deflection magnitude y, at an annular ring of radius r is given by

$y = \dfrac{p}{4}\dfrac{(R^2 - r^2)}{T}$; where T is the tension developed in the diaphragm.

Therefore, for an annular ring with a single capacitor,

$$C_0 + \Delta C = 2\pi\varepsilon_0 \int_0^R \frac{rdr}{d-y} = \int_0^R \left(1+\frac{y}{d}\right) r\,dr \qquad ...(5.56)$$

leads to,

$$\frac{\Delta C}{C_0} = \frac{1}{2}\left(\frac{y_m}{d}\right) = \frac{pR^2}{8Td} \qquad ...(5.57)$$

The single capacitor case as discussed above can be extended to differential arrangement shown in Fig. 5.19(*b*).

As the capacitance reduces in one chamber, it increases in the other. The annular differential change in capacitance therefore would be:

$$\Delta C = \varepsilon_0\varepsilon_r \int_0^R \left\{\left(\frac{2\pi r\,dr}{d-y}\right) - \left(\frac{2\pi rdr}{d+y}\right)\right\} \qquad ...(5.58)$$

which can be simplified to

$$\frac{\Delta C}{C_0} = \frac{1}{2}\left(\frac{y_m}{d}\right) + \frac{1}{3}\left(\frac{y_m}{d}\right)^3 + \frac{1}{4}\left(\frac{y_m}{d}\right)^4 + ...$$

$$\cong \frac{y_m}{2d} \text{ as } y_m << d \qquad ...(5.59)$$

$$= \frac{pR^2}{8Td} \qquad ...(5.60)$$

EXAMPLE 5.13

For a pressure transducer having thin metallic diaphragm as primary sensor and using differential capacitive principle as shown in Fig. 5.23, evaluate the change in capacitance that would be caused.

The data available is :

Gap between fixed plates from diaphragm = 1.5 cm

Radius of the diaphragm = 2 cm

Poisson's ratio, for material = 0.3

Thickness = 0.1 mm

Young's modulus of material = 3 × 10^8 kg/cm^2

Differential pressureis connected (in succession) from 2psi – 10 psi in steps of 2 psi.

Plot the change in capacitance against pressure.

SOLUTION:

From the Eqn. (5.53) the change in capacitance can be calculated as:

$$\Delta C = C_0 \frac{3p(1-\mu^2)R^4}{16Et^2d} = \text{p.K.}$$

where
$$K = \frac{3\,C_0(1-\mu^2)R^4}{16\,Et^2d}$$

$$= \frac{3 \times 0.7 \times 10^{-12} \times 0.91 \times 4 \times 10^{-8}}{16 \times 3 \times 10^{8} \times 0.01 \times 10^{-6} \times 1.5 \times 10^{-2}} = 0.11244 \times 10^{-18}$$

and
$$C_0 = \frac{8.854 \times 10^{-12} \times 12.56 \times 10^{-4}}{1.5 \times 10^{-2}}$$

$$= 74.13 \times 10^{-14} = \mathbf{0.74\ pF}$$

For different values of p, ΔC can be calculated and is tabulated as shown in Table 5.4.

$$1 \text{ p.s.i} = 0.070307 \text{ kg/cm}^2$$

$\therefore$ ΔC = p.K ; where $K = 11.244 \times 10^{-20}$

and for each psi change $\Delta C = 0.070307\ \text{K} = 0.79 \times 10^{-20}$ F.

TABLE 5.4

Input pressure in p.s.i	*Change in capacitance × 10^{-20} F*
2	1.581
4	3.162
6	4.743
8	6.324
10	7.905

It is to be noticed that the changes in capacitance are extremely small and therefore the arrangement requires to be handled carefully so as to avoid the effect of noise and converting this change of capacitance into electrical signal. It will be discussed further in detail under (chapter 8) signal conditioning.

5.3.4 Capacitive Transducers based on Change in Area between Plates

A cylindrical condenser can be formed with a hollow perforated outer and a central electrode placed in a vessel, filled to reasonable height with a dielectric fluid in the vessel as shown in Fig. 5.24. The value of capacitance will change as a function of the level of dielectric fluid in the vessel. The monitoring of capacitance value provides a direct measure of the level in the vessel/tank. The capacitance of such a cylindrical condenser is approximated by

$$C_t = \frac{\varepsilon_t h_1 + \varepsilon_v h_2}{2\ln\left(1+\frac{r_3}{r_2}\right)} \qquad ...(5.61)$$

where ε_l and ε_v are dielectric constants of liquid and vapor above it. h_1 and h_2 are level of liquid in tank and space above the liquid r_2 and r_3 are radius of central electrode and outer cylinder respectively.

The capacitance has a nonlinear variation with height of liquid in tank and its value can be increased by choosing the cell dimensions such that:

$$h_1, h_2 >> r_2 \text{ and } r_2 >> r_3$$

The application of this transducer will be discussed later in eighth chapter in detail.

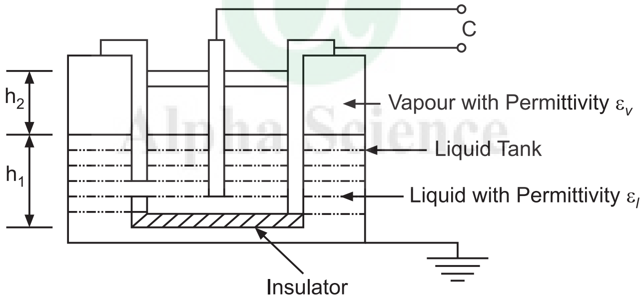


Fig. 5.24 Cylindrical Condenser Type Capacitive Transducer for Level Instrumentation

5.4 FREQUENCY GENERATING OR MODULATING TYPE TRANSDUCERS

A variety of assorted transducers can be grouped in this class that generate pulsed or modulated output and mostly used for speed sensing.

5.4.1 Frequency generating capacitive tacho:

Frequency generating capacitive tacho can be configured in two forms as shown in Fig. 5.25(*a, b*) using a dc source and a capacitor to even number of commutatorsegments. The ac current through the ammeter connected in the system will be calibrated to measure the angular speed ω of the shaft to which the moving wiper is connected. The current is given by:

$$I = \omega C E \quad \text{...(5.62)}$$

$$\omega = \frac{I}{CE} \quad \text{...(5.63)}$$

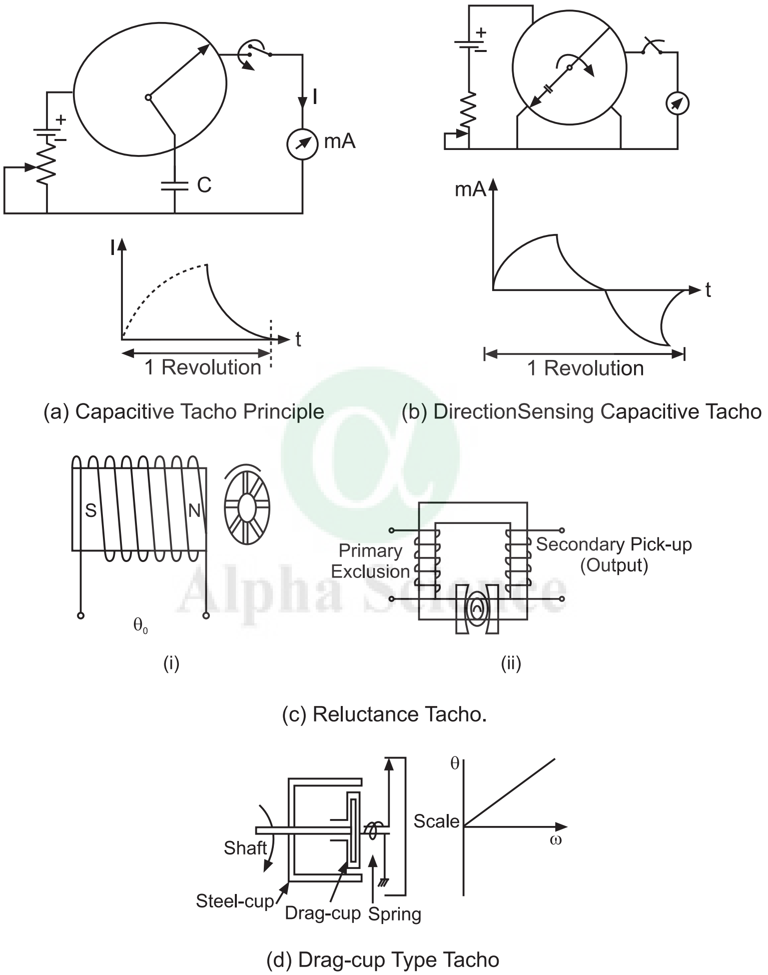


Fig. 5.25 Frequency Generating Modulating Type Techos

5.4.2 Reluctance tachos

These work on the principle of proximity between the rotating device and the sensor. As shown in Fig. 5.25(*c*)-(*i*), a toothed wheel is attached rigidly to the shaft of rotating machine, and a magnet carrying a search coil is brought close to it. The change in reluctance of path of flux due to alternate teeth and gaps during the run of motor, a pulsating emf is induced in the search coil. The frequency of this pulsed emf provides a measure of the speed of rotation. The shape of the pulses depends on teeth profile and really does not matter. The magnitude of pulses depends on the flux strength and speed.

During one rotation of the toothed wheel (and thereby the shaft) number of pulses produced is equal to the number of teeth. Therefore the speed of rotating shaft is,

$$N = (\text{number of pulses}/\text{number of teeth}) \times 60 \text{ RPM}$$

An improved arrangement is shown in Fig. 5.25(*c*)-(*ii*), with reduced leakage of flux resulting in pulses of larger magnitude, which can be further enhanced by having larger number of secondary turns.

EXAMPLE 5.14

For a reluctance tacho, as shown in Fig. 5.25 (c), determine the frequency of pulses produced every second. The number of teeth on the wheel is 800 and the speed of rotation of shaft on which it is mounted is (a) 1200 rpm (b) 900 rpm.

SOLUTION:

The pulse production is often arranged corresponding to the leading edge triggering of the pulse circuit. In one revolution of shaft/toothed wheel, 800 triggering will occur,

∴ Number of pulses produced per revolution = 800

and number of pulses/second = 800 × no of revolutions

(*a*) $800 \times 1200/60 = 16000$

(*b*) $800 \times 900/60 = 12000$.

5.4.3 Drag-cup type Tachos

Yet another type of tacho is configured using a permanent magnet attached to the shaft and rotating inside a drag-cup made of softer material such as aluminium with movement restricted by a spring arrangement as shown in Fig. 5.25(*d*). The assembly is covered by a steel cup to reduce the effect of external fields. The magnet induces eddy currents in the drag cup and tries to pull it along but cup's movement is restricted, a dynamic equilibrium is reached so that the eddy torque is balanced by the controlling torque due to spring. The dynamic equilibrium position is a finction of shaft speed, and the position along a scale indicator system provides the calibration of speed. The characteristic is observed to be quite linear as shown in figure.

5.5 OPTO-ELECTRONIC TRANSDUCERS

These transducers exploit the advantage of electromagnetic properties of the light waves, both in visible and non-visible range on either side of light spectrum. Energy associated is small which is an advantage as well as limitation. Very often they associate with the data transmission and coupling between the different stages of the instrumentation system with significant advantages.

5.5.1 Principle

Electromagnetic spectrum has some very distinct identified regions such as – visible light, radio wave, x-rays, infrared and ultraviolet. There range of variation is shown in Fig. 5.26. Of the total spectrum, infrared is typically useful for temperature sensing, to be discussed in Sec. 7.6.

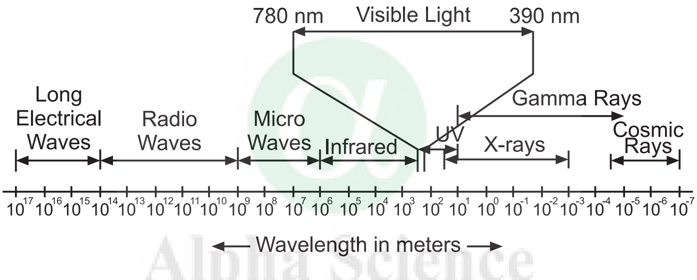


Fig. 5.26 Electromagnetic Spectrum

In this section, we shall discuss the devices related to visible light. Optoelectronics is still a wide topic encompassing lasers, lenses, electronic devices-input and output types, etc., the major properties of visible light spectrum with colors remembered conveniently as ROYGBV is well known. The sequence of colors red, orange, yellow, green, blue and violet are in the visible spectrum and the wave lengths for the colors are shown in Fig. 5.27 and Table 5.5. In modern usage, indigo is not usually distinguished as a separate color in the visible spectrum, hence a new acronym.

The various optical devices converting light into electrical signal are discussed next.

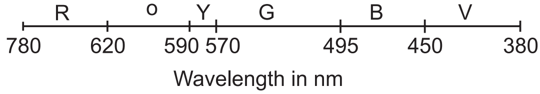


Fig. 5.27 Spectrum of Visible Light

TABLE 5.5 Electromagnetic Spectrum

Region	*Wavelength (Angstrom)*	*Wavelength (centimetres)*	*Frequency (Hz)*	*Energy (eV)*
Radio	$>10^9$	>10	$< 3 \times 10^9$	$< 10^{-5}$
Microwave	$10^9 - 10^6$	$10 - 0.01$	$3 \times 10^9 - 3 \times 10^2$	$10^{-5} - 0.01$
Infrared	$10^6 - 7000$	$0.01 - 7 \times 10^{-5}$	$3 \times 10^{12} - 4.3 \times 10^{14}$	$0.01 - 2$
Visible	7000–8000	$7 \times 10^{-5} - 4 \times 10^{-5}$	$4.3 \times 10^{14} - 7.5 \times 10^{14}$	$2 - 3$
Ultraviolet	$4000 - 10$	$4 \times 10^{-5} - 10^{-7}$	$7.5 \times 10^{14} - 3 \times 10^{17}$	$3 - 10^3$
X-Rays	$10 - 0.1$	$10^{-7} - 10^{-9}$	$3 \times 10^{17} - 3 \times 10^{19}$	$10^3 - 10^5$
Gamma Rays	< 0.1	$< 10^{-9}$	$> 3 \times 10^{19}$	$> 10^5$

The visible part of the spectrum may be further sub divided according to color, with red at the long wavelength end and violet at the short wavelength end, as illustrated (schematically) in the figure. The sequence of colors red, orange, yellow, green, blue, and violet may be remembered by memorizing the name "ROY G. BV". This was originally "ROY G. BIV", because it used to be common to call the region between blue and violet "indigo". In modern usage, indigo is not usually distinguished as a separate color in the visible spectrum.

5.5.2 Photoresistors

These are basically the class of semiconductors having the property that, their terminal resistance changes when light falls on them. They usually have a high resistance at room temperature and dark state, and on receiving sufficient energy from photons falling on them, their conductivity increases due to presence of more free electrons and resistance decreases. The behavior is sensitive to wavelength of the incoming radiation. The relative response of a typical photo sensitive resistor is shown in Fig. 5.28. It is to be noted that, the response peaks for a critical wavelength. Radiations with lower wavelength are absorbed without any appreciable change in resistance whereas those with larger wavelength carry very little energy.

It is known that in intrinsic semiconductor that with increase in energy the valance electrons can jump to conduction band. The increase in energy can be due to the form of energy falling on it. If it occurs due to the photo radiation being received it is called photoconductivity, thus causing more free electrons in conduction band and change occurs in the conductivity of materials. One such device is called photoresistor also called light dependent resistor (LDR). Conductivity is the function of wavelength λ the factors governing the phenomena include:

- Electrons may already be in a state of thermal agitation.
- Width of energy gap varies within the lattice.
- Presence of impurities effects the electron hole recombination.

A threshold value of λ is one above which only the photons have enough energy to cause a change in resistivity, *i.e.* giving energy to already excited electrons.

Some materials show an approximate linear relation between resistance of sensor and intensity of illumination as:

$$R = \left(\frac{1}{R_d} + \frac{I^{\frac{1}{\beta}}}{\alpha}\right)^{-1} \tag{5.64}$$

where R_d is the dark resistance and α, β are material specific constants.

The materials which can be chosen for LDR include CdS, CdSe with doping of Ga, Ag, Cu resulting in peak response for spectral range of 0.530 – 0.70 μm.

It is possible to remove the nonlinearity in the V-I characteristics with the doping of In or Sn in semiconductors. Also in the infrared regions the photons have low energy therefore for detection in this range gold is useful as impurity activator doping Ge. Temperature must always be maintained very low to achieve low response time of the order of μ secs. The deterioration in properties due to oxidation and moisture is controlled by packaging the device in inert or evacuated atmosphere. For the use of LDRs in the visible range the device characteristics are specified for different illumination levels whereas in the infrared range the characteristic shall be about the

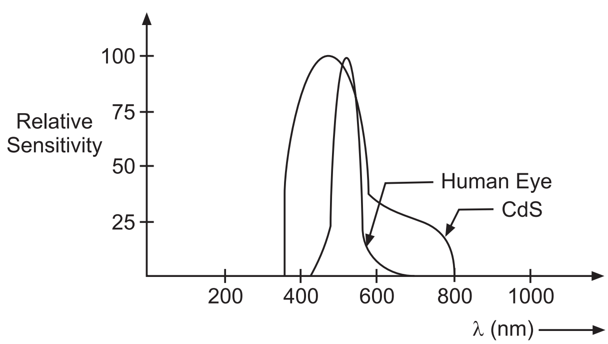


Fig. 5.28 Relative Response of Photo Resistive Device

radiation units. The Table 5.6 presents the indicative behavior of few materials that shows photo resistor characteristics.

TABLE 5.6 Properties of Photo-resistive Materials

Material	*Wavelength range, in nM*	*Critical wavelength, in nM*
CdS	400 – 800	520
CdSe	680 – 750	700
PbS	500 – 3000	2000-2700
PbSe	700 – 5800	4000
InSb	600 – 7000	5500

The LDRs are made by deposition of materials on a specially made ceramic strip. The choice of materials depends on the ratio of resistance change desired, which is a function of illumination level and the excitation supply level being used with LDR as shown in Fig. 5.29.

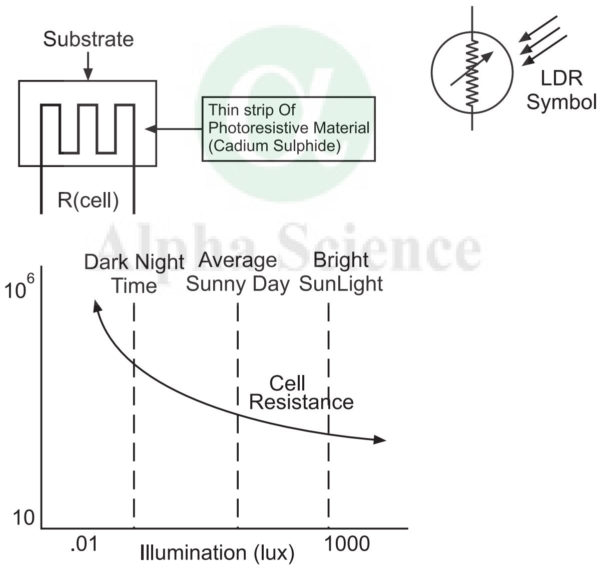


Fig. 5.29 The Light Dependent Resistor Cell

There are a number of applications of these, such as the automatic control of night lights for streets and public places etc., to switch on the lights at dusk and turn off at dawn, in exposure meters of cameras, moving object counters, burglar alarms, signaling etc. Considerations in choosing the device for a given application are sensitive to wavelength range, time response, and optical sensitivity of the material. These are marked by a non linear response and large time constant of the order of *m*-seconds.

5.5.3 Photodiodes

They behave as reversed bias diode under dark condition and the current increases as intensity of incident light increases as shown in Fig. 5.30. The V-I characteristics are shown in figure. These are small in size and have a reasonably flat and fast response of the order of nano-seconds. These are useful for inter-stage coupling without interaction (*i.e.* loading) and optical data transmission (*i.e.* via fiber optic).

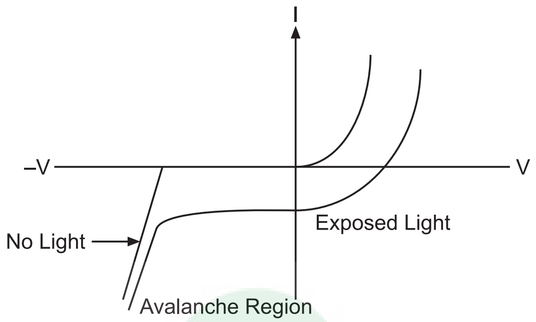


Fig. 5.30 V-I Characteristic of Photodiode

5.5.4 Phototransistors

Phototransistors are configured as special application of photo diode in the collector-base circuit of a transistor, as shown in Fig. 5.31. By variation of base current with light source it is possible to have variation in current gain and collector current, as shown in Fig. 5.31(*b*).

In NPN phototransistor, collector is forward biased with respect to emitter so that base-collector junction is reverse biased and with no light falling the leakage current is very small, as in (*b*).

With the light falling on base more electron-hole pairs are formed and current thus produced is amplified by transistor.

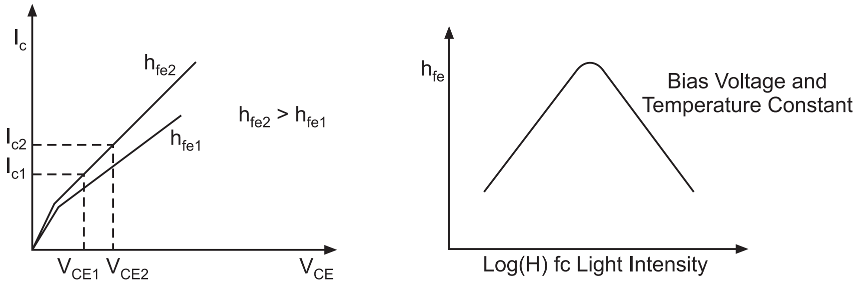
The basic collector junction can be considered as a photodiode with leakage current I_{CBO} that varies with illumination gets amplified by (1 + h_{fe}). In FETs, the illumination causes an increase in leakage current to produce larger voltage drop in the resistance across gate, to result in more drain current

$$v_g = \left(I_{\text{normal gate}} + I_{\text{radiation}}\right)R_g \qquad \text{...(5.65)}$$

Sensitivity of phototransistor is a function of dc current gain of transistor and therefore the overall sensitivity depends on collector current and can be controlled by introducing a resistance between base and emitter.

Phototransistor have typical applications for optoisolation, optical switching, light beam sensing, remote control of equipment such as TV and in fibre optics.

In an analogous manner it is possible to create photo FETS, photocouplers, photothyristors etc.



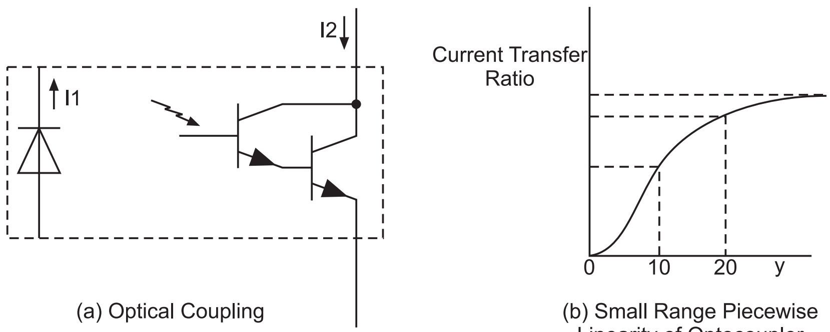
(a) I-V charecteristic (for constant light intensity)

(b) Phototransistor Gain as Function of Light Intensity

Fig. 5.31 Characteristics of Phototransistor

Optocouplers

These are extensively used for providing excellent isolation and their application shall be considered in detail later.The arrangement is shown in Fig. 5.32 (*a*) consists of an LED (light source) and a photocell, both encapsulated to avoid any external optical effects. Since the illumination from LED is a function of current. The transfer function from primary to secondary side through optical coupling can be provided with a current transfer ratio as high as 10 by using Darlington pair configuration. Yet the major problem is the nonlinearity as indicated in Fig. 5.32(*b*), which is reduced to an extent by the use of feedback.



(a) Optical Coupling

(b) Small Range Piecewise Linearity of Optocoupler

Fig. 5.32 Optical Coupling and Nonlinear Characteristic

5.6 NUCLEONIC TRANSDUCERS

These have great importance in nuclear installations for monitoring the radiation levels, with a high degree of accuracy. The expertise gained with these measurements is also being used in clinical level, depth, flow rates etc.

5.6.1 Principle

Four types of radiations to be monitored are:

α particles: with positive charge of 2, relative mass of 4, and Helium nucleus. This is absorbed in many materials.

β Particles: are more penetrating, negatively charged electrons with relative mass of 0.000549.

γ Rays: are high energy electromagnetic waves resulting from nuclear transformations. They do not have mass or charge but produce ionizing effect in their interaction with matter. These are highly penetrating.

Neutrons: have no charge. These have relative mass of unity and are also highly penetrating.

γ rays and neutrons do not interact with Coulomb force fields when entering a material due to high energies interaction of the above particles with different materials is complicated and therefore there is need for nuclear shielding.

5.6.2 Detection of Radiation

The radiation is measured on the basis that by interaction with detecting device ionization will be produced and the degree of ionization shall be measured, by any of the two methods:

(*a*) Measurements of number of interactions of radiation – a counting process, using Geiger-Muller counter or scintillation counter.

(*b*) Measurement of total effect of radiation-mean level measurement by photographic arrangement.

These instruments are not being discussed here any further at this course level, and bibliography may be referred for more details.

5.7 ULTRASONIC TRANSDUCERS

These are based on transmission and reception of high frequency sound waves at about 50 kHz for industrial applications and higher for biomedical applications. Sound waves at a speed of v m/s are sent and if the time elapsed between the instants of transmission and reflection from an interphase plane (*i.e.* liquid-vapor) at a distance d meters is recorded then delay = 2.d/v secs. These are being used for level monitoring in storage tanks, oil wells, mine shafts, marine depths etc., the use for level monitoring in a tank is shown in Fig. 5.33. These are available in easy to mount sizes for use up to 100 ms. The effect of temperature is negligible and overall accuracy is of the order of ± 0.1%.

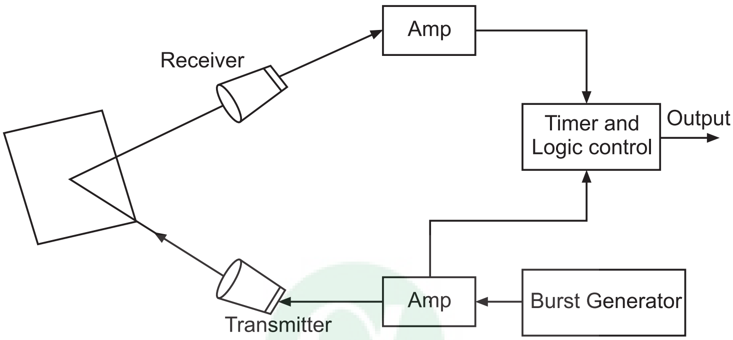


Fig. 5.33 Ultrasound Distance Ranging Principle

As shown in the schematic diagram, a burst generator produces a fixed no of cycles (say 10) at 30 kHz with burst rate of 2 Hz. These burst signals are amplified and applied to a transducer to produce ultrasonic sound waves at a speed of (about) 350 m/sec. Reflected waves arrives at receiver/transducer which converts into electrical signal.

The delay between transmitted and received bursts is used to estimate the distance of target. The method has been used in sound navigation and ranging (SONAR) successfully due to higher density of water (than air). For larger distances high gain receivers are essential as the strength signal falls off as Inverse Square of the distance travelled.

A variation of the same scheme is used for ultrasonic flow meter to monitor the flow rate in pipes with high accuracy. It is discussed in Chapter 7.

5.8 HALL EFFECT TRANSDUCERS

Hall effect was first observed by Edwin Hall in 1879 in semiconductors, under the influence of simultaneous electric and magnetic fields though applied for engineering measurements much later.

5.8.1 Hall effect principle

If a current is passed through a sample in the form of long strip of extrinsic and homogenous semiconductor and a magnetic field B is applied perpendicular to it, then an electrical field is produced along a direction perpendicular to the plane, in which current I (suppose along *x*-axis) and magnetic field B (suppose along *y*-axis) have been applied *i.e. x-y* axis.

As shown in Fig. 5.34 the basic principle of Hall Effect device, a field ε_x applied along *x*-axis causes a current I_x to flow. Along *y*-axis is applied a magnetic field By then at the electrodes placed along the *z*-axis across the faces experiences a generated voltage V_{Hz} along *z*-axis under the field ε_z developed internally.

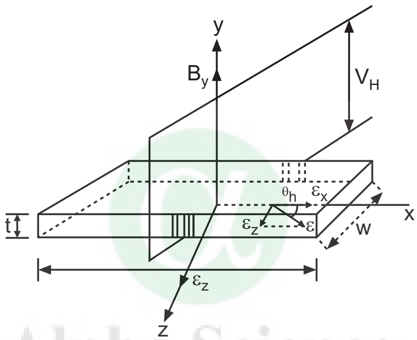


Fig. 5.34 Hall Effect Transducer Principle

The voltage V_{Hz} is referred as Hall voltage and approximated by

$$V_{Hz} \cong B_y \, I_x \qquad \ldots(5.66)$$

It is said to be generated by galvanometric effect due to, Lorentz force on the charge carriers, given by:

$$F_i = q\varepsilon - q\,(\nu \times B) \qquad \ldots(5.67)$$

where, q is the charge of the carrier,

ε is electric field,

ν is carrier velocity,

B is applied magnetic field

We also have carrier transport equation

$$J = (q\varepsilon - q\,D_c\,c) + \mu_H\,[\,(\sigma\varepsilon - q\,D_c\,c)\,B] \qquad \ldots(5.68)$$

where,

c is carrier concentration gradient; J is current density,

D_c is diffusion constant

σ is conductivity of semiconductor material and, μ_H is the Hall mobility.

It is to be noted that, magnetic field also affects the electric field and carrier concentration, hence it is not simple to assume

$$J = q\varepsilon - q\, D_c\, c = J_o \qquad \text{for } B = 0$$

μ_H, σ, D are also called transport coefficients and depend on carrier scattering process. Also, $\mu_H = \gamma\mu$.

where, μ is mobility of carriers

and, γ is Hall scattering factor

Transverse electric field/Hall field ε_x produced is given by:

$$\varepsilon_z = -\,\mu_H B_y \varepsilon_x \qquad \text{...(5.69)}$$

$$V_{HZ} = \int_{y1}^{y2} \varepsilon_{z,} dz \qquad \text{...(5.70)}$$

$$= -\,\mu_H B_y \varepsilon_x \,W$$

the materials that show up Hall effect are characterized by Hall coefficient, defined as

$$R_H = \frac{\varepsilon_z}{J_x B} = -\frac{(-\mu_H B_y \varepsilon_x)}{J_x B_y}$$

$$= \frac{\mu_H \varepsilon_x}{J_x} \qquad \text{...(5.71)}$$

and, $\therefore V_{Hz} = -\mu_H B_y.\left(\frac{R_H J_x}{\mu_H}\right) W = -\,R_H.J_x.B_y.W$ ...(5.72)

and, Hall angle, $\theta_h = \tan^{-1}\frac{\varepsilon_z}{\varepsilon_x} = -\mu_H\, B_y.$ ...(5. 73)

5.8.2 Hall effect sensors

It is basically a magnetic sensor, with a long (practically) rectangular block of semiconductor material, such that $i >> w, t$. The field ε_x across area $t \times W$ applied with supply electrodes, will be resulting in current density,

$$J_x = \frac{I}{txw}$$

and, corresponding Hall voltage, $|V_H| = R_H.J_x.B_y.W$

$$= \frac{R_H.I.By}{t} \qquad ...(5.74)$$

Since, the semiconductor is limited to finite length a geometric correction factor f_g has to be introduced in Eqn. (5.74):

So that, $$|V_H| = f_g \cdot \frac{R_H \cdot I_x \cdot B_y}{t}$$

and resulting sensitivity to magnetic field, shall be:

$$S = \left|\frac{\partial VH}{\partial By}\right| = f_g \frac{R_H I_x}{t} \qquad ...(5.75)$$

Sensitivity is observed to be dependent on temperature and the output decreases with rise in temperature.

Performance measures

(*i*) Sensitivity: the sensor is intended for monitoring magnetic field and therefore its sensitivity is defined as

$$S_a = \frac{\partial V_H}{\partial B_z} / I_x = \text{const.} : \text{Absolute sensitivity} \qquad ...(5.76)$$

If sensitivity to I_x(or V_c) is desired, called relative sensitivity, will be

$$S_{r1} = \frac{1}{I_x}\left(\frac{\partial V_H}{\partial B_z}\right) \qquad ...(5.77)$$

The Hall effect devices are sensitive to pressure, temperature and light. These are called secondary sensitivities and can be evaluated as:

(*ii*) Secondary sensitivity to temperature $S_{sT} = \frac{1}{r_n}\left(\frac{\partial r_n}{\partial T}\right)$ ...(5.78)

where r_n is scattering factor of electrons.

Secondary sensitivity to pressure, $S_{sp} = \frac{1}{R_H}\left(\frac{\partial R_H}{\partial p}\right)$. ...(5.79)

(*iii*) Nonlinearity: It is observed if the parameters $R_{H,}$ geometrical shape factor or the dimensions change, they give rise to nonlinearity for each. For the best fit curve output $V_{HB,}$ the nonlinearity can be defined as:

$$\% \text{ non linearity} = \frac{V_H - V_{HB}}{V_{HB}} \times 100 . \qquad ...(5.80)$$

5.8.3 Applications of Hall Sensors

A practical sensor form, based on Hall Effect is shown in Fig. 5.35. The current I_{ac} from the load circuit magnetizes a core to set up a magnetic field H in the air gap. A current proportional to voltage of load circuit E_{ac} sets up an electric field across the semi conductor placed in the air gap. Under the effect of the two fields, an output Hall voltage V_o is picked up. This dc voltage output is related to power of the load circuit,

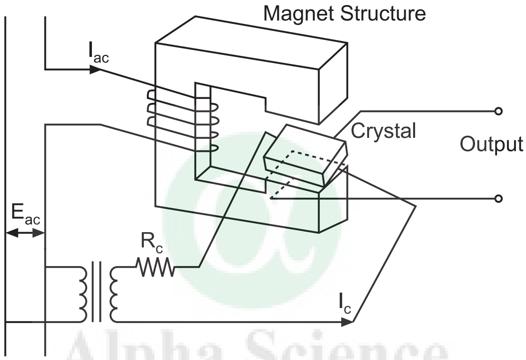
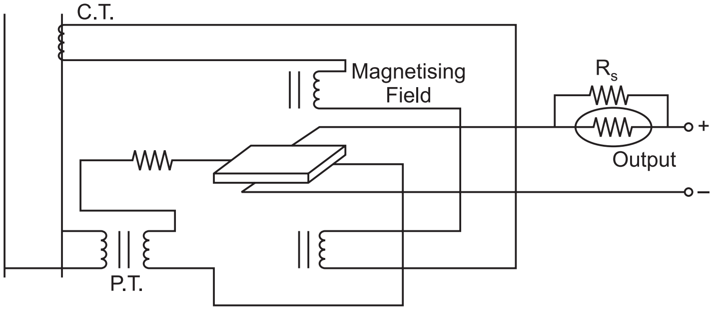


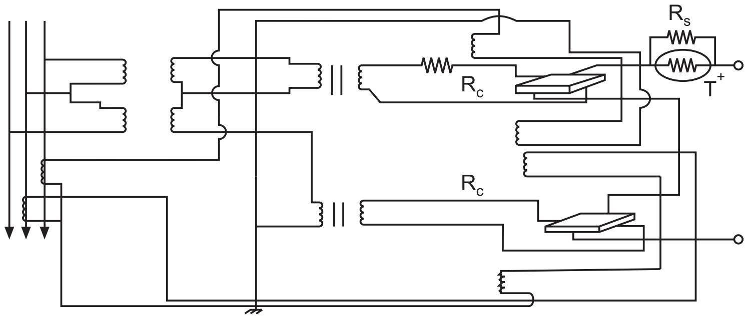
Fig. 5.35 Hall Watt Transducer

$$V_o \propto H\, I_{ac} \cos \phi \propto E_{ac}\, I_{ac} \cos \phi \qquad ...(5.81)$$

Output is dc voltage and consists of true power superimposed with ac voltage at double the frequency. By filtering it is possible to obtain the true power and the transducer can be used as a Wattmeter for both single and three phase cases as in Fig. 5.36.



(a) Single Phase Connection of Hall Watt meter



(b) Three phase connection of Hall Watt meter

Fig. 5.36 Hall Watt meters

In this chapter we have learnt about (*a*) various types of passive transducers (*b*) their principle of operation, mathematical models, (*c*) application ideas.

In the next chapter discussion shall be about the active transducers – their principle, mathematical modeling and pointer to applications.

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REVIEW QUESTIONS

(*i*) In the case of wired potentiometers used for displacement monitoring, how the momentary break in circuit due to jump over consecutive turns, can be avoided?

(*ii*) What are strain rosettes and their advantages?

(*iii*) Discuss the concept of varying gauge factor of semiconductor strain gauges by adjusting doping level.

(*iv*) Arrange the various strain gauges (based on material used) in increasing order of gauge factor.

(*v*) What are load cells and their typical commercial applications?

(*vi*) How load cells can be configured as weighing machine for large bodies?

(*vii*) Why does a half-bridge tends to cancel the effect of temperature in bending measurements and not in axial measurements?

(*viii*) Compare the advantages of bonded strain gauges with unbounded gauges.

(*ix*) Why is platinum preferred for Industrial RTDs?

(*x*) If the piezoresistance effect in strain gauge is not to be neglected, how the G.F. value will be affected, if $E = 2 \times 10^6$ kg/cm^2; Poisson's ratio, μ = 0.3.

(*xi*) Explain the process of monitoring of displacement by using an LVDT.

(*xii*) Explaining why in case of LVDTs, the primary excitation frequency is generally kept much higher than supply frequency?

(*xiii*) How the ac rms output of LVDT for two positions + 5 and – 5 cms can be discriminated?

(*xiv*) What is a RVDT and its applications?

(*xv*) What is a proximity sensor and explain its typical applications in industry.

(*xvi*) Draw the non-linear characteristic for a differential transducer-change in output with change in inductance. Now is differential connection able to reduce the effect of non-linearity?

(*xvii*) How variable inductance (/reluctance) principle can be used to sense rotational speed?

(*xviii*) What is a capacitance microphone? List its feature and most important application.

(*xix*) Which of the parametric characteristic in a parallel plate capacitive transducer provides maximum sensitivity? Give your reasons.

(*xx*) Explain photoelectric effect. How it is related to radiation measurement?

(*xxi*) What is an optocoupler and its advantages over other types of coupling?

(*xxii*) What is the principle of LEDs?

(*xxiii*) How are different colored LEDs made?

(*xxiv*) What is Hall Effect? How a Hall device can be used as current sensor.

PROBLEMS FOR EXERCISE

5.1 What is the principle of strain gauge transducers? Derive the output relation for strain-gauge system used in full-bridge mode of operation.

5.2 For Isoelastic strain gauges available with resistance of 120 ohms and G.F 3.5, calculate the output for quarter, half and full bridge arrangements, for strain of 500 μ strain units. Assume equal arm bridge excited by 10 volt dc source.

5.3 A strain gauge is being used to measure the stresses developed in a structural member by fixing on it rigidly. On subjecting the structure and there by the gauge having GF = 2.2 and nominal resistance 120Ω, a change in gauge resistance was measured to be 1.2Ω, calculate the strain developed at the point where gauge is placed, and the stress if the Young's modulus of elasticity of the structural member is 2×10^8 kgf/m^2.

5.4 A nichrome gauge with a gauge factor of 2 and $\beta_g = 10^{-4}$/°C is attached to a soft steel piece with linear expansion coefficient $\alpha_c = 0.12 \times 10^{-4}$/°C. The coefficient of linear expansion of nichrome is $\alpha_n = 0.13 \times 10^{-4}$/°C. Calculate the percent error in strain for 500 micro strains due to temperature change.

5.5 In a quarter bridge configuration with strain gauge of 120 ohms and G.F. 2.0 in an equal arm bridge with supply current of 25 mA, output corresponds to 30 units for 1000 μ strains. What shall be the output, if current is raised to 50 mA?

5.6 The strain gauges bonded to a cantilever beam under test, connected in full-bridge mode with R_g of 120 Ω and gage factor 2.5. DC excitation source of 5 V with negligible internal resistance has been used.

If the stress applied to the beam is 100 M-n/m^2, calculate:

(*i*) change in strain gauge dimension along load axis,

(*ii*) Output voltage if R_m is 10 KΩ.

Young's modulus of elasticity for the material of gauge is 70 G-N//m^2.

5.7 For the bridge arrangement as shown in Fig. 5.7, with only one active arm (also known as quarter bridge mode of operation), calculate :

(*a*) The current in detector having 50 ohms resistance for a strain of 0.5%.

(*b*) The deflection in detector, if it has deflection sensitivity of 2 mm/μA.

Strain gauge has nominal resistance of 350 ohms and G.F. of 2.5.

5.8 In an application, 1 KΩ strain gages with dc bridge arrangement are used with all active arms (also known as full – bridge mode of operation), for measuring strain in a structural member. Evaluate the output voltage for strain of 0.1% and deflection in output detector having resistance of 1000 Ω and sensitivity 5 mm/μA. Bridge supply voltage is 5 V dc with negligible internal resistance.

5.9 In structural beam testing of a beam, a full bridge configuration of strain gauges were specified to have nominal value of 400 Ω, G.F 2.1 and critical power dissipation of 100 mW. The output indication is made using a sensitive galvanometer of 500 Ù resistance and sensitivity of 5 mm/μA. Calculate the meter deflection, if the steel beam was subjected to uniform stress of 150 M Pa. Young's modulus for steel is 206 G Pa.

5.10 During an experiment with a metallic RTD, resistance recorded at two temperature readings were 368 Ω at 400°C and 200.5 Ω at 150°C. Calculate the temperature coefficient of resistance of the RTD material.

5.11 For a RTD having R_0 of 50 ohms and R_{100}/R_0 of 1.52, what will be the resistance at 70°C?

5.12 A platinum RTD with α = 0.00392 Ω/Ω/°C has a nominal resistance of 100 Ω at 0°C. If the measured resistance is 88.5 Ω, compute the temperature of RTD.

5.13 A platinum RTD has R_0 = 85 ohms, R_{100}/R_0 of 1.39 and δ = 1.5. Find the temperature at which resistance measured is 125 ohms. (Hint: solve the Callender-Van Dusan equation for temperature considering only first two terms).

5.14 For an RTD use to monitor temperature is having nominal resistance of 400 Ω and maximum heat dissipation limited to 10 mW to avoid self-heating. The RTD is included in a 4-arm bridge as one of arms.

Evaluate the maximum supply voltage for the transducer bridge, if the bridge is an equal arm in quarter-bridge mode and the maximum bridge output voltage, for a temperature increase from 35°C to 630°C. α is known to be 2 mΩ/Ω/°C.

5.15 A thermistor is observed to have resistance of 10 KΩ at 25°C. what shall be its resistance at 75°C and 200°C. α and β may be taken 0.02 Ω and 4000/°K respectively.

5.16 A thermistor is observed to have a resistance of 1 K ohms at 30°C and 250 ohms at 80°C. What resistance it shall have at 60°C?

5.17 For a thermistor the resistance was observed to be 1000 Ω at 25°ambient temperatures. If β is known to be 4000°K, calculate the value of its resistance at 40°C, 50°C and 80°C.

5.18 A thermistor element is observed to have a resistance of 2 KΩ at 27°C and 400 Ω at 90°C. Evaluate the resistance of element at 60°C and the difference in resistance for temperature change from 80°C to 30°C.

5.19 A platinum resistance thermometer has resistance 100.0 Ω at 0° respectively. If its resistance becomes 305.3 Ω when it is in contact with a hot gas, determine the temperature of gas. The temperature coefficient of platinum of RTD is $0.0039°C^{-1}$

(*a*) Compute Resistance at T = 25°C, 100°C and –15°C

(*b*) Calculate ΔR for a temperature change ΔT = 10°C

5.20 A resistance sensitive to temperature is connected across a thermistor. Prove that the slope of the combined resistance is reduced with respect to only thermistor.

5.21 Derive the equation for output from LVDT as would be measured by an (indicating type) output meter.

5.22 (*a*) Explain the arrangement, principle, ideal and practical input-output characteristics of LVDT as a displacement transducer. Suggest a suitable network arrangement todiscriminate, between positive and negative input displacements, from the rms volts available at the output.

(*b*) Find the output voltage of an LVDT of range ± 10 cm, when the core is 7 cm from the centre if primary and secondary voltages are 30 and 5V at f = 1 KHz, Rp = 1000 Ω, Lp = 1 mH, Rs = 500Ω, Ls = 5mH, $k = (M_1 - M_2)/d = 0.01$, Rm = 1 KΩ.

5.23 The bridge circuit as shown in Fig. Q. 5.23 is used as a thickness gauge test the uniformity of paint sprayed on a metal surface. One plate of capacitor C_3 is a metal disc of area 6.45 cm^2 held against the painted surface. The other plate of C_3 is the metal sheet. Assume $R_1 = R_2$ = 1 KΩ, f = 1 kHz, source impedance to be negligible and the perfect contacts in disc capacitor. Find

(*a*) The value of C_4 to obtain bridge balance for a point thickness of 0.05 mm.
(*b*) Smallest detectable change in point thickness from its nominal value with applied voltage of 1V (rms), if the smallest readable deflection in detector is 0.1 mV (rms).

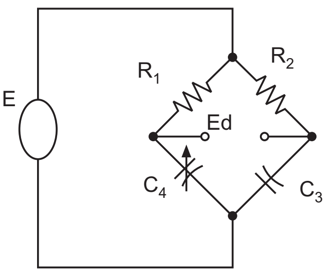


Fig. Q. 5.23

5.24 (*a*) An available reluctance tacho-meter has 100 rotor teethed wheel attached to a motor shaft. The read out of meter is observed to be 2000 counts/sec. What is the speed of motor?

(*b*) If the speed of motor is 1000 r.p.m., what is the meter read-out expected ?

5.25 A capacitive tacho with the configuration as shown in Fig. 5.27(*a*) has capacitance value of 0.1 F with source voltage of 2 volts.

What is the angular speed of the motor to which it is connected if the meter shows a current of 1.5 mA?

CHAPTER 6

Active and Digital Transducers

INTRODUCTION

This class of transducers can be considered as energy converting devices causing change from one form to another. In this chapter, we will consider various principles utilized for the purpose in detail so that the various applications of this devices can be made for monitoring the industrial variables.

Inside the Chapter

6.1 ACTIVE TRANSDUCERS BASED ON THERMOELECTRIC EFFECT

This is one of the most common and useful for many industrial applications. These are made available for wide range of temperature and specific applications. The working is governed by three related phenomenon : Seebeck, Peltier and Thompson effects.

6.1.1 The Three Basic Effects

Seebeck effect, which relates the generation of e.m.f. that, when two dissimilar metals are joined to form junctions, kept at different temperatures. As shown in Fig. 6.1, a thermocouple (TC) so formed, can be used to measure the temperature of the junction, in terms of the e.m.f. generated if temperature of the other junction (usually cold) is known and maintained at a constant temperature (called reference junction).This method can provide a direct measure of the hot junction temperature to a reasonable degree of accuracy. The governing relation is given by:

$$e_0 = \alpha\ (T - T_{ref}) \quad ...(6.1)$$

Where α is resistance temperature coefficient. A linear relationship is obtained, between unknown temperature and the e.m.f. produced. The thermoelectric effect is observed to be reversible in nature,

$$T = \frac{e_0}{\alpha} + T_{ref} \quad ...(6.2)$$

the heat is generated at one of the junctions and absorbed at the other when a current is flowing is known as Peltier effect.

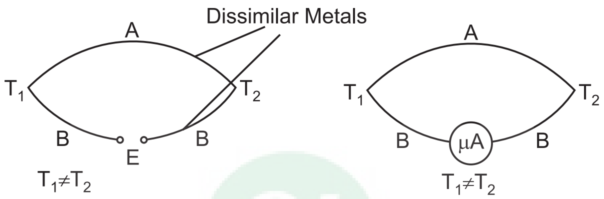


Fig. 6.1 Basic Thermocouple

Another coupled effect is **Thompson effect**, related to reversible heat flow. It describes the influence of heat flow on the temperature of conductors rather than junctions. Heat is liberated where the direction of current flow and heat flow are same and viceversa. Thompson e.m.f.s are proportional to difference of the squares of the temperatures of the junctions. With these corrections, the net voltage equations shall be:

$$E = \alpha\ (T - T_{ref}) + \beta\ (T - T_{ref})^2 \quad ...(6.3)$$

where temperatures are in degree Kelvin and α, β are constants depending on the choice of TC elements. The choice of elements is aimed at increase in α and decrease in β, so that linearization is approximated with minimum error.The other considerations are usable temperature range, speed of response and the size of junction.

Since, the negative effects arise with the flow of circulating currents, an important application consideration is to use the TC in potentiometric or null deflection mode of operation. The use of measuring devices, say a voltmeter, causes errors due to formation of new dissimilar metal junctions coupled with flow of currents is likely to add errors. The various effects are formalized by TC laws, discussed next.

6.1.2 Thermocouples Laws

The first law states, that the TC effects depends only on the temperature of the junctions and is unaffected by the intermediate temperatures along the wires, as shown in Fig. 6.2(*a*).

The second law states, that additional elements can be introduced in the circuit without affecting the potential, provided junctions of each metal are at the same temperature. As shown in Fig. 6.2(*b*), new metals added in between the junctions *A* and *B*, do not effect the performance if $T_A = T_B$ and $T_C = T_D$ as the contact potentials at each intermediate junction cancel.

The third law states, that a third metal can be introduced at either junction, without causing any change, provided that junctions of third metal are the same. This helps to have mechanically strong junctions by use of soldered, brazed or welded joints.The third wire could very well be that of mili-voltmeter, as shown in Fig. 6.2(*c*).

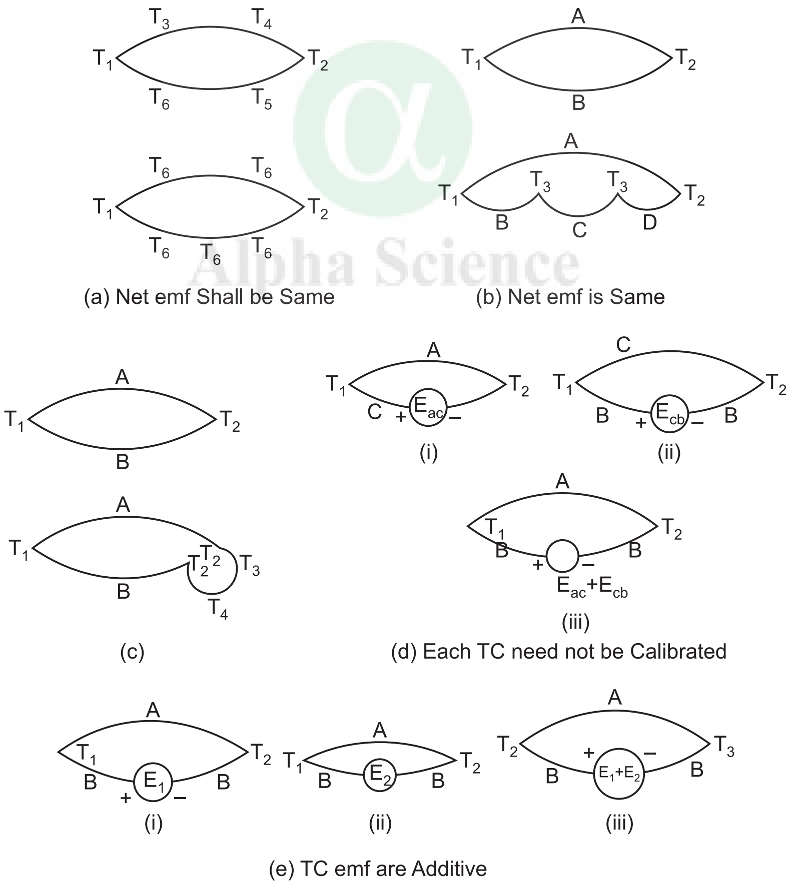


Fig. 6.2 Thermocouple Laws

The fourth law is also the law of intermediate metals and is used to transfer the information from one type of TC to another type of TC. This is illustrated as an example in Fig. 6.2 (*d*).

The fifth law, also known as the law of intermediate temperatures, is useful in deduction and interpolation of intermediate temperatures using TC tables, available for the particular type of TC configuration used. This is necessitated due to nonlinear behaviour of thermo-electric emf with temperature difference between junctions as given earlier in Eqn. (6.3) for total voltage. This law is represented as in Fig. 6.2(*e*) and the use of TC table is illustrated later in connection with their application for temperature instrumentation in Chapter 8.

6.1.3 Common Thermocouple Types

TCs have become the most common type of temperature transducer in industry. The various types are referred as E, T, K, J etc. Their configuration, sensitivity and range of operation are presented in Table 6.I along with some useful remarks. Figure 6.3 shows a comparison of the emf-temperature characteristics of few common TC types. The considerations in the choice of TCs include :

- Linearity
- Corrosion
- Humidity
- Environmental condition *i.e.* oxidizing or reducing type
- Speed of response.

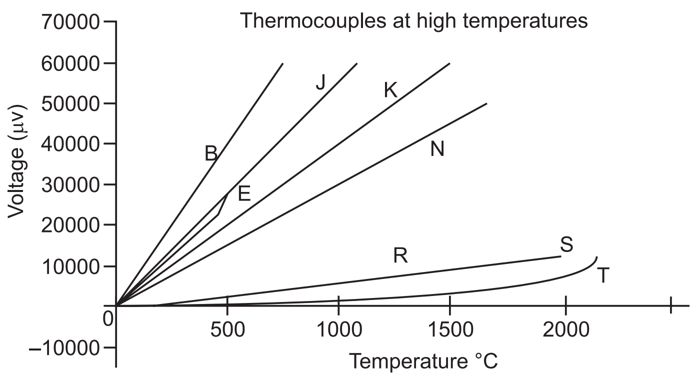


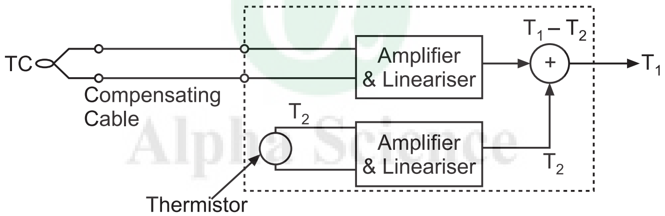
Fig. 6.3 Temperature vs emf Characteristics of Common TCs

6.1.4 Reference Junction and Compensation

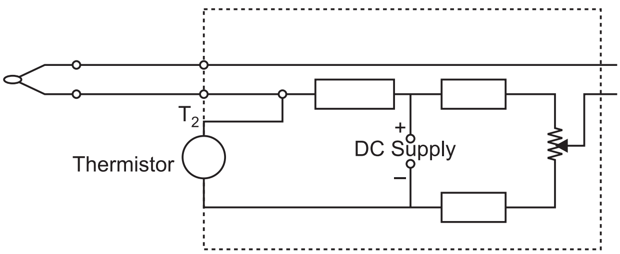
For precise measurement of temperatures using TCs, reference are the cold junction must be maintained be maintained at accurately known value. A simple approach could be the use of an ice bath to keep the reference junction at zero degree as shown in Fig. 6.4 and tables referenced to zero degree can be used directly. However, in industrial environment it is difficult to use ice bath. The other more stable choice in place of ice are:

(*i*)	Methanol	–100° to 600°C
(*ii*)	Silicone oil	50 to 250°C
(*iii*)	Tin	250 to 630°C

A convenient technique referred as cold junction compensation is to measure the reference junction temperature using a RTD and substitute this value to determine the hot junction temperature.This basic approach is represented in Fig. 6.4(*a*). A modified version providing for compensation and then the transfer of signal over a large distance is shown in Fig. 6.4(*b*).



(a) By Addition of Cold Junction Temperature



(b) By Inline Compensation

Fig. 6.4 Cold junction Compensation for Thermocouples

Thermocouple polarity : The emf produced in the TC is differential in the sense that it measures dc potential between the two junctions. In the Table 6.1, first material in each combination is more positive when the temperature being measured is above the reference.

TABLE 6.1 Thermocouple Types and Characteristics (ANSI-15A Standard)

TC Type	Elements		Compensatory cable	Temp. range	Average sensitivity µA/°C	Error
	+	–				
E	Chromel- Ni 90% Cr 10% Ni 43%	Constantan CU 57% Ni 43%	Red	0-900°C	68	± 1.7°C 0.5%
T	Copper	Constantan	Blue- Red	0-350°C –200-0°C	46	± 1°C 0.75%
K	Chromel- Ni 90% Cr 10%	Alumel Ni 94% Mn 03% Al, Si		0-1260°C	42	± 2°C 0.75%
J	Iron-	Constantan	White- Red	0-760°C	46	± 2°C 0.75%
R	Pt/Rh- Pt 13% Rh 87%	Pt (pure)	Black- Red	0-1400°C	08	± 1°C 0.25%
S	Pt/Rh Pt 10% Rh 90%	Pt	Black- Red	0-1400°C	08	± 1°C 0.25%

6.1.5 Structure and Types of TCs

Figure 6.5 shows construction of thermocouples and a typical industrial TC headwell assembly as shown in Fig. 6.6, consists of:

(*a*) Terminal block – made of insulating material and used to support and join termination of conductors.

(*b*) Connection head – housing the terminal block, provided with threaded openings for attachment to protection tube and attachment of conduit.

(*c*) Connection head extension – a threaded fitting between thermo well and connection head.

(*d*) Protection head – used to protect sensor from damaging environmental effects.

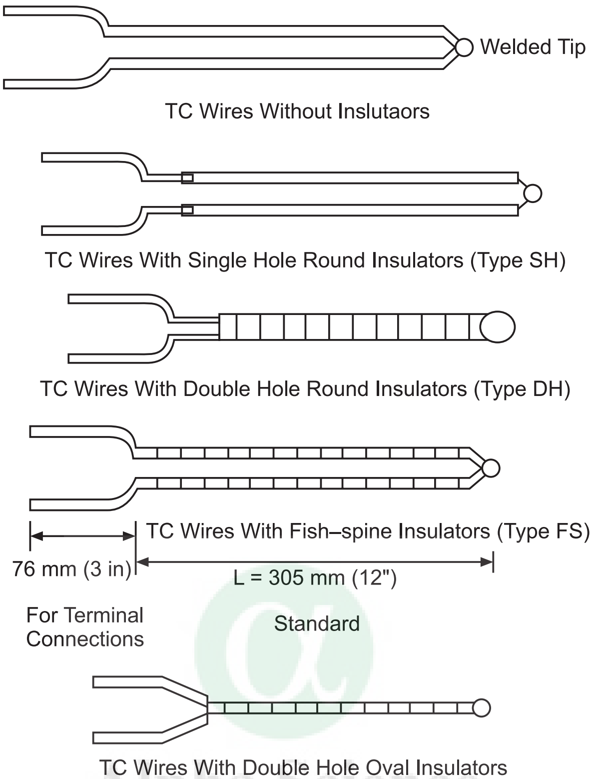


Fig. 6.5 Constructional Details and Types of TCs

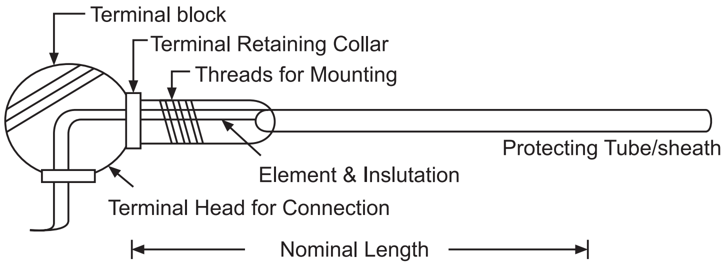


Fig. 6.6 Assembly of Industrial TC

High Temperature Sheath Materials

For industrial TCs working in different environmental conditions the choice of sheath material is important and the choices are listed in Table 6.2.

TABLE 6.2 High Temperature Sheath Materials

Material	*Max operating temperature, °C*	*Workability*	*Remark*
Molybdenum	2205	Brittle	Good hot strength Sensitive to oxidation above 500°C, Resists many liquid metals, molten glass
Tantalum	2482	Malleable	Resists most acids, weak alkalies: sensitive to oxidation above 300°C
Pt-Rh alloy	1677	Malleable	Safe with SO_2 up to 1000°C; silica is harmful
Inconel 600	1150	Malleable	Highly resistant to oxidation at high temperatures; sulphur, H_2 harmful

Recent TC protection tubes are being made of CaO – stabilized zirconia for use up to 2000°C. This offers resistance to corrosion and chemical properties at higher temperatures than with several others. Oxygen molecules in zirconia reduce in inert environment but at a much slower rate. These are usable in directional solidification system furnaces (DSS) up to 1600°C and provide a long life.

TC Probes

These are very similar to the various probes available for RTDs discussed earlier, TC probes are also available in different types and for the particular application data sheets should be referred to. The different types are:

(*a*) Surface probes
- (*i*) Heavy duty
- (*ii*) Moving webs
- (*iii*) High temperature
- (*iv*) Miniature tip
- (*v*) Fast response
- (*vi*) Bolt on
- (*vii*) Pipe clamp

(*b*) Immersion probes
- (*i*) Standard
- (*ii*) Ungrounded
- (*iii*) Heavy duty

(*c*) Penetration probes

(*d*) Air probes

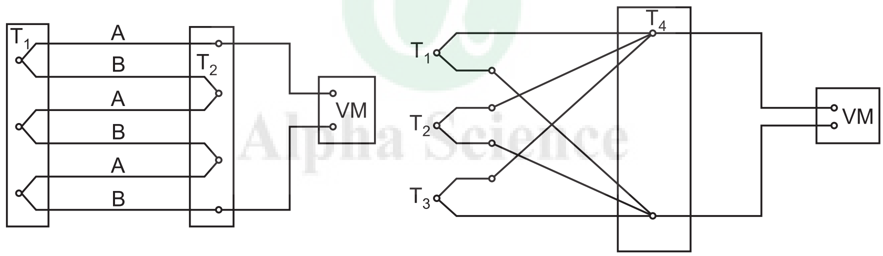
(*e*) Thermo-well probes

The shapes and sizes of the various industrial TCs, available commercially are quite similar to those discussed and shown for RTDs in previous chapter and shown in Fig. 5.6, hence not repeated.

Thermocouple tables provide the resulting voltage for the reference junction at any specified temperature. These tables can be downloaded from the internet site (see bibliography) for any TC of interest, a sample Table is however included for illustration of its use in a real application situation, as Table 6.3.

Thermopiles

A combination of TCs is compiled to for improving the sensitivity of TC assembly as shown in Fig. 6.7. A series combination of N number of TCs connected as shown can improve the sensitivity N times, whereas a parallel can increase the current that may be drawn from the assembly. However, the current trend is to have many fold increase by using smart electronics in the terminal block of the TC assembly itself. The details of the signal conditioning needed for improving sensitivity, removing noise and compensation for nonlinearity are discussed in detail in Chapter 8.



(a) Series Connection (b) Parallel Connection

Fig. 6.7 Thermopile Arrangements

6.1.6 Measurement with Thermocouples

The thermocouple tables provide the voltage resulting for a type of TC with reference at a particular reference temperature and hot junction is the measurand temperature value.

For example:

(A) Say, for a J-type TC

(*a*) With hot junction at 350 with reference at 0 will provide output of 19.09 mV

(*b*) Output of 36.08 mV corresponds to 650°C hot junction temperature if reference is at 0°C.

(B) Say, for a K-type TC

35.54 mV output corresponds to hot junction temperature of 850°C if reference junction is maintained at 0°C.

However the measured value may not exactly coincide with the value in tables. Then, the values have to be interpolated in the closest range of temperature or voltage as the case may be.

In general measured value of temperature can be found from

$$T_{measured} = T_{lower} + \left[\frac{T_{upper} - T_{tower}}{V_{upper} - V_{lower}}\right] \times (V_{measured} - V_{lower})$$

The output voltage of TC is lying between a V_{upper} and V_{lower}, so that the temperature being measured is lying between corresponding T_{upper} and T_{lower}.

EXAMPLE 6.1

A J-type thermocouple with reference junction at 0°C provides an output of 12.30 mV. Evaluate the temperature of hot (monitored) junction.

SOLUTION:

From the table for J-type TC, it is observed that $V_{measured}$ = 12.30 lies between V_{lower}= 12.17 mV and V_{upper} = 12.45 mV. The corresponding temperatures are T_{lower}= 200 + 25 = 225°C T_{upper} = 200 + 30 = 230°C.

$$\therefore \qquad T_{measured} = 225 + \left(\frac{230 - 225}{12.45 - 12.17}\right) \times (12.30 - 12.17)$$

$$= 225 + 2.321 = 227.32°\text{C}$$

A converse situation can also arise when the voltage for an specific measuring junction temperature $T_{measured}$ is little beyond table. It can be interpolated as

$$V_{measuring} = V_{lower} + \left(\frac{V_{upper} - V_{lower}}{T_{upper} - T_{lower}}\right) \times (T_{measured} - T_{lower})$$

The thermocouple tables provide the output voltage of several thermocouple (TC) types over a range of temperature in 5°C increments. In each case, the TC reference temperature is 0°C. The first-named material will be the positive terminal, as iron-constantan; the iron will be the positive lead when the reference temperature is lower than the measurement. The temperature is in °C and the output is mV. Each column is in 5°C increments from the temperature of that row. The Table for J-type TC is given below for example and to illustrate the method of its use. For other TCs the Tables are included in appendix at the end.

TABLE 6.3 Type J : Iron-Constantan

	0	5	10	15	20	25	30	35	40	45
-150	-6.50	-6.66	-6.82	-6.97	-7.12	-7.27	-7.40	-7.54	-7.66	-7.78
-100	-4.63	-4.83	-5.03	-5.23	-5.42	-5.61	-5.80	-5.98	-6.16	-6.33
-50	-2.43	-2.66	-2.89	-3.12	-3.34	-3.56	-3.78	-4.00	-4.21	-4.42
-0	0.00	-0.25	-0.50	-0.75	-1.00	-1.24	-1.48	-1.72	-1.96	-2.20
+0	0.00	0.25	0.50	0.76	1.02	1.28	1.54	1.80	2.06	2.32
50	2.58	2.85	3.11	3.38	3.65	3.92	4.19	4.46	4.73	5.00
100	5.27	5.54	5.81	6.08	6.36	6.63	6.90	7.18	7.45	7.73
150	8.00	8.28	8.56	8.84	9.11	9.39	9.67	9.95	10.22	10.50
200	10.78	11.06	11.34	11.62	11.89	12.17	12.45	12.73	13.01	13.28
250	13.56	13.84	14.12	14.39	14.67	14.94	15.22	15.50	15.77	16.05
300	16.33	16.60	16.88	17.15	17.43	17.71	17.98	18.26	18.54	18.81
350	19.09	19.37	19.64	19.92	20.20	20.47	20.75	21.02	21.30	21.57
400	21.85	22.13	22.40	22.68	22.95	23.23	23.50	23.78	24.06	24.33
450	24.61	24.88	25.16	25.44	25.72	25.99	26.27	26.55	26.83	27.11
500	27.39	27.67	27.95	28.23	28.52	28.80	29.08	29.37	29.65	29.94
550	30.22	30.51	30.80	31.08	31.37	31.66	31.95	32.24	32.53	32.82
600	33.11	33.41	33.70	33.99	34.29	34.58	34.88	35.18	35.48	35.78
650	36.08	36.38	36.69	36.99	37.30	37.60	37.91	38.22	38.53	38.84
700	39.15	39.47	39.78	40.10	40.41	40.73	41.05	41.36	41.68	42.00

EXAMPLE 6.2

For a K-type TC, if the reference junction is maintained at 0°C, find the expected output with hot (measuring) junction at 1357°C.

SOLUTION:

Measuring junction temperature lies between T_{lower} = 1355°C and T_{upper} = 1360°C. Corresponding output voltages are V_{lower} = 54.37 mV and V_{upper} = 54.54 mV.

∴ Expected TC output,

$$V_{measured} = 54.37 + \frac{54.54 - 54.37}{1360 - 1355} \times (1357 - 1350)$$

$$= 54.37 + 0.238 = 54.608 \text{ mV.}$$

In all previous cases, the reference junction had been maintained at 0°C but this situation can be relaxed. In case it is above 0°C, there is a higher voltage associated with this than at 0°C. Therefore, for all such cases with non 0°C reference, corrections have to be applied.

For example, in case of a K-type TC:

If the output voltage for hot junction temperature of 850°C is V_{m1} = 35.34 mV when reference is maintained at 0°C. Now if the reference junction is maintained at 25°C then V_{25} = 1.00 mV (with reference at 0°C)

∴ The same TC with hot junction temperature at 850°C will provide the output

$$V_{m2} = 35.34 - 1.00 = 34.34 \text{ mV}$$

With reference junction at 25°C, this can be written as:

$$V_{850} = 34.34 \text{ mV (K-type, 25°C reference)}.$$

6.1.7 Automation of Temperature Monitoring

In laboratory as well as industrial situations it is often necessary to automate the measurement of temperature by the TC. An arrangement suitable for this purpose is shown in Fig. 6.8.

Consider a system in which the temperature is to be monitored and recorded. In all practical systems the usual problem is to maintain the temperature at a preset desired/reference value. It is usually sufficient and of greater interest to indicate the deviation of process/system temperature from the desired temperature, rather than the absolute value, which in any case can be known, by adding the reference value (also called set point) to the deviation algebraically.

The TC output available is compared with a precise reference voltage set by the potentiometer for the steady state operation of the system, so that initially there is no error *i.e.* $E_{TC} - E_{REF} = E_{dc} = 0$. Capacitor C_f serves to remove any (ac) noise signal picked up by *TC*.

If during operation there is change in the system temperature E_{dc} will have a finite value. This low frequency signal will be converted into a pulsed signal with the help of a chopper arrangement consisting of a vibrator and a permanent magnet. The phase sensitive pulse train signal is fed to a pulse input transformer and the output is further amplified by a voltage amplifier and further by a servo (low frequency power type) amplifier to bring the signal up to an appropriate level, to feed the control winding of a 2-phase servo-motor, the reference winding being supplied from a separate source with 90° phase difference. If a deviation in temperature from steady value occurs, it is fed to the control winding so that the servo-motor will be driven in forward or backward direction, to indicate the calibrated deviation on a connected chart recorder. The stylus (pen) of strip chart recorder is driven by the motor about the central line on the strip chart that corresponds to '0' deviation so that the pen movement marks the deviation from the reference (set point) value. The dynamics of deviation is shown on the chart by moving the chart paper at a pre-selectable speed by using a separate drive motor (not shown in Fig. 6.8). The servo-motor also drives the wiper of the reference potentiometer to try and make E_{DC} zero again. If the deviation is maintained the motor need not move any further and the stylus shall continue to indicate the deviation/error. However, if the TC output changes the motor and the potentiometer shall strive to maintain the balance dynamically. Hence the name self-balancing – potentiometer with arrangement shown in Fig. 6.8. The principle of this arrangement can be extended to any other transducer output in place of TC output and hence it is general in nature.

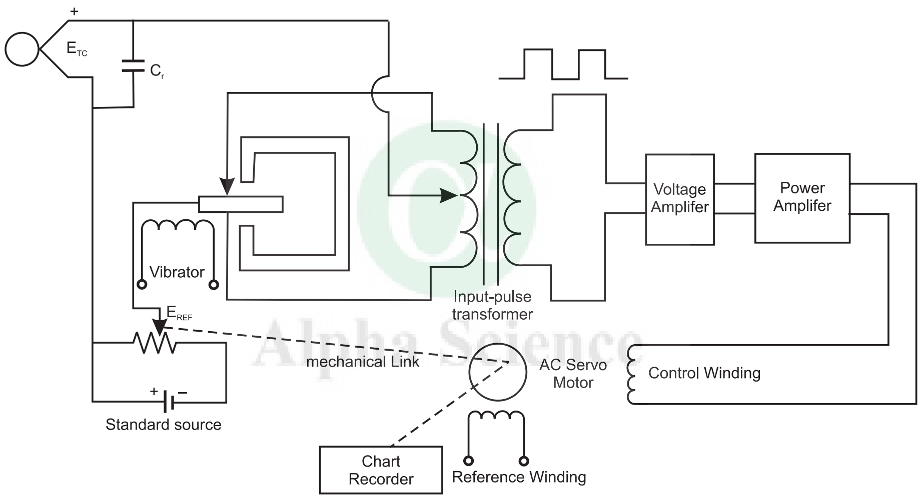


Fig. 6.8 Self-balancing Potentiometer for Instrumenting TC Output

EXAMPLE 6.3

A type-K TC with 27°C reference produces a voltage of 40 mV. What is the temperature being measured ? (See appendix–E for K-type thermocouple data.)

SOLUTION:

Voltage for the reference of 27°C corresponds to 40 mV (from the Table for K-type TC)

The voltage correction factor is determined by using 0°C Table and interpolation. The reference falls between 25°C and 30°C, therefore

$$V_{K-TC(27°C)} = V(25°C) + (V_{27} - V_{25})_{\text{at zero ref}} \text{ divide by } (30 - 25)$$

$$= 1.0 + \left(\frac{1.2 - 1.0}{5}\right) = 1.04 \text{ V}$$

Since the temperature is greater than the table reference *i.e.* 25°C, the correction is added to the measured voltage. Therefore,

$$V_{K-TC(27°C)} = 40 + 1.04 = 41.04 \text{ mV}$$

From the TC table this voltage lies between 40.92 mV at 990°C and 41.93 at 995°C. Using interpolation

$$T = 990 + \frac{(995 - 990) \times (41.04 - 40.92)}{(41.12 - 40.92)}$$

$$= \mathbf{993°C.}$$

6.2 ACTIVE TRANSDUCERS BASED ON PIEZOELECTRIC EFFECT

This is a class of sensors, which produce voltage when subjected to pressure, force, stress or vibration.

6.2.1 Piezoelectric Effect

Certain solid materials, when subjected to mechanical stresses generates a charge on opposite crystal faces. This was observed by brothers Pierre and Jacques Curie in 1880 and is called piezoelectric effect. The effect is reversible, in the sense that, if a charge is applied across the faces of the certain crystals, the mechanical stresses setup cause deformation in the material. This action is also referred as reverse piezoelectric effect or magneto-striction.

These devices can be utilized for monitoring of force, acceleration and pressure, by generating low current high voltage electrical power for use in electrostatic dust filters and spark ignition engines, quartz watches etc.

The materials that show this property are classified as-natural materials such as quartz, Rochelle salt, synthetic materials such as lithium sulphate (LS), ammonium di-hydrogen phosphate (ADP), ethylene, di-amine tartarate, di-potassium tartarate (DKT), and polarised ferroelectric ceramics like barium titanate and lead zirconite.

Due to asymmetrical structure, the material crystals show up the effect without further processing.

Crystals such as quartz have asymmetric structure in natural state, with hexagonal link between Si (positive) and O_2 (negative) molecules.

In normal state the charges are balanced, but on application of force (tensile or compressive) along *x*-axis, the crystal gets deformed, as shown in Fig. 6.9(*a*) and become polarized. The opposite faces become charged. A change in the nature of force applied causes the sign reversal on the charged surfaces of the crystal.

Piezoelectric effect can be observed in different modes depending on shape and orientation of the body relative to the crystal axes and corresponding location of electrodes.

These modes result in 03 types of piezoelectric effects that can be:

(*a*) Longitudinal piezoelectric effect :

As shown in Fig. 6.9(*b*), when a force or pressure is applied the charge developed is given by

$$Q_x = d_{11} F_x n \quad \text{...(6.4)}$$

where d_{11} is charge sensitivity in pico-Coulomb/N.

The effect may be increased by stacking '*n*' crystals as shown in Fig. 6.10(*b*).

(*b*) Transverse piezoelectric effect :

As shown in Fig. 6.9(*c*) on application of force along the vertical-axis, a charge is developed across perpendicular faces and is given by

$$Q_y = -d_{11} F_x b/a \quad \text{...(6.5)}$$

A simplified diagram is shown in Fig. 6.10 (*a*) for transverse effect.

(*c*) Piezoelectric effect under length and face shear :

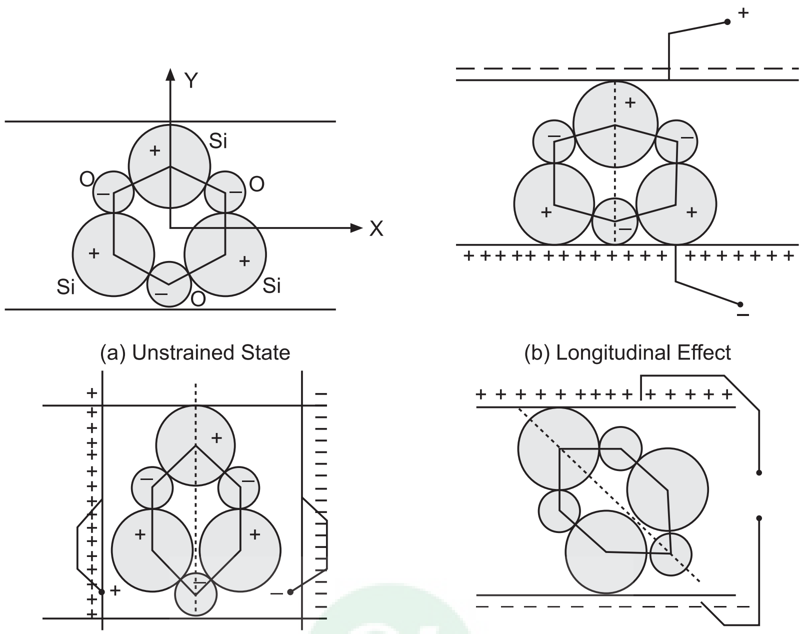
As shown in Fig. 6.9 (*d*), it occurs when the tangential forces are applied in a couple and the charge developed is given by

$$Q = 2\, d_{11} F\, n \quad \text{...(6.6)}$$

where *F* is the shear force applied across the faces responsible for shear of the crystal.

The sensitivity depends on geometry, size and stack number, charge distribution is similar to longitudinal effect.

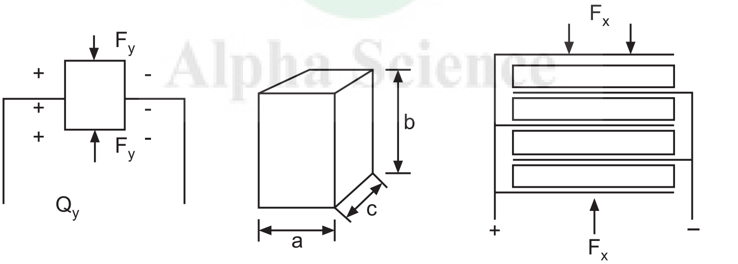
Any of the modes may be used according to the requirements. Whenever a number of crystals are stacked in series to improve the effect as shown in Fig. 6.10(*a*), they are arranged in series for force transmission and in parallel electrically, Fig. 6.10(*b*), to have higher current output. But, a large number of plates, gap resilience may introduce nonlinearity.



(a) Unstrained State (b) Longitudinal Effect

(c) Transverse Effect (d) Shear Effect

Fig. 6.9 Polarisation of Piezoelectric Crystal under Different Types of Forces



(a) Behavior of Piezoelectric Crystals (b) Schematic Stack Assembly

Fig. 6.10

Choice of Crystal

The factors to be considered for the choice of crystal are

(*i*) Mechanical and thermal stability

(*ii*) Capability of sustaining higher stresses

(*iii*) Good frequency response *i.e.* constant sensitivity over large bandwidth

(*iv*) High leakage resistance *i.e.* high source resistance of order 10^{14} W

(*v*) Large time constant 1000 to 100000 sec though capacitance is small

(*vi*) High input-output sensitivity with very good linearity over wide temperature range

(*vii*) High linearity and negligible hysteresis up to 10^{-4} of full-scale output
(*viii*) Large bandwidth and large measurement range in MHz
(*ix*) Effect of changes in ambient temperature and humidity is small
(*x*) High spring stiffness in the range 350 to 400 kN/cm^2
(*xi*) Small size
(*xii*) Usable as inverse transducer *i.e.* with application of electric field, mechanical excitation can be produced.

Properties of various piezoelectric materials are listed in Table 6.4. Rochelle salt is a good choice except for conditions of extremely low and high humidity *i.e.* below 33% and above 88%. Barium titanate is synthetically made to meet the large demand, does not suffer this limitation and offers larger dielectric constant, higher charge sensitivity, larger temperature range and it can be machined in any shape. Quartz offers good measuring properties though its charge yield is low, but has high stiffness (about) 350-400 kN per sq.cm., and almost constant sensitivity over wide temperature range (up to 500°C) besides having high linearity and negligible hysteresis. Piezoelectric ceramics are also used as capacitors, pressure sensors and resonators for industrial applications.

TABLE 6.4 Properties of Piezoelectric Materials

Material	d_{xx} C/N	***Resistivity*** Ω/m	***Temp Range°C***	ε_r	***Remarks***
Natural :					
Quartz	2.3	10^{12}	Up to 550	4.5	High resistivity, and temperature range
Rochelle salt	550	10^{10}	45	350	Low mech. strength, low temps. For microphones, record playing
Tourmaline	2- 3	10^{11}	1000	6.7	Poor sensitivity for acceleration and pressure sensors
Synthetic					
ADP	25-50	10^8	125	15.3	Useful for acceleration and pressure sensors
Lithium Sulphate	12-16	10^{10}	75	10.3	Limited in use
$BaTiO_3$	80-500	10^9 - 10^{12}	200-400	500-700	Common, high charge sensitivity, dielectric strength and reasonable temp. range

6.2.2 Piezoelectric Device Modeling

On application of force(s) the piezoelectric crystal gets polarized and the relationship of polarization vector P expressed in 3-D coordinate system (Fig. 6.11) can be written as:

$$P = P_{xx} + P_{yy} + P_{zz}. \quad ...(6.7)$$

However, the composite model is given by:

$$\begin{bmatrix} P_{xx} \\ P_{yy} \\ P_{zz} \end{bmatrix} = \begin{bmatrix} d_{11} & d_{12} & d_{13} & d_{14} & d_{15} & d_{16} \\ d_{21} & d_{22} & d_{23} & d_{24} & d_{25} & d_{26} \\ d_{31} & d_{32} & d_{33} & d_{34} & d_{35} & d_{36} \end{bmatrix} \begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \psi_x \\ \psi_y \\ \psi_z \end{bmatrix} \quad ...(6.8)$$

where σ*ís* are axial stresses and ψ*ís* are shear stress due to rotational forces. *d's* represent the charge sensitivity are defined next.

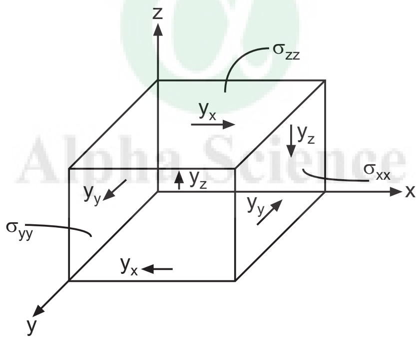


Fig. 6.11 Piezoelectric Crystal in 3-D Space

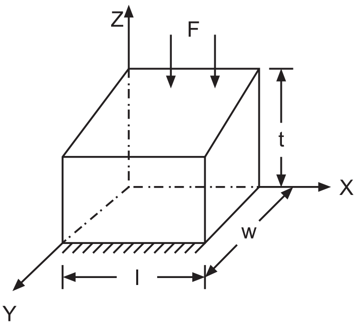


Fig. 6.12 Piezoelectric in Compression Mode

6.2.3 Representation of Properties and Parameters

Piezoelectric crystals are characterised with two constants, with subscripts to denote the axes. First subscript refer to direction of electrical effect and second to that of mechanical effect, using the axis system shown in Fig. 6.12:

Charge Sensitivity,

$$d_{zz} = \frac{\text{Charge generated in direction-}z}{\text{Force applied in direction-}z}$$

$$= \frac{Q}{F} \qquad \text{...(6.9)}$$

and Voltage Sensitivity,

$$g_{zz} = \frac{\text{Field produced in direction-}z}{\text{Stress applied in direction-}z}$$

$$= \frac{e\omega l}{f\,t} \qquad \text{...(6.10)}$$

where e is the voltage applied, f is the force applied, w and l are the dimensions of the crystal as shown in Fig. 6.12.

Typical values of g are 12(mV/M)/(N/m^2) for barium titanate and 50×10^{-3} for quartz.

For the sake of brevity, we consider the case of longitudinal effect. The subscripts with constants are dropped and we have,

$$g = \frac{e}{\varepsilon f}\frac{\varepsilon(\omega l)}{t} = \frac{eC}{\varepsilon f} = \frac{Q}{f}\frac{l}{\varepsilon} = \frac{d}{\varepsilon}$$

or, $$d = g\,\varepsilon \qquad \text{...(6.11)}$$

where ε is the dielectric constant of the crystal material forming a parallel plate capacitor between the electrodes, placed along z-axis (in this case) as shown in Fig. 6.12.

Young's modulus of elasticity is 9×10^{10} N/M^2 for quartz, and 12×10^{10} for barium titanate.

From Eqn. (6.9) $Q = d.F = C\,E_0$ leads to

$$\frac{E_0}{F} = \frac{d}{C} = \frac{dt}{\varepsilon A} \qquad \text{...(6.12)}$$

and change in dimension along force axis can be evaluated from the knowledge that, Young's modulus of elasticity,

$$E = \frac{F/A}{\Delta t/t} = \frac{Ft}{A\Delta t}$$

$$\therefore \qquad \Delta t = \frac{Ft}{EA} \tag{6.13}$$

To use these crystals as transducers for force, pressure, shock, acceleration or vibration the analysis is carried out in next section, considering displacement/deformation due to any of these as the inputs.

6.2.4 Response of Piezoelectric Device

For a dynamic force, thickness of crystal shall vary with time and accordingly the voltage developed shall also vary. Response characteristics can be evaluated by developing equivalent circuits for the device. The voltage developed across the electrodes requires to be amplified and measured in most cases by high input impedance device like oscilloscope or digital voltmeter.

Assume, that, a deformation z has taken place proportional to applied force along the z-axis, resulting in development of charge in the crystal,

$$Q = d\,F = d\,k\,z = K\,z \qquad \text{...(6.14)}$$

where K is a constant in Coulomb/meter.

Crystal is represented as consisting of charge generator, charging the crystal capacitance C_{cr}, with crystal having a leakage resistance in parallel.The output is connected to an amplifier with specified capacitance C_{amp} and resistance R_{amp}. The interconnections are shown in Fig. 6.13(a). Current from the crystal can be evaluated as

$$i = \frac{dQ}{dt} = K.\frac{dz}{dt}$$

This current will flow through

(i) $$R_{eq} = \frac{R_{cr}R_{amp}}{R_{cr} + R_{amp}}$$

(ii) $$C_{eq} = C_{cr} + C_{amp}$$

Referring to Fig. 6.13 (b)

$$i = i_R + i_C$$

and, output voltage

$$e_0 = \frac{1}{C_{eq}}\int i_c dt$$

$$= \frac{1}{C_{eq}}\int (i - i_R)\,dt$$

By differentiation,

$$\frac{de_0}{dt} = \frac{1}{C_{eq}}(i - i_R)$$

or,
$$C_{eq}\frac{de_0}{dt} = K\frac{dz}{dt} - \frac{e_0}{R_{eq}} \quad ...(6.15)$$

By taking Laplace transformation of Eqn. (6.15) and combining the terms,

$$\left(C_{eq}.s + \frac{1}{R_{eq}}\right)E_0(s) = KsZ\,(s)$$

or,
$$\frac{E_0(s)}{Z(s)} = \frac{KsR_{eq}}{(1 + sR_{eq}C_{eq}.s)} = \frac{s(KR_{eq})}{1 + s\tau} \quad ...(6.16)$$

where $\tau = R_{eq}\,C_{eq}$ is the time-constant.

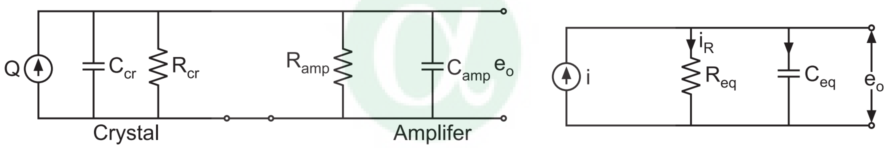


Fig. 6.13 Piezoelectric Device Miodel in Circuit

The T.F. between the voltage output and the force applied can be obtained as:

$$\frac{E_0(s)}{F(s)} = \frac{dt}{\varepsilon A}G(s) \quad ...(6.17)$$

The above transfer function (6-17), indicates that the output will be available only for dynamic inputs and this transducer cannot be used for static measurements. Also,

$$\left|\frac{E_0}{ZK_{eq}}\right| = \frac{\omega}{\sqrt{1 + (\omega\tau)^2}} \quad ...(6.17)$$

where, $K_{eq} = K\,R_{eq}$

and, similarly $\dfrac{E_0(s)}{F(s)} = \dfrac{dt}{\varepsilon A}G(s)$

where $$G(s) = \frac{C_{eq}R_{eq}}{1+\omega C_{eq}R_{eq}} \quad \ldots(6.18)$$

It can be inferred that, for a flat amplitude response the relationship of τ shall be:

TABLE 6.5 Relation of Response to Settling Time

Response within x% of final value	***τ needed to be >***
x = 2%	–
5%	3.04
10%	2

Thus, a larger τ will provide more accurate response at lower frequencies. The case of step or pulse input is important, and with

$$z = A \text{ for } 0 < t < T$$

$$(1 + s\,\tau)\,E_0\,(s) = 0$$

or, $$e_0(t) + \tau \frac{de_0}{dt} = 0 \quad \ldots(6.19)$$

For sudden increase at $t = 0$, e_0 suddenly I increases to KA/C_{eq}, which delays slowly according as

$$e_0 = \frac{KA}{C} e^{-\left(\frac{t}{\tau}\right)} \text{ for } 0 < t < T \quad \ldots(6.20)$$

And as pulse input is removed at $t = T$, there is change in output voltage e_0, as shown in Fig. 6.14.

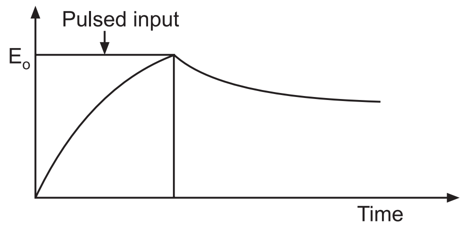


Fig. 6.14 Response of Piezoelectric Device to Pulse Input

From the above analysis, it is obvious that the piezoelectric transducers have a limitation that they are suitable only for dynamic force/pressures and there not suitable for static inputs.

Also, due to their low capacitance and high source resistance they need special care in amplification. Very high input amplifiers called charge amplifiers are needed and shall be discussed later.

EXAMPLE 6.4

A piezoelectric transducer is formed with a quartz crystal 0.1 cm thick, 1 cm^2 in area, held between metal electrodes. This is being used as a force transducer.

If a force f = 0.2 Sin (2000 t) N is applied, find the voltage developed across the electrodes and the maximum change in crystal thickness.

Data : For quartz E = 10 × 10^{10} Pa, charge sensitivity = 2.3 pC/N, ε_r = 5,

ρ = 10^{12}Ω-cm. Connecting cable impedance may be assumed to have resistance of 100 MΩ in parallel with capacitance of 30 pF.

SOLUTION:

$$\text{Peak voltage} = \frac{dt\,F_{\text{peak}}}{\varepsilon A} G(\omega)$$

$$= \frac{2.3 \times 10^{12} \times 0.1 \times 10^{-3} \times 0.2}{8.854 \times 10^{-12} \times 5 \times 1 \times 10^{-4}} G(\omega)\,\text{mV}$$

$$= 10.39\ \text{G}\ (\omega)$$

and, $$G(\omega) = \frac{\omega C_{eq} R_{eq}}{\sqrt{\left(1 + \omega^2 C_{eq}^2 R_{eq}^2\right)}}$$

where $C_{eq} = 54.427$, $R_{eq} = 10^{13} \times 10^{8} \simeq 10^{13}$ MΩ

$G(\omega) = 0.128$

Voltage developed = 10.39 × 0.128 = 1.33 mV

and peak-to-peak voltage = 2.66 mV

$$\text{Change in thickness, } \Delta t = \frac{Ft}{EA} = \frac{0.2 \times 0.1 \times 10^{-3}}{10 \times 10^{10} \times 1 \times 10^{-4}} = 2 \text{ pico-meter}$$

and, p-p change in thickness = 4 pico-meter.

6.2.5 PZT type Sensors

Among the various types of Titanates that are synthetically made to meet the large demand, Barium titanate ($BaTiO_3$) is most common. It has high charge sensitivity, dielectric strength and temperature range.

An improvement has been obtained with compounds of $PbZrO_3$ – $PbTiO_3$ called PZT. The properties depend on *Ti* to *Zr* ratio. *Pb* can be replaced by *Ba*, *Ca*, *Sr*, *Cd*, Ti^{4+} or Sn^{4+} to result in different types of PZT.

These piezoelectric ceramics are used as capacitors, resonators, pressure sensors for industrial applications.

6.3 ACTIVE TRANSDUCERS BASED ON ELECTROMAGNETIC INDUCTION PRINCIPLE

These are commonly used for various types of tachogenerators (tachos in brief) to monitor rotational speed of machinery and drives.

6.3.1 Principle

These are based on generation of emf due to electromagnetic induction effect. The arrangement is so designed that a conductor moves in a magnetic field to cause a change in flux, thereby generating emf, measured as a vector quantity. The principle has been widely used in various types of tachometers for speed measurement and with modifications to measure flow and other variables. Some direct applications are presented here and more will be discussed later under applications.

6.3.2 DC tachogenerators for Rotary Speed

The arrangement is shown in Fig. 6.15 (*a*). These are shaft mounted type, miniaturized magnet type dc generators. The output is given by:

$$E_0 = \frac{\phi PZN}{60A} \text{ volts} \qquad \text{...(6.21)}$$

where, ϕ = flux per pole in webers

P = number of poles

Z = number of conductors

N = speed of rotation of shaft in revolution/minute

A = number of parallel paths between brushes

and $E_0 \propto N$ as all other quantities are constants.

E_0 is direction sensitive and can indicate clockwise or anti-clockwise direction of rotation. A full wave rectifier is invariably used with the arrangement and the practical output shows ripples in the waveform due to non-infinite number of conductors and smoothing filters are required to obtain close to pure dc outputs, see Fig. 6.15(*b*). In case of ripples not exceeding 5% of dc output, it is possible to achieve typical sensitivity of 5V/100 rpm over a range of ± 6000 rpm with linearity of ± 0.01%. Moment of inertia of the shaft mounted rotor assembly, is kept as small as 10^{-6} kg-m^2 and friction torques limited to 1 Nm by having a small size. Source resistance offered is about 300 ohms therefore no appreciable current can be drawn without distorting the magnetic field and degrading the performance.

For instrumentation/control of shaft speeds of the controlled objects, these voltages are directly usable, being a direct measure of the speed of rotation.

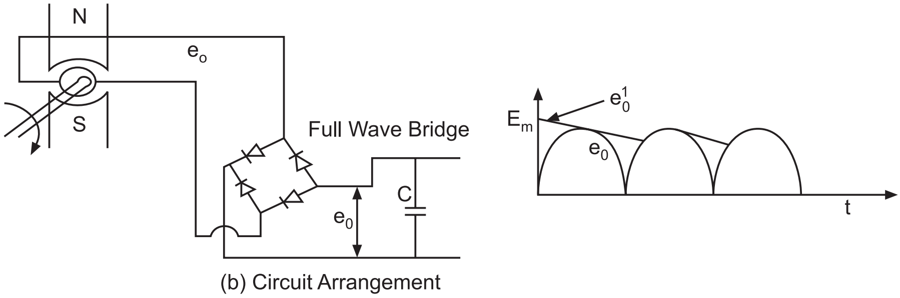


Fig. 6.15 DC Tachnogenerator

6.3.3 AC Tachogenerators

These work on the principle of two-phase servo motor/generator. The rotor is miniaturized and mounted on the shaft whose speed is to be monitored. As shown in Fig. 6.16(*a*) the stator has two windings—a reference winding fed from a constant voltage source to provide magnetization and a control (or output) winding, with a phase difference of 90° with reference winding. An ac output voltage is available at the control winding proportional to the speed of rotation of shaft. The speed-output relationship is shown in Fig. 6.16 (*b*). ac tacho needs an excitation (reference) whereas dc tachos are free from this bother. The ac servomotors have found a more common application in self-balancing potentiometers and in chart recorders as pen drive motor.

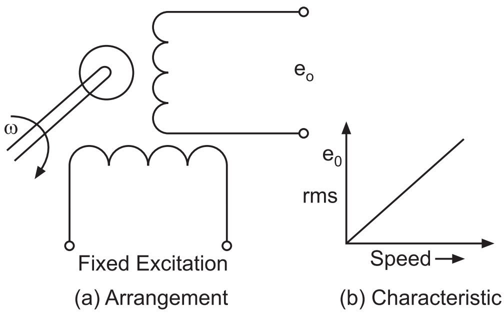


Fig. 6.16 AC Tachogenerator

6.4 ACTIVE TRANSDUCERS BASED ON PHOTOELECTRIC EFFECT

6.4.1 Photoelectric Effect

When radiant energy collides with matter, integral number of quanta – photons are emitted, reflected or absorbed. The governing relation is

Incident photon energy = Energy of electrons emitted + energy required to release the electrons

or, $$hf = 0.5\ mv^2 + W_e e \qquad ...(6.19)$$

where, h : Planck's constant

f : frequency of radiation

v : velocity of electrons emitted due to impact of photons

W_e : work function of the (target) material

e : charge on electron

Since the work-function is different for materials, the emission of electrons is highly variant, depending on incident energy. Resulting photo currents are shown in Fig. 6.17.

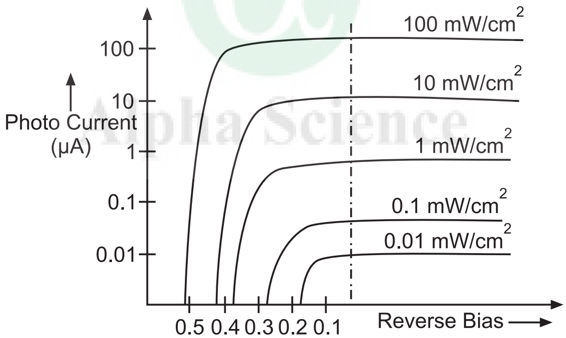


Fig. 6.17 Photovoltaic Effect

Also, the incident energy depends on frequency (or wavelength) of radiation falling on surface, not only of visible light but others such as infrared, ultraviolet, x-rays, α, β, γ rays and affect the release/absorption of incident energy.

These features result in different types of devices such as metallic elements having low work function for photo detection applications, those needing immunity against electronegative ion presence *i.e.* of O_2 and HO.

In general alkali metals have single electron in outermost orbit and therefore have low work-function *i.e.* Na with 1.00 eV, Cs with 1.54 eV compared to Pt with 6.3 eV (having 4 electrons).

In the case of photons striking a silicon *p-n* junction results in release of electron-hole pairs and a voltage is developed across the junction.

6.4.2 Solar Photovoltaic Cell

Solar Photovoltaic (SPV) cells, work on the principle that if a *p-n* junction is exposed to light, a forward voltage appears across it, known as photoelectric emf. By illuminating the junction, it is possible to obtain the V-I characteristics through the fourth quadrant. The voltage is restricted to values less than contact potential, which is generally less than the band gap voltage E_g/q. For silicon, the voltage $V_{oc} \leq 1V$, and current depends on the illuminated area. It is typically in the range of 10 to 100 mA for a junction area of 1 cm^2.To have the operation for maximum power, the open circuit voltage V_{oc} and the short circuit current I_{sc} are determined for a given light level by the cell characteristics. The maximum power delivered to load by the solar cell occurs when the product VI is maximum. Calling this values of voltage and current V_m and I_m, the maximum power delivered will be , as shown by the shaded area in Fig. 6.19(*a*) is less than $V_{sc} . I_{sc.}$ The ratio $V_m \; I_m/V_{sc}.I_{sc}$ is called fill factor and acts as a *figure of merit* for solar cell design.

The equivalent circuit can be represented as shown in Fig. 6.18. It can supply current to an external load and is referred as solar photovoltaic (SPV) cell. A combination of a number of such cells in series provides larger voltage and a further combination of series strings in parallel is able to ensure larger current supply to load.

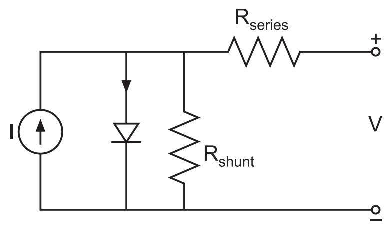


Fig. 6.18 Equivalent Circuit of Solar Cell

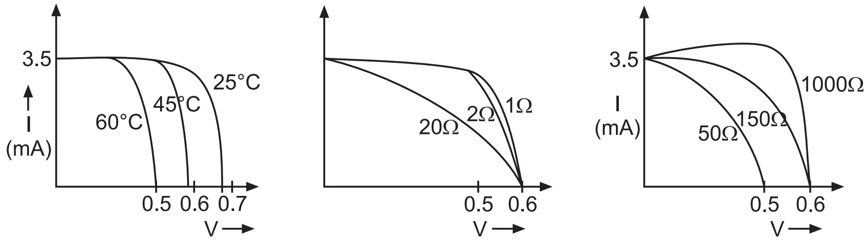
SPV cells have found application as transducer for radiation detection in industrial and biomedical fields, These have been successful as an alternate source to bio and fossil fuels, particularly for remote area applications and moving vehicles *i.e.* solar powered automobiles, spacecrafts, satellites and shall be focus of research.

Behavior of solar cells is affected by various parameters, as shown in Fig. 6.19:

(*a*) Temperature surrounding the device

(*b*) Series resistance in the load circuit

(*c*) Shunt resistance



(a) Effect of Temperature (b) Effect of Series Resistances (c) Effect of Shunt Resistors

Fig. 6.19 Effect of Temperature on Performance of SPV

6.5 DIGITAL TRANSDUCERS

The class of transducers that provide a direct digital out put (without the use of explicit analog-to-digital converter) are termed as digital transducers.

This category may include mechanical or electrical devices. Electrical Digital transducers appear attractive with reference to direct display but for the purposes of any subsequent processing, they require very careful handling in terms of interfacing (handshaking) protocol. A few of digital transducers are described here.

6.5.1 Digital encoder for speed measurement

These are of two types– rotary type and linear type:

Shaft encoder or velocity encoder/tachometer, converts mechanical rotary motions (speed) into binary signals. In earlier models an encoding disc was attached to moving shaft with concentric rings in a coding pattern of conducting and non-conducting segments. Brushes would slide over the concentric rings and the speed would generate the digital output pattern.

It has become obsolete due to wear and tear and problem of mechanical maintenance, nevertheless the principle of arrangement is interesting and has been extended for electronic and digital techniques. It has been replaced by a glass disc mounted on the shaft, with coding pattern printed on the disc. Ink used for making pattern is sensitive to infrared radiation and an optical output code is possible as shown in the Fig. 6.20.

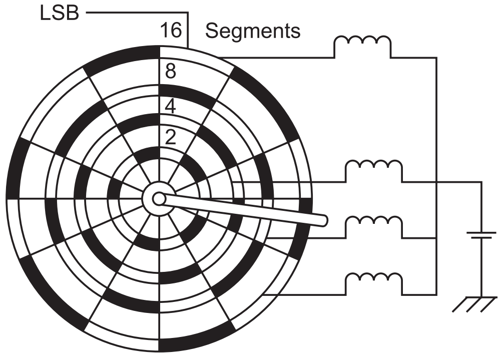


Fig. 6.20 Binary Coded Encoder Disc

Optical shaft encoders of this type have concentric rings. An IR light source or LED provides illumination on one side of disc, one emitter for each bit, with photo detectors on the other side of disc.

Outer most track is LSB and makes most number of changes per revolution of encoder. For example, to resolve the shaft position to 1 part in 1024 *i.e.* 10 bit converter needs 10 tracks on shaft encoder.

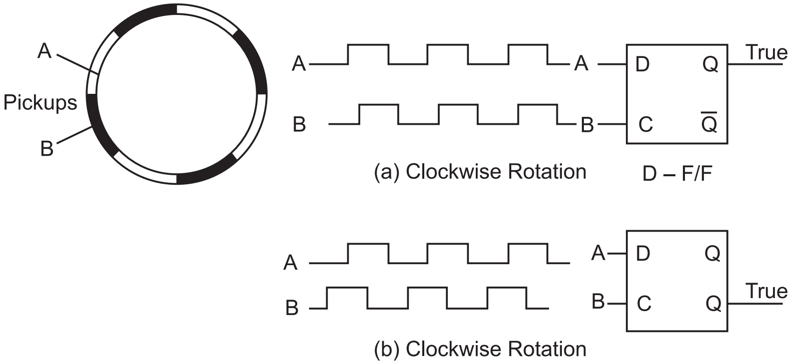
Table 6.6 Speed Encoder with 16-bit Output

msb	-	-	lsb	
0	0	0	0	
0	0	0	1	Outer most orbit: 16 segments
0	0	1	0	Middle - 1 : 8 segments
0	0	1	1	Middle - 1 : 4 segments
1	1	0	0	Innermost : 2 segments
....				
....				

Typical encoder provides 32-1042 pulses/record, outputs are square waves for constant rate of rotor. Additionally, code converter chips/microprocessor can be used to have any other desired code, (Example 16-bit encoder in Table 6.6).

Resolution is set up by the number of output pulses per revolution of shaft, say if 1024 pulses are generated per revolution, then each output pulse corresponds to (360/1024) degrees and corresponding phase shift can be known but the direction of rotation is still unknown! To discriminate between the two directions of rotation, a D flip-flop can be used with signals picked up from two additional, pick ups as shown in the Fig. 6.21.

The output of the D type flip-flop (F/F) will be Q or $\bar{Q}$ true for clockwise or counter-clockwise direction.



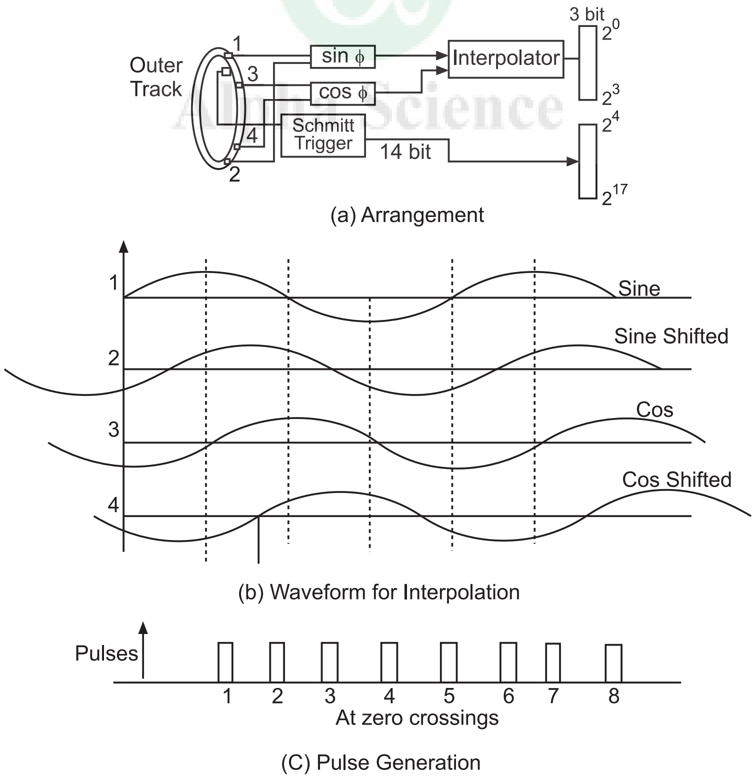
(a) Clockwise Rotation

(b) Clockwise Rotation

Fig. 6.21 Direction Sensing Arrangement with Encoder

Enhanced resolution encoders

Output of the cells of outer track (with special arrangement) are arranged to produce a sine wave output. By providing two more sensors on this track both sine and cosine waveforms are obtained (see Fig. 6.22).



(a) Arrangement

(b) Waveform for Interpolation

(C) Pulse Generation

Fig. 6.22 Enhanced Resolution Encoder

An additional signal is obtained by inverting the first (sine) signal. These 03 signals are fed into an interpolator, with phase changes introduced by producing a succession of sine waves converted to square waves so that level detector identifies 08 states resulting in 03 additional bits as shown in figure.

6.5.2 Incremental Linear Position Optical Encoders

In several manufacturing system applications, where a linear motion is to be monitored *i.e.* product movement over conveyor belt as in case of filling of tea boxes, filling of pills in bottles/cartons, filling cold drink/milk in bottles, definite amount of solid material/pellets to be filled into box etc. In all such applications the speed of conveyor at the belt on which the boxes/bottles are placed at the starting point have to travel a definite distance before coming below a hopper timed to release requisite amount of material only and then move the pack for further action.

Three possible arrangements are shown in the Fig. 6.23:

In Fig. 6.23 (*a*) there are alternate insulating and conducting surfaces are prepared along a track, on conveyor belt and there is another conducting track. A wiper moves over the first track to complete the electric circuit alternately producing pulses at the output. The frequency of pulse output is coded and calibrated to provide speed of conveyor belt or the number of boxes/bottles filled.

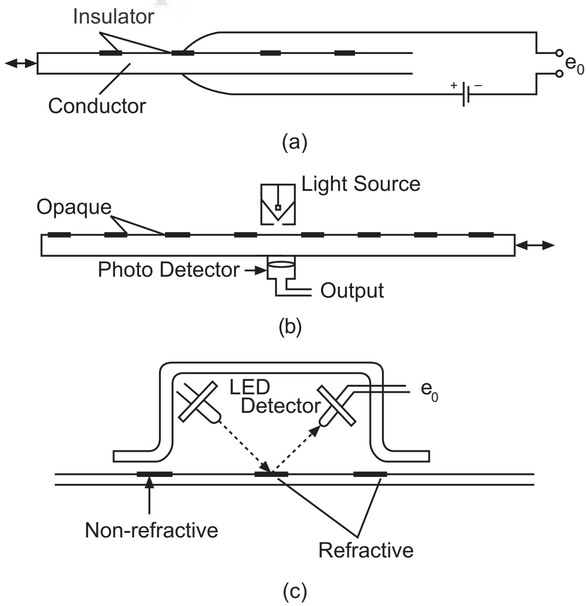


Fig. 6.23 Pulse Based Instrumentation Scheme

In Fig. 6.23 (*b*) there are opaque and transparent windows along a track. The light emission from the source is picked up by a photo detector and the pulses produced are calibrated to indicate the speed.

In Fig. 6.23 (*c*) along a track, there are alternate coating of reflective and non-reflective material coating. A LED and photo detector assembly in a casing (as shown) also results in a pulses output, on movement of conveyor in either direction.

6.5.3 Digital Tachometers

Electromagnetic transducer with AC output have frequency proportional to rotational speed (as also in case of flow meters), is designed to have the wave shape similar to pulses by designing teeth to produce square shape instead of sine. The pulses are generated at zero crossings that trigger output and pulses are counted over a time and pulse rate used to calibrate speed. The basic arrangement useful in all such applications is shown in Fig. 6.24. Control logic block is a programmed one and controls the operations.

In case of digital flow meters, a sensing head provided–with a coil and core to develop pulses whenever a magnet embedded in one of the blades sweeps the region of head. It shall be discussed in Chapter 7 in more detail. A (Geiger-Muller) pulse counter may also be used to count the number of sweeps the blade makes near the detector.

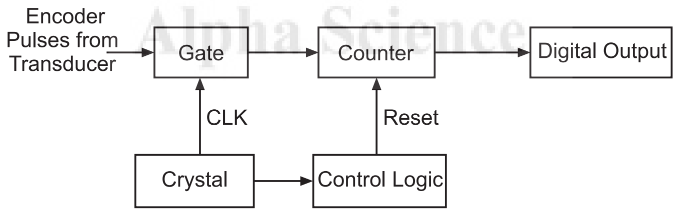


Fig. 6.24 Pulses Based Instrumentation Scheme

6.5.4 Quartz Temperature Transducer

Quartz crystal oscillator is stable at the frequency of oscillation. However when temperature variations occur about a particular temperature, the new frequency is related to temperature as

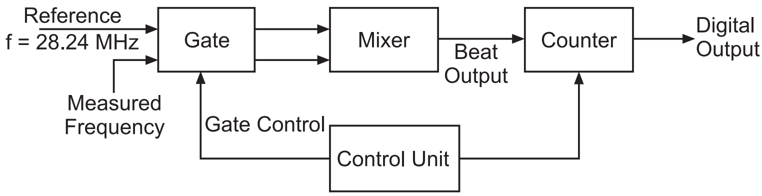
$$f_T = f_0\ (1 + \alpha\Delta T + \beta\Delta T^2 ...) \qquad ...(6.22)$$

where f_0 is the frequency at 0°C.

If Quartz crystal is cut in a specific direction, linear relationship can be obtained.

f_0 depends on thickness and can be adjusted to a value that yields a change in frequency of 1kHz/°C., where $\alpha = 35.4 \times 10^{-6}$/°C. The natural frequency f_0 is about 28.24 MHz.

Schematic arrangement is shown in Fig. 6.25 which is a modification of the arrangement shown in Fig. 6.24. Another quartz oscillator operating at fixed – known temperature provides the measured frequency and the two frequencies are compared by hetrodyning or beating together.



For Crystal Diameter of 6.5 mm

Fig. 6.25 Quartz Temperature Transducer

The crystal is kept sealed in inert atmosphere of a small container. It is possible to achieve a detection as low as 1 Hz change in frequency *i.e.* 1/1000 = ±0.001°C. The frequency of crystal under test and the natural frequency without stress are mixed to beat together and the difference frequency is counted to produce a digit output in desired format. This transducer can be operated over a limited temperature range of –80 to 250°C with an accuracy of ±0.075°C.

6.5.5 Piezoelectric/Quartz Pressure Transducer

If piezoelectric crystal is used as resonator for oscillator frequency variation of up to 2 Hz are noticed for change in pressure of 1 atmosphere. Temperature of crystal is maintained constant and high pressures applied to crystal result in change of frequency.

Measurement scheme is same as for temperature, the scheme as shown in Fig. 6.25 shall be used with conditions altered, and can measure up to 700 atmosphere, with resolution of 1 in 10^6 over 1 second counting period.

6.5.6 Vibrating Diaphragm Pressure Transducer

A diaphragm (membrane) is maintained in a constant state of vibration by using positive feedback by using a sensor and a frequency coil energized by an amplifier.

Another diaphragm undergoing vibration due to measurand pressure, causes a change in frequency of first one (with insensitivity of temperature) as shown in Fig. 6.26 (*a*).

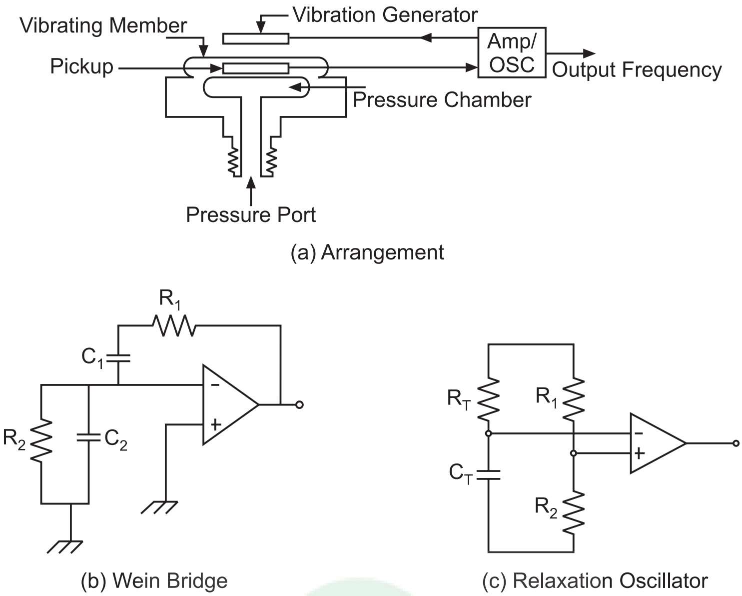


Fig. 6.26 Vibrating Diaphragm Pressure Transducer

For $$R_1 = R_2; C_1 = C_2\ ; \quad \omega^2 = \frac{1}{R_1R_2C_1C_2}$$

With Wein bridge being a common choice, bridge attenuation = 1/3, therefore minimum gain should be 3. As shown in figure the two capacitances formed can be used in a Wien Bridge as $C_{1,}$ C_2 to result in a frequency output which can be calibrated for pressure/change in pressure. A relaxation oscillator alternately can be used as shown in Fig. 6.26 (*c*) as an astable MV with capacitor C_T charging through R_T. When voltage across C_T equals to that across R_T, comparator switches off. The pulse produced is used to discharge capacitor, and cycle starts again.

Repetition period,

$$T = \left[\ln\left(1+\frac{R_2}{R_1}\right)\right]R_TC_T$$

Sensor is made to change R_T or C_T resulting in proportional change in signal period. Thus monitoring of time-period and hence frequency is calibrated for pressure variations.

Comment

In this and previous two chapters we have become familiar with various principle of passive and active transducers' working, on the basis of which transducers have been developed and a large number of these have been realized. The relevant input–output relationships have also been developed. In the next chapter we shall consider the application and choice of transducers for some of the common system variables to be monitored in industry such as temperature, pressure, flow, level, position, speed, acceleration.

SUGGESTED READINGS

Doeblin, E.O. – Measurement systems (McGraw Hill)

Rangan, Sarma, Mani – Instrumentation systems and devices (TMH)

Patranabis, D. – Principles of industrial instrumentation (TMH)

Streetman, G – Solid state devices (Prentice Hall)

Parr, E.A. – Industrial control handbook vol. 1 (Collins)

Seippel, R.G. – Transducers, sensors and detectors (Reston pub)

REVIEW PROBLEMS

(*i*) What is the principle of thermocouple?

(*ii*) What are the various effects that help in understanding the phenomenon of thermoelectricity?

(*iii*) Who were the early scientists who contributed to understanding of thermoelectric effect?

(*iv*) Why the specific combinations of metals have been chosen ti form thermocouples?

(*v*) What are the laws of thermocouples? State and explain.

How they help in industrial thermometry?

(vi) Why the thermocouple elements need protection?

(vii) What are the factors in making a choice of thermocouple for an industrial application?

(viii) What is the range of TC output voltages?

(ix) Why it is important to maintain reference junction at constant temperature?

What are various approaches to achieve this?

(x) What are the advantages of servo-balance potentiometer in measurement with TC?

(xi) What type of materials show piezoelectric effect? Is it reversible too?

(xii) What are the typical industrial and consumer oriented applications of piezoelectric devices?

Give 03 examples of each.

(xiii) What is the major limitation of piezotransducers?

(xiv) Which property(ies) of piezodevices makes it eminently suitable for acceleration/vibration pickups.

(xv) Do the reluctance type or capacitive type tacho-meters have significant applications now?

Explain either way.

(xvi) If the wheels of an automobile skid (say over snow) how the speed can be measured?

(Answer will be available in Chapter 7).

PROBLEMS FOR EXERCISE

6.1 Explain the operation of an industrial servo-balance type of potentiometric arrangement used with chart recorders.

6.2 What is the approach to TC linearization? Explain with an example.

6.3 In an a arrangement of temperature monitoring with K-type thermocouple, find the output voltage for the following cases

Reference junction	***Measuring junction temperature***
(*a*) 0°c	300°c
(*b*) 40°c	300°c
(*c*) 40°c	450°c
(*d*) 25°c	450°c
(*e*) 30°c	600°c
(*f*) 60°c	900°c

(Use TC table available in appendix)

6.4 A copper-constantan thermocouple was found to have linear calibration between 0°C and 400°C. Thermo-emf at maximum temperature is 20.7 mV with reference at 0°C. Determine:

(*a*) the temperature of hot junction if the indicated emf from TC is 8.96 mV.

(*b*) the maximum correction to be made if the cold junction (reference) is at 25°C.

6.5 A nickel resistance having temperature coefficient of resistance of 0.006/°C, is connected across the indicator meter which in turn is connected with the thermo couple with a series resistance R. If the ambient temperature changes from 20°C to 30°C and the output of the thermocouple changes from 30 and 29.5 mV, Calculate the nickel resistance and R for complete compensation when meter has a rated current of 100 μA and a resistance of 50 ohms.

6.6 For calibration of TCs, potentiometric method of voltage measurement is used with temperature measured by another accurate arrangement. During one such calibration testing, it is observed that, for a Alumel-Chromel TC with reference junction maintained at 35°C and output voltage measured with potentiometer (*i.e.* open circuit measurement) is 45.26m V. What is the hot junction temperature being measured ?

6.7 Explain the piezoelectric phenomenon. How it can be utilized for force transducers?

Derive relevant input-output relation.

6.8 A peizoelectric crystal having dimension of 5 mm × 5 mm × 1.5 mm and a voltage sensitivity of 0.055V-m/N. Is used for foce measurement. Calculate the force if the voltage developed is 100V?

6.9 A piezoelectric transducer has a capacitance of 2000 pF and a charge sensitivity of the resistance of 0.055V-m/N. Transducer is 10^6MΩ. The impedance of the measuring system consists of a capacitance of 500pF in parallel with a resistance of 1MΩ. Find the response if the applied force is: $F = 0.1N$ for $0 < t < 2$ ms and $F = 0N$ for 2ms $< t < \infty$.

Find the voltage just before and after the impulse is terminated. Also find the voltage after 10ms of application of pulse.

6.10 A barium titanate pickup has the dimension of 5 mm × 5 mm × 1.25 mm. The force acting on it is 5N. The charge sensitivity of barium titanate is 150 pC/Nand its permittivity is 12.5×10^{-9} F/m. If the modulus of elasticity is 12, calculate the strain. Also calculate the charge and the capacitance.

6.11 Explain the principle of operation of piezoelectric transducer. Derive the transfer function between E_0 and deformation $z(s)$along the axis.

A piezo electric transducer with 0.1 cm thickness and 1 cm^2 area of cross section quartz crystal held between metal electrodes is used to monitor the changes in force applied across it. Find the p-p voltage swing across electrodes if a force $F = 0.01 \sin(2000t)$ N is applied. Also find the maximum changes in thickness, if $E = 9 \times 10^{10}$ Pa, charge sensitivity 3.5 pC/N, $\varepsilon_r = 5$, $\rho = 10^{14}$ Ω-m/cm^2. Effect of connecting cable and amplifier can be approximated by a 10 pF capacitance in parallel with a 50 MΩ, resistance.

6.12 A piezoelectric transducers has capacitance of 1000 pF and K_q of 10^{-5} C/cm with connecting cable of capacitance 100 pF is outputting to an oscilloscope with input impedance of 1M ohm in parallel with 50 pF. Express the sensitivity of transducer with and without connecting cable and CRO.

Using formula determine the minimum frequency which can be measured with flat response within 5%.

How the range extension can be extended on low frequency side.

6.13 Explain the piezoelectric phenomenon. How it can be utilized for force transducers?

Derive relevant input-output relation.

6.14 A piezo electric crystal transducer is used for measuring the force transmitted from a structure to its support in Fig. Q.6.14.The crystal in form of disk of dia. 2 cm, thickness 1mm with a dielectric constant of crystal 5 and its Young's modulus is 8×10^{10} N/m^2. Capacitance of cable is 20 pF; the charge amplifier has input resistance of 20 MΩ in parallel with a capacitance of 50 pF & gain of 50. If the charge constant is 60×10^{-3} C/m, find amplitude of force transmitted if the output signal E_0 has amplitude of 5V at a frequency of 100 Hz.

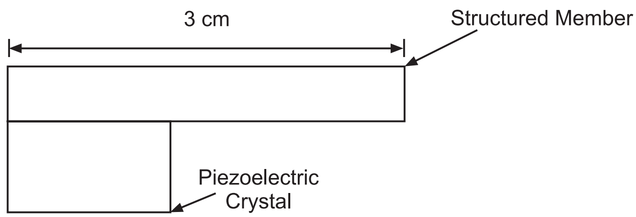


Fig. Q.6.14

CHAPTER 7

Transducers for Industrial Applications

Inside the Chapter

7.1 INTRODUCTION

In previous chapters the theories of transducers have been discussed along with the primary sensors needed for actual use of pressure transducers. As has been notified, for instrumentation of physical variables, more than one type of transducer may be applicable. In order to make the choice of appropriate transducer, a revisit is made in this chapter from application specific point of view and the comparison of various options presented for few important variables. Scope of new applications, for the same transducers is always open and depends on the innovation capability of user.

This chapter will present the industrial transducers for most common process variables in power and process industry viz. temperature, pressure, flow, level and the variables related to manufacturing and avitation industry such as position, speed – linear, rotational, acceleration, vibration etc.

Temperature is one of the most widely monitored variables for operation, preventive maintenance, and disturbance effect mitigation when environmental changes are considered. It is a dynamically slow variable but has wide range to encounter from sub-zero to thousand of degree Celsius and hence the need for various types of sensors and techniques.

7.1.1 Various Temperature Instrumentation Methods

Based on the principle of various temperature transducers discussed earlier, Table 7.1 provides a comparison of various methods and their application suitability for different cases. It must be noted that, in the present day industry, electrical methods are being used commonly as they are convenient, precise, and economical and offer economic and reliable data transmissibility with far greater flexibility for processing.

Also, for very high temperatures, a radiation method seems to be the only possible solution and the principle used in radiation pyrometers has provided a convenient technique for non contact thermometry.

For an economical setup RTD may be justified, although it depends on a number of factors such as range, speed of response, accuracy, stability, cost of installation and maintenance. For the temperature range being considered if either copper or nickel is selected, is put in one of the arms of Wheatstone bridge and the bridge balanced at ambient temperature. As soon as the temperature begins to rise, the RTD placed in the bath undergoes change in the resistance and results in imbalance of the bridge. The output meter connected at the bridge output is calibrated in terms of change of temperature from the ambient.

Such an arrangement can be easily integrated in a control system but the related instrumentation needs to improve the accuracy. Muller's bridge configuration is used to avoid the effect of lead resistances, as shown and presented in Appendix–B.

However for thermocouple applications, the use of servo-balance principle is more practical. As shown in Fig. 7.2, a dc-to-ac converter using chopper principle, a pulse transformer for coupling, driver stage for chart recorder-pen and a reference potentiometer are used. The arrangement offers advantage of low power consumption and automatic recording of temperature-deviation of signals (from the reference/desired steady value). The arrangement uses the feedback principle with the reference signal made available from a standard cell (or any other constant reference voltage) and potentiometer combination with the recorder motor moving only to minimize the deviation between actual and reference temperatures.

The principle is general and can be extended to recording of any other variable with comparable dynamics.

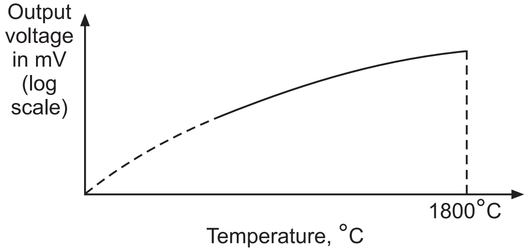


Fig. 7.1 Callibration Graph of Radiation Detector

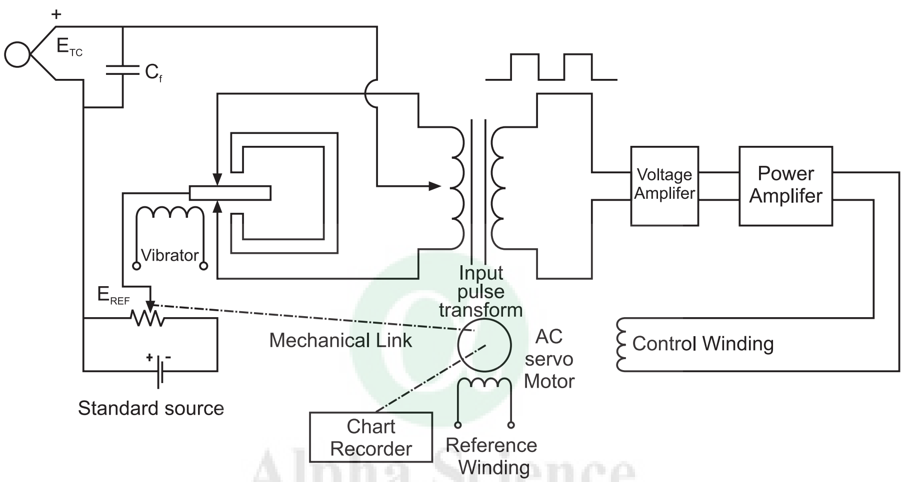


Fig. 7.2 Application of Self-balancing Potentiometer with TC

7.1.2 High Temperature Monitoring

For high temperature ranges *i.e.* above 1000°C, contact type sensors are not feasible, such as in case of continuous monitoring of temperature in blast furnace in steel plants, glass furnaces, foundry and forging shops. Radiation pyrometers are invariably used for:

(*i*) Monitoring temperatures from a distance of cement kilns, furnaces, moulds, reactors, steam pipes, pulp digesters in paper industry.

(*ii*) Monitoring temperatures of moving materials as in the case of plastic film sheets, hot rolled strips, paper, textile, rubber where transducers cannot be mounted and in accessible components such as bearings.

(*iii*) Monitoring temperature of very small mass materials, bodies such as electronic components where temperatures may not be high but using contact type transducers is simply not feasible.

(*iv*) Quick measurements as in case of opening and closing of injection molding dies, rotating machinery.

(*v*) Monitoring temperature of rough surfaces where contact type transducers cannot have perfect contact for thermal transfer to respond with accuracy.

TABLE 7.1 Techniques of Temperature Instrumentation

Sl. No.	Type of device/ sensor	Temperature range, °C	Error in % of FS	Transmis-sibility	Major limitation	Advantage
1.	Mechanical/classical Liquid in glass					
	Not wetting	–40 to 620	1 - 1.2	No	Direct reading	
	Wetting type	–200 to 200	2	No		
	Liquid filled	–30 to 500	1 - 2	Yes		
	Vapor pressure	–40 to 350	1 - 2	Yes		
2.	Electrical sensors (*i*) Resistance thermometer (*a*) With PTC	–190 to 620	0.3 to 0.5%	Yes	Bridge measurement, lead comp-ensation, self-heating.	Electrical output
	(*b*) With NTC	–100 to 200	0.2%	Yes	Poor linea-rity, load compensation, advanced electronics	Electrical output, very sensitive, small size
	(*ii*) Thermocouple	–200 to 400	0.75%	Yes	Signal conditioning, cold junction compensation	Remote indication
	(*a*) Cu-constantan	0 to 1000		Yes		
	(*b*) Chromel-Alumel	0 to 1300	0.75%	Yes	”	”
	(*c*) Platimun-Platimun Rhodium	–100 to 1300	0.5%	Yes	Careful handling needed	High sensitivity, small size,
	(*iii*) Semiconductor (IC) sensosrs	–55 to 150	0.5 to 1.5%	Yes	Care needed	Low range, nonlinear

7.1.3 Principle and Operation of Thermal radiation Instruments

These are based on the principle of radiation from a hot body. All hot bodies emit visible radiation with wavelength in the range of 0.3 μm – 0.72 μm (micron).

The black body is considered a perfect radiator with absorptive and emissive powers of unity or 100%.

Total emissive power = $\Sigma\lambda_i$

where i = visible and IR wavelengths and depends on the wavelength as shown in Fig. 7.3 and, total energy emitted according to Stephen Boltzmann's law is given by

$$E = \sigma T^4 \qquad ...(7.1)$$

where, σ = Stephan's constant $= 5.672 \times 10^{-12}$ N/cm^2 –sec-deg^4

Net absorbed energy from radiation,

$$E = \sigma(T^4 - T_d^{\,4}) \qquad ...(7.2)$$

$$= \sigma T^4, \text{ if } T >> T_d \qquad ...(7.3)$$

where T_d is detector temperature.

For high sensitivity and fast response, detector should be small so as to have low thermal capacity. The radiation detectors can be made around thin strip of balance plate foil, TC or a thermistor. Accordingly, we can have two major types of detectors also called radiation pyrometers/bolometers.

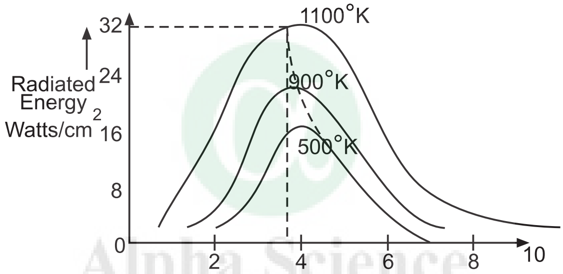


Fig. 7.3 Radiant Energy of Black Body

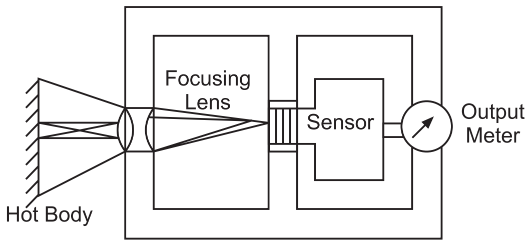


Fig. 7.4 Thermal Type of Radiation Pyrometer

7.1.4 Types of Radiation Detectors/Bolometers

(*a*) Thermal or photonic type based on total radiation

$$K_o(T_2 - T_0) = \varepsilon\, T_1^{\,4} = \text{Heat input} \qquad ...(7.4)$$

where ε is the emissivity of the surface of the equipment emitting heat *i.e.* the surface, whose temperature is to be monitored.

Empirical output voltage, $V = k_v T^n$ ...(7.5) where k_v is obtained from the experimental graph, n has a range of 3.5–4.5 depending on the choice of material. The choice of sensor is among thermocouple/thermopile/and thermistor-typically for faster (but nonlinear) response and metallic sensors based on RTD principle.

The considerations in selection of radiation detector for a particular application include:

(*i*) Temperature range
(*ii*) Accuracy
(*iii*) Reproducibility
(*iv*) Speed of response
(*v*) Measurement conditions-target size, medium, distance etc.

It is observed that thermocouples/thermopile provide largest output with low time-constant. Resistance bolometers have speedier response, good sensitivity but they are costly. Thermistor have poor repetitiveness and have compensation difficulties but they have no limitation of wavelength range.

(*b*) Photon Detector Type

Incoming radiation (photons) frees electrons in detector and produce measurable electrical effect. Being at the molecular/atomic level provides higher speed of response but limited spectral sensitivity and range. Various types of detectors in this category are:

(*i*) photoconductive (LDR)
(*ii*) photovoltaic (solar photovoltaic/SPV cell)
(*iii*) photoelectromagnetic

The relative response of few common types is presented in Table 7.2 and in Fig. 7.5 and Table 7.3 shows in brief the features and range of applications.

7.1.5 Remarks on Use of Infrared Thermometers

These are portable, hand held very common in industry being available with telematics(measuring from a distance) facility also. The arrangement shown in Fig. 7.4, consists of a convexo-concave lens used to focus the infrared rays from target on to a thermopile to produce mV signal. Cold junction compensation is provided in standard way, using thermistor or any other suitable approach.

A small non-contact IR sensor can be permanently fitted, to monitor key components for monitoring the malfunctioning of motor, pumps, drive bearings, gearboxes etc., which often causes rise of temperature.The approach can be used for preventive maintenance by monitoring unusual rise in temperature inside control cabinets. It is economical compared to thermal imaging camera technique being used presently and can provide 24 × 7 monitoring, with reliability as much as 1000 years mean time between failures (MTBF).

Small size of these sensors, typically (say) 6 mm in diameter and length up to 25 mm suits the monitoring microscopically, with remote indication of differential temperature (with reference to ambient). Response criteria of radiation detector are provided in Table 7.3, to help in selection of appropriate type for the particular application.

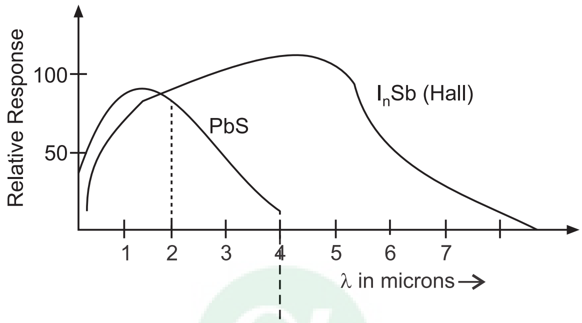


Fig. 7.5 Relative Response of Photon Detector

TABLE 7.2 Comparison of IR Thermometers

Type	*Temp Range (C°)*	*Target size (mm)*	*Distance (Ms)*	*Spectral range (Å)*
General	0-205	50	1.2	1.8-40
Purpose	0-320	40	1.2	4.8-20
	0-450	50	1.2	7-20
	0-600	40	1.2	4.8-20
High	0-1000	50	1.2	70
Temp.	600-1700	76	2.4-4.8	60-70
Low temp.	40-60	50	1.2	7-20
Telematic	20-200	40	12	10-50

TABLE 7.3

Type	*Responsivity**	*N.E.P.***	*Response time*
Metal bolometer	0.4	0.07 μW	3-5 m sec
Hall transducer	1.0	0.01 μW	1 μ Sec
Thermopile	1-100	~3-7 mW	0.1-0.5 sec
Thermistor	1000	~0.03 μW	2-4 m sec
Photon detector	5000-15000	~0.004 μW	0.05-2.7 m sec

*Output Volts/watt of Incidence Light
**Noise Equivalent Power

Telematic type pyrometers are very useful for temperature scanning of transmission lines and sub-station and also for trouble shooting in refineries, steel, chemical processing etc. For accurate measurement of true temperature target emissivity must be known which corresponds to the measured radiant temperature. The true material emissivity keeps on changing as a function of material properties and application factors during the heat cycle. It also depends on wavelength, surface physical properties *viz.* – size, shape, roughness, surface crystallization, coating, and operating environment – oxidizing, reducing etc.

7.1.6 Semiconductor Temperature Sensors

This class of thermometers is usually in the form of ICs with many types, sizes and models. Most of these are quite small and their basic design is based on semiconductor diodes and transistors, having temperature sensitive voltage – current characteristics. These have smaller temperature range compared to RTDs and TCs, but are quite accurate (about ±0.5°C), inexpensive and easy to interface with other electronics for display and control.

Temperature sensor suppliers include Analog devices, AdSem Inc., Maxim IC devices, MicRed, National semiconductors, Sensirion, TPI corporation. The sensors are available in typical range of –55 to 150°C with analog or digital output in each case from 10 mV/°C with temperature error within ±1°C up to 30 mV/°C with error of ±2.5°C. The features include linear current output and calibration accuracy up to ±0.5°C *e.g.* AD590 (analog), AD7814 (digital).

Semiconductor ICs have been designed on the principle that a BJT working in active region has a linear relationship

$$V_{BE} = \frac{kT}{q} \ln \frac{I_C}{I_s} \qquad \text{...(7.6)}$$

where, V_{BE} is base-emitter voltage
I_c is collector current
I_s is reverse saturation current
T is temperature of junction in °k
k is Boltzmann's constant (1.381×10^{-23} J/°k)
q is charge on electron (1.602×10^{-19} C)

By using a pair of identical transistors with feedback using an Op-Amp, a signal proportional to logarithm of the ratio of input currents can be obtained.

$$\Delta V_{BE} = \frac{kT}{q} \ln \frac{I_1}{I_2} \qquad \text{...(7.7)}$$

IC sensor is a 2 terminal device and exhibits proportional change in collector currents corresponding to change in device temperature, over a range of—55 to 150°C.

These are characterized by linear variation, low cost but limited accuracy. Calibration is needed for each unit with voltage-temperature sensitivity of the order of 10 mV/°C.

Figure 7.6 show the time-response of a typical IC temperature sensor. The speed of response varies with the time taken to reach 100% of final value being 3 minutes in case of still air and 3 sec for stirred oil bath.

In the network of Fig. 7.7(*a*) V_{Ref} is reference voltage such that, the voltage divider with sensor and R_1 provides output V_2 measurable output over whole temperature range. Another voltage divider with a resistance R_2 and a potentiometer is adjusted so that voltage V_1 with differential from V_2 provides a null initially.

As temperature of sensor increases, $(V_2 - V_1)$ will increase and (gain adjustable) output amplifier with reasonable sensitivity, provides voltage whose value can be calibrated to temperature. Fig. 7.7 (*b*) shows the advantage with typical IC LM35 (from National semiconductors) for temperature sensing with advantages such as:

- calibrated for direct reading of temperature in °C
- accuracy ±0.5°C
- linear with sensitivity of 10 mV/°C; nonlinearity ≤ ±0.25°C
- wide temperature range from –55 to 150°C
- draws less than 60μA current
- suitable for remote applications
- low self heating
- low output impedance *i.e.* 0.1Ω for 1 mA load
- low cost

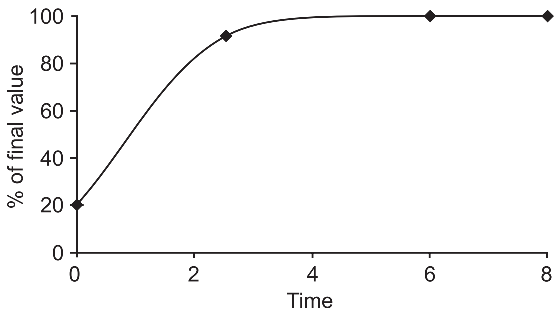
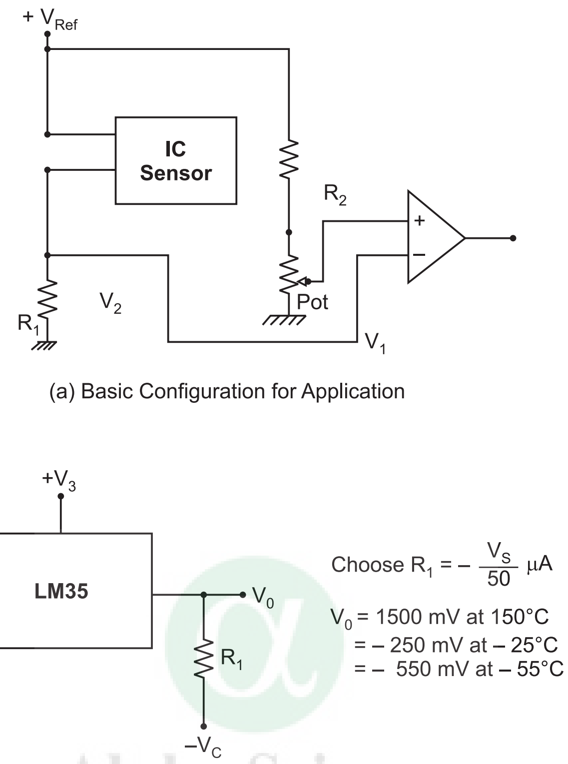


Fig. 7.6 Response of IC Temperature Sensor



(a) Basic Configuration for Application

(b) Full range °C Temperature Sensor

Fig. 7.7 IC Temperature Sensor

IC temperature sensors are new, have limited temperature range and their potential is yet to be fully exploited.

EXAMPLE 7.1

In an industrial high temperature instrumentation with a total radiation pyrometer is used to track the temperature profile of a steel plate (rolled) chimney, if the media absorption of radiation heat due to fog, rain etc., is 3% and pyrometer indication is 1000, calculate the surface temperature of chimney (at the focused point). Assume emissivity of rolled steel surface to be 0.77.

SOLUTION:

Energy radiated by chimney surface

= emissivity × (surface temperature)

= 0.77 T.

Energy received by pyrometer = 0.97 × 0.77 T

This energy to pyrometer temperature indication = 1000°C

$$\therefore \qquad T = \frac{1000}{0.97 \times 0.77} = 1338.86°C.$$

7.2 PRESSURE MONITORING

Monitoring and control of pressure is an important activity in industry, more so in process industry. The common applications are in food, pharmaceutical, (petro) chemical, fermentation pressure in bio-technology, fuel-cell technology, protective gas pressure in extrusion moulding process etc.

The pressures may range from vacuum to low to very high values, depending upon the equipment and the point of application.

The instrumentation of flow is closely related with pressure since both liquid and gas flows occur between any two points in space, only when a pressure difference (or head) exists between them.

The types of pressures (see Fig. 7.8) are classified as:

(*a*) Absolute pressure
(*b*) Gauge pressure
(*c*) Sealed gage pressure
(*d*) Differential pressure
(*e*) Static over pressure
(*f*) Dynamic over pressure

The choice of the instrumentation hardware and configuration shall be governed by the type of pressure to be measured. The reference for the pressure measurement is either atmospheric or perfect vacuum *i.e.* absolute zero and these pressures are shown in Fig. 7.8.

Gauge pressure is the measured value of pressure above atmospheric pressure and used most often.

Vacuum pressure is the value of pressure measured below atmospheric pressure.

Manometric/barometric pressure is the pressure measured with reference to absolute zero.

• Also 1000 Bar = 15,000 p.s.i.

For engineering applications, the measured pressures are classified according to magnitude as:

Very low pressures	< 0.1 p.s.i./0.6895 KPa
Medium pressure	0.1 p.s.i. to 10^4 p.s.i./0.69 to 69 MPa
High pressure	> 10^4 p.s.i./69MPa

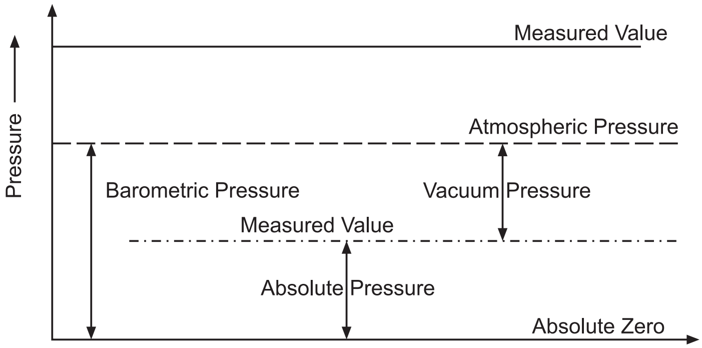


Fig. 7.8 Classification of Pressure Variable

Most commonly monitored pressure is medium pressure and there are various options available.

Pressure has been measured for a long time by mechanical methods and there are good references available to provide details of manometer, gauges and pneumatic devices, please see bibliography for these.

These are not covered here instead an attempt is made to cover the electrical transducers and the schemes currently in industrial practice.

The importance of mechanical elements can never be eliminated but has to be utilized more judiciously for the purpose of more accurate measurements and instrumentation of the same.

Pressure is almost always instrumented in conjunction with various types of primary sensors discussed earlier.

These primary sensors are used to convert the pressure variable into an intermediate variable which can then be transduced into an electrical variable by using any of the following principles:

(*a*) Resistive

(*b*) Inductive

(*c*) Capacitive

(*d*) Piezoelectric.

Of the above types, resistive are used only for static pressure and piezoelectric only for dynamic pressures. The others can be used for both types subject to certain limitations. A comparison of the various transducers is presented along with the features of each, in Table 7.4 at the end of this section.

7.2.1 Resistive Pressure Transducers

Resistive pressure transducers use the principle of the change of the resistance in a device due to pressure being measured as the input or a change in the pressure already being impressed. This may happen in any of the three modes, resulting in 03 different types of resistive transducers as:

(A) Potentiometric pressure transducers

The principle is shown in Fig. 7.9 (*a*), for low pressure ranges an arrangement used where in the measurand pressure causes the deflection of diaphragm (used as a primary sensor) and causes the movement of the potentiometer's wiper, resulting in the change of voltage across the terminals.

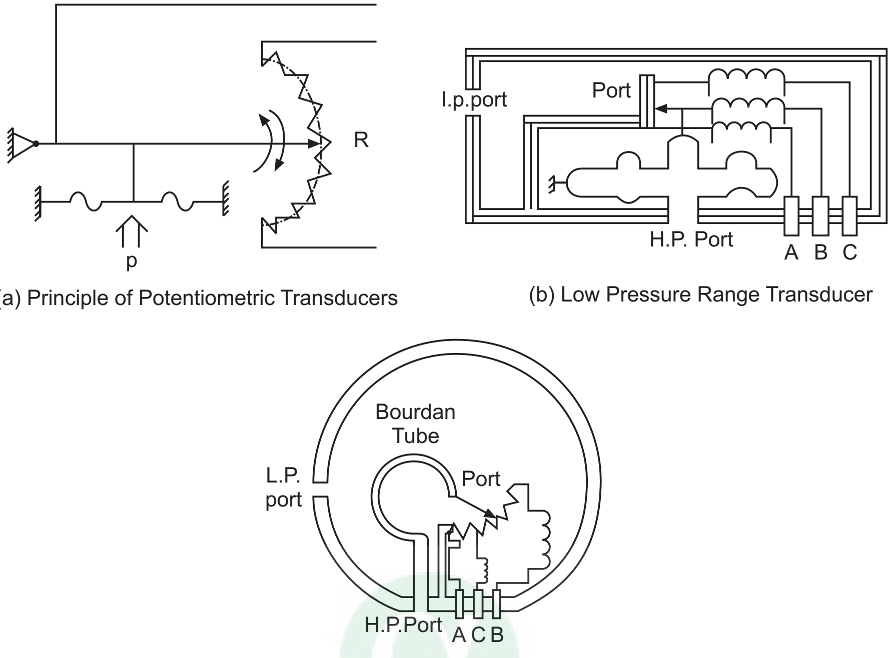
Transducers based on this principle can provide results up to:

Resolution	0.2%
Linearity	±0.1%
Repeatability	±0.25%
Hysteresis	±0.5%

An industrial transducer configured on the above principle, has been realized by having a metal capsule as the sensing element, consisting of a pair of symmetrical corrugated diaphragms, welded together at the periphery. This forms a hollow flexible member with predictable motion on application of fluid or gas pressure externally or internally. The arrangement is shown in Fig. 7.9 (*b*). Pressure being monitored is connected to the high pressure (h.p.) port and the reference pressure is connected to the low pressure (l.p.) port. Appropriate dc supply is connected between terminals A, B and the output is available across terminals A, C and is calibrated for pressure difference between P_{HP} and P_{LP}.

For monitoring high pressures, the sensing element is replaced by a Bourdon tube which can sustain pressures up to 5000 psig (35 MPa). The tube is brazed closed at the other end.

On the application of the pressure, the bourdon is actuated and the tip moves in a predetermined path, to cause a change in resistance at the potentiometer due to movable contact. In the normal configuration as shown in Fig. 7.9(*c*), the absolute pressure device is used as differential pressure transducer. The same devices can be used as a transducer by completely evacuating and sealing the unit. HP port is closed and LO pressure port is used as input port.



(a) Principle of Potentiometric Transducers

(b) Low Pressure Range Transducer

(c) High Pressure Range Transducer

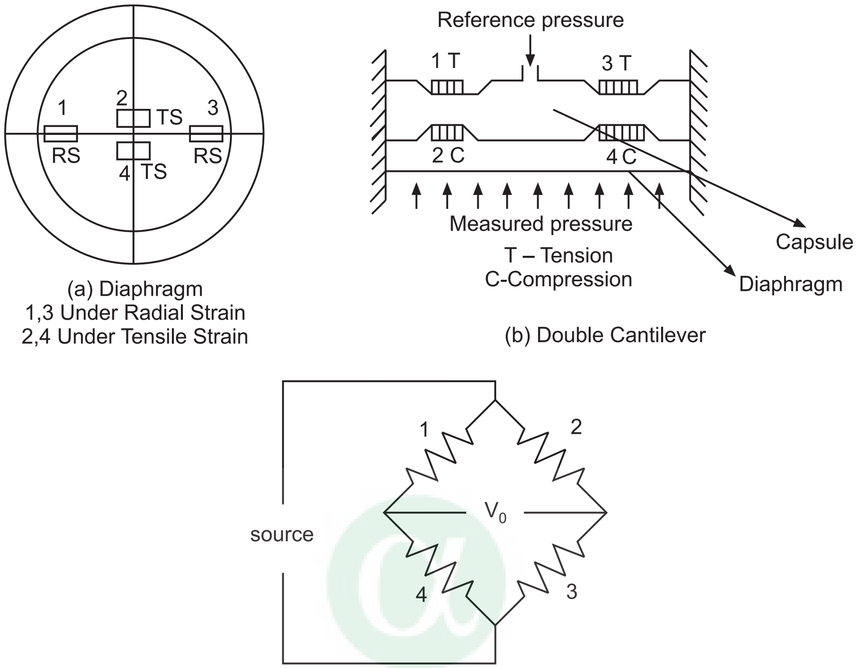
Fig. 7.9 Potentiometric pressure transducers

To use the same devices as a gauge pressure transducer *i.e.* input with reference to ambient atmospheric pressure, input is at the HP port and LP port is vented (open to air). One of the advantages of this device is the provision of special outputs by suitable designing of potentiometers so as to produce sine, ramp, or exponential output; also a close regulation of the input voltage is not mandatory as the résistance ratio provides output. Loading effect must be taken care of, as it commonly occurs in Potentiometric devices.

(B) Strain gauge based pressure transducers

The principle of strain gauges monitoring stress, force, load, pressure has been already discussed in previous chapter on passive transducers. These are useful for monitoring static and slowly varying force/pressures as in case of structures, where these are mounted on the surfaces affected by the concerned variables. Utilizing this potential of the strain gauges, these are mounted on the diaphragm, as shown in Fig. 7.10 for diaphragm.

Capsules are used as primary sensors for the input pressure. In Fig. 7.10(*a*), the strain gauges 1, 3 are under radial strain and 2, 4 under tensile strain. In Fig. 7.10 (*b*), gauges 1, 3 are under tension and 2, 4 are under compression. The four strain gauges shall form the arms of the bridge as shown in Fig. 7.10 (*c*).



(a) Diaphragm
1,3 Under Radial Strain
2,4 Under Tensile Strain

(b) Double Cantilever

(c) Bridge Circuit

Fig. 7.10 Mounting of Strain Gauges

The arrangement can provide high sensitivity and good temperature linearity. Range is limited by the nonlinearity of strain – pressure relationship above a critical strain value. For different types of diaphragms the features are:

(*i*) For clamped circular diaphragms

Radial stress $\sigma_r = \frac{3}{4} p \frac{R^2}{t^2}$ ...(7.8)

and, within linear range, strain $\in = \frac{3}{4} p \frac{R^2}{t^2 E}$ ...(7.9)

(*ii*) For thick diaphragms (R/t = 10), linear relationship is possible up to pressures of 70×10^6 Pa and stress levels can be very high with restrictions imposed for safe operation.

(*iii*) For thin diaphragms (R/t = 100), the maximum pressure for linear operation is limited resulting in low stress values. These are simple and preferred for high frequency pressures to provide good dynamic response but with low sensitivity.

A very high performance is obtained by using thin film strain gauges deposited on sensing diaphragm by sputtering technique. Such gauges are immune to problem of organic backing material, workable at higher temperatures, provide excellent reliability and reproducibility.

The industrial pressure transducers of this type are shown in Fig. 7.11. In each case diaphragm is used as the primary sensor and the strain gauge as the transducer.

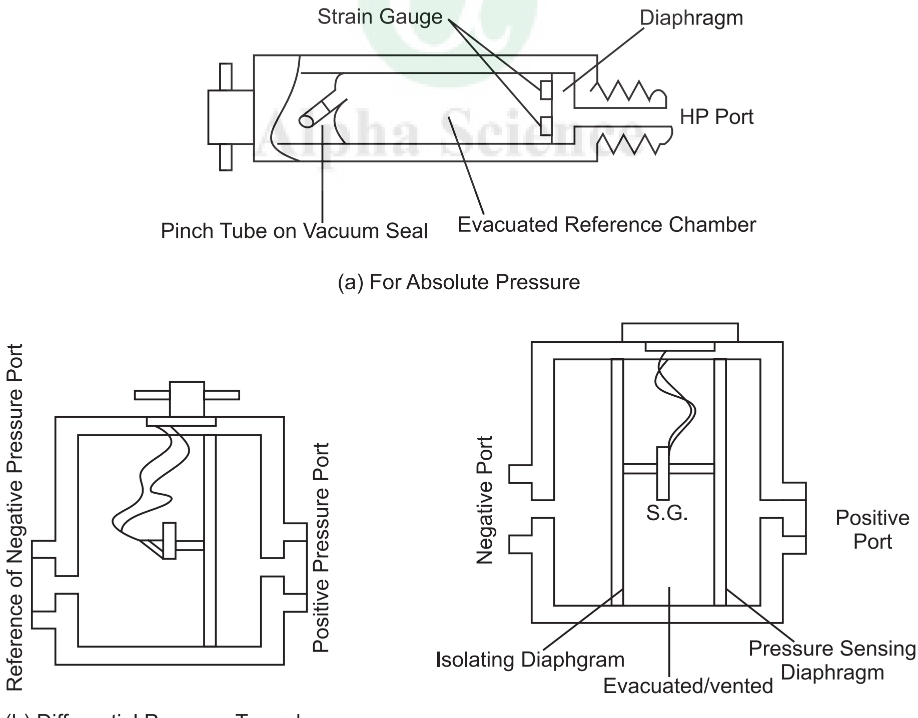
The configuration shown in Fig. 7.11(*a*), can be used as:

(*i*) transducer for absolute pressure: by sealing the pinch tube on vacuum seal

(*ii*) gauge pressure by venting the pinch tube to ambient atmosphere

(*iii*) sealed gauge pressure by putting pinch tube on vent sealed at a mixture of helium at atmospheric pressure.

With little modification, it is possible to realize the differential pressure transducer, Fig. 7.11(*b*). Here the pressure is applied at the LP (negative) and HP (positive) pressure ports.



(a) For Absolute Pressure

(b) Differential Pressure Transducer

(c) Isolating/Evacuated/vented d.p Transducer

Fig 7.11 Strain gauge Based Transducers

Another available configuration is that of isolated evacuated vented differential pressure transducer as shown in the Fig. 7.11(*c*), which stipulates forces on the strain gauge due to pressure from both diaphragms in opposition. In all the strain gauge based pressure transducers, the change in resistance experienced by the gauge is detected by a strain gauge bridge which converts this into an electrical signal, varying as a function of pressure/differential pressure being measured. The requirement of the electrically excited strain-gauge bridge is similar to that required for RTDs. These bridges can be configured according to the desired features and will be discussed in detail in a later chapter.

7.2.2 Inductive Pressure Transducers

There are several possible to cause change in inductance as a function of applied pressure or differential pressure. Of these only Linear Variables Differential Transformer (LVDT) is discussed in detail here, as it has become almost the industry standard. Normally excitation of 50 or 60 Hz can used but higher frequencies are invariably used, to have reduced size and mass of sensor components. The excitation frequency is of the order of few kilo Hz, and has reasonable sensitivity with flat response in the range of interest.The sensitivity is a trade off in design between core sizes and turn ratio. With relatively larger core, LVDTs can be used for acceleration and vibration monitoring also.

In commercial versions, LVDT's mechanism is incorporated into a package and is capable of performing under severe environments. These are usable for gauges for absolute or differential pressure applications, with limited over-pressure ratings. Pressure media interacts only with metal parts and electronics is totally isolated. Hence corrosion and hazardous environment can be tolerated by use of suitable isolating diaphragms, filters, seals and plugs. Mechanical components such as levers, gears etc. are totally avoided.

In the configuration shown in Fig. 7.12, pressure entering through HP port causes expansion of capsule (or Bellow or Bourdon tube) used as a primary sensor causes displacement of LVDT core, resulting in an output voltage which is converted into a 4-20 mA current in the electrical unit of the transducer. The output current is proportional to the gauge pressure at HP port if LP port is vented to atmosphere. For absolute pressure measurement the capsule is evacuated and sealed, with input pressure applied only to low-pressure port. For differential pressure measurements, the two pressures are simultaneously applied at the HP and LP ports.

If metal masses exist close to unit, adequate shielding has to be provided to eliminate any stray magnetic field effect.

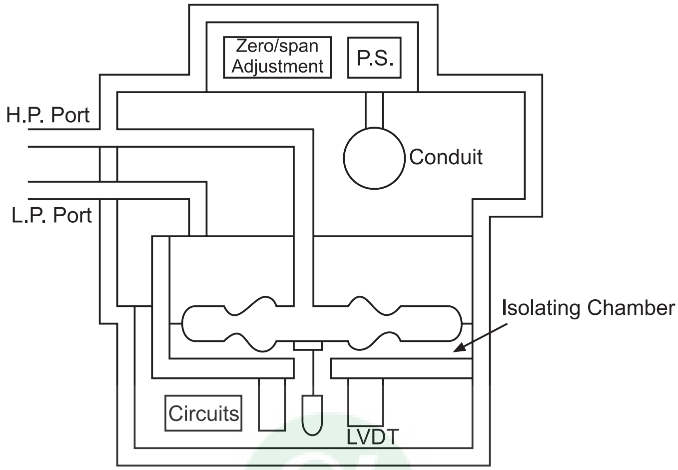


Fig. 7.12 LVDT Based Pressure Transducer

7.2.3 Capacitive pressure transducers

For using capacitive variation as a function of input pressure, three approaches have been discussed earlier during discussion on passive transducers. It was also concluded that the change in gap length of parallel plate capacitor provides maximum sensitivity as also the linearized relation between change in capacitance and voltage output by use of a differential arrangement.

A sensitive pressure transducer based on this principle is shown in Fig. 7.13 (*a*), which can be used over a range of medium vacuum up to 100 p.s.i. (about 690 KPa) making use of a bellow as the primary sensing element. The arrangement also provides excellent frequency response, standard hysteresis, repeatability, stability and excellent resolution. High output impedance can be realized with additional circuitry for impedance matching and this arrangement is sensitive to temperature variations.

Other configurations utilizing this principle are shown in Fig. (*b*), for low pressures with thin stainless steel diaphragm and as in Fig. (*c*), for sensing high pressure with thicker diaphragm, additional electrode. For a general differential pressure transducer based on change in capacitance principle, the relationship is derived next.

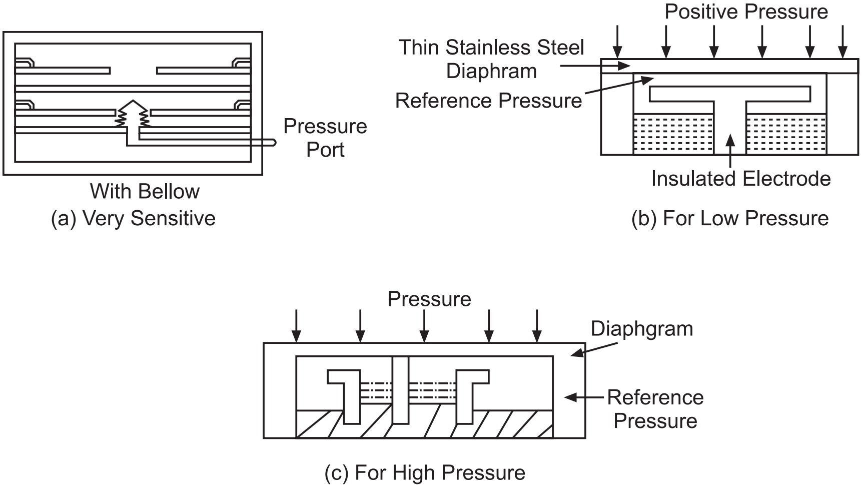


Fig. 7.13 Capacitive Pressure Transducers

The Fig. 7.15 shows the arrangement where p_1, p_2 are the high and low pressures and the central vane is allowed to be deformed due to $P = p_1 - p_2$. The two capacitances are formed with fixed plates, on either side of a deformable central vane.

The deflection occurring in the central vane is a function of the differential pressure P and can be monitored with a strain gauge arrangement or capacitance measurement or by other options such as push-pull transducer-bridge discussed in the next chapter on signal-conditioning.

Evaluation of variable capacitance value

Referring to Fig. 7.14 for the arrangement of capacitive differential pressure transducer

$$P = p_1 - p_2$$

$$y_0 = \frac{3P(1-v^2)}{16\,Et^3} R^4 \qquad \text{...(7.10)}$$

where R = radius of curvature of diaphragm

v, is the Poission ratio of the material of the diaphragm

and a, is the radius of diaphragm

If a thin membrane is used, then deflection

$$y = \frac{P(R^2 - a^2)}{4T} \qquad \text{...(7.11)}$$

Equation for centenary:

$$(y_m - y)[2R - (y_m - y)] = x^2 \qquad \text{...(7.12)}$$

$\therefore \quad 2R = (y_m - y) + x^2/(y_m - y);$

also, $\quad 2R = y_m + a^2/y_m$

$\therefore \quad x^2/(y_m - y) - y \ = a^2/y_m;$

Since $\quad y_m/a^2 << 1 \ ; \therefore \ (y/a) << 1$

$\therefore \quad y/y_m = 1 - x^2/a^2$

Capacitance of annular element of width ∂x at radius x, can be evaluated as

$$\partial(C_1 - C_2) = \varepsilon_o \varepsilon_r \left[\frac{2\pi x \partial x}{d - y} - \frac{2\pi x \partial x}{d + y} \right] \qquad ...(7.13)$$

$$= \frac{2\pi\varepsilon_o\varepsilon_r}{y_m} \left[\frac{x\partial x}{\frac{d}{y_m} - \frac{y}{y_m}} - \frac{x\partial x}{\frac{d}{y_m} + \frac{y}{y_m}} \right]$$

$$\therefore \qquad C_1 - C_2 = \frac{\pi\varepsilon_o\varepsilon_r a^2}{y_m} \log e \left[\frac{(d/y_m)}{(d/y_m) - 1} \right] \qquad ...(7.14)$$

under equal pressure condition, we have

$$C = \frac{\pi\varepsilon_o\varepsilon_r a^2}{d^2}$$

$$\therefore \qquad \frac{\Delta c}{c} = \frac{d}{2y_m} \left[1 + \frac{y_m^2}{2d^2} + \frac{y_m^4}{3d^4} + - - - \right] \qquad ...(7.15)$$

$$\approx \frac{d}{2y_m}, \text{ as } \frac{y_m}{d} \ll 1$$

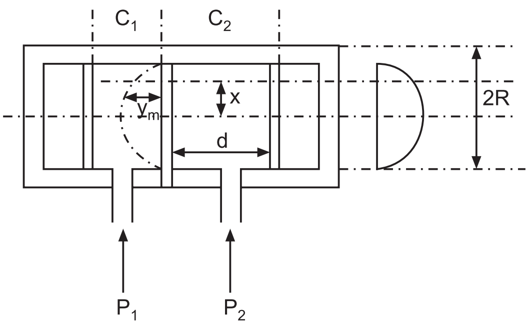


Fig. 7.14 Capacitive Differential Pressure Transducer

It results in a larger change even for small value of y_m *i.e.* sensitivity is thus obtained, but at the cost of linearity, being inversely proportional!

In more recent arrangements, capacitances are formed with sputtered film electrode on ceramic substrate on a highly stable diaphragm. This results in a small size, high frequency response, temperature insensitivity, good linearity and high resolution. These can be effectively used for low and dynamic pressures.

7.2.4 Monitoring of Dynamic Pressures

The ideal device for dynamic pressure variable is piezoelectric transducer. The basic transducer is in the form of a crystal used for sensing force, pressure, vibration, acceleration etc. The relevant theory has been already discussed in Chapter 6 under active transducers. As pressure transducer it is typically useful for compression, combustion, explosion, pulsation, cavitations, fluidic, pneumatic, blast, turbulence and sound pressure measurement as well. A typical system in Fig. 7.15 shows interconnection of transducer to a charge amplifier through a low noise cable.

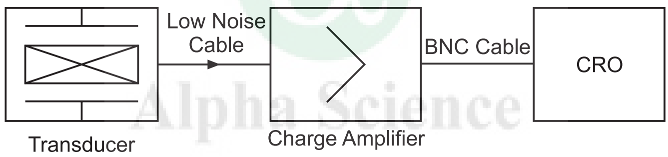


Fig. 7.15 Quartz Pressure Transducer

Typical specifications for pressure transducer include the following parameters:

Accuracy	±0.5% of F.S. (including linearity and hysteresis)
Range	1 – 50 p.s.i. (2 – 100%)
Repeatability	≤ 0.1 %
Response time	≤ 2 m sec
Temperature range	– 10 to + 70°C
Temperature sensitivity	0.1% of FS/°C
Analog output	0 – 5 (10) V dc; 4 – 20 mA
Minimum load impedance,	Z > 2 KΩ
Maximum load	< 375 Ω
Calibration	ISO 10725 Certification

More details can be downloaded from the sites mentioned in appendix.

TABLE 7.4 Comparison of Pressure Transducers

Sl. No.	Charac-teristics	1. Strain gauges			2. Reluc-tance	3. Capa-citive	4. Poten-tiometric	5. LVDT	6. Force Balance	7. Piezo-electric	8. Vibra-Diaph
		Bonded	Un-bonded	Semi-cond							
1.	Pressure range, Kpa	10 to 2×10^5	3 to 7×10^4	0.1 to 7×10^4	0.1 to 7×10^4	0.1 to 7×10^4	30 to 7×10^4	100 to 7×10^4	0.1 to $\times 10^4$	100 to 7×10^4	0-300
2.	Sensitivity per 10 KPa	3mV/v	4mV/v	20mV/v	40mV/v	5 V.F.S	5 V.F.S	2mV/v	5 V.F.S (servo)	3%	10000%
3.	Accuracy as % of F.S.	0.15	0.25	0.25	0.50	0.1	1	0.5	0.1	1%	0.2
4.	BW, Hz	2000	5000	1×10^5	1	3K	50	400	10	1×10^5	1
5.	Temp. range °C	-40 to 100	-40 to 125	-40 to 100	-40 to 300	-10 to 300	-20 to 120	-20 to 100	10 to 150	-40 to 200	-20 to 100
6.	Remark	Good lin., repeat-ability, rugged, small temp effect	Stable, small size	High sensiti-vity, high dyn. Respo-nse, good repeata-bility, small size	High sensiti-vity, good for d.p. rugged, suscep-tible to stray mag. field	Good dyn respo-nse good for d.p. small size	Low cost high o/p poor reso-lution, short life	Good lin., susce-ptible to stray mag. Field	High accuracy, high o/p, large size, low dyn. respo-nse	Good high freq. resp rugged, sensiti-vity to temp., dyn. Press. only	Good accuracy repeat., ideal for remote operation

7.3 FLOW INSTRUMENTATION

Flow is an important physical variable to be monitored in industries *viz*. chemical, petroleum, pharmaceutical, fertilizer, power and in supply system distributed networks such as for gas, oil, water and power utilities, manufacturing and service industry for inventory control, fuel loading/unloading of ships and tankers. A few of the methods used for liquid flow monitoring are useful for gases also, and shall be indicated alongside the discussions.

In most cases the flow of liquids – corrosive/non corrosive, with different viscosity, toxic/nontoxic, at different temperatures, at different pressure gradient (particularly for gases) is to be monitored in closed pipes. Open channel flow as a special case is encountered in canals and sewers and has not been considered in this treatment for reasons of brevity.

The flow of solids also needs to be monitored, such as coal in thermal power plants, rocks, clinkers and powder products in cement plants, ore in steel plants, wheat and other cereals for transportation, loading, unloading at rail, shipping terminals, etc. Methods for these are discussed towards the end of this section.

7.3.1 Types of Flow Sensors

To present an overall view of the flow instrumentation techniques, the available techniques are classified into 06 groups as follows:

(*a*) **Positive displacement methods** (for both gas and liquid quantity measurements) resulting in few common types, such as :

(*i*) Nutating disk type

(*ii*) Rotary vane type

(*iii*) Reciprocating piston type

(*iv*) Wet gas meters (only for gases).

(*b*) **Flow obstruction methods/Head meters (flow rate measurement)**

Common primary sensors in use have been resulting in pressure difference as the intermediate variable:

(*i*) Venturi meters

(*ii*) Flow nozzles

(*iii*) Orifices (for gases and liquids both)

Electrical output is obtained by converting the pressure difference into change of capacitance by diaphragm displacement as discussed in the case of pressure instrumentation.

(*c*) Flow rate measurement by drag effects, in case of liquids only:
   (*i*) Rotameters
   (*ii*) Turbine flowmeters

(*d*) Thermal flowmeters/hot wire anemometers (only for air/gas)

(*e*) Electrical (electromagnetic) flowmeters

(*f*) Ultrasonic flowmeters.

The choice of the transducer type now-a-days is largely in favor of pneumatic and to a still larger degree in favor of electrical methods, due to advantages in meeting the subsequent requirements of remote monitoring, efficient display, recording, processing for generation of control signals with appropriate signal conditioning of control signals from transducers. Table 7.5 at the end, provides a comparative performance of various schemes and can be helpful in the final choice of the appropriate device for the specific application situation.

7.3.2 Flow Measurement—Classical Techniques

Only few techniques are being considered which have been in common use over the history, interested reader may refer to bibliography for more details.

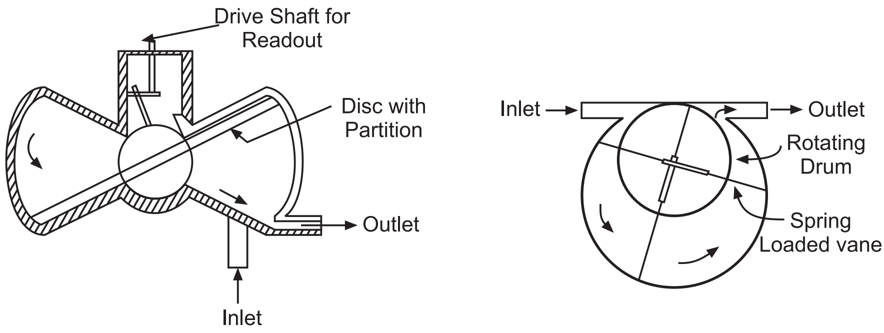
(A) Positive displacement methods:

These are mechanical devices used for consistently high accuracy under steady conditions, successfully over the decades. These are basically quantity meters. A few of these are described below:

(*a*) Home water meters work on nutating disk principle as shown in the Fig. 7.16(*a*).

The entering water strikes the eccentrically mounted disk. For the fluid to move through, the disk remains in contact with the mounting chamber. A partition separates the inlet and outlet chambers of disk. As disk nutates, it gives indication of the volume of fluid passing through. They can work under maximum pressure of 10 kg/cm^2 in a temperature range of –100ºC to 120ºC with up to ±2 % accuracy.

(*b*) In the **rotary-vane meter**, the vanes are spring loaded as shown in Fig. 7.16(*b*), so that the drum always maintains contact with casing. Thus a fixed quantity of fluid is trapped in each section as the registration is through the shaft connected to eccentric drum; uncertainties are about 0.5% with insensitivity to viscosity.



(a) Nutating-disc meter

(b) Rotary vane meter

Fig. 7.16 Positive Displacement Type Flowmeters

(B) Inferential or flow obstruction methods (head meters)

These do not measure volume or flow directly rather the flow rate is inferred from a measurable physical phenomenon associated with the fluid flow.

These are based on any of the following strategies:

- Differential pressure
- Variable area
- Target
- Velocity flow

These are characterized by insufficient accuracy, uncertainty, non linearity-typically dead-zone, low sensitivity, poor performance with dirty fluids and slurries. Nevertheless the advantages include:

- Low Cost
- Versatility of use
- Ease of installation procedure
- Robustness against ambient variations, noise.

Differential pressure flowmeters

Their operating principle relies on differential pressure(dp) between two pressure taps. The differential pressure is caused by a flow restriction, giving rise to pressure drop that cannot be recovered. Restrictions are dependent on a number of factors such as:

- Fluid and pipe characteristics
- Fluid velocity profile
- Reynolds number
- Pressure and temperature of tap locations

The most common primary sensing devices in this class areorifice, venturi, and nozzle, elbows may also be used. These can be used for liquid and gaseous fluids. The output presentation needs square-root scale with a 4:1 span range. The typical achievable accuracies with these devices are:

with orifice	±0.6%
with venturi	±1%
with nozzle	±1%
with elbow	±5%

In modern instrumentation, these devices are considered to be primary sensors (as discussed in Chapter 4 earlier) and the output of these primary sensors which is still non-electrical is converted into electrical signal by using resistive, inductive or more often capacitive transducers.

EXAMPLE 7.6

If the flow in a pipe of 40 cm diameter is observed to be under a head of 3 kg/cm², what is the fluid velocity and volume flow rate?

SOLUTION:

Flow velocity,

$$V = \sqrt{2gh}$$
$$= \sqrt{2 \times 9.8 \times 30}$$
$$= 24.2487 \text{ M/Sec}$$

($\because$ 1 kg = 10 M of water head)

And, volume flow rate,

$$Q = AV$$
$$= \frac{\pi \times (0.4)^2}{4} \times 24.2487$$
$$= 3.04718 \text{ M}^3\text{/Sec.}$$

(C) Flow measurement by drag effect

The force of drag due to flow of liquids in tube is used as in a variable area type of inferential flowmeter and common as a rotameter or glass tube flowmeter. These have to be installed vertically and cause negligible pressure loss during flow. It consist of a floating mass under dynamic balance of the force of gravity, upward thrust due to liquid flow and viscous drag on the float inside a transparent tapered tube as shown in Fig. 7.17.

The upward thrust varies with flow rate and the float moves up for higher rate of flow to reach a steady position of dynamic balance of drag forces against weight and force of buoyancy. The diameter of tube is designed to provide a linear scale and position of float is indication of flow rate.

Under dynamic balance of forces:

Gravity force, F_g = upward thrust, F_u + dragging force, F_d

$$P_1 V_1 g = P_2 V_1 g + C_g A_F P_2 \frac{V^2}{2} \quad \text{...(7.16)}$$

where P_2 : volumetric mass of fluid
P_1 : volumetric mass of float
V_1 : volume of float
A_F : area of cross section of float at the reading edge
C_g : constant, depending on geometry of rotameter
V : flow rate (speed of fluid)

Volumetric flow rate,

$$Q_v = V_1 \cdot A_1$$
$$= \text{V}\,\pi\,(A_c{}^2 - A_F{}^{2)})/4 \quad \text{...(7.16}a\text{)}$$

where

A_c : internal diameter of rotameter cone at the reading edge.
A_F : diameter of float.

Rotameters are low cost solution with simple design and are suitable for different application one with low accuracy. Their use is restricted by the pipe diameter and Reynolds number of flow.

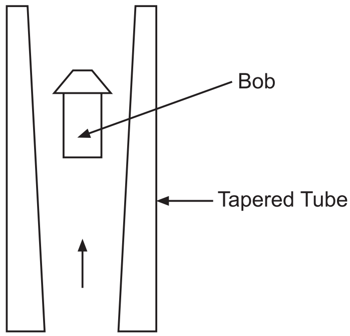


Fig. 7.17 Flow Rotameter

EXAMPLE 7.8

In a rotameter arrangement for monitoring water flow rate in a pipe line system, evaluate maximum flow rate that can be allowed. Data available: float dia 2 cm, height 3 cm, density 2700 kg/M^3*, largest diameter of rotameter, pipe connection is 5 cms.*

SOLUTION:

Volume of float, $V_f = \dfrac{\pi \times 2^2 \times 10^{-4}}{4} \times 3 \times 10^{-2} = 9.42 \times 10^{-6}$ M^3

Assume, $Cd = 0.6$ (for water)

∴ Volumetric flow rate from Eqn. (7.16(*a*))

$$q = C_d \frac{d_p^2 - D_f^2}{D_f} \sqrt{\frac{\pi g V_f (f - p)}{2p}}$$

$$= 0.6 \left\{ \frac{5^2 \times 10^{-4} - 3^2 \times 10^{-4}}{3 \times 10^{-2}} \right\} \sqrt{\frac{\pi \times 9.8 \times (9.42 \times 10^{-6}) \times (2.7 - 1) \times 10^3}{2 \times 1 \times 10^3}}$$

$= 0.5024$ M^3/Sec.

7.3.3 Electrical Transducers for Flow Instrumentation

(A) Turbine flowmeters

The drag force has been used in this device. Fluid flow in the pipe causes rotation of a small turbine wheel in a permanent magnet field as shown in Fig. 7.18. Turbine blade movement is steady with laminar flow and interacts with the electromagnetic field created close to the pipe periphery with pickup coils to sense the emf produced due to movement of turbine, based on proximity principle. It is observed that, the voltage output is a function of variable reluctance due to conducting blades cutting the magnetic field and the flow rate that causes the rotation of turbine.

Thus a change in reluctance due to blades of turbine produces pulses in the output coil, proportional to rotation of turbine *i.e.* rate flow of liquid. Frequency of the pulsed output depends upon the product of speed of rotation and the number of blades in the turbine wheel.

Flow rate $Q = K.f;$ ...(7.17)

f being pulse frequency and K is a flow coefficient of device and Acount of pulses is calibrated to indicate the rate/amount of total flow.

The actual relationship for the device is given by,

$$\frac{Q}{nD^3} = \frac{\pi}{4}\frac{L}{D}\left[1 - \alpha^2 - \frac{2m(Db - Dh)}{\pi D^2}\sqrt{1 + \left(\frac{\pi Db}{L}\right)^2}\,\right] \quad ...(7.18)$$

where, Q = volume flow rate
n = rotor/turbine angular velocity
D = bore diameter of flow meter
ν = kinematic velocity
m = no of blades
L = rotor speed
α = Dh/Db = rotor hub dia/rotor blade tip dia
t = rotor blade thickness.

This can be simplified to

$$Q = k_1 n \quad ..(7.19)$$

and, the speed of turbine n has a direct relation with number of pulses produced/sec

$$n = k_2.f \quad ...(7.20)$$

Therefore, flow rate

$$Q = K.f$$

The calibration constant K can vary with viscosity of liquid/gas as shown in Fig. 7.18 (*b*), and a linear region of operation is preferred. These are useful for wide range of flow rates with negligible pressure drop, for any pipe line of diameter size 10 cms and above.

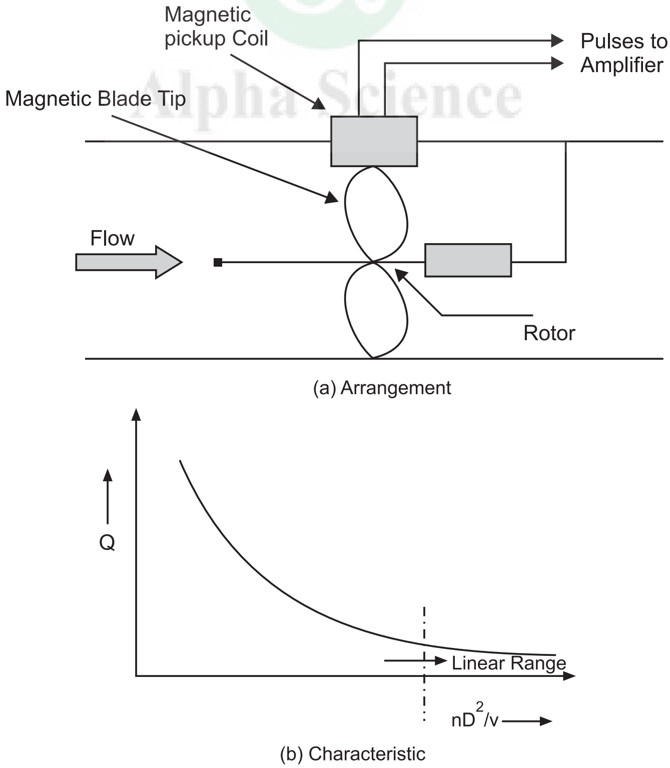


Fig. 7.18 Turbine Flowmeter

For line size greater than 10 cms the delay caused can be approximated by first order system with time constant of 10 msec. Size of the device should be at least 5 times the diameter of the pipeline in which it is connected to ensure laminar flow pattern.

Turbine flowmeters are rugged but expensive and useful for fluids (only) in limited viscosity range. These are used to monitor fuel loading/unloading in ships and tankers, nonconductive solvents, acids, and other chemicals in food, petrochemical, chemical and pharmaceutical industry.

(B) Electromagnetic Flowmeters

This class of transducers has the advantage that they are non-obstructive and can be applicable even for liquids with heavy suspended particles like wood pulp, sewage.

Their performance is not affected by variation in density, viscosity, temperature and pressure. These are also useful for acidic/alkaline and corrosive liquids.

The operation of these flowmeters is based on principle of electromagnetic induction and can be realized as either dc or ac type:

(*a*) **dc type flowmeters** work on the principle of electromagnetic induction in a conductor moving in a constant magnetic field, as shown in the Fig. 7.19, the conducting fluid acts as a conductor and its flow (movement) causes an emf to be induced and the value of induced emf.

$$E = B.d.v \qquad ...(7.21)$$

where, B is the magnetic field applied,

d is the diameter of the pipe (assumed to be running full with liquid) and acts as the fluidic element conductor between electrodes,

and, v is the rate at which conductor moves *i.e.* the linear flow rate of fluid.

These are useful for conducting fluids only and are characterized by good accuracy, reliability, ruggedness, simplicity due to absence of any moving parts. In these flowmeters the voltage developed is of small order say a few microvolts, as it depends on electrical conductivity of liquid in pipe (much poor compared to metals) and needs large amplification which is a major problem being dc and this source has very high internal resistance. Also the pipe should be run full to obtain accurate results. These are expensive for smaller pipe length and field application faces difficulty due to the need of strong dc magnetic field, typically $H = 75 \times 10^4$ Amp/m for flowrates greater than 10^{-6} m/sec. dc electromagnetic flowmeters are useful for bidirectional movement of liquids, slurries, corrosive and solid contaminated fluids. It is no more popular due to difficulties in signal conditioning.

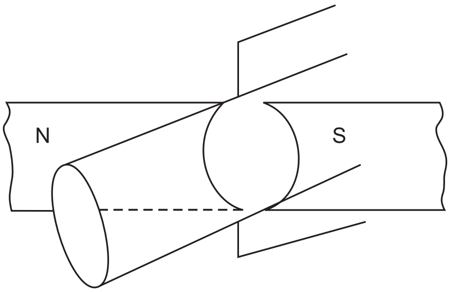


Fig. 7.19 DC Electromagnetic Flowmeter

EXAMPLE 7.9

In an electromagnetic flowmeter used to monitor the flow rate of the conducting fluid, the dc voltage picked up across the 8 cm diameter of pipe is 0.3 mV. If the magnetic field applied is 100 mWb/m², find the velocity of flow of fluid and volume flow rate.

SOLUTION:

From equation

Induced emf (pick up), $e = Bdv$

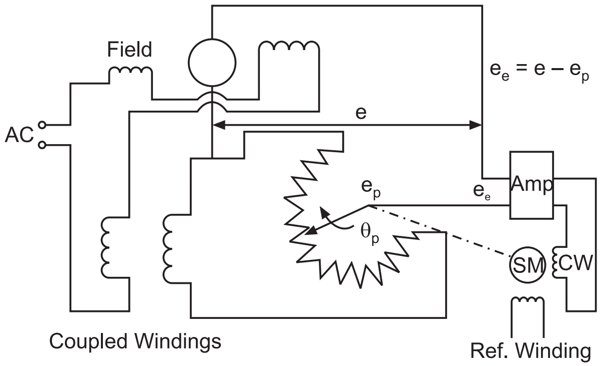
$$\therefore \text{ velocity of flow, } v = \frac{e}{Bd} = \frac{0.3 \times 10^{-3}}{100 \times 10^{-3} \times 8 \times 10^{-2}} = \frac{3}{80} = 0.0375 \text{ M/Sec}$$

Volume flow rate, $q = A \times v$

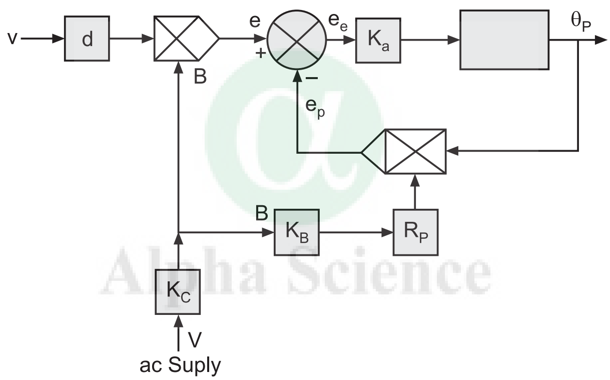
$$= \frac{\pi}{4} \times \left(8 \times 10^{-2}\right)^2 \times \frac{3}{80} = 1.884 \times 10^{-4} \text{ M}^3\text{/Sec}$$

(*b*) ac type electromagnetic flowmeters use alternating current to produce the magnetic field across the fluid, principle remaining the same. An arrangement including the servo-balance potentiometer can be used for recording the variations from the set point for the flow employing automatic null adjustment scheme as shown in Fig. 7.20(*a*). This feature is desirable for industrial systems.

In Fig. 7.20(*b*) a block diagram of the ac flowmeter system is shown which may be used for analysis/simulation.



(a) Servo-balance Recording Arrangement with ac Electromagnetic Flowmeter



(b) Block Diagram

Fig. 7.20 AC Electromagnetic Flowmeter

The voltage produced is alternating but has small magnitude is therefore susceptible to noise. Pipe should be non magnetic and non conducting which may often be a problem. Usually stainless steel (non-magnetic) pipes are used with a coating of non-conducting coating of non conductive material on the inner side of pipe.

They have no moving parts, non obstructive, not affected by density, viscosity of liquid and disturbances in flow. Like for dc case ac flowmeters also must be run full.

These are useful in the velocity range 1 m/sec to 10 m/sec with average speed of 4 m/sec for best results, under temperatures up to 200°C and pressure 10 to 20 p.s.i. (about 70 to 140 KPa). Accuracy is up to 2% of full range for use with pipes diameter up to 8′.

These flowmeters are not suitable for liquids with low conductivity say organic fluids, crude, gases.

EXAMPLE 7.10

During the flow measurement in a 10 cm (diameter) pipe, using electromagnetic flowmeter. The voltage picked up had been low, and an amplifier with input impedance of 500 KΩ and gain adjusted to 400 was used. If the impedance of measuring system looked into from electrodes is 400 KΩ and the voltage measured at the amplifier output is 0.5V (p-p), what is the velocity of the liquid in pipe? Flux density in the liquid may be assumed 0.15wb/m².

SOLUTION:

The electrical equivalent of the system shall be:

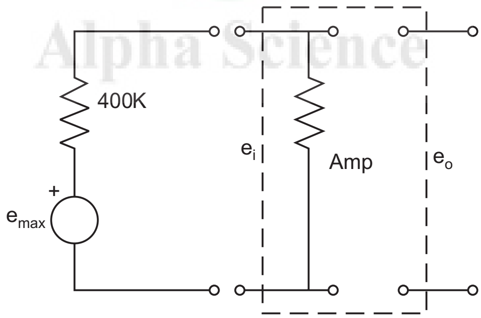
Voltage output from amplifier = $0.5\ V_{p-p}$

$= 0.25\ V_{max}$

Voltage input to amplifier

$= 0.25/400$ V

$= 0.625 \text{ mV} = e_i$



$$e_i = 400/(500 + 400) \times e_{max} = 0.444\, e_{max}$$

$$e_{max} = 1.406 \text{ mV}$$

and ∴ $e_{max} = B\ d\ v \quad \therefore\ v = e_{max}/(\text{B.d})$

$$= 1.406 \times 10^{-3}/(0.15 \times 0.1)$$

$= 0.09375$ M/sec = **9.375 cm/sec.**

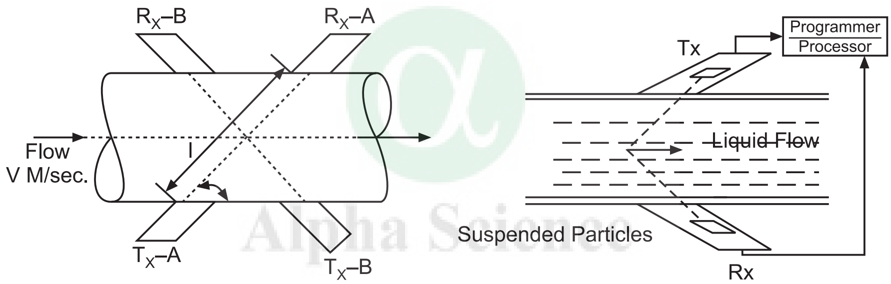
7.3.4 Ultrasonic Flowmeters

These are most often used in water and waste water applications.

These are of two types:

(*i*) Working on the basis of transit-time measurement (or frequency measurement). For this class the liquid should be free of solids and bubbles, to achieve better results. The unit comprises of two interrelated components-sensors, consisting of precalibrated, fused epoxy-coated flow tube with externally mounted electro-acoustic transducers and transmitters, with suitable jelly to make perfect contact. Size of tube may be 10 cms to 120 cms. The typical mounting in epoxy isolates transducers from the process. Thus saves it from corrosion and contamination.

The arrangement shown in Fig. 7.21(*a*), utilizes a pair of ultrasonic transducers mounted on the exterior at an angle θ. Each transducer is capable of sending and receiving ultrasonic pressure pulses. Pulses are transmitted in two directions: with and against the flow to make downstream and upstream measurements. Particles suspended in the fluid provide a frequency shift in direct proportion to the particle velocity.



(a) Arrangement of Transducers for Transit time Approach

(b) 2-Transducer Doppler Flowmeter

Fig. 7.21 Ultrasonic Flowmeters

If l = distance between transmitter and receiver and
c = velocity of sound through the pipe.

frequency of the pulses received shall be given by

$$f_A = \frac{c + v\cos\theta}{l} \quad ...(7.22)$$

$$f_B = \frac{c - v\cos\theta}{l} \quad ...(7.23)$$

where v is the velocity of fluid in the pipe.

$$\therefore \quad \Delta f = f_A - f_B = \frac{2v\cos\theta}{l} \quad ...(7.24)$$

$$\therefore \quad \Delta T = \frac{1}{\Delta f} = \frac{1}{2v\cos\theta} \quad ...(7.25)$$

Velocity flow rate can be computed from the measurement of difference between the two frequencies. A choice for ultrasonic transducer (both transmitter and receiver) can be piezoelectric crystal tunable in the frequency range 0.2 – 5 MHz.

The method is recommended for high accuracy with insensitiveness to changes in viscosity, pressure and temperature variations in the range -30° to 250°C for velocities in the range of 0.3 m/sec to 30 m/sec with linear output scale.The scheme works best for clean and clear liquids and the liquid should be able to conduct sound energy through it. It has bidirectional capacity, fast response, and wide frequency range. These can be battery operated portable units and can be used throughout the length of pipe. Analog or digital output can be selected through a switch. However it is necessary that the pipe diameter be large compared to the thickness of the pipe. These are susceptible to acoustic short circuiting due to reflection from inner surface of pipe. High cost and accurate calibration for flow rate of liquid under consideration are the major challenges.

(*ii*) Working on the principle of Doppler's effect:

The ultrasonic wave is sent through the liquid in pipe, the moving particles in the liquid (at velocity v); deflect the ultrasound wave (at velocity, c). A change in the frequency occurs which is proportional to the difference of the frequencies. The beat-frequency, Δf is obtained by the processing the transmitted and received ultrasound signals, to provide the measure of the velocity of fluid, as:

$$V = \Delta f . c/2\, f_0 \cos\theta = K\,\Delta f \qquad \text{...(7.26)}$$

where θ = angle of transducer and receiver with respect to axis of pipe in both cases.

The results are reliable only for full pipe flows, flows be fast enough to have bubbles and suspended particles active. A minimum measuring distance from valves and pumps should be 10 – 20 times the diameter of pipe upstream and 5 times the diameter downstream. Also, the pipe section for the device must be sonically conductive, up to 100°C for this flowmeter to work properly.

7.3.5 Electrothermal Methods of Flow Instrumentation

These work on the principle of removal of heat constantly due to the flow of liquid/gas/air at a rate depending upon the flow rate and thermal properties of liquid/gas, assumed constant.

(A) Hot wire and hot film anemometers

These are used to monitor rapidly varying flow conditions of gases. A fine wire placed in flow system is heated electrically as shown in Fig. 7.22(*a*). For measurement purpose the heated element is connected in bridge. The change in gas flow rate causes change in resistance of heating element and results in output voltage. The variation in the output voltage is calibrated for the corresponding change in the temperature being monitored as shown in Fig. 7.22(*b*). This works excellently for small variations and the range can be extended with corrections incorporated. The corrections and the nonlinearities that are present, shall be discussed in next chapter.

Even otherwise, the current can be determined by measuring voltage drop across standard resistance Rs and wire response is determined from bridge. With I and R determined, the flow rate is computed.

Heat transfer from wire,

$$q = (a + bu)\,(T_2 - T_1) \qquad \text{...(7.27)}$$

where T_2 = wire temperature

T_1 = free stream temperature of fluid

u = fluid velocity of flow and is responsible for dissipation of heat produced in the heated wire element.

a, b = constants to be obtained from calibration.

Also,

$$q = i^2R_w = i^2R_0\,[1 + \alpha(T_2 - T_1)] \qquad \text{...(7.28)}$$

where R_0 = resistance of wire at reference temperature T_0

I = current flowing in the heating element

α = temperature coefficient of resistance.

Full account should be taken of transient response of both terminal and electrical resistance characteristics of wire.

Compensation schemes

(*a*) Constant current arrangement–with large resistance connected in series with hot wire and a thermal compensating circuit is applied to output voltage.

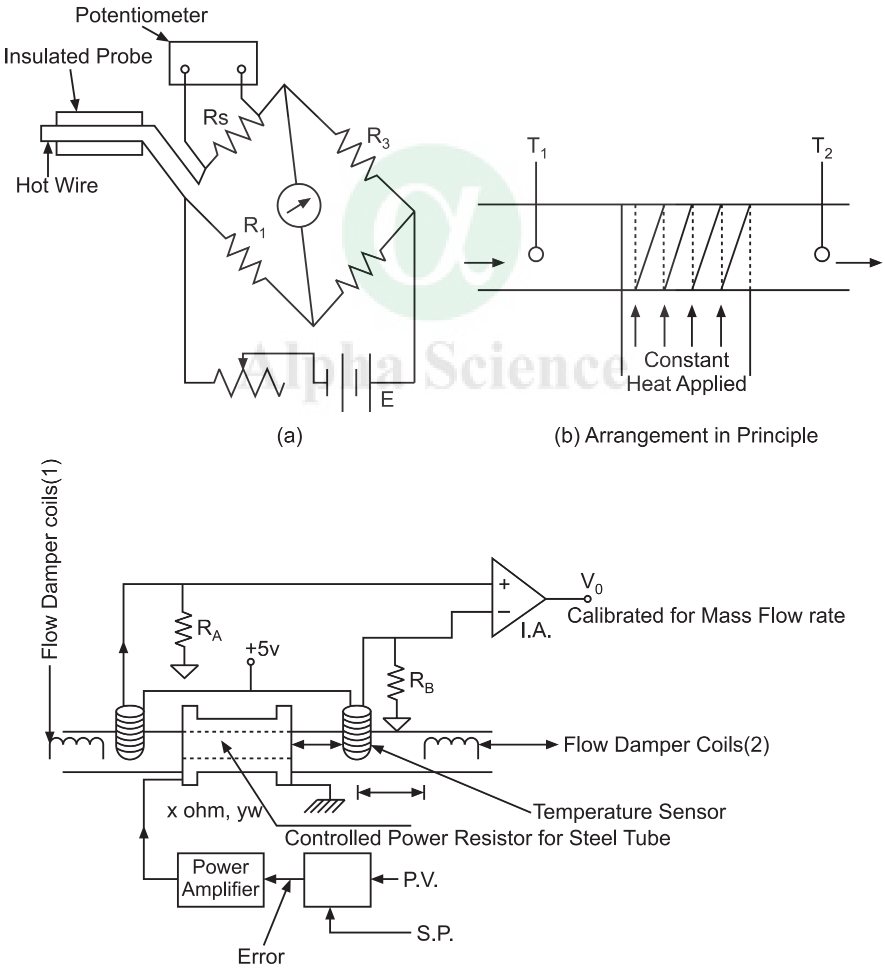
(*b*) Constant temperature arrangement–with feedback circuit added to vary the current so that the wire temperature remains constant.

Response depends on angle of flow velocity with the wire axis, length to diameter ratio which should be typically 50.

A modification is, use of insulating cylinder coated with thin metallic film, referred as hot film probe. These are extremely sensitive to changes in fluid velocity and used up to frequency of 50 kHz.

(B) Thermal flow meters

It is based on the principle that, if a heat source is placed centrally with respect to two sensors, as shown in Fig. 7.22(*b*, *c*), the temperature difference between the points as measured by the sensors is a function of the rate of flow.



(a) (b) Arrangement in Principle

(c) Complete Arrangement

Fig. 7.22 Thermal Flowmeters

For an arrangement shown in Fig. 7.22(*c*), a resistor wound on a steel tube carries an accurately controlled current to provide heating. Two temperature sensors are placed symmetrically upstream and downstream from the powered resistor and the difference of the temperatures is a measure of the flow of liquid in the flow pipe. Flow damping coils are used at both ends of the device which needs to be inserted into the pipeline system to ensure laminar flow.

EXAMPLE 7.4

Liquid flow in a pipe is being measured by an orifice meter. A bellow-LVDT combination used provides output of 0.4 V/KPa. What is the range of output for flow variation between 0.1 M^3 to 0.5 M^3/minute?

Orifice flow constant, $K = 0.006\ M^3/min/\sqrt{KPa}$.

SOLUTION:

Since $Q = K\sqrt{\Delta P}$

Therefore $\Delta P = (Q/K)^2$

For lowest flow rate,

$$\Delta P = (0.1/0.006)^2$$
$$= 0.01/36 \times 10^{-6}$$
$$= 1000/36 \times 10^3 = 2.7 \text{ KPa}$$

Therefore minimum output = **1.8 V**

For largest flow rate

$$\Delta P = (0.5/0.006)^2 = (500/6)^2$$
$$= 250/36 \times 10^3 = 6.9 \text{ KPa}$$

Therefore, maximum output = **27.6 V.**

A comparison of the various methods of flow instrumentation is presented in Table 7.5 and the important features in Table 7.6 to make the choice of appropriate method for any given application situation.

Typical specifications achieved for flow meters are:

Accuracy ±0.5 % of full-scale

Linearity ±0.25% of full-scale

Long life

Operating temperature 0 – 50°C

Temperature sensitivity ± 0.2% of F.S./°C

Output 0-5 (/10) V dc or 4-20 mA

Calibration H_2O/IPA (Isopropyl alcohol)

Response is linear and good over a limited range, negligible pressure drop.

Websites of some manufacturers are included in appendix and may be looked into for more specific details.

TABLE 7.5 Flow Instrumentation-Application Comparative

Type of flow meter	Range M^3/Sec	Linearity % of F.S.	Repeatability	Accuracy % FS	Pressure loss	Immunity to viscous flow	Advantages	Application		
								Corrosive liquid	Corrosive gas	Viscous liquid
Head type:										
(i) Orifice plate	1×10^{-7} to 5	N.L.	0.1	2	High	Good	Low cost	√	√	NL
(ii) Venturi tube	1×10^{-7} to 5	N.L.	0.1	2	Medium	Good	High cost, for large flows	√	√	NL
(iii) Flow nozzle	1×10^{-7} to 5	N.L.	0.1	2	Medium	Good	High Press./ Temp. flows moderate pipe size	√	√	NL
(iv) Pilot tube	N.A.	N.L.	0.05	1	Nil	Poor	For aerody-namic measmt	NA	√	NA
Variable area type:										
(v) Rota meter	1×10^{-7} to 0.1	0.1%	0.5	2	Low	Poor	Low cost; for small pipe size	√	√	NL
Mechanical										
(vi) Vortex flow meter	5.0×10^{-3} to 0.1	0.5%	0.1	0.5	Low	Good	High cost; variety of chemical	√	√	√
(vii) Turbine meter	5.0×10^{-3} to 1	0.2%	0.2	0.25	Low	Good	Repeatability good, limited range for viscous materials, easy install & maintain.	NL	NA	NL
Others:										
(viii) Electro-magnetic	5×10^{-2} to 5	0.2%	0.1	0.5	Nil	Good	For conducting fluids,	√	√	√
(ix) Ultrasonic	55×10^{-3} to 1	0.2%	0.1	1	Nil	Good	Costly, large pipe size and capacity for sonically conductive liq.	NA	NA	NA

N.L.—Nonlinear squareroot relation NA–Not Applicable √ Applicable

TABLE 7.6 Flowmeter Applications

Type	*Water*	*H.P. gas*	*Hot liquid*	*Hot gases*	*Highly visc-ous*	*Low visc-ous*	*Solids in liquid*	*L.P. gas*	*Accuracy ± %*
Orifice meter	√	√	√	√	√	√	√	√	2
Venturi meter	√	√	√	-	-	√	-	√	1
Nozzle	√	√	√	√					1.5
Turbine	√	√	-	-	-	√	-	-	2
Rotameter	√	√	√	√	-	√	-	√	2
Electromagnetic	√	-	√	-	√	-	√	-	0.5
Ultrasound	√	-	-	-	-	√	√	-	1
Hotwire	-	√	-	-	-	-	-	√	2

√ Applicable

7.3.6 Solid Flow Measurements

In industry it is required to measure the flow rate of solids and powders such as iron, cement coal, chemicals, fertilizers, paper, iron ingots etc., within the plant. These are of weighing type and measured at a specified point in the moving/conveyer system, as shown in Fig. 7.23. These are used in mining industry for the ore – coal, iron, bauxite etc. mined at the pit site to be transported over long distances through the conveyor belt drives, in motion by driving motors at both ends and the speed is maintained by use of roller motors. The distances could be in kilometers as many as 20 and still being more economical and reliable than other modes. Such conveyor belt systems are also seen at the railway stations and airports-for transferring luggage, and visitors through escalators and travelators at large airport terminals.

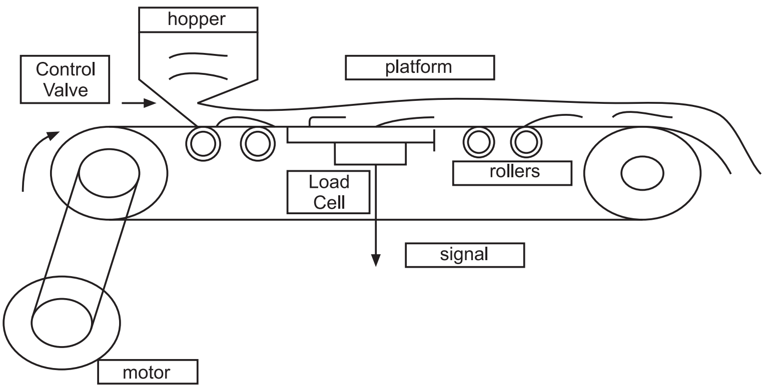


Fig. 7.23 Conveyor Belt system for Solid flows

EXAMPLE 7.5

A solid ore conveyor belt system as shown in Fig. 7.23 moves at 30 m/min. a weighing platform 2 m in length shows the weight of 40 kg on the platform. Find the ore delivery in kg/hour.

SOLUTION:

The load cell will measure the amount of ore on the conveyor just above it and causing a compressive force on it. If the weight over the length *L* meters is *W* kgs then weight per unit length is *W*/*L* which is same as the flow rate of material

$$\therefore \qquad W/L = \frac{F \text{ in kg/min}}{S\text{, speed of conveyor belt in m/min}}$$

$$\therefore \text{ Flow rate,} \qquad F = \frac{W}{L}\, s \text{ kg/min}$$

For the given problem:

$$F = \frac{40}{2} \times 30 = 600 \text{ kg/min}$$

$$= 36000 \text{ kg/hour.}$$

It may be noted that the signal from load cell can be converted into flow rate and compared with the desired rate of flow using a controller which shall actuate the hopper control valve to control flow rate on the conveyor belt.

7.4 LEVEL INSTRUMENTATION

It is very usual to maintain a specified stock of the raw materials for uninterrupted supply in case of industries requiring raw materials in different form, more so for industries, such as – oil refinery, fertilizer, power, steel, aluminum and cement where continuity of production is critically important. In all such industries, even a brief break in the processing can be very expensive not only from production point of view but also the material that get stuck up in various stages and restarting is costly and time consuming.

A specified stock needs to be maintained and before it falls below a critical level replenishment of the resource is expected to be achieved. A high level of stock is also not desirable to economize the cost of inventory.

In the current discussion, the focus will be on liquid level instrumentation and methods applicable to solids also will be considered.

The characteristics of level variable which help in making measurements are:

— Slow nature of variation, due to high capacity of storage tanks.

— Property to find the uniform level all over the surface.

— Direct relationship with weight, specific gravity and head, so that indirect measurement is also possible.

The characteristics which make the level instrumentation difficult include:

(*a*) Sputtering due to incoming liquid falling on the top surfaces in the tank-making the level non-uniform during such periods.

(*b*) Pressure of vapor and the liquid vapor interface not sharp in many cases.

(*c*) pH value of the liquid in tank. The extreme values demand sensors in contact to be of appropriate material, so that they do not get damaged with continuous use for extreme pH values on either side of scale.

7.4.1 Relation with Other Variables

The level or height, h is directly related to pressure through the relation:

$$h = \frac{p}{\rho} = \frac{p}{\rho_\omega . G} \qquad ...(7.29)$$

where p = pressure

ρ = density of liquid

ρ_ω = density of water usually at 15°C

G = specific gravity.

If the purpose of level measurement is to determine the stock/ volume of liquid in the tank, head measurement is preferable, since

$$V = \int A dh + C \qquad ...(7.30)$$

where A is area of cross section of storage tank and no other factors need to be known.

If pressure measurement has to be used because of details such as non-cylindrical nature of tank, then

$$V = \int \frac{A}{\rho} dp + C = \int \frac{A}{\rho_\omega G} dp + C \qquad ...(7.31)$$

and measurement of volume depends on density or specific gravity.

If the purpose of level instrumentation is to determine the weight of liquid contained, then pressure measurement is preferable,

$$\because \qquad W = \int A d\rho + C \qquad ...(7.32)$$

and no other factors are required to be known.

If head measurement is needed for use, then

$$W = \int A\rho dh + C = \int \dot{A}\rho_{\omega} G dh + C \qquad ...(7.33)$$

and the measurement of weight depends on density/specific gravity.

At times, it is of interest to know the pressure at the outlet (usually at the bottom), and then pressure measurement is to be preferred. Using the head measurement,

$$p = \rho_h = \rho_{\omega} G_h$$

and the pressure measurement depends on density/specific gravity.

The above relations give rise to various methods of measuring level, depending on the purpose.

Density and specific gravity can be evaluated or indirectly measured from pressure measurement, so that at constant head, pressure is directly proportional to density.

$$\because \qquad \rho = \frac{p}{h}; \quad \therefore G = \frac{p}{\rho_{\omega} h}. \qquad ...(7.34)$$

EXAMPLE 7.6

A cylindrical liquid reservoir holds the liquid of specific gravity 1200 kg/m^3 up to a level of 4 meters. Calculate the pressure at the bottom.

SOLUTION:

$$P = \rho \times g \times h$$
$$= 1200 \times 9.81 \times 4$$
$$= 48.93 \text{ KPa} = \mathbf{6.99 \text{ psi}}.$$

7.4.2 Liquid Level Instrumentation—Classical Techniques

Mechanical methods have been use for a very long time based on any of the various options indicated earlier. These are very efficient, accurate and have been preferred over a long time. These are eminently suitable for level indication with benefit of economic solution.

These methods include:

(A) Direct measurement of level (see Fig. 7.24):

(*a*) Using ordinary sight glass on the tank.

(*b*) Using a float guided by vertical rods and following the free surface.

(*c*) Float and shaft type, in open vessels or in pressure vessels up to 1000 psi.

(*d*) Float with bellow acting as transmitting device and transferring the level indication over a distance.

(*e*) Differential bellow arrangement with a float.

For details of these methods please see bibliography at the end.

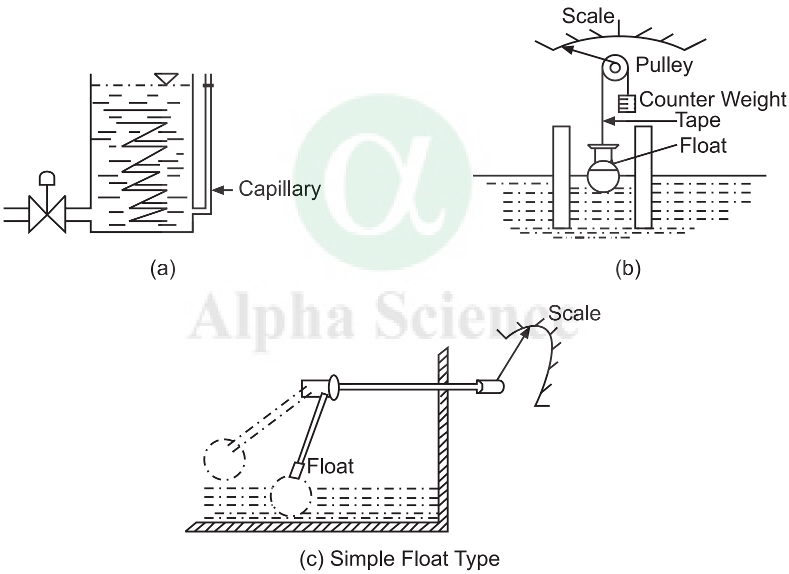


Fig. 7.24 Direct Methods of Level Measurement

(B) Indirect level monitoring with pressure measurement methods:

(*a*)The most common pressure measurement system for liquid levels is the **bubbler system** as shown in Fig. 7.25.

It is applicable for almost all liquids even those having suspended solids and corrosive properties. The specific gravity of the liquid must be known and the clogging of bubbler tube is to be avoided. A pipe of about 3 cm diameter is lowered into the liquid so that the open tip is about 5–7 cms above the sediment (solid deposit) level. Air is supplied into the pipe through a sight-feed bubbler and the air bubbles come out in the tank at a rate of about 1 bubble per minute. A pressure gauge/recorder as shown is connected to the other end of bubbler pipe, when bubble appears at the bottom end, pressure goes up in the gauge/recorder and drops as the bubble is realized. Recorder provides reading depending on level in tank, and can be calibrated in terms of head or level. Supply pressure is maintained 2-5 psi larger than the anticipated maximum static pressure of liquid column and before the regulator it is 1.5 to 2 times of the supply in bubbler with maximum limit of 10 kg/cm^2. This device can be used for liquid levels ranging from 15 cms to 100 meters.

Before filling the tank, purging gas/air is turned on and it is turned-off (if need be) only after draining the tank. These are suitable also for remote indication/recording up to a distance of 150 m.

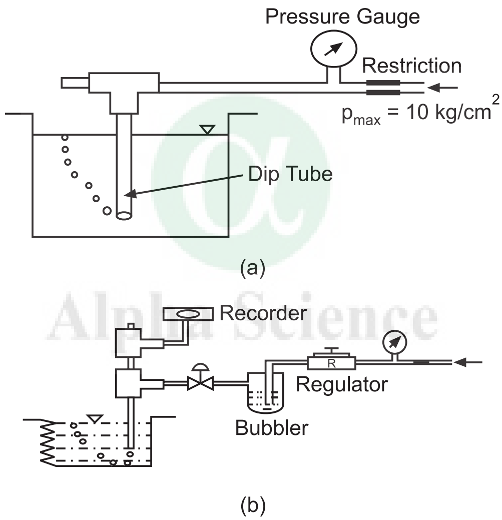
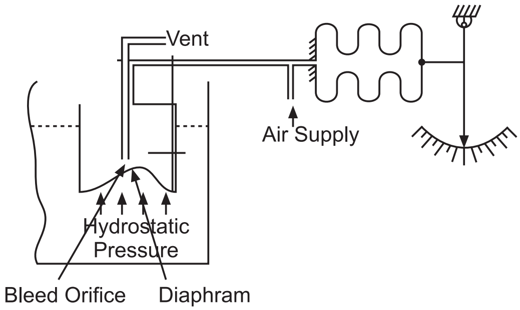


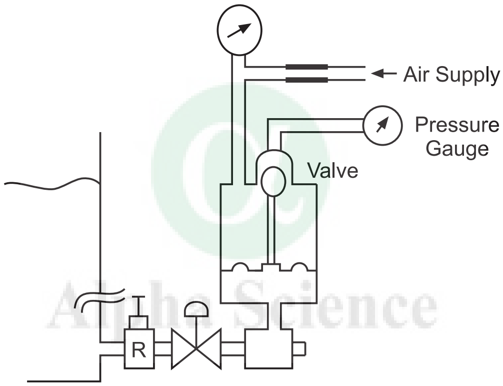
Fig. 7.25 Air-purge Method for Level Monitoring

(C) Pneumatic force balance method

Utilizing the principle of balancing the force due to liquid column by an air pressure on a diaphragm, the measured pressure of air supplied is calibrated to indicate the liquid column height. Two possible arrangements are shown in Fig. 7.26. As in Fig. 7.26 (*a*), with the rise of level in tank, the bleed orifice gap becomes smaller and less air leaks through the vent and a back-pressure develops in bellow chamber to obtain a dynamic balance and bellow tip movement to the right side causes corresponding change in level indicator. In Fig. 7.26 (*b*), with the rise of level, there is increased pressure on the diaphragm and the ball of the valve moves up, creating large back-pressure to indicate the change in level. The scheme is very sensitive and highly accurate but is good only for indicating instruments.



(a) Bellow Actuated Diaphragm Type



(b) Ball / valve Actuated Diaphragm

Fig. 7.26 Pneumatic Force Balance Method for Liquid Level Monitoring

7.4.3 Level Instrumentation—Electrical Methods

The classical techniques of level instrumentation are reliable, accurate and economical yet they are suffer from serious limitations (as discussed earlier) in Chapter 4, of data transmission over large distances, programmable processing, convenient display and fast data recording, retrieval for analysis etc.

The electrical methods are superior in this context and therefore being widely adopted currently. These can be classified as contact or non-contact type of methods.

Contact methods

(*a*) Thermal type applicable for conducting fluids and are based on the principle that the heat transfer from a heated element is faster in liquids than in gas/air. As shown in Fig. 7.27, a current carrying conductor placed in a liquid tank shall experience, effective values of resistance in the liquid and outside the liquid to be different say,

where r_1 = resistance per unit length in liquid

r_2 = resistance per unit length of same wire in air/vapor

Total effective resistance

$$R = \frac{V}{i} = r_1 x + r_2 (l - x) \quad \text{...(7.35)}$$

$$= r_1 \left[x + \frac{r_2}{r_1} l - \frac{r_2}{r_1} x \right] \quad \text{...(7.36)}$$

$$= r_1 [\alpha l + x(1 - \alpha)]; \ \alpha \triangleq \frac{r_2}{r_1}$$

$$= A + Bx. \quad \text{...(7.37)}$$

A calibration graph between level of liquid in tank x against the resistance, shows a linear variation as shown in Fig. 7.27 (*b*). The tracking of resistance value of wire resistance provides a direct indication of level. The change in resistance can be conditioned to provide a more convenient change in voltage using the techniques discussed in next chapter.

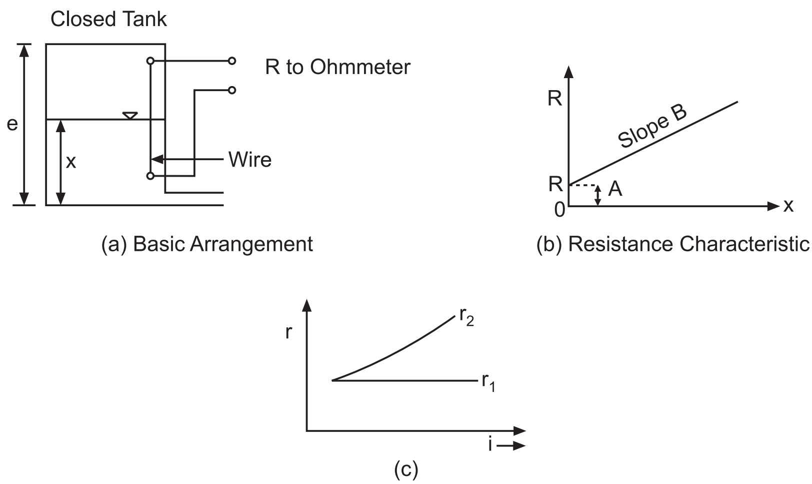


Fig. 7.27 Level Indicator Based on Thermal Principle

The arrangement however has some limitations, that the wire should be very fine with diameter of the order 10 microns, preferably platinum to ensure linear variation of r_1 and r_2. Also the linear relation is more true if liquid and vapor in above it are at same temperature and level changes to the detected are of very low order as in the case of level measurement in case of liquefied gases.

However, a change of resistance is noticed with magnitude of current for both r_1 and r_2 as shown in Fig. 7.27 (*c*), and demands a correction for accurate measurements.

(*b*) Contact method for nonconducting fluids

In many process industry applications for level instrumentation of oil, gasoline, liquid gas, corrosive liquids with good dielectric properties, a cylindrical condenser assembly as shown in Fig. 7.28(*a*) can be used.

The principle have already been discussed in Chapter 5 and it must be added that this unit referred as cell, shall have ideal capacitance of

$$C_l = \frac{\varepsilon_l l_1}{2\ln\left(\frac{r_3}{r_2}\right)};\ l_1 = (l - l_2) \qquad \text{...(7.38)}$$

this in the presence of vapors is modified to:

$$C_l = \frac{\varepsilon_l l_1 + \varepsilon_v l_2}{2\ln\left(\frac{r_3}{r_2}\right)} \qquad \text{...(7.39)}$$

and the effective value can be increased with the choice as: l_1, $l_2 >> r_2$, $r_3 >> r_2$; r_3 and r_2 are radii of outer cylinder and electrode.

The effect of associated capacitors in the system can be accounted as shown in equivalent circuit (*b*), so that the effective capacitance is given by

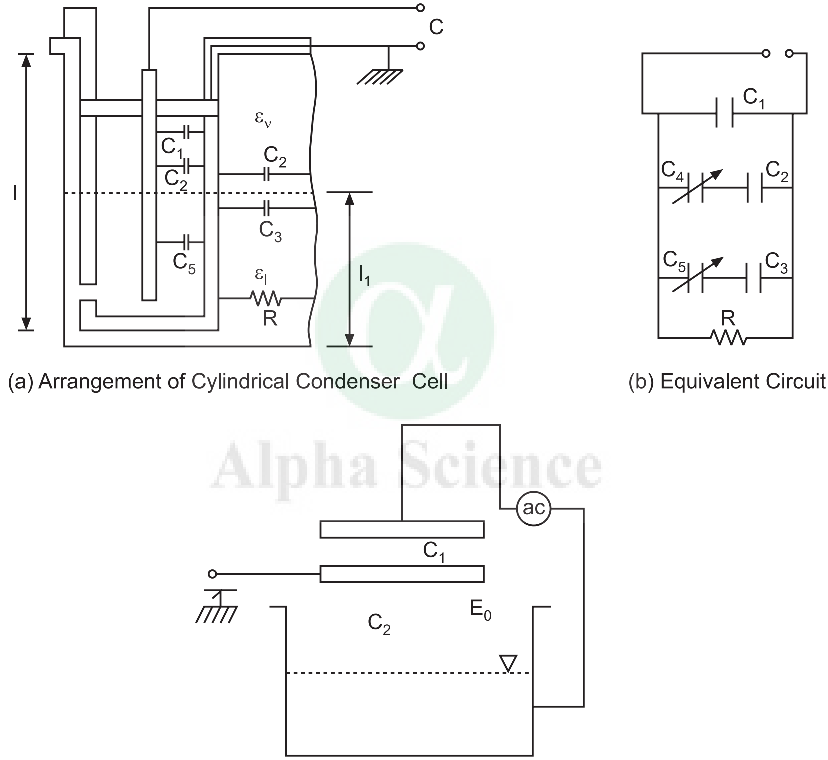
$$C_l = C_1 + \frac{C_2 C_4}{C_2 + C_4} + \frac{C_3 C_5}{C_3 + C_5} \qquad \text{...(7.40)}$$

and the cell factor is given by $F \cong \frac{\Delta C}{\Delta \varepsilon_l}$

where ε_l is the permittivity of liquid in tank. Temperatures errors occur due to changes in ε_1 and ε_v for vapor and taken care during calibration.

The capacitance shall be monitored using appropriate signal conditioning and is calibrated for monitoring the height of liquid in the tank.

The capacitance probe method can be extended for monitoring the height of conducting fluids by having a set of parallel plates a little above the maximum expected level in the tank, as shown in Fig. 7.28 (*c*). Two capacitances are formed and the output voltage is measured across the capacitance C_2, which shall be a measure of level in the tank.



(a) Arrangement of Cylindrical Condenser Cell (b) Equivalent Circuit

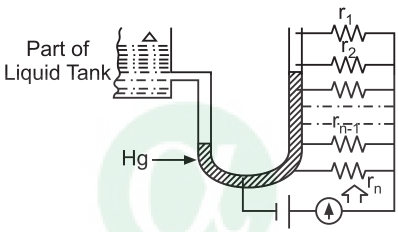
(c) Parallel Plate Condenser Scheme for Conducting Fluids

Fig. 7.28 Condenser Based Transducer for Level Instrumentation

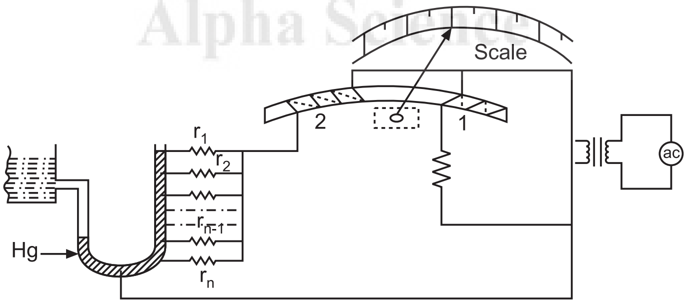
Non contact electrical resistance method for level instrumentation

As shown in Fig. 7.29(*a*), a tube assembly is connected to the liquid tank with mercury filled in. At a number of contact points resistance of pre-calculated values are connected, coming in parallel and in series with dc source and current indicator as shown. Corresponding to the height of liquid in tank, a pressure is exerted of the mercury column to rise in the right hand side of tube depending upon the ratio of the specific gravity of the liquid in tank to that of mercury. The rise of mercury is much smaller than the highest level of the liquid in tank due to larger specific gravity of mercury. Besides this, mercury being conducting material helps to complete the electrical circuit, with one or more external resistances come in the circuit depending upon the height of mercury column in the right limb, which varies with the level in the tank.

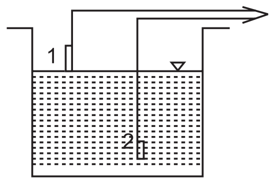
Variation in the current of electrical circuit is a function of resistances coming in contact, which depends on the liquid level and provides its direct measure. Resolution of current in the indicator depends on the closeness of contacts (with resistances) and since this has a limit due to a finite number of contacts being possible, the variation is in discrete steps.



(a) Typical Arrangement



(b) Null Balance Method



(c) Conductive Probe Method

Fig. 7.29 Non-contact Type Electrical Instrumentation of Level

A modified form of the above arrangement is shown in the Fig. 7.29 (*b*) with the deflection of a moving system, in the magnetic field of two solenoids. Current through the solenoid-2 carries a current that changes with level.

In either case, in order to have linear change of current, the values of resistances r_1, r_2, ...r_n have to be very carefully calculated. And, it is possible to replace the deflection system for local indication by arrangement for remote signaling and data transfer.

The method is typically suitable for liquids having high resistivity and contacts can be mounted directly on the tank.

As in Fig. 7.29 (*c*), resistance between the conductance probes, across the liquid height is sensed, converted into an electrical output and calibrated in terms of height.

7.4.4 Advanced Methods for Level Instrumentation

Next we discuss two advanced techniques based on non contact approach used for high accuracy, special applications but involving high cost also.

(A) Ultrasonic level detectors

These are based on the principle of reflection of acoustic wave from liquid-vapor inter phase plane. As shown in the Fig. 7.30(*a*), a pair of transmitter-receiver is used and time elapsed between the signal transmitted and received back from liquid-air interface is used as a direct measure of the level in the tank. Since it is usually hazardous and impractical to use the T-R pair from top, special arrangement has to be made to house them at the bottom of the tank. Such detectors find used for oil and chemical storage tanks and able to achieve accuracy of the order of 0.1%.

Another useful application of the technique is made in reverse position for underground storages, Fig. 7.30 (*b*), such as oil well or mine shafts and useful as fathometers to monitor the marine depths for sea going vessels-ship, submarines etc.

Principle remains same and with careful processing of reflected signals received from the inter phase, it can be calibrated to locate various layers and materials underground.

A block diagram indicating the signal handling is shown in Fig. 7.30(*a*) and its timing diagram in Fig. 7.30 (*d*).

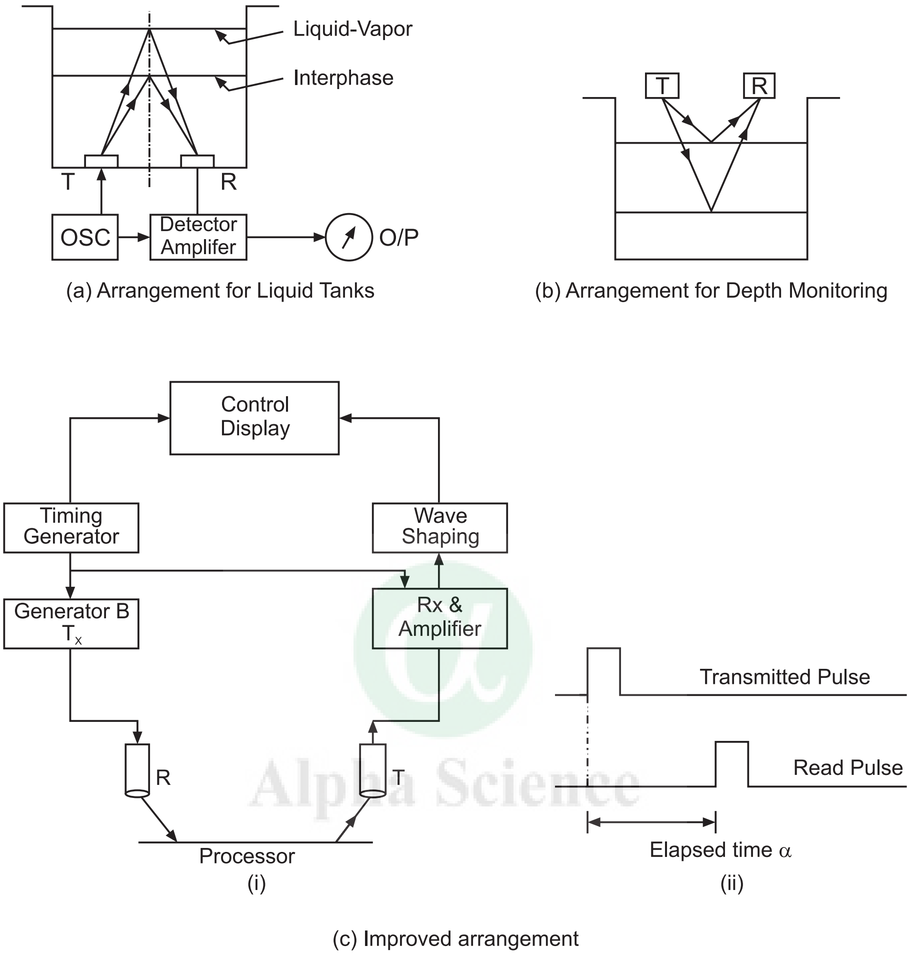


Fig. 7.30 Ultrasonic Level Detector

(B) Level detection by microwave method

Microwave radiation is at low energy level and cannot cause change in atomic structure, through minor heating effect may result, can be used to detect level or position of liquid, solid material or objects.

Any object entering into the microwave field between transmitter and receiver either absorbs or reflects enough energy to cause a change in the signal at the receiver. The change is detected and finally results in a desired output action. The attenuation/reflection are governed by law of electromagnetic energy propagation.

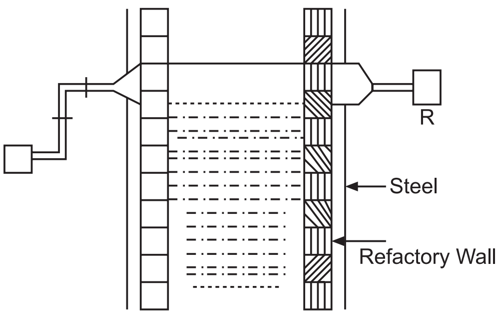
When propagated energy strikes on a material surface, both reflection and transmission take place. Energy travelling in any direction is a function of the angle of incidence, polarization, wave length of signal and electrical properties of striking surface material conductivity, permeability and permittivity. It is interesting to note that, low resistance materials such as conductors offer a high resistance to microwaves *e.g.* copper reflects off the microwave energy and vice versa. Permittivity of material is therefore a measure of the energy with microwaves that can be stored or absorbed. Where as permeability is a measure of readiness with which materials can be magnetized *e.g.* iron has large permeability and dielectrics such as air, plastics, and non-ferrous metals equal to one. Since microwave cannot pass through ferrous and non-ferrous metals due to high conductivity therefore not suitable and avoided in the measurement path. And therefore, permeability is not considered as variable in microwave measurements.

For transmission of microwave energy into a tank/vessel for a measurement application, metal walls will reflect therefore the pressure vessel need to be provided with a transparent window, at the proper point along the wall. Window material shall be allowing the transmission of microwaves and may be of UHMW polythene, plastics or glass with resistance to impact, abrasive wear, high temperatures, pressure, chemical corrosion.

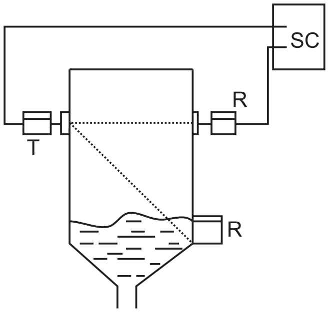
A few possible arrangements for level detection are shown in Fig. 7.31 and in Fig. 7.31 (*a*) application in steel/glass furnace is shown. The inside temperature is very high and an appropriate window is provided and it is required to assure that the furnace has been packed up to the desired level in a non-metallic tank.

In Fig. 7.31 (*b*), a scheme is shown for monitoring level of solid material in a closed tank, based on same principle.

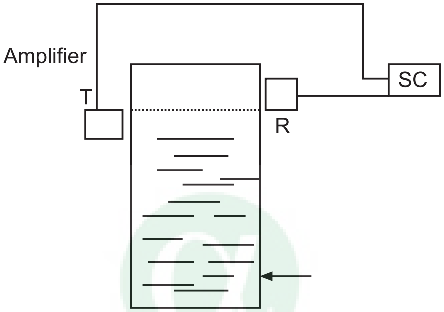
In Fig. 7.31 (*c*) is shown a scheme for monitoring a scheme for liquid level sensing about the desired level to be maintained.



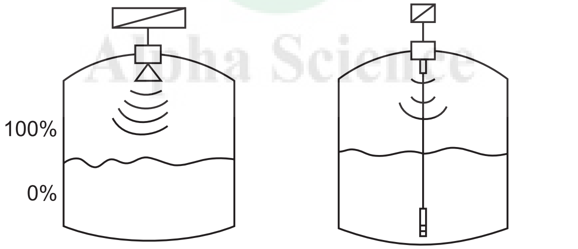
(a) Level Control at High Temperature



(b) Monitoring of Solid Level in Metallic Vessel



(c) For Non-metallic Vessel



(d) For Conducting Liquids (e) For Non-conducting Liquids

Fig. 7.31 Microwave Technique of Level Detection

In Fig. 7.31 (*d*), an arrangement is shown for monitoring the level of conducting liquid, reflecting the microwaves from the surface and the time elapsed is more for low heights and vice versa.

The same approach cannot be used for non conducting liquids as it will allow the microwaves to pass through, therefore a metallic float has to hung from the top, which shall take a position depending on the specific gravity of the liquid, to provide a reflector. The time elapsed shall be corrected for the specific gravity of the liquid and the correction can be part of signal conditioning, to provide the height of liquid in the tank.

Table 7.7 presents a comparison of various techniques of level sensing.

TABLE 7.7 Comparison of Level Measurement Techniques

Sl.No.	Method	Types	Level Range (in mtrs)	Inaccuracy	Available Design	Applications	Limitations	Remark
Classical Methods for Level Measurement								
1.	Direct Measurement	Hook-type Sight Glass Float type Displacer type	0.6-34	0.5% FS	SwitchLocal Indicator Transmitter	In clear liquids	Not recommended for sludge or slurry services.	Cheap & maximum temperature is 850 °F
2.	Indirect Measurement	Air Bubbler or Air Purge System	0.6-60	1-2% FS	Switch Local Indicator Transmitter	In corrosive or abrasive liquids but can also be used for viscous	High maintenance, Interface between conductive layers & Detection of foams causes problems	Hydrostatic Pressure Type, Cheap & maximum temperature is unlimited
3.	Pneumatic Force Balance	—	0.5-32	0.5% FS	Switch Transmitter	In viscous liquids but can also be used for clear liquids	Slow response to sudden load change & air or other gases used as a operating medium must be dry enough	Cheap, can be used in hazardous or explosive areas, free from temperature related errors & maximum temperature is 350 °F
4.	Electrical Contact Method	Capacitance Level Indicator	0.6-60	1-2% FS	Switch Transmitter	In clear liquids, slurries but can also be used for viscous	Interface between conductive layers & detection of foam causes problem;Affected by change in temperature & high maintenance	Indirect Method, comparatively expen-sive & maximum temperature is 2000°F

TABLE 7.7 Comparison of Level Measurement Techniques

Sl.No.	Method	Types	Level Range (in meters)	Inaccuracy	Available Design	Applications	Limitations	Remark
5.	Electrical Non-Contact Method	Radiation Level Detector	0.6-32	6 mm	Switch Transmitter	Suitable for molten metals as well as liquids of all types *i.e.* corrosive, viscous etc.	Accuracy is affected by density change of liquid	Indirect Method, expensive, bulky & maximum temperature is unlimited
6.	Ultrasonic Level Detector	—	0.6-67	1% FS	Switch Transmitter	Suitable for liquids & solids with large & hard particles	Presence of dust, foam in vapor space causes problem	Non-contact type measurement, unaffected by change in density, moisture contents, electrical conductivity or dielectric constant of process fluid & max. temperature is 300°F
7.	Microwave Level Switches	Reflection Beam-Breaker	Point Sensor	12 mm	Switch	Suitable for all types of liquids & solids	Thick coating is undesirable	Expensive, presence of dust, mist & non-metallic foam has negligible effect on the accuracy & max. temperature is 400°F
Other Methods for Level Measurement								
8.	Eddy Current Level sensor	—	0-0.2 (from liquid surface)	—	Local Indicator	Control of molten metal liquids in steel plants	Limited level range	Non-contact type measurement, cheap, highly stable & minimize the influence of noise
9.	Optical Level Detector	—	0-0.3	—	Local Indicator	Suitable for corrosive, sticking or coating processes	Affected by the reflectivity of the process	Non-contact type measurement, used in wastewater treatment plants, high precision & temperature range is-40°F to-150°F

FS: Full Scale;

7.5 INSTRUMENTATION OF MECHANICAL VARIABLES

The instrumentation of mechanical variables is particularly important in manufacturing industry as well as in other industries.

7.5.1 Displacement Monitoring

The actual device for pickup shall vary according to application, though the basic principle as discussed earlier in Chapter 5 and 6 – potentiometers, LDR, LVDT, bellows, capsules, capacitive transducers, proximity sensors, flapper – nozzle, etc., remains the same. Table 7.8 provides a comparison of the various types of transducers and then a few specific application based sensors are discussed in this section.

TABLE 7.8 Instrumentation of Displacement– A Comparison of Transducers

Sl. No.	*Transducer Principle*	*Range in mms*	*Linearity % of F.S.*	*Temperature range in °C*	*Resolution in microns*	*Frequency response, Hz*	*Remarks*
1.	**Resistive**						
	(a) Wire wound	100	0.25	-10 to 75	50	5	Economical, Large Range
	(b) Conductive coating type	100	0.5	,,	10	10	Poor resolution, high noise
	(c) Strain gauge	10	0.5	,,	10	100	Small size, good resolution, low range
2.	**Inductive**						
	(a) LVDT	50	0.1	-10 to 75	1	1k	Good linearity, high resolution, large output
	(b) Proximity	10	0.75	,,	2	5k	Non contact type
3.	**Capacitive**						
	(a) variable gap	5	0.5	-10 to 500	0.1	2k	Nonlinear, large range
	(b) variable area	50	0.1	-40 to 200	0.1	50	

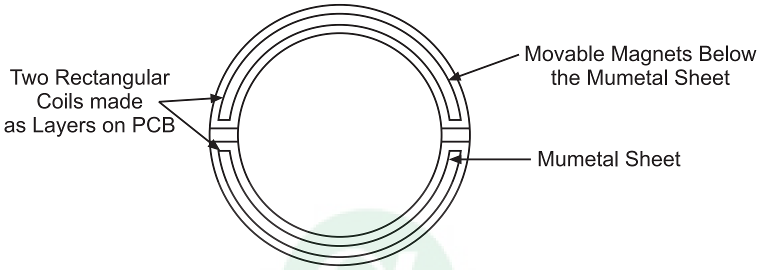
Special displacement sensor-Planar: Coil Displacement Type

These have been in use for automotive applications for high accuracy. Compared to the common resistive potentiometers being used, this type offers contactless device at low cost and high reliability. A movable magnet and set of differentially connected coils create a field in a magnetic sheet of Mu-metal.

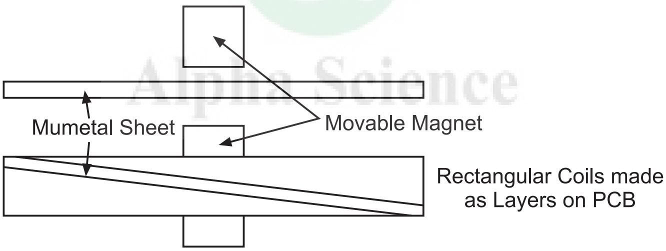
Two identical coils are differentially connected so avoid nonlinearity undergo a change in inductance due to movement of magnet, through the magnetic fields (sheets) undergoing saturation over the different areas.

It can be used for both liner and rotary positions.

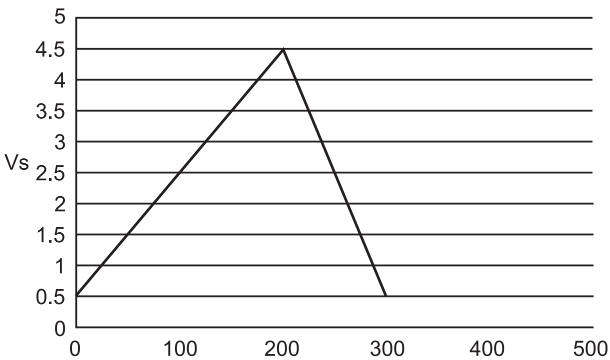
Arrangement is shown in Fig. 7.32:



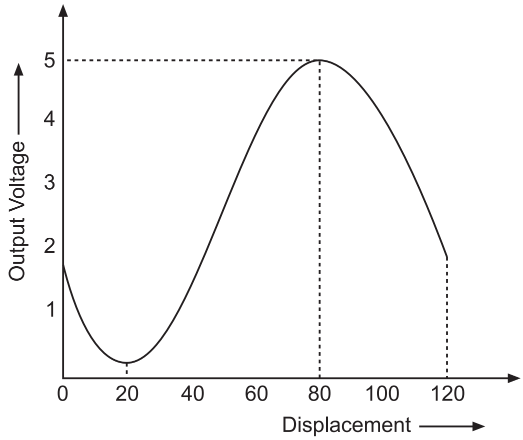
(a) Rotary Sensor Design



(b) Linear Sensor Design



(c) Output of Linear Sensor



(d) Displacement Output of Rotary Sensosr

Fig. 7.32 Planar Coil Type Displacement Sensor

(*a*) for rotation sensors,

(*b*) for linear sensors, two coils with magnetic material of high permeability are printed on a PCB as layers, connected in opposition; a moving magnet creates a saturation area as a function of the position and causes a change in inductance. The linkage between moving magnet and coils is improved by the Mu-metal sheet.

The signal conditioning is provided or be from the same PCB to provide a scaled electronic output.

Planar Coil Type Displacement Sensor

It is usable for linear, rotary, 2-D displacements inductance of coils is determined by the equation

$$L = L_0(f, T) + \alpha(f, T) . \iint \mu_f . dv \qquad \text{...(7.41)}$$

where L_0 is the sensors' inductance under saturation state of Mu-metal, α is a parameter depending on frequency and temperature.

The differential output of the sensor is given by:

$$S(f, T) = \frac{\iint\limits_{MS_1} \mu_r . dv - \iint\limits_{MS_2} \mu_r dv}{\iint\limits_{MS_1} \mu_r . dv + \iint\limits_{MS_2} \mu_r . dv + 2 . \dfrac{L(0)(f, T)}{\alpha(f, T)}} \qquad \text{...(7.42)}$$

The likely nature of output signal is shown in Fig. 7.32 (*c*) for rotary sensor and Fig. 7.32 (*d*), for linear sensor. It is to notice that there is no edge effect in rotary sensor which appears in case of linear sensors causing non linearity.

The excitation applied to coils is a rectangular voltage signal. All signal conditioning including analog and digital is contained on one ASIC with programmable gain and provides digital output with built-in provision for off-set, temperature compensation and analog output.

The achievable linearity, hysteresis and temperature drift are indicated in Table 7.9.

TABLE 7.9 Properties of Planar Coil Displacement Sensor

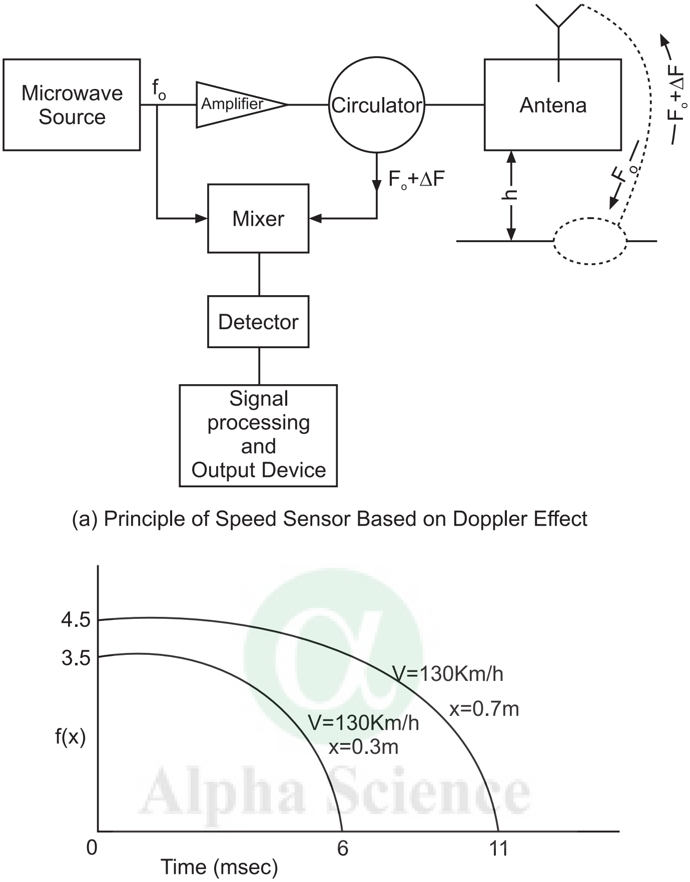
Property	*For rotary sensor*	*For linear sensor nms*
Linearity	0.4°	0.35
Hysteresis	0.2°	0.1
Drift due to temp-40° to 135°C	1°	0.2

7.5.2 Instrumentation of Speed—a new Technique

In Chapters 5 and 6, several transducers for speed monitoring have been discussed, based on wheel/drive speed. However, in some of the cases it may lead to incorrect/unreliable or no measurement. For example, an automobile skidding on a wet/icy road surface, when it is all the more important to measure the speed of vehicle under full brakes with no wheel rotation and safety mechanism is to be operated depending on skidding speed of vehicle!

Doppler Effect can be used for more reliable measurement of absolute speed. As shown in Fig. 7.33 (*i*) an antenna sends a narrow beam signal towards road surface which is partially reflected back from the ground (obstacle). The reflected wave with frequency shifted by Δf proportional to the vehicle speed and cosine of the angle from radar to ground and the speed of vehicle can be determined as from Eqns. (7.41) – (7.42) defined earlier.

However, under the circumstances mentioned earlier, the obstacle surface may be scattering type instead of reflective; therefore a broad beam is preferable with angle not known precisely. The use of variable frequency facilitates the determination of vehicle speed as also the angle at the cost of hardware and data processing. In a new approach a broad – beam antenna with single frequency is used with monolithic microwave (MMIC) technology.



(a) Principle of Speed Sensor Based on Doppler Effect

(b) Time Dependence of Doppler Frequency for Parameters v and x

Fig. 7.33 Speed Monitoring by Microwave Radio Technique

A beam of frequency f_0 is transmitted to the ground during a time slot ΔT. Doppler shift of reflected signal,

$$\Delta f(v, x, h) = \frac{2.f_0.v.\cos\alpha}{c} \quad \text{...(7.43)}$$

where c is the propagation speed of wave

v absolute speed of vehicle

x position of scattering obstacle at the beginning of time – slot relative to projection on road surface.

h height of the sensor above the road

f_0 the frequency of radiated waves

The time slot is chosen to be short so that during the period ΔT, the vehicle is constant.

Since f_0 is constant, frequency variation of the Doppler signal is only due to vehicle movement, therefore Doppler shift

$$\Delta f(t) = 2.\frac{f_0.v}{c\sqrt{1+\frac{h^2}{(x-v.t)^2}}} \quad ...(7.44)$$

Vehicle speed is considered positive if the vehicle is approaching the obstacle else otherwise.

Time dependence of Doppler frequency for different value of vehicle speed v and target distance is shown in Fig. 7.33(*b*).

The frequency evolution of the Doppler signal during time slot ΔT can be calculated by using FFT algorithm on moving windows ST(analysis window) with overlapping to achieve good frequency tracking.

The broad beam microwaves have resulted in far superior performance in terms of speed measurement error compared to narrow beam sensors and limited to +0.5% error.

7.5.3 Instrumentation of Acceleration and Vibration

The electromechanical devices are used to measure/monitor acceleration–static such as gravitational or dynamic due to movement or vibration. With static acceleration it is possible to monitor inclination of the body with respect to earth and by sensing dynamic acceleration the way the object is moving. The applications include saving the hard disk from damage during and after the sudden fall of lap tops, and detecting potential car crashes and saving the front seat persons in a car just before crashing with timely use of airbags.

Instrumentation of dynamic displacement, velocity, acceleration is intimately related through differentiation process as:

$$\int \ddot{x} = \dot{x}; \int \dot{x} = x$$

and reverse relation also holds.

The various accelerometer types are:

Seismic Sensors

For vibration instrumentation a seismic pickup is a common device. The configuration is shown in Fig. 7.34 is used for absolute displacement.

A proof mass supported by a spring and a damper assembly is mounted rigidly on the surface (or the body) in which the acceleration and vibration is to be monitored. The relative displacement x_0 is picked, and is converted into the voltage signal by a sensitive LVDT (or any other device).

The force balance equation can be written as:

$$K_s x_0(t) + B\dot{x}_0(t) = M\ddot{x}_m(t) = M\left(\ddot{x}_i(t) - \ddot{x}_0(t)\right) \quad \text{...(7.45)}$$

where, K_s is stiffness of the spring

x_0 is the relative displacement cause due to input displacement

M is the proof mass

B is the damping constant of the damper

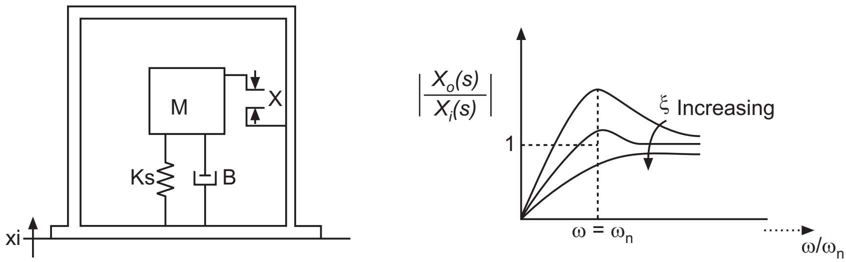
x_i is the time variable displacement due to acceleration/vibration

transfer function relation can be obtained as

$$\frac{x_0(s)}{x_i(s)} = \frac{\dfrac{s^2}{\omega_n^2}}{\dfrac{s^2}{\omega_n^2} + \dfrac{2\xi}{\omega_n}s + 1} \quad \text{...(7.46)}$$

where $\omega_n \triangleq \sqrt{\dfrac{K_s}{M}}\ ;\ \xi \triangleq \dfrac{B}{2\sqrt{K_s M}}$

The frequency response of this second order system will be as shown in Fig. 7.34.



Configuration of Seismic Transducer

Fig. 7.34 Configuration and Response of Seismic Transducers

It is observed that for static input/steady motion of the body, there will be no output.

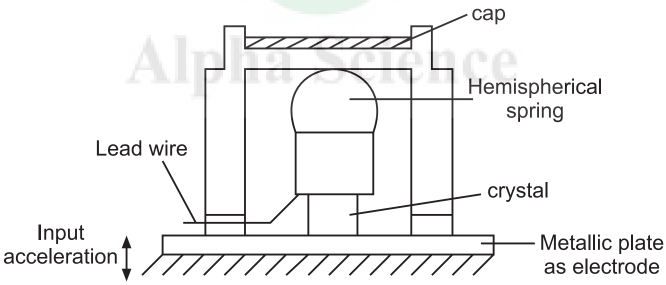
With the use of relative velocity transducer, providing output voltage $e_0 = K_e \dot{x}_0$, it is possible to obtain

$$\frac{E_0(s)}{\dot{x}_i(s)} = \frac{K_e \dfrac{s^2}{\omega_n^2}}{\dfrac{s^2}{\omega_n^2} + \dfrac{2\xi}{\omega_n} + 1}. \qquad \text{...(7.47)}$$

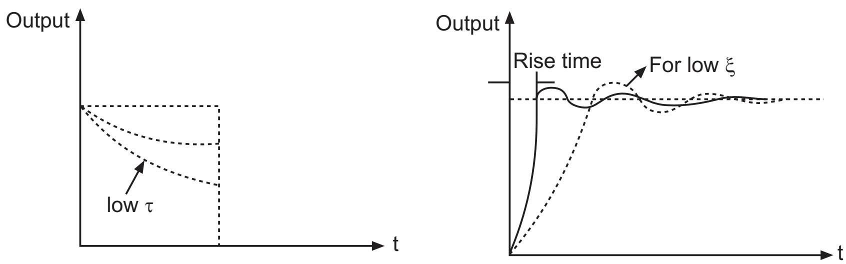
Piezoelectric Type Accelerometer

Earlier the piezoelectric transducer principle and characteristics have been considered. It has also been noted that, these can only be used for dynamic inputs.

The piezoelectric crystal is enclosed in a case of about 1'' cube with hemispherical spring. The vibration/acceleration can be given as input through the bottom surface of the device, as shown in Fig. 7.35 (*a*), transfers the instantaneous changes to the crystal which in turn generates a voltage output. The spring serves to limit the excessive changes in acceleration or vibration. The time response and the frequency response are as shown in Figs. 7.35 (*b*) and (*c*).

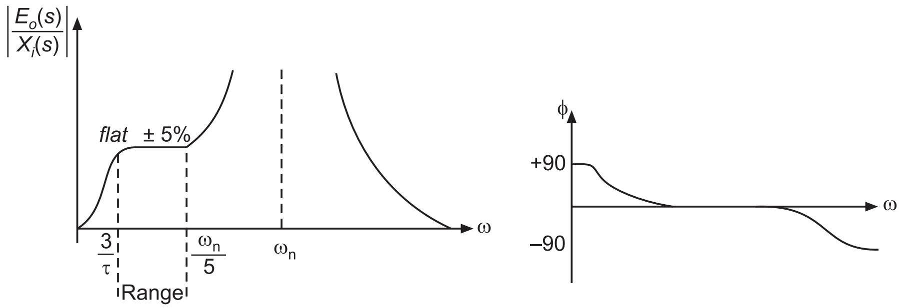


(a) Configuration of peizo electric accelerometer



(i) Response for low frequency signals (ii) Response for high frequency signals

(b) Time response



(c) Frequency Response of Peizoelectric Crystal

Fig. 7.35 Configuration and Response of peizo electric accelerometer

The typical capacitance of the crystal is 7000 pF and the connecting cable is negligible. This class of accelerometer is able to provide peak-measurement accuracy of ±5% and the low frequency signals generally cause problems in measurement, and it is desired that $\frac{2}{\omega_n}$ should be less than $t_{rise}/3$ for accurate measurement or time constant > 20T the natural period of crystal frequency.

Electrodynamic Type of Accelerometers

These are based on EMF generation principle. The voltage induced in a coil, placed in magnetic field has a voltage induced when a movement occurs due to change in velocity (acceleration)the arrangement is shown in Fig. 7.36, wherein a movable coil is hanging in a magnetic field of a permanent magnet.

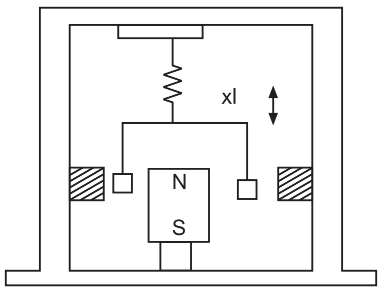


Fig. 7.36 Electrodynamic Type of Accelerometer

The emf produced $e_0 = B \cdot l \cdot \dot{x}$ is a measure of the acceleration and it is possible to achieve the sensitivity up to 200 mV/cm/sec with this class of accelerometers with typical second order under-damped response.

Electromagnetic Type of Accelerometers

These are based on the principle of generation of emf due to change in reluctance of magnetic circuit. The arrangement is shown in Fig. 7.37, where in a coil is wound on a permanent magnet and the magnetic path is completed through an air gap, a ferrous plate through which the input(measurand) is provided.

If y_0 is the normal gap between the magnetic coil and the plate and x is the change that occurs due to measurand acceleration across the instantaneous gap, $y = y_0 \pm x$ and the output from the search coil placed on the primary coil shall be,

$$e_0 = K\frac{d\phi}{dt} = K\frac{d\phi}{dy}\frac{dy}{dt} \qquad ...(7.48)$$

$$= K\left(\frac{d\phi}{dy}\right)\frac{d(y_0 + x)}{dt} = K\left(\frac{d\phi}{dy}\right)\frac{dx}{dt} \qquad ...(7.49)$$

$\left(\frac{d\phi}{dy}\right)$ is referred as sensitivity factor. The output is directly proportional to the change in position. A differentiator as the part of signal conditioning, provides the measure of acceleration.

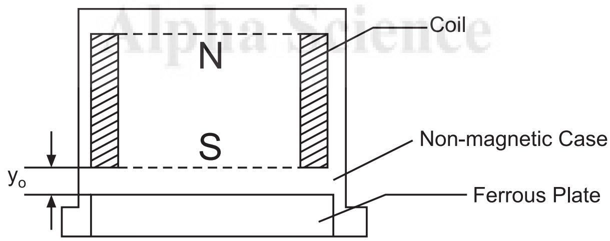


Fig. 7.37 Electromagnetic Type Accelerometer

7.6 MONITORING OF HUMIDITY AND MOISTURE

In industrial processes the monitoring (and correction) of humidity is often decisive for the quality of product and competitiveness. It can also result in savings of energy and has far reaching influence in our well being and important during summer and monsoon seasons.

In several processes water content of the air can produce/influence chemical or physical properties and it becomes important to monitor continuously. Referred as psychrometer, these are usable in atmosphere of corrosive gasses, solvents, meat and cheese production as well as domestic and office buildings.

7.6.1 Definitions

Humidity content of air can be characterized by two parameters – relative humidity and absolute humidity.

Relative humidity can be defined as

$$RH = \frac{\text{Actual partial vapours pressure, } P_w \text{ in a gas}}{\text{Maximum possible vapour pressure (saturation V.P.), } P_s \text{ at particular temp.}} \quad ...(7.50)$$

$$RH = \frac{P_w}{P_s(t)} \times 100\% \quad ...(7.51)$$

Thus relative humidity depends on temperature and it decreases with increasing temperature.

Table 7.10 shows the influence of temperature.

TABLE 7.10 Influence of Temperature Variation of 1°C at Different Temperature and Humidity on Humidity

	10°C	*20°C*	*30°C*	*50°C*
10% RH	±0.7%	±0.6%	±0.6%	±0.5%
50% RH	±3.5%	±3.2%	±3.0%	±2.6%
90% RH	±6.3%	±5.7%	±5.4%	±4.6%

Absolute Humidity

It is defined as the quantity of water vapor contained in certain amount of air,

$$a = \frac{\text{mass of water vapour}}{\text{volume of air}} \frac{\text{gm}}{\text{m}^3} \quad ...(7.52)$$

This is independent of temperature.

Mixing Ratio

This indicates the mass of water vapor to the mass of the dry gas. It is expressed in gm/kg of dry air.

The ratio specifies the number of grams of water vapor contained in a kilogram of dry air. Sometimes it is more informative then relative humidity.

There is interrelationship between temperature, moisture content and relative humidity but these are expressed through graphs, (Mollier diagrams).

7.6.2 Measurement of Humidity

Psychometric methods have been in use for a very long time. These are based on heat exchange and consist of two independent probes-one is used as wet bulb and other used as dry bulb probe. Wet probe is actually covered by a water saturated cloth/tissue. A flow of air over this probe causes evaporation depending upon temperature and humidity due to cooling effect. The dry probe measures the ambient air temperature. The temperature difference between the two sensors is a measure of relative humidity of surrounding air. Such mechanical psychrometers with glass thermometers are restricted to climatic range *i.e.* 60ºC. They do not need electrical supply and are not useful for continuous monitoring, remote logging and digital display.

7.6.3 Electrical Psychrometers

(a) RTD type

These are more useful for industrial applications. Herein the dry and wet bulb are replaced by RTD *i.e.* Pt 100. With the help of suitable electronics *i.e.* differential amplifiers, it is possible the range up to 100ºC the arrangement is shown in Fig. 7.38.

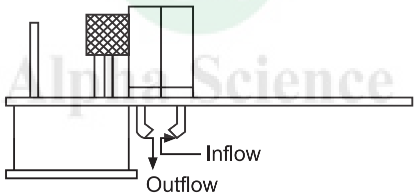


Fig. 7.38 Electrical Psychrometer RTD Type

(b) Capacitive type

As shown in Fig. 7.39, are more convenient to use, sensitive and robust.

In between top and bottom electrodes, a thin polymer film is placed as humidity sensor. The removal from or absorption of water molecules into the sensor causes the capacitance value of the condenser to change. The top electrode which is hygroscopic allows the water vapor to pass through the active film sensor. The change in capacity is proportional to change in humidity and converted into electrical signal in desired format *i.e.* analog voltage/current, digital and passive (resistive) output.

This hygrometer (capacitive) sensor has fast response due to low mass of sensors and is quite immune to dust, noise, corrosive gas/solvent environment. Measuring range is from 10-90% relative humidity, extendable to 100% and temperature range is from -40 to 80ºC with simultaneous measurement. Accuracy of measurements is ±2% to ±5% RH with option up to ±1%.

The device is protected again human contact by plastic encapsulation.

The humidity sensors are finding applications in building automation, climate and ventilation control of storage rooms, hospitals, and hotels.

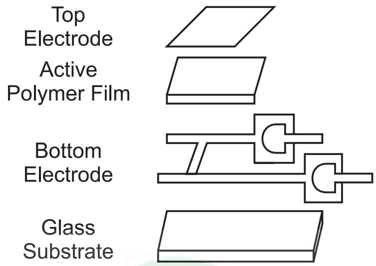


Fig. 7.39 Capacitive Type Psychrometer

Concluding remarks

In this chapter a link has been established between theory of sensors/ transducers in Chapters 5 for passive and in chapter 6 for active types with the industrial applications. A large number of applications have been discussed for various types of variables from mechanical to those in process systems. The discussion can be further pursued with the follow up of manufacturers' web sites, available in appendix.

In the next chapter the next stage of instrumentation system channel is discussed. This is related to transformation of electrical signal to desired format as may be most suitable by processing for transmission/telemetering over distances ranging from several meters to hundreds of meters to kilometers to thousands of kilometers in some cases. The various activities needed have been grouped as signal conditioning, and shall be discussed next.

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REVIEW PROBLEMS

(*i*) What are the advantages of radiation pyrometers?

(*ii*) What are the typical applications of radiation pyrometers at medium high/ moderate temperatures?

(*iii*) What is equivalent noise source? How it is determined for any device?

(*iv*) Explain the laws of thermocouple?

(*v*) What are the laws of electromagnetic induction?

(*vi*) What are the important features in selection of temperature transducer for an industrial application?

(*vii*) What are different types of Bourdons? Explain the conversion of resulting displacement of tip into electrical signal.

(*viii*) Explain the principle used in the mouth piece and headphone in a telephone set.

(*ix*) What is the principle of operation of a capacitance microphone?

PROBLEMS FOR EXERCISE

7.1 Identify the choice of transducer for monitoring the temperature of water from a domestic geyser. Suggest a scheme for display andcontrol the outgoing water temperature at 40°C.

7.2 Calculate (*a*) gauge pressure

(*b*) absolute pressure at the depth of 40 meters in a water tank.

7.3 Calculate the likely reading of Bourdon gauge when used for measuring pressure at a point 30 below the pipeline. Assume waterline pressure to be 5 kg/cm^2.

7.4 An incompressible chemical is transported through pipeline of 30 cms diameter under a pressure head of 4 kg/cm^2. Calculate the flow velocity and volumetric flow rate of chemical.

7.5 Calculate the induced emf in an electromagnetic flowmeter, due to the flow of a conductive liquid, if the volume flow rate is 2 litres/min. inner diameter of pipeline is 2.5 cm and the magnetic field strength being applied is 60 Wb/m^2.

7.6 For an electromagnetic flowmeter, determine the magnetic field which must be applied across the 20 cm diameter pipe, carrying conducting fluid, such that the voltage picked-up is 1.0 mV and above, for minimum flow velocity of 1 cm/sec.

7.7 For a rotameter used to measure flow rate in a pipe, the cylindrical float has area of cross section 10.5 cm^2, height 3.5 cm and density of its material 3000 kg/M^3. Find the minimum flow rate (corresponding to float at the bottom of measuring tube) and maximum flow rate (for float at the top) if the density of liquid is 0.6 and the diameter of the measuring tube at top and bottom are 6 cm and 2 cm respectively.

CHAPTER 8

Signal Conditioning and Data Conversion

INTRODUCTION

Inside the Chapter

It is now the time to move, towards perfection by invoking the advantages of electronics. The signal obtained from passive/active transducer needs to be brought into a format suitable for further operations to be performed on them, by the display and units in follow up stages. It is necessary to ensure proper interfacing of the signal, with the monitoring devices, recorders for permanent record, for processing to control and analysis, with required levels of accuracy, reliability, presentation in desirable format. Very often there is need for pre-processing/conditioning of the signal.

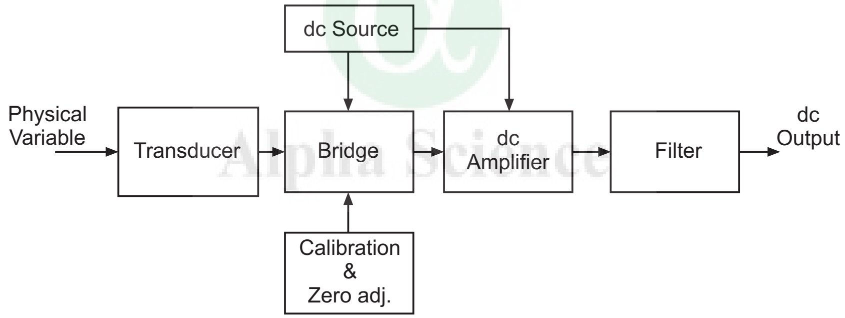
The term signal conditioning operations include a host of activities performed through units in cascade as per the need based on the features of typical signal. A list of such operations is included in Table 8.1. The devices include:

Transducer bridges dc and ac, balancing and calibration network, amplifiers/attenuators, rectifiers…

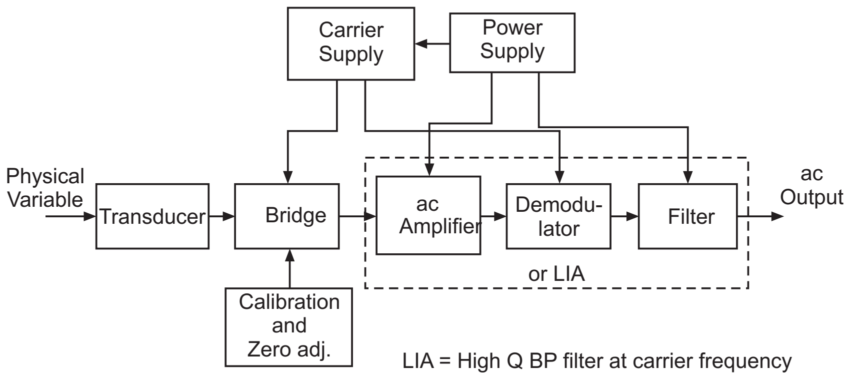
TABLE 8.1 Signal Conditioning Operations/devices

Common devices	*Common operations*	*Specialized operations*
Transducer bridges	Filtering	Linearising, Zero crossing detection
Balancing and calibration network	Signal conversion, Multiplexing	Signal compression, Multiplication
Amplifiers/attenuators	Data conversion-analog to digital, digital to analog conversion	Peak & p-p detection Limiting
Rectifiers	Coding/decoding	Function synthesis, Integration, phase detection, lock in amplifiers

In Fig. 8.1. the analog signal conditioning elements generally required and the configurations are shown. It is not necessary that all these or these only will be needed for every signal. Figure 8.1(*a*) shows typical elements for dc signal conditioning system and 8.1(*b*) presents the configuration of an ac signal conditioning system.



(a) dc type



(b) ac type

Fig. 8.1 Configuration of Signal Conditioning Systems

8.1 TRANSDUCER BRIDGES

In Figs. 8.2 and 8.3, the bridges employed in dc and ac configurations are shown for use with passive transducers. For resistive transducers *viz.* strain gages, RTDs, etc., dc-bridges will be sufficient and preferred to keep the overall arrangement simple, efficient and accurate. For inductive and capacitive transducers, often used in differential mode, we utilize the ac bridge in push-pull connection (Fig. 8.3) which provides better results.

8.1.1 Bridges for Resistive Transducers

These are normally Wheatstone bridge with added features for zeroing, sensitivity adjustment and calibration as shown in Fig. 8.2(*a*). The supply or excitation voltage of bridge E_i is limited by the self-heating in the transducer arm, forming one or more arms of the bridge and have to be kept small (within 10v) and, regulated by sensitivity adjust resistance which may result in low voltage output.

The low voltage output from bridge is susceptible to noise and therefore needs amplification and filtering in subsequent stages. The various operations usual, special and highly special clubbed together are referred to as signal conditioning.

Consider the bridge circuit of Fig. 8.2(*a*) with initial balance obtained; by the help of zero adjust resistance potentiometer. With only one of the four arms being active *i.e.* containing resistive transducer (say RTD or thermistor) in one of the arms, will be referred as quarter bridge. R_C is the calibrating resistance.

Whereas, if the bridge has two active arms, for example strain gauges in two adjacent arms say R_1, R_2, with one under tension and the other under compression, on the same specimen, then deviations of resistance of same magnitude but opposite in sign will be produced. This arrangement results in doubling of output, compared to previous case, is referred as Half-bridge R_c is the calibrating resistance.

An extension to all active arms bridge is possible with (say) strain gauges, such that each pair of opposite-arms experiences forces of opposite nature *viz.* R_1, R_3 under tension and R_2, R_4 under compression. This will result in redoubling of output in this full bridge mode of operation. This can be obtained by simple calculations as follows:

Consider the bridge of Fig. 8.2(*a*) again; assuming that all arms undergo change due to mechanical stress, so that all four resistances undergo incremental change, resulting in unbalanced output voltage.

$$e_o = V_b - V_d = \left[\frac{E_i(R_1 + \Delta R_1)}{(R_1 + \Delta R_1) + (R_4 + \Delta R_4)} - \frac{E_i(R_2 + \Delta R_2)}{(R_2 + \Delta R_2) + (R_3 + \Delta R_3)} \right]$$

$$= E_i \left[\frac{(R_1 + \Delta R_1)}{(R_1 + \Delta R_1) + (R_4 + \Delta R_4)} - \frac{(R_2 + \Delta R_2)}{(R_2 + \Delta R_2) + (R_3 + \Delta R_3)} \right] \qquad \text{...(8.1)}$$

It can be assumed reasonably with strain gauges of same lot that,

$$R_1 = R_2 = R_3 = R_4 = R \qquad \text{...(8.2)}$$

and considering the 3 bridge configurations:

(*i*) For quarter arm bridge configuration:

$\Delta R_1 = \Delta R_3 = \Delta R_4 = 0$; only R_2 changes to $R_2 \pm \Delta R_2$

depending upon nature of force-tensile or compressive, output of bridge,

$$e_0 = |V_{BD}| = E_i \frac{\Delta R_2}{4\left(R_2 + \frac{\Delta R_2}{2}\right)} \simeq Ei \frac{\Delta R}{4R} \qquad \text{...(8.3)}$$

for $\Delta R_2 = \Delta R$ and $\Delta R << R$

(*i*) For half bridge mode/configuration:

Assume, $\Delta R_1 = -\Delta R_2$; $|\Delta R_1| = |\Delta R_2| = \Delta R$; $\Delta R_3 = \Delta R_4 = 0$

output $$e_0 = |V_{BD}| \cong E_i \frac{\Delta R}{2R} \qquad \text{...(8.4)}$$

(*ii*) For Full bridge configuration :

$\Delta R_1 = \Delta R_3 = \pm \Delta R$ and, $\Delta R_2 = \Delta R_4 = \mp \Delta R$

so that, the full bridge output, $e_0 = |V_{BD}| = E_i \dfrac{\Delta R}{R}$

So that, $e_o \propto \Delta R$

The proportional relationship is valid for $\dfrac{\Delta R}{R} <= 1\%$ and the loss of signal magnitude, due to loading when the detector is connected, depends on the ratio of internal or equivalent Thevenin's resistance (R_{Th}) of bridge to detector resistance *i.e.* R_{Th}/R_m.

Effect of variation in temperature of strain gauge during measurement can be significant and can be compensated by use of a dummy gauge in the adjacent arm instead of a pure resistance as is normally used in a Wheatstone bridge. Now both the gauges will be affected by change in ambient temperature equally and its effect gets nullified.

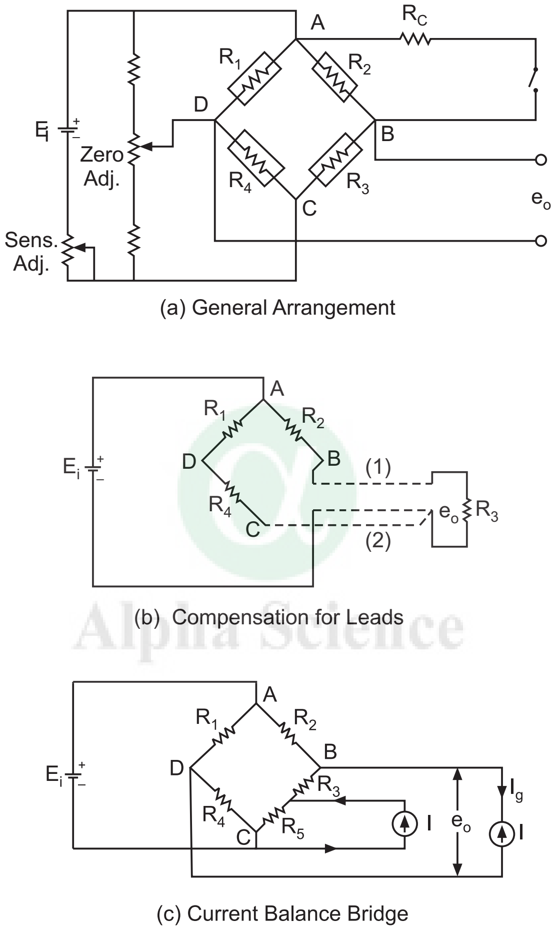


Fig. 8.2 DC Bridge for Resistive Transducers

Lead compensation problem arises in situations where the sensor (in the process) is remotely located, from control room, housing the measuring bridge. The lead resistance of long lead wires may vary due to temperature, frequency, stresses, effect of surrounding gases etc. these effects can be off-setted by introducing them equally into both lead cables as shown in Fig. 8.2(*b*) and the bridge balance is unaffected. For higher accuracy Mueller's bridge arrangement is used and has been discussed in Appendix-B.

Transmission of the voltage output signal from the bridge is used for remote logging at the control room. The signal transmission is required and the number of sensor signals to be sent simultaneously pose a formidable challenge in industry. This is complicated by the distance, speed requirement and the environmental electrical noise. It will be topic of discussion in ninth chapter.

EXAMPLE 8.1

For RTD used to monitor temperature is having nominal resistance of 400 Ω and maximum heat dissipation limited to 10 mW to avoid self heating. Evaluate the maximum supply voltage for the transducer bridge, if the bridge is equal arm quarter bridge and the maximum bridge output is for a temperature increase from 35°C to 630°C. Temperature coefficient of resistance á is known to be 2 mΩ/°C.

SOLUTION:

Maximum current allowed

$$= \frac{\sqrt{10 \text{ mW}}}{400} = \sqrt{\frac{10 \times 10^{-3}}{400}} = \frac{10^{-1}}{20} = 5 \text{ mA}$$

$$\therefore\ E_i = 2 \times 400 \times (5 \times 10^{-3}) = 4\text{V}$$

Therefore maximum output

$$E_0 = \frac{E_i}{4R}.\Delta R = \frac{4}{4 \times 400} \times (400 \times 2 \times 10^{-3} \times (630 - 35))$$

$$= 2 \times 10^{-3} \times 595 = 1.190 \text{ V}$$

Therefore amplification of output voltage signal appears necessary.

EXAMPLE 8.2

In a temperature instrumentation scheme an RTD is used in equal arm quarter bridge mode. RTD has linear relation with temperature with $\alpha = 0.004$, $R_{25} = 1K\ \Omega$ and maximum power dissipation capacity of 50 mW/°C. Bridge excitation supply E_i is 10 V dc as in Fig. 8.2(a). If the RTD connected as arm R_2 is placed in a heated bath at 50°C, find the change in resistance of RTD and bridge output if the effect of self-heating is (a) neglected (b) considered.

SOLUTION:

Resistance of *RTD* at 50°C

$$R_{50} = 1000\ [1 + 0.004\ (50 - 25)]$$
$$= 1100\ \Omega$$

Change in resistance = 100 Ω

(*a*) If the effect of self heating is neglected:

$$E_o = \frac{10 \times 1100}{(1000 + 1100)} - 5.0 = 0.238095\ \text{V}$$
$$= 238.095\ \text{mV}$$

(*b*) Considering the effect of self heating:

Power consumed by *RTD* = $I^2R_{50} = (4.76 \times 10^{-3})^2 \times 1100$ W

$= 24.943$ mW

∴ Additional temperature rise due to self heating $= \frac{24.943}{50}$ = 0.4988°C.

∴ Actual RTD temp = 50.4988°C,

and, RTD resistance = 1000 [1 + 0.004 (50.4988-25)]

= 1101.995 Ω

Bridge output, $e_o = \frac{10 \times 1101.995}{1000 + 1101.995} - 5.0$ = 0.242614 V = **242.614 mV.**

Current Balance Bridge

The balance of Wheatstone bridge is obtained by tedious process of choosing appropriate values of resistances. This can be avoided by adopting a slightly different configuration as shown in Fig. 8.2(*c*), known as current balance bridge.

Starting from an initially balanced four-arm bridge, for any one of the arms (say R_3) undergoing change in resistance due to effect of measurand will create unbalance and can be brought back to null condition again, by allowing additional current from an external current source. This current required I, can be calibrated for instrumenting the physical variable causing change of resistance. Thus a small current from an external (current) source through R_5, compensates the unbalanced potential V_{BD}, providing a nulling facility.

For, $R_3 > R_5$ and $(R_2 + R_3) >> R_5$

$$V_{BD} = \left(\frac{E_i}{R_1 + R_4}\right) R_4 - \left(\frac{E_i}{R_2 + R_3 + R_5}\right)(R_3 + R_5) - IR5 \qquad \text{...(8.5)}$$

Bridge balance can be easily obtained by adjusting direction and magnitude of I and the complexity of self balancing potentiometer type electromechanical device can be avoided.

Thus a very small current from the source is able to provide a very accurate measurement without any appreciable heating. This is shown through an example next.

EXAMPLE 8.3

For a current balance bridge as shown in Fig. 8.2(c), the resistance are known to be $R_1 = R_2 = 400\Omega$, $R_3 = 300\Omega$, $R_4 = 400\Omega$ and $R_5 = 100\Omega$. The bridge has a d.c supply of 10V and null detector of high input resistance. Calculate the current required through R_5 to achieve the null condition if the resistive transducer represented by resistance R_3 changes by + 1Ω.

SOLUTION:

Under unbalanced condition without current, I being supplied:

$$V_d = \frac{10 \times 401}{(400 + 401)} = 5.006242 \text{ V}$$

$$V_b = \frac{10 \times 400}{(400 + 400)} = 5.000 \text{ V}$$

$$\therefore \qquad V_d - V_b = V_{db} = 6.242 \text{ mV}$$

Therefore to re-null the bridge the voltage must be increased by

$$100\, I = 6.242 \times 10^{-3}$$

$$\therefore \qquad I = \frac{6.242 \times 10^{-3}}{100} = 62.42 \ \mu\text{A}.$$

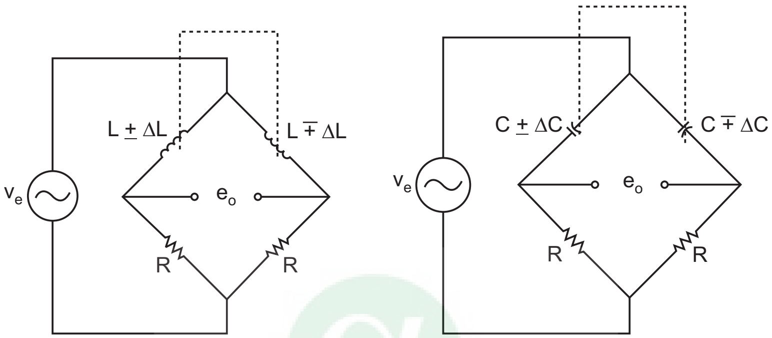
Thus an extremely small current is required to flow into the meter and a high sensitivity is obtained with high accuracy. The current can be calibrated to indicate the change in measurand.

8.1.2 Transducer Bridges for Reactive Transducers

These bridges are typically preferred in push-pull connection in differential mode, for both inductive and capacitive type of transducers, as shown in Fig. 8.3. In such arrangements the change in one arm is coupled with a change of opposite nature in the other arm.

Arrangements for differential inductive and capacitive transducer are shown in Fig. 8.3(*a* & *b*). The inductive and capacitive transducers have already been, considered earlier in Chapter 5 on passive transducers, hence these details are not repeated.

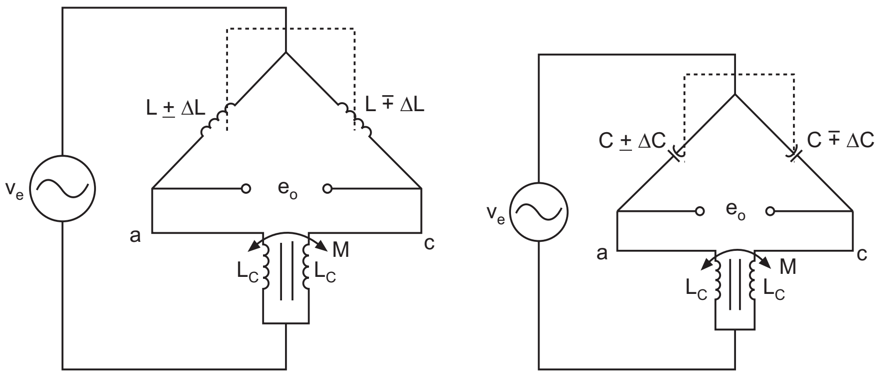
The push-pull transducer generates more linear output, proportional to the physical measured quantity, than a single element transducer. Also, the temperature effects in the two arms tend to cancel in the output.



(a) For Inductive Transducers (b) For Capacitive Transducers

Fig. 8.3 AC Push-Pull Bridge for Reactive Transducers

An alternative form of ac bridge, with resistive ratio arms replaced by closely coupled inductive ratio arms, as shown in Fig. 8.4, is known as Blumlein bridge. The tightly coupled arms have self inductance Lc and mutual inductance *M* with iron core. This configuration provides increased immunity against external fields and simplifies earthing and shielding problems.



(a) For Inductive Transducer (b) For Capacitive Transducer

Fig. 8.4 Blumlein Bridge Configuration for Reactive Transducers

To analyze this bridge and evaluate sensitivity, consider the equivalent circuit for the inductively coupled lower arms, as shown in Fig. 8.5, as an equivalent symmetrical T-network. The component block values of T-model can be easily deduced as:

$$Z_{ab} = Z_s + Zp = j\omega\, Lc \qquad ...(8.6)$$

and

$$Z_{ac} = 2Z_s = 2j\omega\,(Lc\text{-}M) \qquad ...(8.7)$$

For the winding sense indicated in Fig. 8.5(*a*)

$$Z_s = j\omega(Lc\text{-}M);\ Z_p = j\omega M \qquad ...(8.8)$$

The coupling factor for the two coils is $k = \pm\dfrac{M}{Lc}$

which would maximize to +1 for tight coupling? When the bridge is under balanced condition,

$$Z_{ac} = 2\ Zs = 0;\ \text{ for } k = 1,$$

This results in no voltage drop across ratio arms and effect of cables and stray capacitances across them is eliminated!

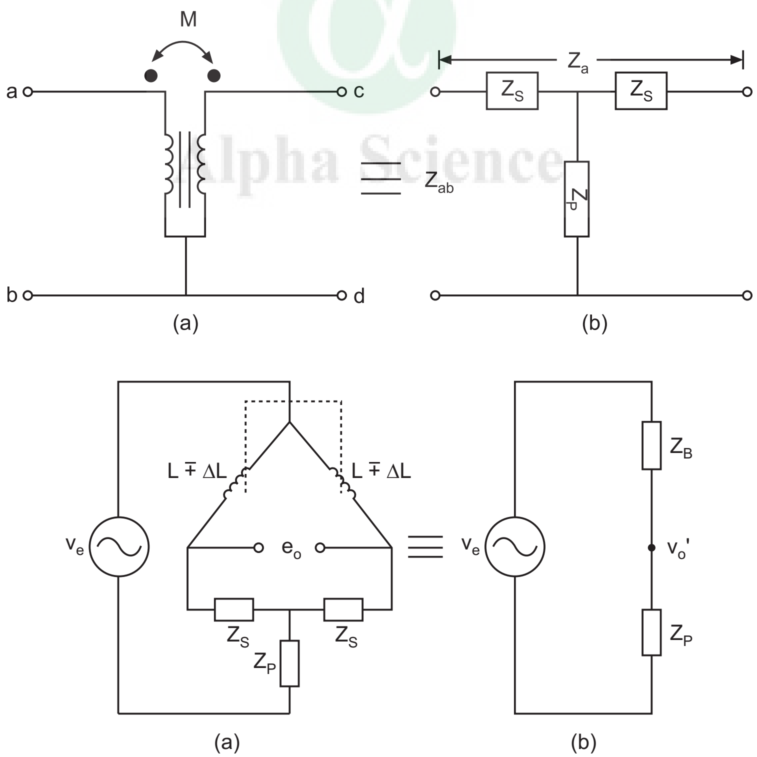


Fig. 8.5 Equivalent Circuit with Inductive Differential Transducer

Under the measuring condition, the direction of current in the 2 sides of bridge change to oppose and coupling therefore will change to –1, resulting in

$$2\ Zs = 4\ j\omega\ Lc$$

The sensitivity can be obtained through the following steps:

$$Z_B = \frac{jL\omega\left(1+2\frac{Lc}{L}+\frac{\Delta L}{L}\right)\left(1+2\frac{Lc}{L}-\frac{\Delta L}{L}\right)}{2\left[1+2\frac{Lc}{L}\right]}$$

$$\times \frac{j\omega L}{2}\left(1+2\frac{Lc}{L}\right) \quad ...(8.9)$$

with $\dfrac{Z_p}{Z_B} = \dfrac{1}{2}\left(\dfrac{Lc}{L}\right) << 1,$

and, open circuit output voltage would be

$$e_0 = Ve\left[\frac{j\omega(L+\Delta L)}{j\omega(L+\Delta L)+2j\omega Lc} - \frac{j\omega(L-\Delta L)}{j\omega(L-\Delta L)+2j\omega Lc}\right] \quad ...(8.10)$$

$$\cong V_e\left(\frac{\Delta L}{L}\right)\left(\frac{4\frac{Lc}{L}}{1+2\frac{Lc}{L}}\right); \text{ for } \frac{\Delta L}{L} << 1 \quad ...(8.11)$$

Therefore, bridge sensitivity $S_L = \dfrac{e_0/V_e}{\left(\dfrac{\Delta L}{L}\right)} = \dfrac{4\frac{Lc}{L}}{1+2\frac{Lc}{L}}$ ...(8.12)

The variation of sensitivity for variations of (Lc/L) has a linear rise, and tends to saturate for values larger than unity with $k = -1$ as shown in Fig. 8.6(*a*).

A similar analysis for push-pull capacitive transducer in Blumlein bridge yields, sensitivity to be:

$$S_c = \frac{e_0/V_e}{\left(\frac{\Delta C}{C}\right)} = \frac{4\omega^2 LcC}{C(2\omega^2 LcC-1)} \quad ...(8.13)$$

Amplifier output should be in the range of 5–10 V (from forward interfacing consideration), for both dc and ac signals. The sensitivity plots against $\omega^2 L_C C$ indicates, a resonance occurrence as shown in Fig. 8.6(*b*), for $\omega^2 L_C C = \frac{1}{2}$, and therefore bridge should be operated for values larger than this, over which the response shows constant sensitivity.

It can be noticed that, for both inductive and capacitive transducers, the sensitivity of Blumlein bridge output in the limiting case approximates to 2 and for most cases needs additional sensitivity by using suitable amplifier, discussed in next section.

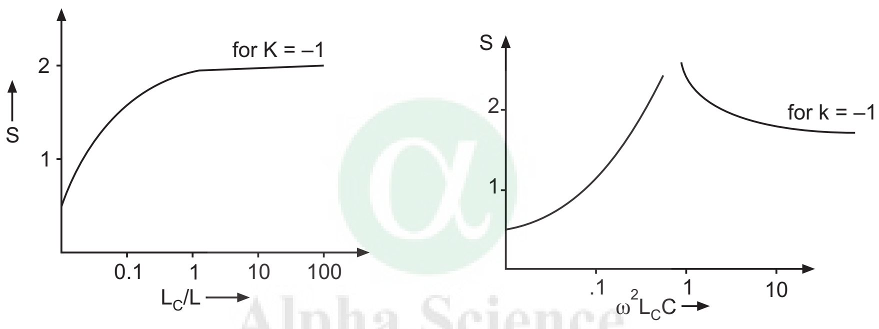


Fig. 8.6 Sensitivity Variation of Blumlein Bridges

8.2 AMPLIFIERS

In instrumentation applications, the need of amplifiers is widely varied. The amplification may be needed for the transducer bridge output and considered necessary in most arrangement. Therefore, in this section are discussed the characteristics of amplifiers required in general, followed by basics of operational amplifiers (OP-amps) as a building block for common ac amplifiers, typical instrumentation amplifier, chopper amplifier for low frequency/dc type signal, charge amplifiers, isolation amplifiers and programmable gain data amplifiers. For a detailed study of OP-amps and circuits based on these, texts are included in bibliography.

8.2.1 Characteristics Features of the Amplifier for use in Instrumentation Systems

- Amplifier should provide low output impedance so as to avoid impedance matching problems with the device connected at the output for display, data conversion, telemetry besides increasing the bandwidth of operation.
- Common mode rejection capability typically for the differential input stage and thus leading to overall high CMRR which should be larger than 100 dB. This is usually not available with general purpose OP-amps whereas the common mode noise in the industrial environment is high. Therefore special provision may have to be made to achieve higher CMRR, typically 120 db and higher.
- High input impedance typically in $M\Omega s$, to avoid input device loading problem.

Operational amplifiers of various types offer the above characteristics, to different degrees.

Classification of OP-amps can be made as:

(*a*) General purpose

(*b*) FET input

(*c*) Electrometer type

(*d*) High accuracy, low drift with differential input

(*e*) Chopper type

(*f*) Fast wide band

(*g*) High output

(*h*) Isolation type

Of the above *a*, *b* and *d* are relevant for transducer interfacing whereas *c* and *e* offer very high input impedance characteristic and needed frequently. The fast wide band type is not common and high output type needs proprietary design).

A comparison of available OP-amps is presented in Table 8.2. Among these low cost general purpose, FET input type with low bias current, high accuracy low drift differential-input types are used quite often and isolation amplifier are typically useful for biomedical applications.

For OP-amp basics Appendix-C be referred and the related definitions are also included therein.

Table 8.2 Comparison of Operation Amplifier characteristics

Type of OP AMP	Input offset volt	Slew rate	Drift voltage	CMRR	Input Z	Output Z	Supply Voltage	Output Current	Operating Temp Range	Applications	Remarks
1	2	3	4	5	6	7	8	9	10	11	12
General Purpose 741	0.8 mV	0.3 V/μs	15 μV/°C	80dB	1 MΩ	75 Ω	±22 V	10 mA	-55°C to 125°C	(1) Offset nulling circuit input and output	Overload protection on the
High Output Opamp	10 mV	10 V/μs	30 μV/°C	80 dB	6 pF, 10^7 Ω	1000 pF	+8 to +60V	3 A conti-nuous 5A peak	-40°C to 125°C	(1) Valve, Actuator Drive (2) Synchro, Servo Drivers (3) Power Supplies (4) Transducer Excitation (5) Audio amplifier	Wide supply range, high output current, high slew rate
Chopper Type Opamp	0.005 mV	0.5 V/μs	0.01 μ V/°C	110 dB	10^{12} Ω	5 Ω	5 to 16V	0.1 mA	0°C to 70°C	(1) Instrumentation amplifier (2) Thermocouple amplifier (3) Thermistor amplifier (4) Strain Gauge amplifier	Low offset volt, High gain, CMRR and PSRR
Isolation Type OpAmp	0.6 mV	15 KV/μs	1 μV/°C	63dB	700 KΩ	15 Ω	0 to 6V	9.9 mA	–40°C to 100°C	(1) Low-power inverter current sensing (2) Motor phase and rail current sensing (3) Switched mode power supply signal isolation	High CMR capability, High CMV, Low input offset volt drift

Table 8.2 Comparison of Operation Amplifier characteristics

1	2	3	4	5	6	7	8	9	10	11	12
Fast Wide-band OpAmp	30 mV	6 V/μs	12 μV/°C	38 dB	2.4 pF, 250KΩ	2 Ω	±20 V	200 mA	–25°C to 85°C	(1) Co-axial line driving (2) DAC current to volt amplifier (3) Flash A to D driving (4) Radar &IF processor	Wide band width, fast settling, linear phase, low harmonic distortion
General Purpose FET input electro-meter type OpAmp	3 mV	0.3V/μs	50 μV/°C	66 dB	1.6 pF, $10^{13}\Omega$	1000 pF	±20 V	10 mA	0°C to 70°C	(1) Photo current detection (2) Vacuum ion gauge measurement (3) low drift sample/hold application (4) Long term precision integration	Low Power, Low Offset, Low Drift

8.2.2 Selection of Operational Amplifiers

Very often a single operational amplifier is not sufficient for the typical situation arising due to stringent demand. This can be illustrated by an example:

The signal picked-up from the active transducer or the bridge output in case of passive transducer is of the order of mVs but the common mode noise picked-up would be of the order of volts. It is desired that the signal be amplified and the noise (common mode) should be reduced at the same time. This is shown in Fig. 8.7(*a*), with schematic representation in Fig. 8.7(*b*).

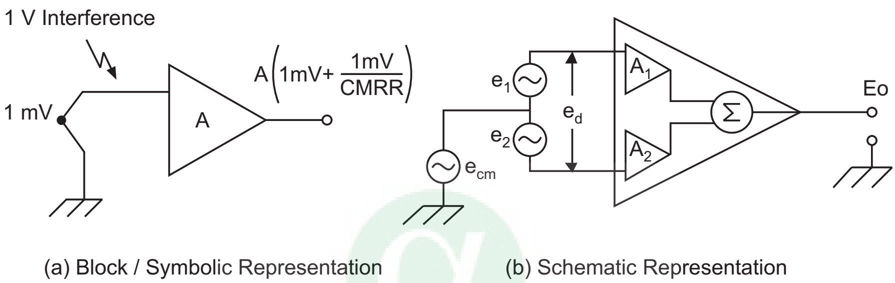


Fig. 8.7 Representation of Operational Amplifier

Figure 8.7 shows the symbolic representation for a 1 mV differential signal from transducer, embedded in 1 V common mode signal. Using the basic relation

$$e_0 = (DMG)\, e_d + (CMG)\, e_{CM}$$

$$= (DMG)\, e_d \left(1 + \frac{e_{cm}}{e_d} \frac{1}{(CMRR)}\right) \qquad \text{...(8.14)}$$

where *DMG* is differential mode gain and *CMG* is common mode gain.

The second term inside the bracket is the undesirable part of output signal and is referred as the common mode error,

$$\therefore \qquad \text{C.M. error} = \frac{e_{cm}}{e_d} \cdot \frac{1}{(CMRR)} \qquad \text{...(8.15)}$$

To achieve a C.M. error less than 0.1%, the CMRR required has to be least

$$\frac{1}{10^{-3}} \times \frac{1}{\frac{0.1}{100}} = 10^6 \text{ or } 120\ dB$$

which may not be achieved by a single OP-amp, therefore a typical instrumentation amplifier configuration suitable for the need of such a problem has to be employed.

8.2.3 Common ac Amplifiers

With several transducers, it is possible to get the signal in the range of mV and volts with acceptable common mode noise and common active amplifiers can be directly employed. Such amplifiers are classified into 3 common types, as:

(*a*) Inverting amplifier with dc component block by a capacitor: At the input and resistor R_1 sets the lower 3 db frequency of amplifier as shown in Fig. 8.8(*a*)

$$V_0 = -IR_f = -\frac{V_i}{R_1 + \frac{1}{sC}} R_f \qquad \text{...(8.16)}$$

and

$$A_{CL} = \frac{V_0}{V_i} = -\frac{R_f}{R_i}\left(\frac{s}{\left(s + \frac{1}{R_1 C}\right)}\right) \qquad \text{...(8.17)}$$

where, lower cut-off frequency $f_L = \frac{1}{2\Pi R_1 C}$ and, in the mid-frequency range C acts as short circuit to yield

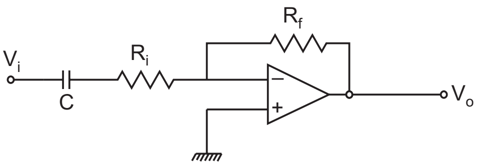
$$A_{CL} = -\frac{R_f}{R_i}. \qquad \text{...(8.18)}$$

(*b*) Non-inverting ac amplifier: Most commonly used with R_2 providing a dc return to ground as shown in Fig. 8.8 (*b*), but at the cost of over all input-impedance of the amplifier. It can be improved, by connecting an additional capacitor C_2 large enough to act as short circuit to ac signal. Non-inverting terminal and node a are almost at the same potential, so that R_2 carries no current practically, and the setup offers very high input impedance of the order MΩ closed-loop gain can be obtained to be:

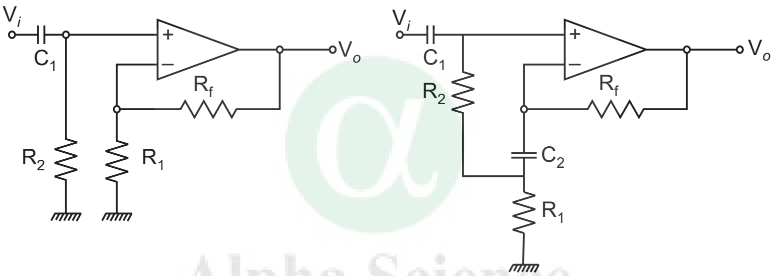
$$A_f = 1 + \frac{R_f}{R_1}. \qquad \text{...(8.19)}$$

(*c*) ac voltage follower: This are designed for unity gain and used as buffer to connect high impedance signal source to a low impedance load which may even be capacitive. Capacitor C_1, C_2 (Fig. 8.8*c*) are chosen high enough to provide short circuit over whole bandwidth of operation. C_2 acts as bootstrapping capacitor and connects R_1 to output terminal for ac operation.

Input resistance looked into from the source, approximates to, resulting in high input impedance as A_{cL} the gain of voltage follower is close to unity.

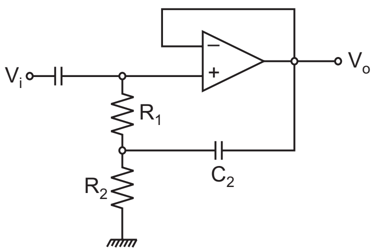


(a) Inverting ac Amplifier



(i) (ii)

(b) Non-inverting ac Amplifiers



(c) ac Voltage Follower

Fig. 8.8 AC Amplifiers

EXAMPLE 8.4

For the adder-subtractor circuit shown below evaluate output V_o *if* $R_1 = 40$ *K;* $R_2 = 25$ *K;* $R_3 = 10$ *K;* $R_4 = 20$ *K;* $R_f = 50$ *K;* $R = 30$ *K and* $V_1 = 1V$*;* $V_2 = 2$ *V;* $V_3 = -3$ *V;* $V_4 = 4$ *V.*

SOLUTION:

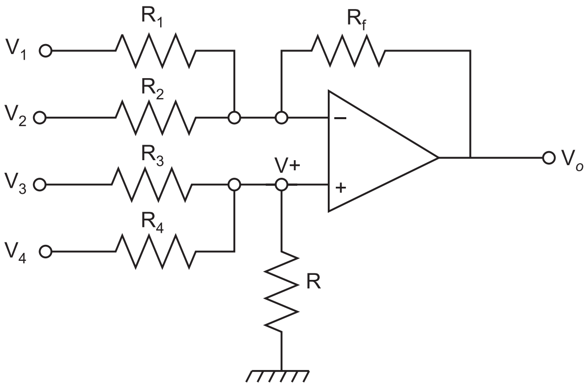


Fig. Ex. 8.4

Output due to inputs at inverting terminal, with $V_3 = 0$, $V_4 = 0$,

$$V_0' = -\frac{R_f}{R_1}V_1 - \frac{R_f}{R_2}V_2$$

$$= -\frac{50}{40}V_1 - \frac{50}{25}V_2 = -1.25V_1 - 2V_2$$

To get output due to V^+ first find V^+:

(*i*) When $V_4 = 0$, output due to only V_3,

$$V'^{+} = \frac{V_3}{R_3 + (R_4 \| R)}.(R_4 \| R)$$

$$= \frac{V_3}{10+12}.12 = 0.545.V_3$$

(*ii*) When $V_3 = 0$, output due to only V_4,

$$V''^{+} = \frac{V_4}{R_4 + (R_3 \| R)}.(R_3 \| R)$$

$$= \frac{7.5}{27.5}.V_4 = 0.273.V_4$$

∴ **Output due to V^+,**

$$V_0'' = (0.545V_3 + 0.273V_4)\left(1 + \frac{R_f}{R_i}\right)$$

where, $R_i = R_1 \| R_2$ (for input V_0'' at non-inverting input terminal)

$$= (0.545V_3 + 0.273V_4)\left(1+\frac{50}{15.38}\right)$$

$\therefore$ $V_0'' = 2.32V_3 + 1.16V_4$

Therefore total voltage = $V_0 = V_0' + V_0''$

$\therefore$ $V_0 = -1.254V_1 - 2V_2 + 2.32V_3 + 1.16V_3$

$= -1.254(-1) - 2 \times (-2) + 2.32(-3) + 1.16 \times 4$

$= 1.73$ Volts.

8.2.4 Three OP AMP based Configuration of Instrumentation Amplifier

To meet the requirement of CMRR 100 db and above with high input and low output impedance a 3 OP-amp arrangement is shown in Fig. 8.9 is used. This has FET differential input stage providing high input impedance and CMRR of about 1000. This is followed by a subtractor stage to reduce the common mode signal.

To analyze the circuit, consider applying voltage V_1 at terminal 1 and having 2 grounded, the outputs observed shall be: (for $V_1 > V_2$)

$$V_{01}' = V_1\left(1+\frac{R_f}{R_i}\right) \quad \ldots(8.20)$$

and,
$$V_{02}' = -V_1\left(\frac{R_f}{R_i}\right) \quad \ldots(8.21)$$

and when V_2 applied at terminal 2, and 1 is kept grounded,

$$V_{01}'' = -V_2\left(\frac{R_f}{R_i}\right) \quad \ldots(8.22)$$

$$V_{02}'' = V_2\left(1+\frac{R_f}{R_i}\right) \quad \ldots(8.23)$$

Net effect of applying V_1 and V_2 at terminal 1 and 2, by Superposition we obtain,

$$V_{01} = \left(1+\frac{R_f}{R_i}\right)V_1 - \left(\frac{R_f}{R_i}\right)V_2 + e_{cm} \quad \ldots(8.24)$$

$$V_{02} = \left(1+\frac{R_f}{R_i}\right)V_2 - \left(\frac{R_f}{R_i}\right)V_1 + e_{cm} \quad \ldots(8.25)$$

$$e_d = V_{01} - V_{02} = \left(1+\frac{R_f}{R_i}\right)(V_1 - V_2) + \frac{R_f}{R_i}(V_1 - V_2)$$

$$= \left(1+\frac{2R_f}{R_i}\right)(V_1 - V_2) \quad ...(8.26)$$

CMG is distributed over the II stages, such that, (say) for I stage of differential input is 1, and for II ≅ stage 50 by choice of resistor tolerances. (see Table 8.3)

$$\text{For subtractor or II stage, Gain} = \frac{R_2}{R_1} \quad ...(8.27)$$

$$\therefore \quad \text{Overall Gain} = \left(1+\frac{2R_f}{R_i}\right)\frac{R_2}{R_1} \quad ...(8.28)$$

The over all gain for instrumentation amplifier is controllable from single precision resistance, R_i made of metal film resistance as a potentiometer, but this of gain control does not provide a linear gain variation.

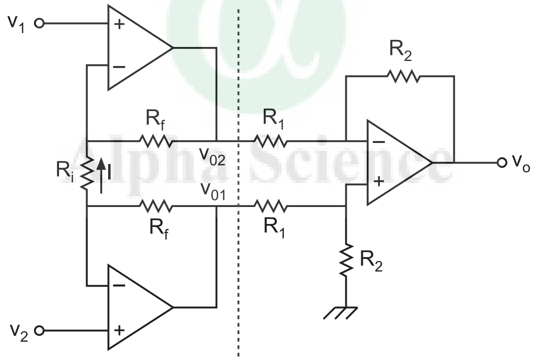


Fig. 8.9 3-Op-amp Based Instrumentation Amplifier

The overall *CMRR* depends on the individual values of *CMRR* of each stage as if organized in parallel. Also, the individual *CMRR* of each stage depends upon the design values typically the *DMG* of OP-amp used and *CMG* which is governed by the tolerance of the gain determining resistor as shown in Table 8.3.

TABLE 8.3 Dependence of CMG on Resistor Tolerance

Tolerance %(of gain determining resistor)	5	2	1	0.5	0.1
CMG Obtainable	0.1	0.04	0.02	0.01	0.002

EXAMPLE 8.5

For an instrumentation amplifier using OP-amp 741C, obtain and verify a DMG of 1000 for 2 V output with enough CMRR by having 1% tolerance resistors and Common Mode error limited to 1%. Maximum common mode voltage may be assumed limited to 1 volt.

SOLUTION :

With a choice of 3 OP/amp configuration of I/A and choice of resistors

$R_f = 500\ \Omega$; $R_i = 1\ k\Omega$; $R_1 = 10\ k\Omega$; $R_2 = 10\ k\Omega$.

From Equn. (8.15), Overall *CMRR* required = $\dfrac{1}{(CM_{\text{error}})} \times \dfrac{e_{cm}}{e_d}$

Given, $\quad CM_{\text{error}} = 1\% = \dfrac{1}{100}$,

With gain of 1000 and 2V output to be obtained, differential input signal is = 2 mV

$\therefore$ *CMRR* needed would be = $\dfrac{1}{0.01} \times \dfrac{1V}{2 \times 10^{-3}} = 50{,}000$

Total required *CMRR* of 50 000 can be distributed over the two stages as 1000 and 50 so that:

CMRR for Input section = $\dfrac{DMG}{CMG} = \dfrac{1000}{1} = 10^3$ (*CMG* chosen = 1 for the differential input, I stage)

$$\therefore \quad \text{Actual CMRR} = \frac{CMRR \times CMRR\ \text{intrinsic}}{CMRR\ +\ CMRR\ \text{intrinsic}}$$

$$= \frac{1000 \times 20000}{2.1 \times 10^4}$$

(for *O/A* 741 : *CMRR* = 86db = 20000)

$$= 0.95 \times 10^3$$

$$= 950$$

For subtractor stage

$$CMRR = \frac{DMG}{CMG} = \frac{1}{0.02} = 50$$

$\therefore$ Effective $\quad CMRR = \dfrac{50 \times 20000}{20050} = 49.9$

$\therefore$ For 3 O/A configuration $CMRR = 950 \times 49.9 = 47400$

$= 93.51$ dB.

Being close enough, it may be accepted, else for better value, the steps can be reworked so that the overall CMRR is closer to the desired.

The features of instrumentation amplifier can be summarized as:

1. Amplifying unit is available as a package with, gain selection by variation of R_i $\left(\leq 10^4\right)$ by using precision metal film resistance potentiometer for achieving high accuracy.
2. High $CMRR$ helps to reduce the effect of noise, pickups and ground drop.
3. Gain accuracy, stability and drift performance are high. Offset voltages of A_1, A_2 track the temperature variation.
4. Achieves high $CMRR$ even with source impedance, $Z_{in} > 1\text{M}\Omega$ and loss in performance is low even if source impedance changes.
5. High linearity up to an order of 0.01% is possible, up to gain $\cong 10^4$ (80 db) and for line frequency rejection ≥ 140 dB though the gain is practically limited to 100.
6. An output impedance $Z_o \cong 3$ mΩ is achievable and practically resolves any output impedance matching problem.
7. For optimum rejection $\dfrac{R_2}{R_1}$ ratio should be same for both inputs in subtractor section.

Linear gain Control Instrumentation Amplifier

With a modification made by providing an output feedback to instrumentation amplifier, as shown in Fig. 8.10. the modified gain shall be:

$$\text{Gain} = \frac{e_0}{e_1 - e_2} = \left(1 + \frac{2R_f}{R_i}\right) \times \frac{R_x}{R_3} \qquad \text{...(8.29)}$$

Now gain control can be exercised by choice of R_x, after adjustment of R_i to an appropriate value.

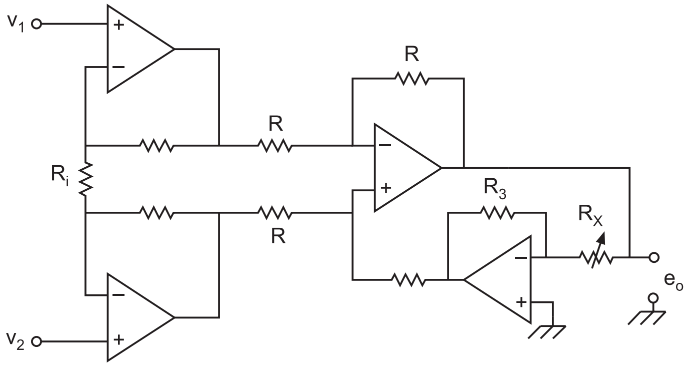


Fig. 8.10 Linear Gain Instrumentation Amplifier

Available instrumentation amplifiers

AD 521,524,624	Analog Devices		
LH 0036, 0037	National	INA 104,3626,3629	Burr-Brown

It should be noted that the design of instrumentation amplifiers is possible with discrete components and three OP-amps but in practice it is extremely difficult to maintain the exactly same ratios for R_1 and R_2 for the second stage and this results in poorer CMRR, whereas in monolithic IAs it is possible to achieve much higher accuracy, hence it is standard practice to use ICs mentioned above.

8.2.5 Special Purpose Amplifiers

For many special situations, specific characteristic are needed. This section deals with few of these unique types. Most of these are for use in instrumentation systems where the signals are invariably of low frequency and therefore also referred as dc amplifiers.

(A) Chopper amplifiers : This class of amplifiers is used for very low frequency or dc type signals, such as those obtained from temperature and level control system having bandwidth up to 10 Hz.

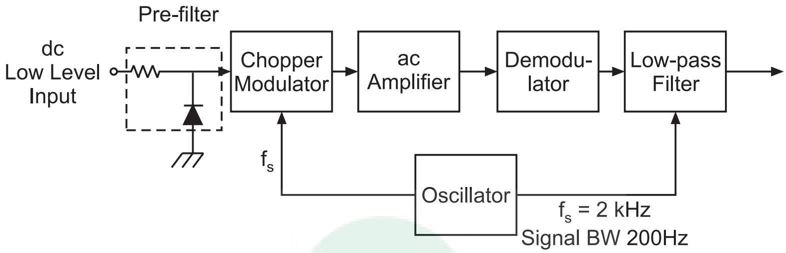
These amplifiers are characterized by:

- High stability with time and temperature
- Low drift and high dc gain
- Useful for increasing bandwidth of dc amplifiers

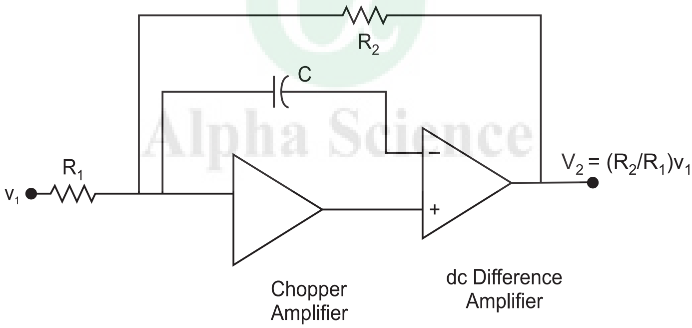
This class of amplifiers also offer additional isolation due to the technique used.

The principle of chopper amplifier is explained through the arrangement shown in Fig. 8.11(*a*).

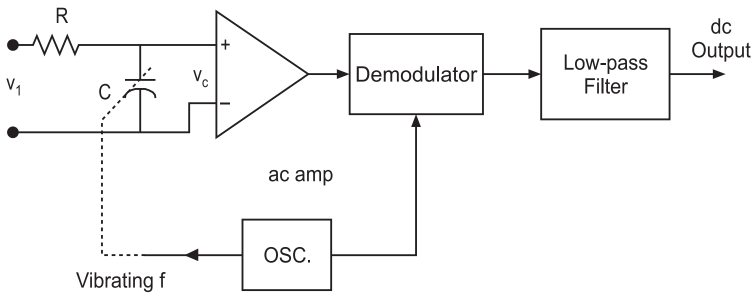
The low level dc signal is fed to a chopper-modulator through a pre-filter to remove high frequency ac noise. Chopper driven by an oscillator with sampling frequency of the order 2 kHz generates a pulse modulated signal, with peak-to-peak amplitude corresponding to dc-input level. The amplitude modulated carrier is amplified by a high gain ac amplifier without drift. Chopper amplifiers have a limited signal bandwidth but a combination as shown in Fig. 8.11(*b*) is able to improve bandwidth up to 125 KHz, using feedback technique. In this chopper stabilized dc amplifier, high frequency components bypass the chopper amplifiers which are again combined in the difference amplifier. The overall feedback is useful to provide uniform gain characteristic for increased bandwidth.



(a) Chopper Amplifier Arrangement



(b) Chopper Stabilized Type dc-Amplifier



(c) Vibrating Capacitor Type Amplifier

Fig. 8.11 Chopper Amplifiers

(B) Vibrating Capacitor Amplifier: These are typically useful for very small voltage signal received from high resistance sources. The arrangement is shown in Fig. 8.11(*c*). The input voltage (measured) charges a vibrating capacitor *C*, to a value $\bar{C}\,v_1$, where $\bar{C}$ is the mean value of capacitor, which is also the input to an ac amplifier with required gain adjustment provided. The amplifier output is demodulated and filtered to obtain the amplified dc output.

The arrangement with suitable values is able to provide input impedance up to $10^{15}\ \Omega$ with drift limited to ±100 μV over 12 hours.

The voltage across vibrating capacitor,

$$V_c = \frac{\bar{C}V_1}{C} \qquad \text{...(8.30)}$$

and gets modulated with change in value of *C*, at frequency

$f = \dfrac{1}{2\Pi RC}$ therefore $V_c \propto V_1$, gets amplified.

The chopper or carrier methods offer the advantage of reduced drift and they also provide isolation between amplifier input and output. Ground loop is broken and high common mode voltage can be handled safely.

(C) Charge Amplifier: These are typically designed and useful for high resistance – low output capacitive transducers such as piezoelectric type. The arrangement in Fig. 8.12 shows a piezoelectric transducer model connected to amplifier through screened cable. The cable connections have significant role with these devices and need special care so as not to load the piezoelectric crystal. Also, the amplifier must have very high input resistance and may have a FET input stage. The input-output relationship can be established as:

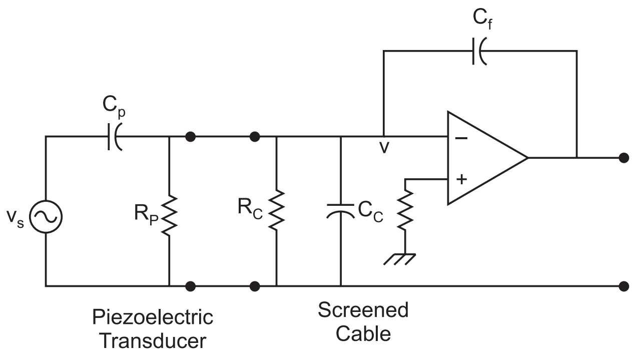


Fig. 8.12 Charge Amplifier

Charge generated by transducer, $Q = V_{S.} C_p$

And, on applying KCL at the input of amplifier:

$$(V_s - V)j\omega C_p = (V - V_0)\, j\omega C_f + V\left(\frac{1}{R_x} + j\omega C_c\right) \quad ...(8.31)$$

where, $R_x = R_p \| R_c \cong R_c$ $\quad \because R_p >> R_c$

for OP-amp, $A_v = -\dfrac{V_0}{V}$

by substituting $V = -\dfrac{V_0}{A_V}$ in the Eqn. (8.31),

and by simplification,

$$\frac{V_0}{V_s} \cong \frac{j\omega A_v R_c C_p}{\left[1 + j\omega R_c \left\{C_p + C_c + (1 + A_v) C_f\right\}\right]}$$

$$= \frac{C_p}{C_f} \times \frac{j\omega A_v R_c C_f}{1 + j\omega R_c \left\{C_p + C_c + (1 + A_v) C_f\right\}}$$

$$\cong \frac{C_p}{C_f} \times \frac{j\omega A_v R_c C_f}{1 + j\omega R_c A_v C_f} = -\frac{C_p}{C_f} \quad ...(8.32)$$

$\because A_v >> 1$; $A_v C_f >> (C_p + C_c)$; and, $\omega >> \dfrac{1}{A_v R_c C_f}$

(D) Isolation amplifier: These are employed for protection from large voltages by providing isolation and reducing leakage currents.

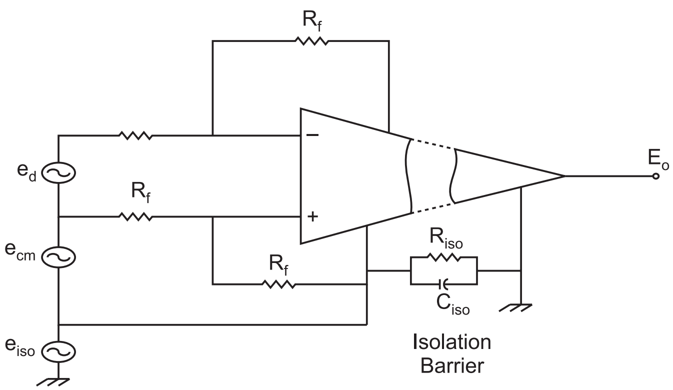


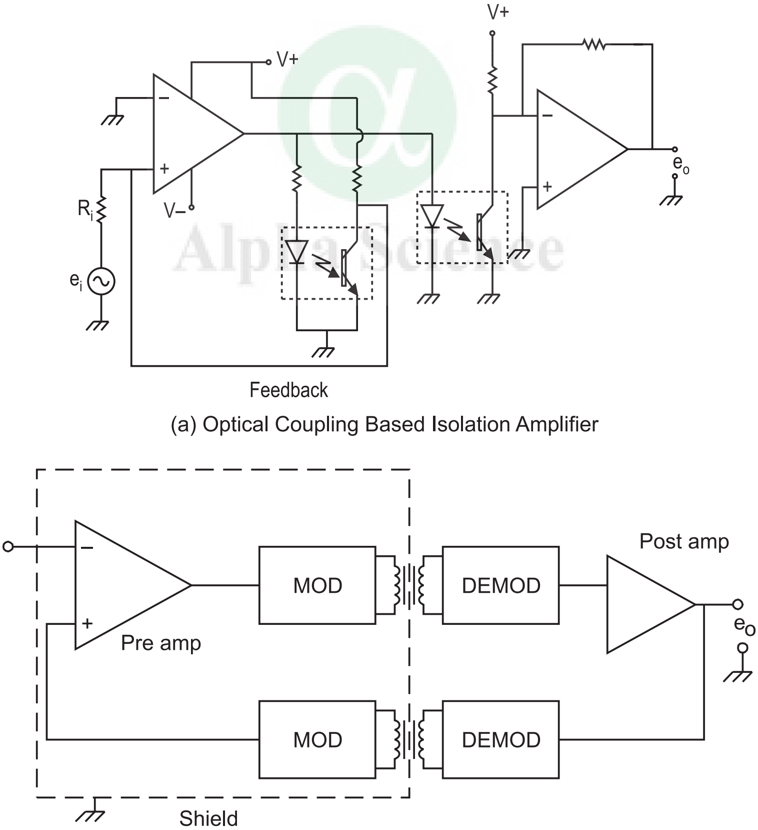
Fig. 8.13 Representation of Isolation Amplifier

Additionally ground loop is also eliminated. These are represented as shown in Fig. 8.13 and the governing equation is given by:

$$e_o = DMG.e_d\left(1+\frac{1}{(CMRR)}\frac{e_{cm}}{e_d}\right)+\frac{e_{iso}}{IMRR} \quad ...(8.33)$$

where, e_{iso} represents the voltage to be isolated *e.g.* 5000 volts in a X-ray machine, IMRR represents the Isolation Mode Rejection Ratio – the factor by which the isolation voltage is to be reduced.

These are two approaches available to realize high electrical isolation barrier (see Fig. 8.14) with required DMG and CMRR, provided by differential input stage and output stage of unity gain. Common mode signal is made negligible and e_{iso} up to 5000V can be reduced to milli volts by realizing IMRR of the order 10^9 or 180 dB. Typical values of R_{iso} and C_{iso} are of the order of 10^{12} and 10 pF respectively.



(a) Optical Coupling Based Isolation Amplifier

(b) Transformer Coupled Isolation Amplifier

Fig. 8.14 Isolation Amplifiers

It is possible to obtain such isolation by:

(*i*) **Optical coupling** between input and output stages as shown in Fig. 8.14(*a*), using LED and photodiode combination. Linearity is reduced but bandwidth of the order of 10 kHz is achievable.

(*ii*) **Transformer coupling** shown in Fig. 8.14 (*b*) with appropriate shielding, and the operation at modulated carrier frequencies, provides high linearity, although the bandwidth is limited to 1 kHz, and needs more elaborate arrangement to maintain.

8.3 SIGNAL CONVERTERS

In the instrumentation channel, it is often required to process the signal in a format other than which it is available *e.g.* voltage to current conversion for transmission over distances in hundreds of meters, voltage to frequency for noise immunity, current to voltage for operation of control motors etc.

8.3.1 Voltage-to-current Converters (VIC)

In chapter 1 it has been already mentioned that in process industry, the prevalent current telemetry standard for signal transmission is 4-20 mA which can be obtained by suitable choice of OP-amp based circuits. Based upon the particular need, 2 types of V/I converters are configured.

V/I Converters with floating load

As shown in Fig. 8.15(*a*), the circuit satisfies the Norton's equivalent network requirement. The output of current source can be terminated in a load up to 250 Ω. For stable and accurate transfer operation OP-amp of suitable type, capable to deliver the current over the full range, is chosen.

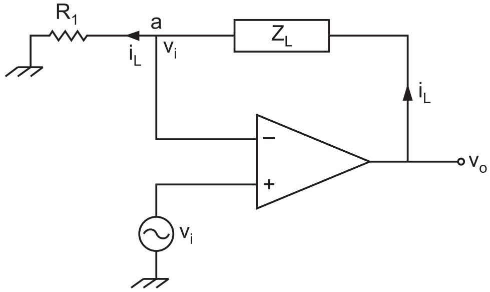
To derive the transfer relationship, the *KCL* at node '*a*' in the circuit of V/I converter (also called Operational Transconductance Amplifier or *OTA*) shown in Fig. 8.15 (*a*), is written as:

$$V_i = i_L R_i \quad \because \; I_B = 0$$

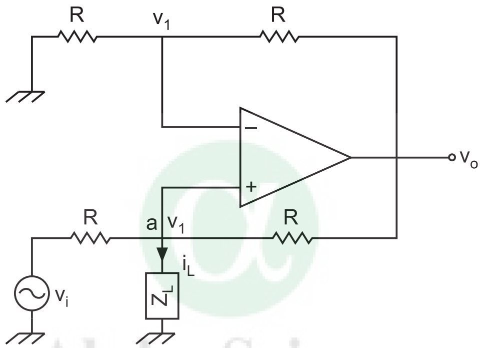
$$\because \qquad i_L = \frac{V_i}{R_1} \text{ or, } i_L \propto V_i \qquad ...(8.34)$$

i.e. the output current is proportional to input voltage signal and limited by R_1 the total loop resistance composed of line resistance and indicating/display devices in cascade at both ends.

If the indicating device is not floating type or the facility of ground return is to be then the grounded load type is used.



(a) With Floating Load



(b) With Grounded Load

Fig. 8.15 V/I Converters

V/I converter with grounded load

As shown in Fig. 8.15 (*b*), the grounded load is connected at non-inverting terminal. Load impedance R_L represents the total effective load connected.

The transfer relation is derived next, by writing KCL at node '*a*':

$$i_1 + i_2 = i_L$$

or, $$\frac{V_i - V_1}{R} + \frac{V_o - V_1}{R} = i_L$$

or, $$V_i + V_o - 2V_1 = i_L R \qquad \therefore\ 2V_1 = V_i + V_o - i_L R$$

The network being used in non-inverting mode, amplification

(gain) = $1 + \dfrac{R}{R} = 2$.

$$\therefore V_o = 2V_1 = V_i + V_o - i_L R$$

∴ $$V_i = i_L R$$

and, $$i_L = \frac{V_i}{R} \quad ...(8.35)$$

Thus, output current is directly related to input voltage and is limited by load resistance. High input impedance in this non-inverting mode ensures a very low input current being drawn and no loading of input voltage signal.

This configuration of V/I converter is also useful for low voltage dc and ac voltage measurement, zener diode testers, *LED* indicators, current switches. OTAs: CA3080, LMI 3600/700, NE 5517(Signetics) are useful for such applications. The symbolic representation of *OTA* is shown in Fig. 8.16.

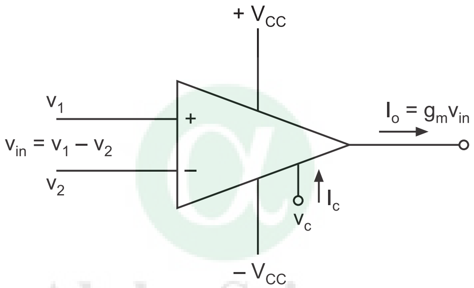


Fig. 8.16 OTA Schematic

8.3.2 Current to Voltage (I/V) Converter or Trans-resistance Amplifier

Several of the sensors/devices provide current output photodiode, photocell, and photovoltaic cell proportional to incident light energy. This current can be converted to voltage by using I/V converter.

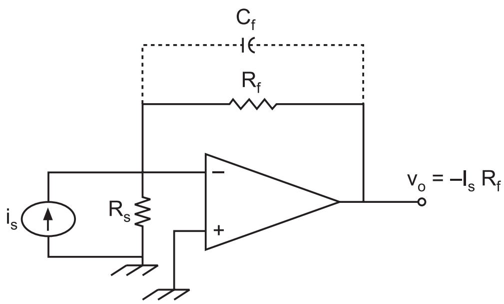


Fig. 8.17 I/V Converter

I/V conversion can be implemented by a configuration of Fig. 8.17. From the circuit, it is obvious that, negative input terminal is at virtual ground and no current passes through R_s and whole of the source current passes through feedback resistance. C_f is used to reduce high frequency noise by shunting and eliminates possible oscillations.

Output, $$V_o = -\, i_s\, R_f.$$

8.3.3 Voltage to Frequency Converters: (VFC)

A VFC is an oscillator whose frequency varies in a linear proportion to a control voltage. A VFC counter based ADC is monotonic and free of missing codes, consumes very little power but integrates noise. It is typically used for wireless signal data telemetry, being low powered and small in size and offers economical solution.

The two common types of VFCs available:

(*a*) **Current driven multivibrator VFC** which involves an input stage of V-I converter. As shown in Fig. 8.18 the current discharges the capacitor until a specified threshold is reached then the capacitor terminals are interchanged and the process repeats itself. The waveform of voltage across capacitor is observed to be linear and triangular, for small time period and when excites a Flip-Flop, provides square output as shown.

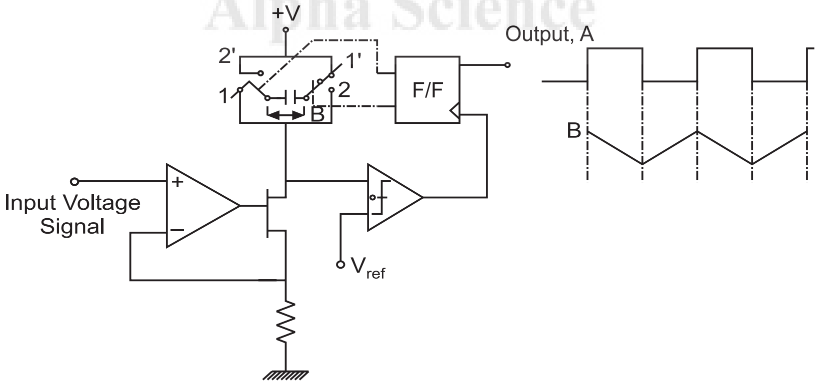


Fig. 8.18 Current Driven *VFC*

(*b*) **Charge-balance VFC** with the configuration, as shown in the Fig. 8.19, the integrating capacitor at input stage is charged. As soon as this out put exceeds a threshold (adjustable by V_{ref}), a fixed charge is removed from capacitor, but no charge is lost as the input current is available all the time to replenish. A precision current source defines the fixed charge as also the pulse width of mono stable. Output pulse rate is proportional to the rate of charging of integrator from the input (magnitude).

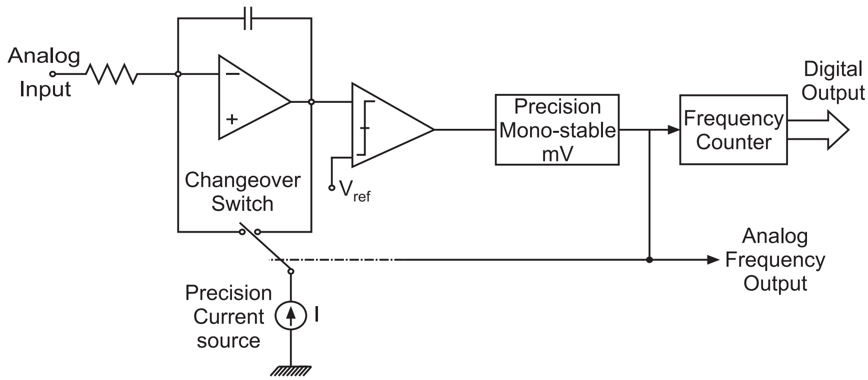


Fig. 8.19 Change Balance Type *VFC*

At low frequencies the performance of *VFC* is limited by the stability of current source and the (capacitor controlled) time period of mono stable vibrator. Properties of integrating capacitors *viz.* leakage resistance, dielectric strength, affect the performance. At high frequency, the transients begin to affect the performance. Switching of both capacitor and mono stable during retriggering after the end of a pulse, affects the accuracy and linearity. This is known as second order effect.

The problem is mitigated by using the change over switch, such that, transients associated with current source are reduced and the impedance conditions at the integrator output do not change appreciably. With change over switch it is ensured that the current flows directly into the output stage (most of the time) and during charge balance through the integrator.

To improve the performance of precision Mono, it can be replaced by a clocked bistable MV and is referred as synchronous VFC/SVFC. For more details see bibliography.

VFCs and FVCs will be further discussed later in context of data telemetry for transmitting frequency signal for remote logging along with FVCs.

8.4 Rectifiers and Applications

In several applications, the conversion of alternating signal to dc format provides economical and noise free signal for display, recording as well as discrimination. Typically in a LVDT the ac output measured is r.m.s. value and will not discriminate between positive and negative displacements from initial null position. To discriminate between the two types of inputs, discriminator circuits (based on rectification) becomes mandatory.

However, with all rectifiers there is cut-in voltage problem, that no output appears for very small inputs of the order of 200 mVs for germanium and less than 600 mVs for silicon type rectifiers in the forward or conducting half of the cycle, Fig. 8.20. A dead-zone characteristic will appear and in many of the instrumentation situations, it needs to be reduced drastically to save on the avoidable amplification need. These two aspects are the main features of this section.

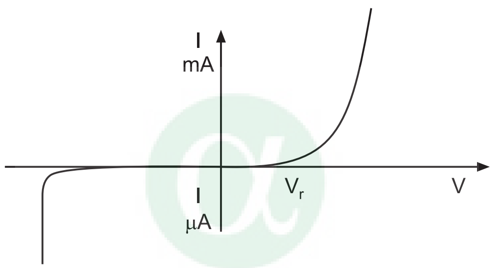


Fig. 8.20 p-n Junction Diode Characteristic

8.4.1 Rectifiers for Phase Discrimination

Bridge rectifier can be used to provide phase discrimination, by causing positive or negative input to (for forward or backward displacement in LVDT), into a centre zero type of current or voltage detector. The amount of deflection can be calibrated for the amount of core displacement. The arrangement is shown in Fig. 8.21.

For the LVDT core displacement in forward or backward direction with the arrangement shown in Fig. 8.21, the output is rectified using a bridge rectifier, resulting in corresponding positive or negative dc output.

In general, if the output signals from a device is sensitive not only to magnitude but phase too. Considering the noise in the system, particularly at small signal amplitudes, it may be more prudent to use the information contained in phase change. Rectification may not be helpful in such a situation and phase sensitive detection based on signal processing shall have to be used.

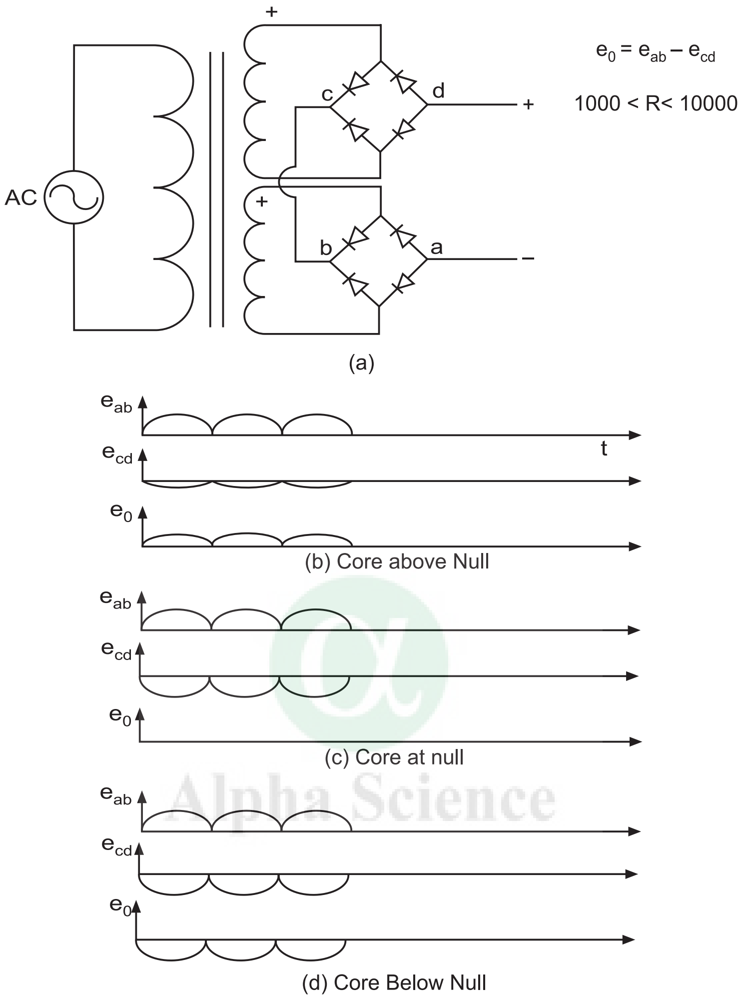


Fig. 8.21 Rectifier network as phase discriminator (with LVDT)

8.4.2 Precision Rectifiers

The limitation of diodes resulting in a dead-zone for signals below 0.6 V for silicon and 0.2 V for germanium diodes, can be overcome by using the diodes in feedback circuit of OP-amp, so that the cut-in voltage of diode is effectively reduced by a factor equal to the open-loop gain of the OP-amp.

As shown in Fig. 8.22 the diode cut-in voltage $V_r = 0.6$ V can be reduced to $0.6/10^4$H ≈ 60μV, with a gain setting of 1000, making it almost ideal and therefore referred as precision diode. It cannot only be used as voltage follower as shown, but it can also be used for half wave and full wave rectification, peak value detection, etc.

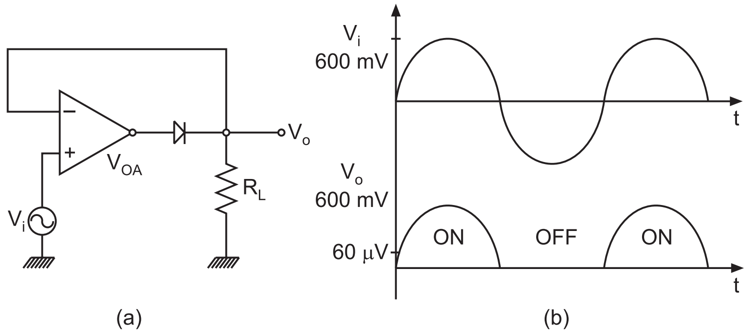


Fig. 8.22 Operation of Precision Diode

8.4.3 Half-wave Precision Rectifiers

Half-wave rectification can be realized with precision diodes used with an inverting OP-amp based amplifier as shown in Fig. 8.23 along with the resulting output.

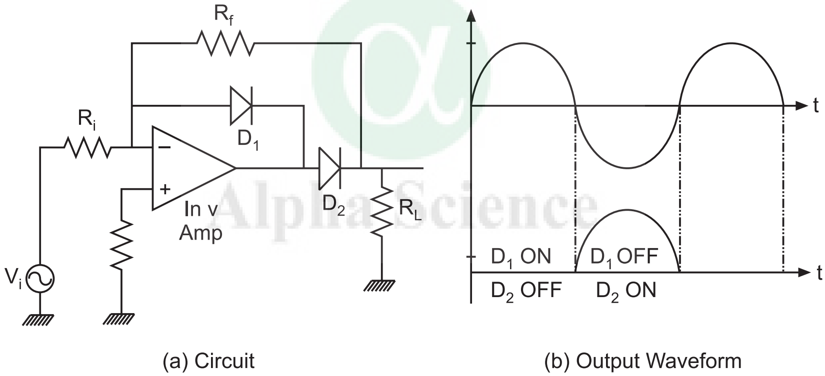


Fig. 8.23 Operation of Precision Half-wave Rectifier Network

During positive half cycle of the input V_i diode D_1 conducts with V_{OA} to become negative, so that D_2 does not conduct and output remains zero. Whereas, during negative half wave, D_1 is reversed bias and D_2 conducts as V_{OA} becomes positive. R_f/R_i provides amplification if so desired in inverting mode.

Due to frequent switching required for these diodes, the operation will be limited by the slew rate or the switching capability of the OP-amp being used in the circuit.

8.4.4 Precision Full-Wave Rectifiers

An arrangement to realize full wave rectification can be realized by using one more OP-amp and configured as shown in Fig. 8.24.

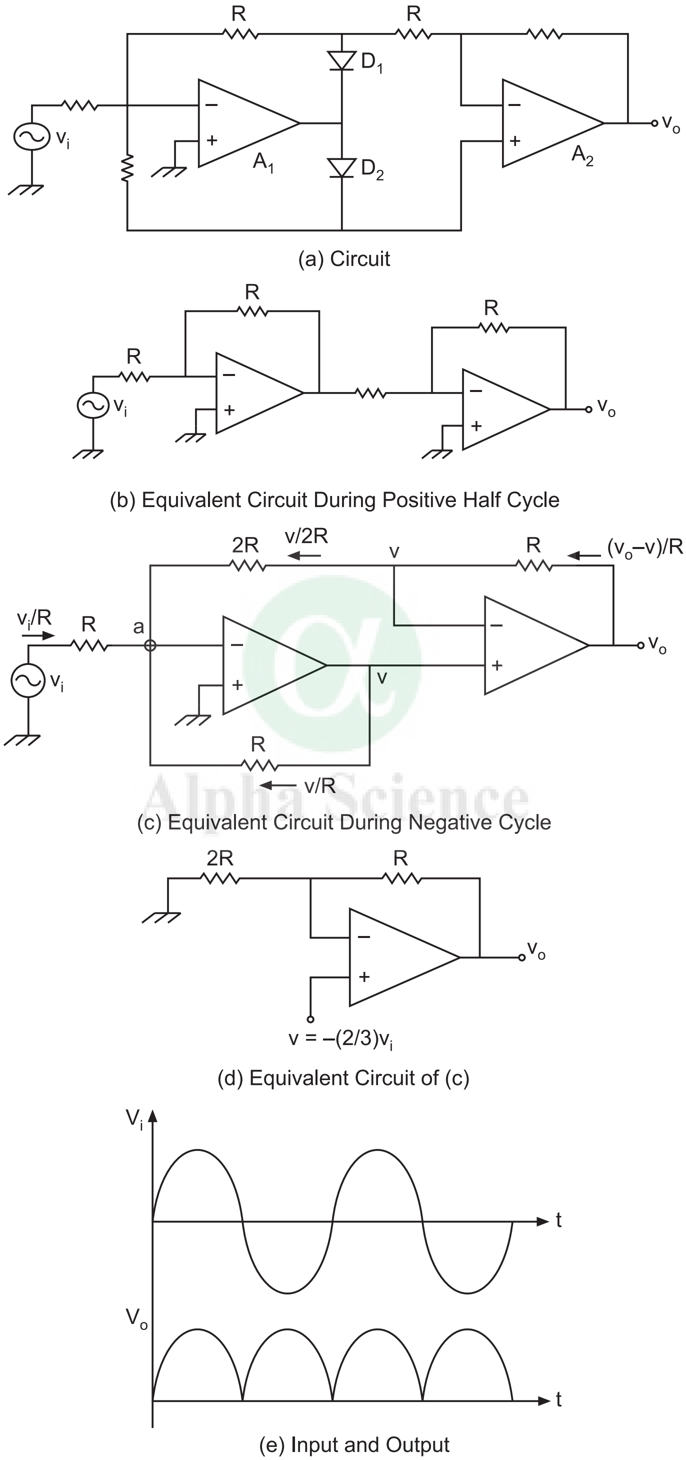


Fig. 8.24 Operation of Precision Full-wave Rectifier

During the positive half cycle as in Fig. 8.24 (*b*), D_1 shall conduct and D_2 will be off. Both OP-amps will act as inverter and output V_o will follow V_i.

During the negative half cycle as in Fig. 8.24(*c*), diode D_1 shall be off and D_2 will be ON. Voltage v can be evaluated by applying *KCL* at the input node '*a*', as

$$\frac{V_i}{R}+\frac{v}{2R}+\frac{v}{R}=0 \qquad \because\ v=-\frac{2}{3}v_i \qquad ...(8.36)$$

So that the output v_{ow} can be evaluated from the reduced equivalent circuit, Fig. 8.24 (*d*), with A_2 in non-inverting mode, as:

$$V_o=\left(1+\frac{R}{2R}\right)\left(-\frac{2}{3}v_i\right)=v_i \qquad \text{(for all } V_i<0) \qquad ...(8.37)$$

The output waveform shall take the form as shown in Fig. 8.24 (*e*).

8.5 ACTIVE FILTERS

The filters form an essential stage in processing of signals, typically for removal of noise as; all practical signals picked-up by transducers are contaminated with noise. The quantum and the source of noise may vary and in addition to the common mode noise (already discussed in third chapter) may include electromagnetic and electrostatic noise and harmonics. Filters are therefore integral component in all instrumentation systems. The filters in general separate the signals of different frequencies. Their other applications include audio and video signal shaping, signal enhancement using equalizers, smoothening of DAC outputs etc.

The filters have been configured for a long time with passive components – resistance, inductance, capacitance and crystals. Currently, the realization with operational amplifiers, resistors and capacitors is the standard practice for instrumentation and for most of the common applications. These are also referred as active filters and help to keep the size of assembly small, a desirable feature in most systems.

8.5.1 Characteristics of Filters

The performance of filter is specified in terms of frequency response measures – gain and phase variations required at different frequencies of input signal. Frequency response of typical low – pass and high – pass filters is shown in Fig. 8.25. In all such plots the frequency scale is chosen to be logarithmic to cover a wide range. Also, it is standard practice to normalize the frequency by the critical frequency of the filter, to plot the gain variations against f/fc. Gain is also on a logarithmic scale and expressed in decibels, dB.

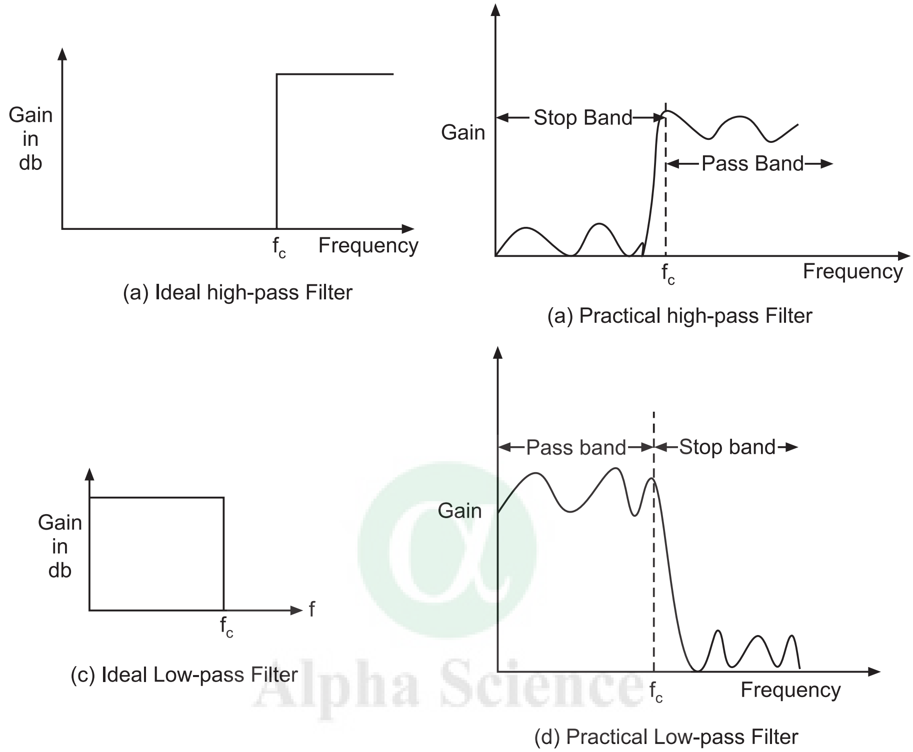
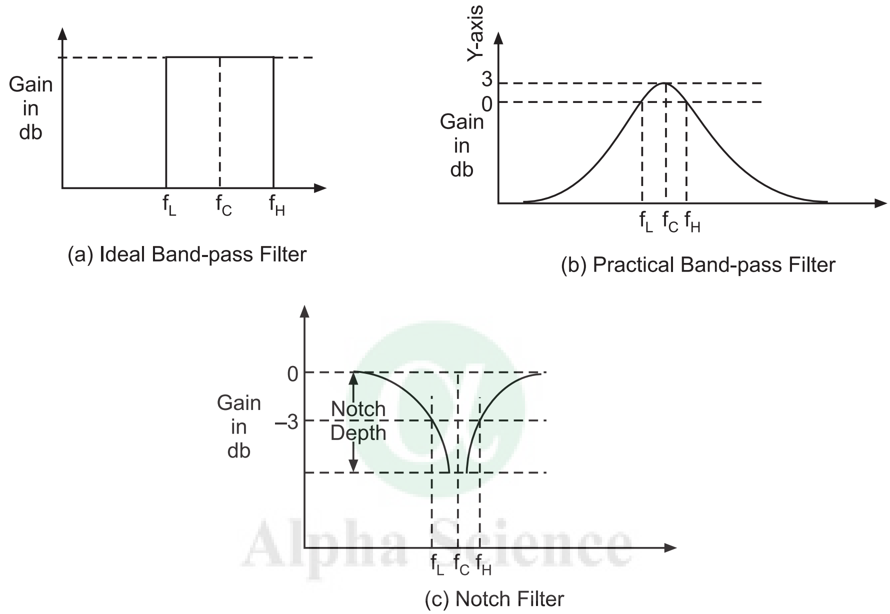


Fig. 8.25 Gain Response of Filters

The ideal filter characteristics with such sharp cut-offs is practically not possible to realize and the response of (say) a typical low-pass filter is considered in two parts. A critical frequency f_c forms a boundary between a low frequency ($< f_c$) pass-band with unity gain and a high frequency ($> f_c$) stop – band with very-very low (= 0) gain. Gain falls off as the stop band is entered. The rate of decrement of gain called roll-off is an important design parameter of filters and is directly related to the order of the filter. For some filter configurations the gains may not be very strictly constant due to a left over noise content in the signal referred as ripple. The ripple content as percentage of the maximum value of signal is also a design parameter, usually kept smaller than 1%. These are used for removing unwanted components in the spectral range of input signal above the specified value of frequency. They need to be used also to help reduce the problem of anti-aliasing by using as a band limiter put before sampling and multiplexing operations.

Band-pass filters allow the frequencies in a specified band to pass through without attenuation and suppress unwanted frequency and bandwidth. They do not allow frequencies outside the pass-band. In Fig. 8.26 are shown the response of band-pass filter (*a*) ideal (*b*) practical and (*c*) response of notch filter, which are typically useful in allowing or rejecting a specified frequency band or frequency for sharp selectivity.



(a) Ideal Band-pass Filter

(b) Practical Band-pass Filter

(c) Notch Filter

Fig. 8.26 Gain Characteristics of Band-pass and Notch Filters

Passive filters are simple to design and they work very well in RF range. For lower frequencies (audio and lower) range, the inductances tend to become larger, heavy, expensive and performance (and Q-factor) degrades. Passive filters also have problem of low input impedance resulting in loading of the input signal (source) and are frequency dependent. Output impedance is usually high, resulting in impedance matching problem with next stage. Also, any change in load (impedance) affects the behavior of filter because there is no isolation between filter and load.

Active filters on the other hand, use an active element (OP-amp) with resistors and capacitors only. Output of OP-amp drives the load providing isolation, resulting in output impedance of the order of few Ohms. With incorporation of operational amplifiers (OP-amps), it is now possible to adjust gain and ripple in the pass-band, critical/cut-off frequency and rate of roll-off. With the active configuration offering higher input impedance, large value resistors can be chosen to keep the capacitor size(s) small. (A quick review of operational amplifiers is available in appendix-A, at the end of the text for students not familiar with these).

Limitations of active filters include:

- High frequency response limited by gain and slew rate
- Need for additional power supply
- Need for decoupling strategy in multi-stage filter design
- Susceptibility to RF interference
- Restricted value of Q (usually < 50)

In this chapter, we will consider only active filters of low-pass and band-pass type which are usually needed in instrumentation applications.

Specifications and Design Considerations

It is sufficient to design first and second order filters and any higher order required can be realized by a cascaded combination of these basic units. The common design specifications include:

- Cut-off/critical frequency
- Rate of cut-off/slope of magnitude beyond critical frequency
- Ripple/noise in percent that may be tolerated/allowed in the output
- DC gain, generally tried to be chosen unity
- For band-pass/reject filters both upper and lower frequencies need be specified

FIRST ORDER LOW-PASS FILTER

A possible hardware configuration to realize the low-pass I order filter is shown in Fig. 8.27. The OP AMP is used in non inverting mode to provide high input impedance with dc gain. The overall transfer function can be evaluated to be

$$A_0 = 1 + \frac{R_f}{R_i}. \qquad \text{...(8.37)}$$

The gain is A_0 at very low values of frequency and it tends to drop as frequency increases. The frequency at which the gain drops to 0.707 is called critical frequency and is evaluated by putting,

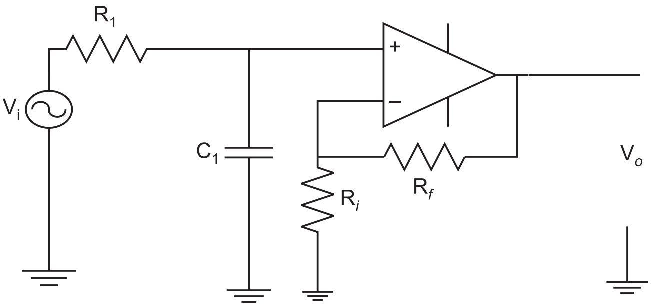


Fig. 8.27 First order Low-pass Filter

$$|A_c(s)| = 0.707A = \left|\frac{A_0}{1 + j.\omega_c.R_1.C_1}\right| = \frac{A_0}{\left(1 + \omega_c^2.R_1^2.C_1^2\right)^{1/2}}$$

where $$\omega_c = \frac{1}{R_1.C_1} \quad \text{or,} \quad f_c = \frac{1}{2.\Pi.R_1.C_1} \qquad (8.38)$$

and the phase shift at critical frequency f_c can be found from Eqn. (8.37):

$$Arg\{A(s)\}_{\omega = \omega_c} = -\tan^{-1}\left(\frac{1}{\omega_c.R_1.C_1}\right) = -45°$$

It is also to be noted that the gain is maximum for frequency close to zero and drops as $\omega \approx \omega_c$ and finally becomes zero as ω tends to infinity.

Frequency response of first order filter shall be same as for any first order system as discussed earlier in Chapter 2.

The design values can be obtained as:

$$A_0 = 1 + \frac{R_f}{R_i}; \quad \omega_c R_1 C_1 = 1$$

In a typical design problem, the corner/cut-off frequency f_c the dc gain A_0 shall be specified. The value of capacitor has to be chosen to be some practically available value and the values of R_1 and R_f can be obtained as:

$$R_1 = \frac{1}{2\pi f_c C_1}; R_f = R_i(A_0 - 1)$$

Choice of R_i is independent and, depending on dc gain desired *e.g.* > 1, values of R_f and R_i provide the flexibility.

EXAMPLE 8.6

Design a first order non-inverting low pass filter with critical frequency of 1 kHz and gain of 1.5, choosing $C_1 = 0.1\ \mu F$; $a_1 = 1$

SOLUTION:

$$R_1 = \frac{a_1}{2\pi f_c C_1} = \frac{1}{2\pi \times 10^3 \times 0.1 \times 10^{-6}} = 1.59\ \Omega$$

$$\because\ A_0 = 1.5; \qquad \frac{R_f}{R_i} = 0.5 \quad \text{or} \quad R_f = 0.5\ R_i$$

A choice of $R_i = 10\ K\Omega$ allows $R_f = 5\ K\Omega$.

SECOND ORDER FILTERS

As has been observed earlier, the actual L.P filter characteristics is not as sharp as the ideal one and the roll off rate of-20 dB/decade may not be sufficient to cut down the effect of higher frequencies, with desired effect.

An improved response can be obtained by using a second order filter. It consists of two R-C pairs and has a roll off rate of -40 dB/decade.

The results derived next can be used for analyzing both low pass and high pass filters.

For the general second order filter as shown in the Fig. 8.28 the values used for various elements are initially not specified and later it will be shown that by the appropriate choice of elements, various filter characteristics can be realized.

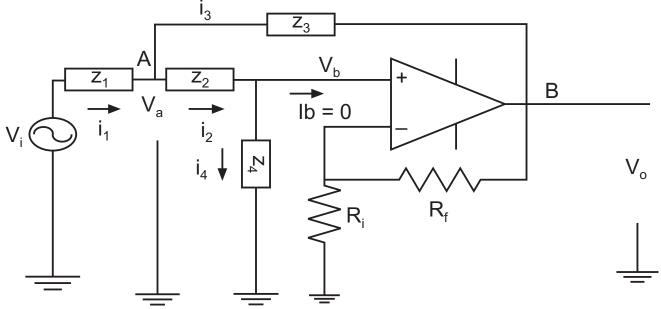


Fig. 8.28 General Second Order Filter

By applying KCL at node A:

$$i_1 = i_2 + i_3$$

where $$i_1 = \frac{V_i - V_A}{Z_1} = \frac{V_i}{Z_1} - \frac{V_A}{Z_1} \quad ...(8.39)$$

$$= \frac{V_i}{Z_1} - \frac{1}{Z_1}\frac{V_b}{Z_4}(Z_2 + Z_4)$$

$\because$ $$i_3 = i_1 - i_2 = i_1 - i_4 \ (\because\ i_b = 0)$$

$$= \left[\frac{V_i}{Z_1} - \frac{V_b}{Z_4}(Z_2 + Z_4)\right] - \frac{V_b}{Z_4}V$$

Applying *KVL* through the loop *A*, Z_3, *B*, earth, *A*:

$$V_A - i_3 Z_3 - V_0 = 0$$

$\therefore$ $$V_0 = V_a - i_3 Z_3$$

$$= \frac{V_b}{Z_4}(Z_2 + Z_4) - Z_3\left[\frac{V_i}{Z_1} - \frac{V_b}{Z_4}(Z_2 + Z_4) - \frac{V_b}{Z_4}\right]$$

Replacing V_b by $\frac{V_0}{A_0}$ and simplifying,

$$\frac{V_0}{V_i} = \frac{A_0 Z_3 Z_4}{Z_1 Z_2 + Z_2 Z_3 + Z_3 Z_4 + Z_1 Z_4 (1 - A_0)} \quad ...(8.40)$$

A second order low-pass filter in standard form is realized with the choice of

$Z_1 = R_1, Z_2 = R_2 . Z_3 = \frac{1}{sC_1}, Z_4 = \frac{1}{sC_2}$ is shown in Fig. 8.29,

so that, $$A(s) = \frac{V_0(s)}{V_i(s)} = \frac{\dfrac{A_0}{R_1 R_2 C_1 C_2}}{s^2 + \left\{\dfrac{R_2 C_2 + R_1 C_2 + R_1 C_1 (1 - A_0)}{R_1 R_2 C_1 C_2}\right\} s + \dfrac{1}{R_1 R_2 C_1 C_2}}$$

$$= \frac{\omega_c^2}{s^2 + \alpha \omega_c s + \omega_c^2} \quad ...(8.41)$$

where ω_c is upper cut-off frequency = $\frac{1}{\sqrt{R_1 R_2 C_1 C_2}}$ and α is damping co-efficient for the choice of $R_1 = R_2 = 1$ MΩ, $C_1 = C_2 = 1$ μ*F*.

A unity gain filter can be realized by having output directly connected to inverting terminals of OP-AMP.

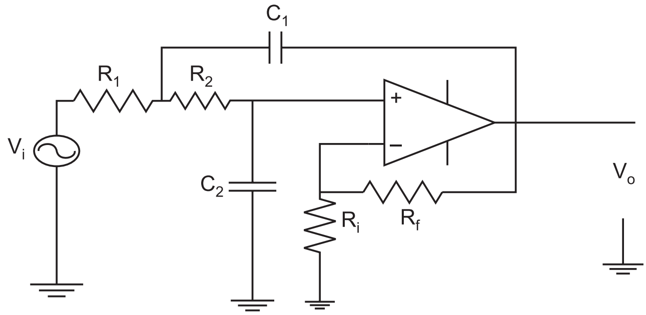


Fig. 8.29 Second Order Low-pass Filter

By substituting $s = j\omega$ in Eqn. (8.41), we obtain

$$A\,(j\omega) = \frac{V_o(j\omega)}{V_i(j\omega)} = \frac{A_0}{\left(\frac{j\omega}{\omega_c}\right)^2 + j\alpha\left(\frac{\omega}{\omega_c}\right) + 1}$$

and the normalized equation for low-pass filter is

$$A(s) = \frac{A_0}{s^2 + \alpha s + 1} \qquad \ldots(8.42)$$

where normalized frequency $s = j\left(\frac{\omega}{\omega_c}\right)$

The expression for magnitude in dB of the transfer function is

$$20\log|A(j\omega)| = 20\log\left|\frac{A_0}{\left(\frac{\omega}{\omega_c}\right)^2 + j\alpha\left(\frac{\omega}{\omega_c}\right) + 1}\right|$$

$$= 20\log\frac{A_0}{\sqrt{\left(1 - \frac{\omega^2}{\omega_c^2}\right) + \alpha\left(\frac{\omega}{\omega_c}\right)^2}}.$$

The frequency response of filter for different values of α is shown in the Fig. 8.30. It is to be noted that for α > 1.7 the response is heavily damped, stable and the roll off starts early in the pass-band it self referred as Bessel filter and provide good pulse response. The flattest pass-band results for α = 1.414 referred to as Butterworth filter, and the characteristic is typically useful for audio filters.

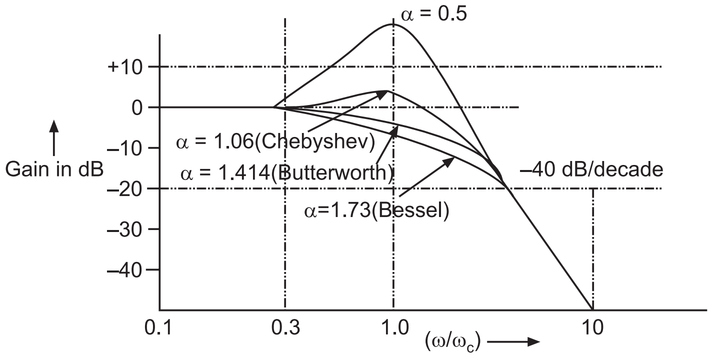


Fig. 8.30 Types of Second order Low-pass Filters (for $A_0 = 1$)

Comparatively, the Chebyshev filters are lightly damped with α = 1.06. With Chebyshev response the over shoot increases and ringing may occur due to ripples and pulse response may be poor.

Butterworth response is typically suitable for instrumentation applications hence discussed in further detail. (for others see bibliography).

Rewriting Eqn. 8.42 for α = 1.414,

$$A_{dB} = 20\log|A(j\omega)| = 20\log\left|\frac{v_0}{v_i}\right|$$

$$= 20\log\frac{A_0}{\sqrt{1+\left(\frac{\omega}{\omega_c}\right)^2}} \qquad ...(8.43)$$

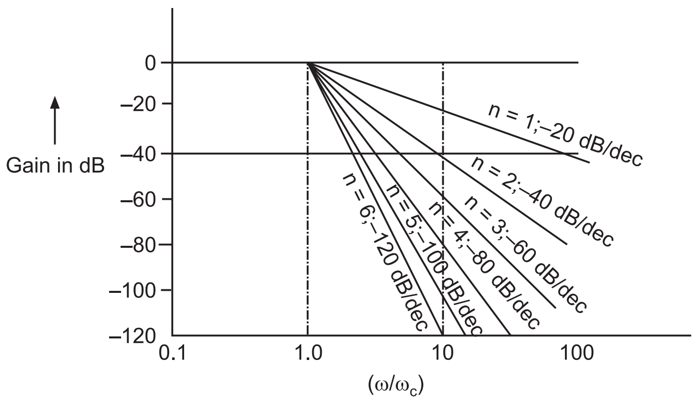


Fig. 8.31 Roll-off Rates for Filters of Different Orders

Therefore for n^{th} order Butterworth filter

$$\left|\frac{A(j\omega)}{A_0}\right| = \frac{1}{\sqrt{1+\left(\frac{\omega}{\omega_c}\right)^{2n}}}. \qquad ...(8.44)$$

Asymptotic gain plot shall indicate a slope of – 20n db/decade. The Fig. 8.31 shows the roll-off rate for different values of n.

For the Sallen-Key configuration shown in Fig. 8.29, the OP-amp is connected as non inverting amplifier and hence

$$\because \quad V_0 = A_0 V_b\left(1+\frac{R_f}{R_i}\right) \qquad ...(8.45)$$

EXAMPLE 8.7

A stepper motor is receiving pulses at 1 kHz. Design a filter to reduce 50 Hz now but attenuation of pulses is to be no more than 3 dB.

SOLUTION:

$$P_{dB} = 20\log\left(\frac{V_0}{V_i}\right) = -3 \; \therefore \frac{V_0}{V_i} = 10^{\left(\frac{-3}{20}\right)} = 0.707$$

i.e. same as for critical frequency. $\therefore f_c = 1000$ kHz

Effect on 50 Hz noise is found by:

$$\left(\frac{V_0}{V_i}\right) = \frac{\frac{f}{f_c}}{\sqrt{1+\left(\frac{f}{f_c}\right)^2}} = \frac{\frac{50}{1000}}{\sqrt{1+\left(\frac{50}{1000}\right)^2}} = \frac{\frac{1}{20}}{\sqrt{\frac{401}{400}}}$$

$$= \frac{1}{\sqrt{401}} = 0.04993$$

$\therefore$ Only 4.99% noise remains!

Let $C = 0.01\ \mu F$, then

$$R = \frac{1}{2\pi f \times 0.01 \times 10^{-6}} = \frac{10^{-8}}{2\pi \times 1000} = 15.91 K\Omega$$

$$\cong 16\ K\Omega.$$

Higher Order Filters

To improve the performance of signals from transducers against noise, very often higher order filters are desirable and these can be designed by having a cascading of first and second order stages. The transfer function in general can be written as

$$A(s) = \frac{A_0}{s+1} \cdot \frac{A_{01}}{s^2+\alpha_1 s+1} \cdot \frac{A_{02}}{s^2+\alpha_2 s+1} \cdots$$

Table 8.4 shows the denominator polynomial choice up to 6th order used commonly for design of Butterworth filters. Similar sets of tables are available for Chebyshev with different ripple factors and Bessel filters.

TABLE 8.4 Normalized Butterworth Filter Polynomials

Order, n	*Factors of polynomial*
1	$s+1$
2	$s^2 + 1.414\,s + 1$
3	$(s + 1)(s^2 + 1.414\,s + 1)$
4	$(s^2 + 0.765\,s + 1)\,(s^2 + 1.848\,s + 1)$
5	$(s + 1)(s^2 + 0.618\,s + 1)\,(s^2 + 1.618\,s + 1)$
6	$(s + 1)(s^2 + 0.518\,s + 1)\,(s^2 + 1.414\,s + 1)(s^2 + 1.932\,s + 1)$

EXAMPLE 8.8

Design a second order low-pass Butterworth filter with upper cut-off frequency of 2 kHz.

SOLUTION:

Given $$f_c = 2KHz = \frac{1}{2\pi\sqrt{R_1R_2C_1C_2}}$$

For $n = 2$; $\alpha = 1.414$ (from the table for Butterworth filters)

Therefore, gain in pass-band, $A_0 = 3 - \alpha = 1.586$

Therefore the transfer function of the filter will be:

$$\because \quad A_0 = 1 + \frac{R_f}{R_i} = 1.586; \qquad \therefore \frac{R_f}{R_i} = 0.586$$

With the choice of $R_i = 10$ KΩ and $R_f = 5.86$ *K*Ω.

(*i*) If dc-offset problem can be neglected for compensated OP-amps, *C* can be chosen independently (say) 0.1 μ*F*. then

$$\because \quad A_0 = 1 = \frac{R_f}{R_i} = 1.586; \qquad \therefore \frac{R_f}{R_i} = 0.586$$

(*ii*) To keep the dc offset to minimum, it is necessary to satisfy $R_i \| R_f = R_1 + R_2$ assuming

$$R_1 = R_2 = R = \frac{10 \times 5.86}{15.86} K\Omega$$

$$= 3.695 \text{ K}\Omega$$

and, if

$$C_1 = C_2 = C = \frac{1}{2\pi \times 2 \times 10^3 \times R} = 0.02153 \ \mu F$$

Band-Pass Filters

The band-pass filters are classified as:

(*a*) Narrow band-pass ($Q > 10$)

(*b*) Wide band-pass ($Q < 10$), where Q is the quality factor or figure of merit.

Following relationships are important to meet the design criterion:

$$Q = \frac{f_0}{BW} = \frac{f_0}{f_h - f_i} \qquad \ldots(8.46)$$

and $$f_0 = \sqrt{f_h \cdot f_l} \qquad \ldots(8.47)$$

where f_0 = central frequency

f_h = upper cut-off frequency

f_l = lower cut-off frequency

Narrow Band-Pass Filters

Consider the network shown in Fig. 8.32 (*a*) with two feedback paths and Op-amp in inverting mode, writing the *KCL* at node *A*.

$$V_i Y_i + V_0 Y_3 = (Y_1 + Y_2 + Y_3 + Y_4) \qquad \ldots(8.48)$$

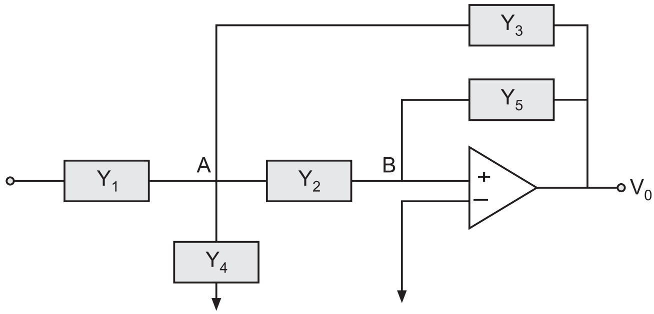
Assuming $V_B = 0$ (the virtual ground), the *KCL* at node B will

$$V_A Y_2 + V_0 Y_5 = 0$$

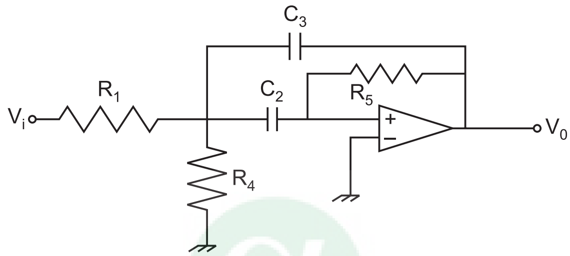
$$\therefore \quad V_A = -V_0 \frac{Y_5}{Y_2} \qquad \ldots(8.49)$$

By substituting V_A in Eqn. (8.48),

$$V_i Y_i + V_0 Y_3 = -V_0 \frac{Y_5}{Y_2}(Y_1 + Y_2 + Y_3 + Y_4)$$



(a) Band-pass Filter General Configuration



(b) Second Order BP Filter Realisation

Fig. 8.32 Second Order Band-pass Filter

$$\therefore \qquad V_i Y_i = -V_0 \left[\frac{Y_5 Y_1 + Y_5 Y_2 + Y_5 Y_3 + Y_5 Y_4 + Y_2 Y_3}{Y_2} \right]$$

Or,
$$\frac{V_0}{V_i} = -\left[\frac{Y_1 Y_2}{Y_5 Y_1 + Y_5 Y_2 + Y_5 Y_3 + Y_5 Y_4 + Y_2 Y_3} \right]$$

To realize a band-pass filter with this configuration, we choose

$$Y_1 = \frac{1}{R_1}, Y_2 = sC_2, Y_3 = sC_3, Y_4 = \frac{1}{R_4}, Y_5 = \frac{1}{R_5}$$

as shown in the Fig. 8.32 (*b*), and T.F will be:

$$H(s) = \frac{V_0(s)}{V_i(s)} = \frac{-\frac{1}{R_1}.sC_2}{\frac{1}{R_1 R_5} + sC_2 sC_3 + sC_2\frac{1}{R_5} + sC_3\frac{1}{R_5} + \frac{1}{R_4 R_5}}$$

$$= \frac{-\frac{1}{R_1}}{sC_3 + \frac{1}{R_5} + \frac{C_3}{C_2 R_5} + \frac{1}{sC_2}\left(\frac{1}{R_1} + \frac{1}{R_4}\right)\frac{1}{R_5}}$$

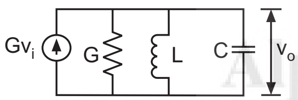
$$= \frac{-\frac{1}{R_1}}{sC_3 + \frac{1}{R_5}\left(1+\frac{C_3}{C_2}\right) + \frac{1}{s}\cdot\frac{1}{C_2}\left(\frac{1}{R_1}+\frac{1}{R_4}\right)\frac{1}{R_5}}$$

$$= \frac{-\frac{1}{R_1}}{sC + \frac{1}{R} + \frac{1}{sL}} \qquad \text{...(8.50)}$$

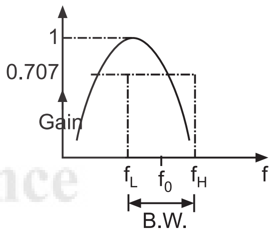
where

$$C = C_3,\ R = \frac{R_5C_2}{(C_2+C_3)}, \qquad L = \frac{C_2R_5}{\left(\frac{1}{R_1}+\frac{1}{R_4}\right)}$$

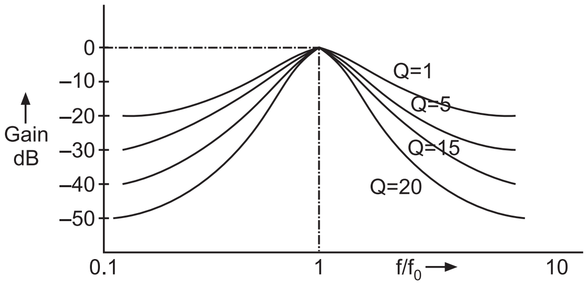
Equation (8.50) can be shown as a parallel RLC circuit as in Fig. 8.33(*a*) with current source $\frac{V_i}{R_1}$ with band-pass characteristics as shown in the Fig. 8.33(*b*).



(a) Parallel R-L-C circuit



(b) Band-pass Filter Characteristic



(c) Frequency Response with Variation of Q

Fig. 8.33 Band-pass filter characteristics

At resonance the circuit has power factor and resonant frequency ω_0 would be:

$$\omega_0 = \frac{1}{LC} = \frac{\left(\frac{1}{R_1}+\frac{1}{R_4}\right)}{C_2C_3R_5} \qquad \text{...(8.51)}$$

Gain at resonance shall be

$$\left.\frac{V_0}{V_i}\right|_{\omega=\omega_0} = \frac{-\dfrac{1}{R_1}}{\dfrac{1}{R_5}\left(1+\dfrac{C_3}{C_2}\right)} = -\frac{\left(\dfrac{R_5}{R_1}\right).C_2}{(C_2+C_3)} \quad \text{...(8.52)}$$

and, Q – factor at resonance will be

$$Q_0 = \frac{\omega_0 L}{R} = \omega_0 RC = \frac{\omega_0 C_2 C_3 R_5}{(C_2+C_3)} \quad \text{...(8.53)}$$

and band-width

$$BW = f_H - f_L = \frac{f_0}{Q_0} = \frac{\omega_0}{2\pi Q_0}$$

$$= \frac{(C_2+C_3)}{2\pi R_5 C_2 C_3} \quad \text{...(8.54)}$$

Centre frequency is given by, $f_0 = \sqrt{f_H \cdot f_L}$

If $C_2 = C_3 = C$ is to chosen to simplify the selection, gain at resonant frequency

$$\frac{V_0}{V_i} = -\frac{R_5}{2R_1} = -A_0 \quad \text{...(8.55)}$$

Band width $$BW = \frac{1}{\pi R_5 C} \quad \text{...(8.56)}$$

and $$\omega_0 = \frac{1}{C}\sqrt{\frac{1}{R_5\left(\dfrac{1}{R_1}+\dfrac{1}{R_4}\right)}}. \quad \text{...(8.57)}$$

The gain A_0, resonant frequency ω_0 and band width BW are part of design specifications and required to satisfy the 3 design equations, but the component to chose are C, R_1, R_4, R_5, therefore one of these usually C is chosen arbitrary as per component value available and the resistances can be calculated as from the Eqns. (8.55), (8.56) and (8.57).

Response of filter is largely dependent on value of Q which should be chosen as high as possible for sharp performance. A typical gain response is shown in Fig. 8.33 (*c*) for different values of Q. In a narrow range about the resonant frequency roll-off rate is –20 dB/decade independent of Q, and for better roll-off rate more such sections can be cascaded.

A simpler approach used to realize wide band pass filters is to configure it as a combination of 2 – first order filters in cascade – one a high-pass and a low-pass, as shown in Fig. 8.34 for a first order BP filter with slopes of-20 dB/decade. And, extending this approach a second order BPF can be realized with two sections each of second – order – one as HPF followed by a LPF.

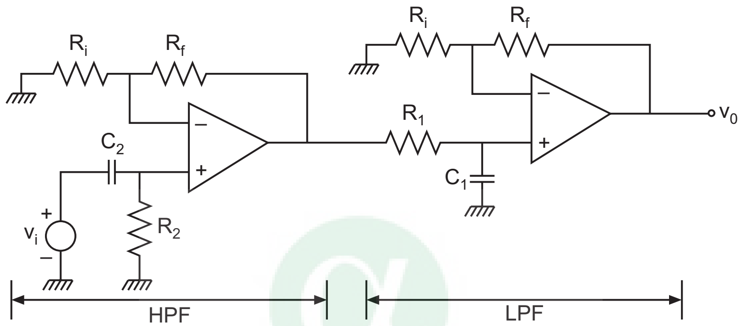


Fig. 8.34 Realization of Wide Band-pass Filter

For more details on wide band-pass filters, band reject filters and notch filters bibliography should be looked into.

8.6 LINEARISATION OF TRANSDUCER CHARACTERISTICS

Inherent nonlinearities in the transducer input-output characteristics involve corrections to be invoked for any change from the operating point, even the piecewise linearity is difficult to assume at times. Therefore, to improve upon the accuracy of result, it is considered useful to attempt linearization of characteristic by hardware approach. It is attempted, over the working range of transducer, or, for as large the variations as possible, about the steady-state operating point. It is possible to reduce the errors and consider linear or piecewise linear characteristic. In this section are discussed a few approaches, already in use.

8.6.1 Linearization by Modification of Transducer Circuitry

The approach does not linearise fully but reduces the effect of non-linearity so that the characteristic can be considered at least piecewise linear. Application to two cases is considered next:

(*a*) Improving thermistor characteristic

This is achieved by shunting the thermistor being used by a resistor practically insensitive to temperature variations.. It results in terminal characteristic with smoother resistance-temperature characteristic as shown in Fig. 8.35(*a*). This can be demonstrated by considering shunted thermistor characteristic as follows:

$R_T = ae^{b/T}$ in parallel with a constant resistance R_c to from,

$$R = R_c \parallel R_T = \frac{R_c R_T}{R_c + R_T} \quad \text{...(8.58)}$$

$$= \frac{R_c . ae^{b/T}}{R_c + ae^{b/T}} \quad \text{...(8.59)}$$

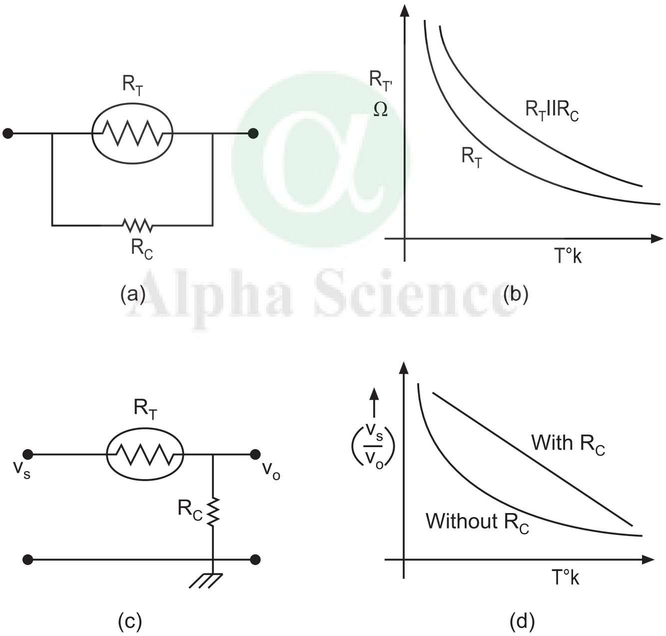


Fig. 8.35 Compensation of Thermistor Nonlinearity

Now the rate of change of resistance with temperature in both the cases can be obtained. For the original thermistor alone and for combination (*a*), it can be written as:

I case: $$\left(\frac{dR}{dT}\right)1 = ae^{b/T}\left(-\frac{b}{T^2}\right) \quad \text{...(8.60)}$$

$$= R_T\left(-\frac{b}{T^2}\right)$$

II case: $$\left(\frac{dR}{dT}\right)2 = \frac{R_c^2 R_T}{(R_c+R_T)^2}\left(-\frac{b}{T^2}\right) \quad \text{...(8.61)}$$

So that, $$\frac{\left(\frac{dR}{dT}\right)1}{\left(\frac{dR}{dT}\right)2} = \frac{1}{\frac{R_c^{\,2}}{(R_c+R_T)^2}} = \frac{(R_c+R_T)^2}{R_c^{\,2}} >> 1 \quad \text{...(8.62)}$$

Thus the steep rate of drop in the original characteristic is modified to a slowed down one, as shown in Fig. 8.35(*b*), the exact extent depends on the values of R_T and R_C. The modified characteristic is better suited for piecewise linear approximation.

(*b*) A similar result can also be achieved by having a resistance R_c across R_{Th}, as shown in Fig. 8.35(*c*). In order to achieve a linear variation of output voltage V_o with a constant R_c,

Assume, $A = R_T/R_{25}$

It is sufficient to have,

$$\frac{V_o}{R_c} = \frac{V_s - V_o}{A.R_{25}} \quad \text{...(8.63)}$$

So that, $$V_o = \frac{V_s}{A.R_{25}} - \frac{V_o R_c}{A.R_{25}} \quad \text{...(8.64)}$$

Or $$\frac{V_o}{V_s} = \frac{1}{(1 + AR_{25}/R_c)} \quad \text{...(8.65)}$$

If A is chosen $\cong \alpha\, e^{b/T}$, it can be shown for typical values $\alpha = 1.443 \times 10^{-6}$, $\beta = 4016$, that for a ratio $R_{25}/R_c \cong 0.61$

$$\frac{d}{dt}\left(\frac{V_o}{V_s}\right) = \frac{-1.443\times10^{-6}\,\frac{R_{25}}{R_c}\,\frac{4016}{T}\,e^{4016/T}}{\left(1.443\times10^{6}\,\frac{R_{25}}{R_c}\,e^{4016/T}+1\right)^2} \quad \text{...(8.66)}$$

has almost linear relation T°C V_s (V_o/V_s) in the temperature range of 0° to 25°C as shown in Fig. 8.35(*d*).

8.6.2 Linearization by Improved Conditioning

This approach is general and is applied for different class of arrangements mostly as an improvement in signal conditioning.

(*a*) Modification in transducer bridge

The transducer bridge is modified as shown in Fig. 8.36 with transducer such as strain gauge, RTD or any other resistance transducer, in one of the arms.

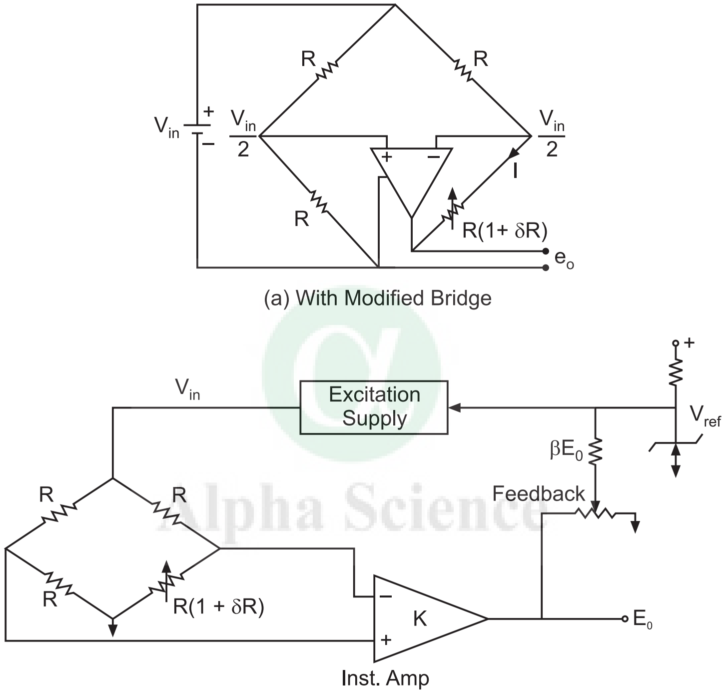


Fig. 8.36 Linearization by Improvement in Transducer Bridge

For the original bridge, as considered in Fig. 8.2 with resistive transducer, we know that;

$$e_0 = \frac{V_{in}}{4R} \frac{\Delta R}{1+\dfrac{\Delta R}{2R}}$$

$$= \frac{V_{in}}{4} . \frac{\dfrac{\Delta R}{R}}{1+\dfrac{\Delta R}{2R}} = \frac{V_{in}}{4} . \frac{\delta R}{1+\dfrac{\delta R}{2}}$$

where $\delta R = \Delta R/R$, ΔR being the change in Ohmic value of arm due to measurand and δR is the fractional change in value of R.

$$\cong \frac{V_{in}}{4R} \cdot \Delta R \qquad ...(8.67)$$

generally $\delta R < 1\%$ to avoid nonlinearity error.

For the modified bridge (Fig. 8.36*a*), on applying KVL, we have:

$$\frac{V_{in}}{2} = IR\,(1 + \delta R)$$

$$= e_0 + \frac{V_{in}}{2}(1+\delta R)$$

$$\therefore \qquad e_0 = -\frac{V_{in}}{2} \cdot \frac{\Delta R}{R} \qquad ...(8.68)$$

with no approximation involved the arrangement provides a gain of 2 over the standard bridge and shows linearity with ΔR for a large range of variation.

(*b*) Modification in transducer circuitry by using feedback

This arrangement is considered particularly useful for eliminating the effect of nonlinearity and there by extending the range over which the device can be used as a linear output device.

As shown in Fig. 8.36 (*b*), a negative feedback voltage component is used from the highly regulated supply to proportional relationship with the change ΔR.

For the arrangement shown

$$V_{in} = V_{\text{ref}} + \beta E_0 \qquad (8.69)$$

where, $E_0 = k\, V_{in}\, f(x)$; $\quad f(x) = \dfrac{\delta R}{1+\dfrac{\delta R}{2}}$ ...(8.70)

$$\therefore \qquad E_0 = k\,(V_{ref} + \beta E_0)\, f(x)$$

$$= \frac{k.V_{ref}.\ f(x)}{1-k.\beta.f(x)}$$

$$= k\, V_{\text{ref}} \cdot \frac{\delta R}{1+\delta R\left(\dfrac{1}{2}-k\beta\right)} \qquad ...(8.71)$$

Nonlinearity effect due to the variable term in denominator, can be eliminated by choosing $k\beta = 1/2$ and, finally obtaining

$$E_0 = k\, V_{\text{ref}}\, \frac{\Delta R}{R} \qquad ...(8.72)$$

Thus, the output voltage is directly proportional to the change in resistance.

8.6.3 Linearization by Processing of Output Signal

Special analog processing devices/circuits can be applied to compensate for the nonlinearities in the signal obtained as transducer output or bridge output. These are specific to the type and therefore discussed through two examples:

(*a*) Compensation of inherent nonlinearity by complementation:

As in the case of thermistor corresponding to the exponential resistance vs temperature characteristic, an output voltage $V_2 = V_1 e^{\theta}$ is inputted to a logarithmic amplifier, as shown in Fig. 8.37(*a*), to obtain

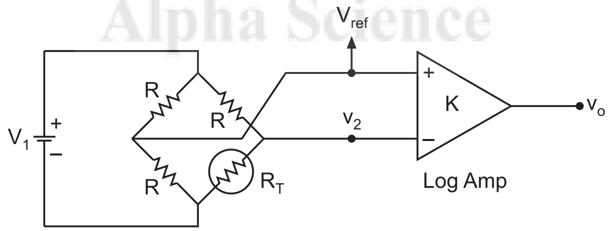
$$V_o = -k.\log\left(\frac{V_2}{V_{ref}}\right) \qquad \text{...(8.73)}$$

$$= -k.\log\left[\frac{\left(V_1 \cdot e^{\theta}\right)}{V_{ref}}\right]$$

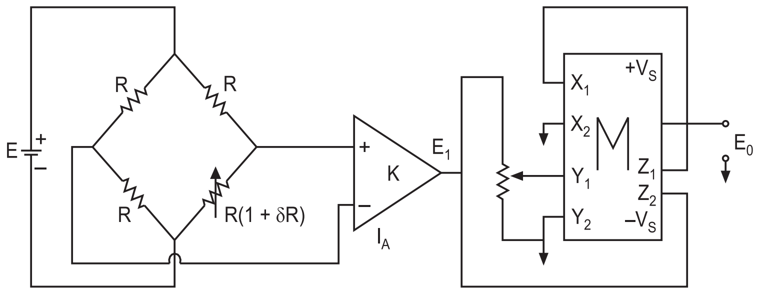
$$= -k\,[\log\,(V_1 - V_{ref}) + \theta] \qquad \text{...(8.74)}$$

$$= -k\theta;\ \text{with the choice of } V_1 = V_{ref} \qquad \text{...(8.75)}$$

This approach has a major limitation, that, it can be useful for known functional nonlinearities only. However it is one of the most effective when complete information is available.



(a) Compensation for Well-posed Functional nonlinearity



(b) Nonlinearity Compensation by a Processing Circuit

Fig. 8.37 Linearization by Processing of Output

(*b*) Compensation for off-null bridge nonlinearities

The approach is to neutralize the effect of nonlinearities on the output by using processing circuit, to satisfy appropriate conditions by hardware adjustment.

As an example, consider the bridge circuit for resistive transducer whose output is amplified and given to a multiplier (as shown in Fig. 8.37(*b*)) which multiplies so that the following relation is satisfied, say typically with multiplier IC AD534 analog device,

$$(X_1 - X_2)\,(Y_1 - Y_2) = 10\,(Z_1 - Z_2)V \qquad \text{...(8.76)}$$

With the bridge output after amplifier,

$$E_1 = kE\frac{\delta R}{1+\dfrac{\delta R}{2}} \qquad \text{...(8.77)}$$

and, the multiplier output shall be:

$$E_0\left(\beta.k.E.\frac{\delta R}{\left(1+\dfrac{\delta R}{2}\right)}\right) = 10\left(E_0 - k.E.\frac{\delta R}{\left(1+\dfrac{\delta R}{2}\right)}\right) \qquad \text{...(8.78)}$$

$$E_0\left(\beta.k.E\frac{\delta R}{\left(1+\dfrac{\delta R}{2}\right)} - 10\right) = \frac{10.k.E.\delta R}{\left(1+\dfrac{\delta R}{2}\right)}$$

$$E_0 = \frac{-10.k.E.\delta R}{\beta.k.E.\delta R - 10.\left(1+\dfrac{\delta R}{2}\right)} = \frac{-k.E.\delta R}{-1-\dfrac{\delta R}{2}+\dfrac{\beta.k.E.\delta R}{10}}$$

$$= \frac{k.E.\delta R}{1+\dfrac{\delta R}{2}-\dfrac{\beta.k.E.\delta R}{10}}$$

$$\equiv k.E.\delta R$$

This will be true provided

$$\frac{\delta R}{2} = \frac{\beta.k.E\delta R}{10}$$

or,
$$k\beta = \frac{5}{E} \qquad \text{...(8.80)}$$

This is not difficult to adjust, and therefore it shall be possible to have linear, output for changes in transducer arm resistance.

8.6.4 Function Fitting Approach to Linearization

In many applications, one may not be fortunate enough to be able to have compensation as shown in previous section. In such cases a general approach to linearization is adopted. This is based on the concept of nonlinearity discussed in Chapter 2 and a terminal linearity in the range of operation is considered.

The approach is typically useful for thermocouple type of characteristic which are marked by a linear region in beginning but output falls off as the temperature increases.

Suppose that a transducer has an I/O transfer characteristic as shown in Fig. 8.38(*b*). For a linear curve fitting, assume

$$Y = \text{(slope) (input)} + \text{intercept-correction} \quad \text{...(8.81)}$$

$$= A\,X + O - A\,f(x) \quad \text{...(8.82)}$$

$$= A\,(X - f(x)) \quad \text{...(8.83)}$$

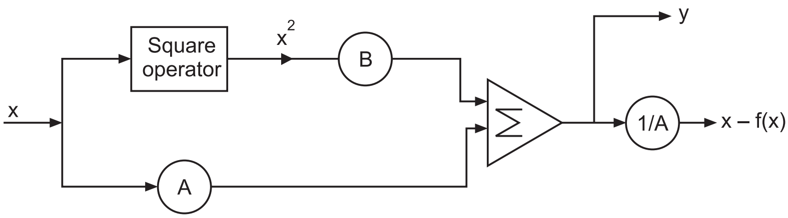
For a quadratic fit: $Y = AX + BX^2$ ...(8.84)

or, $$X\text{-}f(x) = \frac{AX + BX^2}{A} \quad \text{...(8.85)}$$

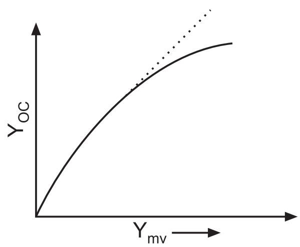
The coefficients A, B can be determined by selecting two intermediate points in the range of operation.

(*a*) Block diagram for computing

(*b*) Thermocouple characteristic



(a) Block Diagram for Computing



(b) Thermocouple Characteristic

Fig. 8.38 Function Fitting Approach to Linearization of TC Characteristic

EXAMPLE 8.9

A sensor develops output of 20 and 200 mV as the input (measurand) varies from minimum to maximum of range. Develop a signal conditioning scheme with high input impedance, low output impedance and output voltage between 0-5 volts.

SOLUTION:

To meet the desired voltage relations, we can assume a straight line transformation

$$V_0 = AV_i + C$$

For the given conditions:

$$0 = A\ (0.02) + C$$
$$5 = A\ (0.02) + C$$

$\therefore \quad A = 27.78;\ C = -\ 0.56$

$\therefore \quad V_0 = 27.78v_i - 0.56 \qquad \ldots(i)$

$\qquad = 27.78(v_i - 0.02) \qquad \ldots(ii)$

In either form (*i*) or (*ii*) the conditioning can be applied, as shown in the figure below:

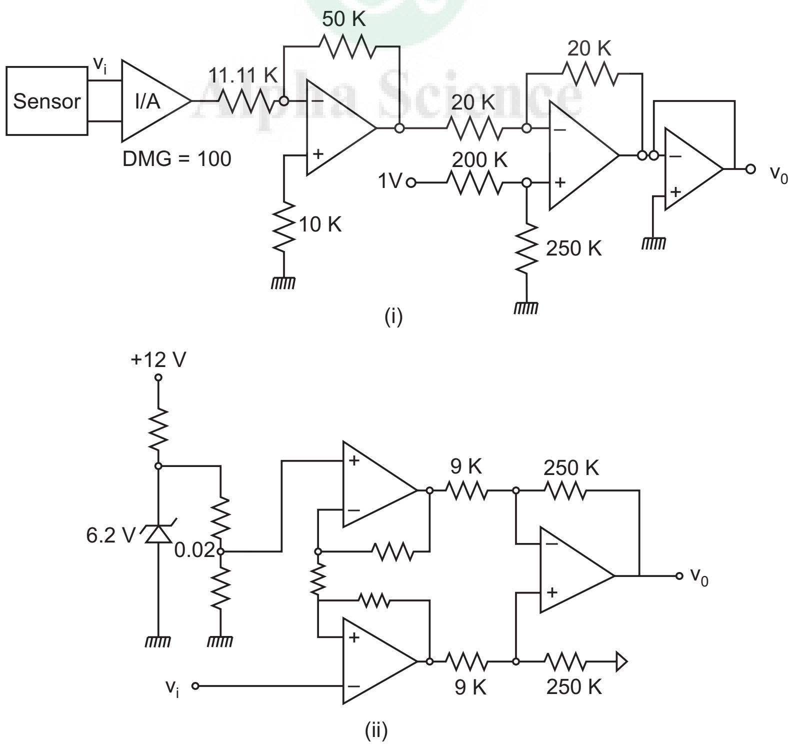


Fig. Ex. 8.9

(*i*) $$V_o = AV_i + C$$

$$A = \frac{250}{9} \cong 27.78; c = -\frac{5}{9} = -0.56 = -\frac{250}{450}$$

(*ii*) $$V_o = AV_i + C = \frac{250}{9}(v_i - 0.02)$$

EXAMPLE 8.10

A K-type thermocouple is used in a temperature instrumentation scheme to monitor temperature at about 150°C with voltage out put of 5V. if a solid state sensor is used to provide the reference with sensitivity 8 mV/°C, suggest a design to implement the monitoring of temperature and calibration. Considering reference has been maintained at 25°C.

SOLUTION:

For type K-TC, at 150°C, output is 6.13 mv if the reference is 0°C (from TC table in the appendix).

Gain required to achieved o/p of 5V,

$$= \frac{5V}{6.13 \times 10^{-3}} = 815.6$$

(Given) Slope/sensitivity of type K-TC is 0.20 mV/5°C = 40 μV/°C

∴ Reference sensor speed of response with reference to *TC*

$$= \frac{8\,mV}{40\,\mu V/°C} = \frac{8000}{40} = 200$$

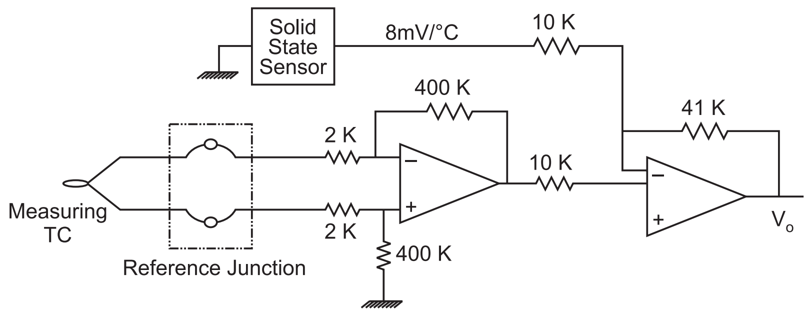


Fig. Ex. 8.10

∴ Connection can be applied by amplifying *TC* output by gain of 200 and then add sensor reference connection.

To make for additional gain to meet 815.6, additional amplification needed,

$$= \frac{815.6}{200} = 4.078 \cong 4.1$$

$\therefore$ $$V_o = 4.1(200\ V_{TC} + V_C)$$

V_{TC} is TC output and V_C is correction term.

Result:

Temp °C	*V_{TC} (ref.0°C)mv*	*V_{TC} × 815*	*V_0 (25°C)*
50	2.02	1.646	1.652
100	4.10	3.341	3.357
150	6.13	4.995	5.022

EXAMPLE 8.11

Assume that for a TC, for two values of input temperature 250°C and 750°C the output voltages are observed to be 13.5 mV and 42.3 mV.

Then, the required two equations to determine the two unknowns A and B can be formed as:

SOLUTION:

Assuming the governing relation with linear plus quadratic nonlinearity to be

$$Y \text{ (temperature)} = A.X \ (m \text{ Volts input}) + B.X^2$$

For the given data:

$$250 = 13.5\ A + B\ (13.5)^2$$

or, $$18.5 = A + 13.5\ B \quad ...(8.86\text{-}a)$$

and $$750 = 42.3\ A + (42.3)^2\ B \quad ...(8.86\text{-}b)$$

and by solving equations 8.86:

$$A = 18.85°\text{C/mV} \ ; B = -\ 0.026°\text{C/(mV)}^2$$

$$Y = 18.85\ X - 0.026\ X^2 \quad ...(8.87)$$

represents the characteristics over the range 250°C to 750°C. The linearising model in terms of basic blocks can be represented as shown in Fig. 8. 38(a) providing the measure of error also. The block diagram can be realized with electronic circuit as shown in Fig. 8.39. The calibration Table 8.5 is prepared to present a comparison and indication of errors as below:

TABLE 8.5 Calibration Table for Linearised Thermocouple

X MVs	*Y°C*	*Linearly interpolated value (X-f(x))*	*Actually*	*% FS error*
0	0	0	0	0
13.5	250	10	250	0
27.4	500	19.9	498	-0.2
43.3	750	30	750	0
59.8	1000	41.6	1040	4

By implementing this approach of design for linearising the transducer characteristic, the results for various TCs are as follows in Table 8.6.

TABLE 8.6 Linearization of Thermocouples

Type of TC	*Linearising coefficients*		*Temperature range °C*
	A	*B*	
J	18.9	– 0.026	0 – 800
K	24.4	– 0.022	– 50 – 1200
T	32.3	– 0.63	– 150 – 400

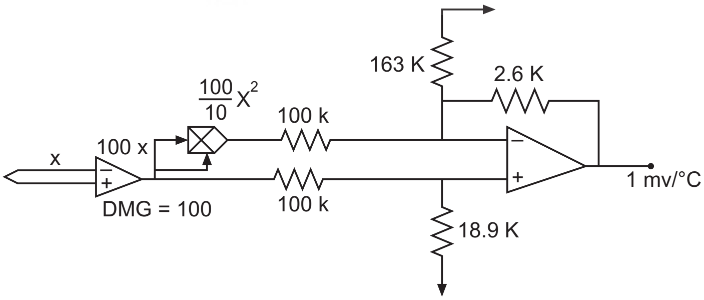


Fig. 8.39 Implementation of Function Fitting Approach to Linearisation

8.7 DATA CONVERTERS AND DIGITAL SIGNAL CONDITIONING

This section deals with the handling of basic input from transducer and output after conditioning of signal/processing with digital devices and techniques. The discussions here are basic for interfacing of instrumentation system with computers.

The reader is assumed to have undergone a course in digital electronics and number systems. For any help on these aspects a textbook on digital electronics may be referred.

The need for digital conditioning arose as the instrumentation problems increased with the number and types of signals rising at fast rate, need for storage & retrieval of signals at fast rate, transmission channel optimization, tighter requirements of noise control, signal processing of advanced nature to take care of nonlinearities-difficult so far with analog techniques, computing for control actions and networking with other systems. At times, data processors chips may be included in digital signal conditioning scheme but their justification is possible only if the number of such assemblies is large or data logging and designer displays are needed on site, which may not be the case very often. DSP chips at times are included for faster data processing to have dedicated functions such as extracting information from data of vibration for machine health monitoring, processing of noisy ultrasound signal to form acceptable image etc. These are isolated special cases and therefore data processors have not been included, in the discussions here.

Typically in process industries, flight control, cruise and automobile control or in any other system, where a computer is brought into the loop, the processing operations with digital techniques are grouped as digital signal conditioning and may include analog operations as well as digital operations and devices. Thus the overall system becomes mixed mode.

8.7.1 Sampling Process and Samplers

Interfacing of controlled systems with computers involves a number of devices as shown in Fig. 8.40, for an industrial process. The elements of instrumentation channel include:

Sample and hold
Buffers
Analog to digital converters
Digital to analog converters

Sample and Hold Device (S/H device)

Sampling is the process of converting analog voltage signal into pulses appearing at uniform interval. According to Shannon's sampling theorem the rate of sampling is required to be at least twice the highest significant frequency component f_h of the signal being sampled, so that the reverse process of reconstruction of analog signal from samples is uniquely possible with reasonable degree of accuracy. However, in practice the rate of sampling is recommended to be 5 to 10 times of the highest frequency component in the signal, f_h. The Fig. 8.40 shows an analog signal, corresponding sampled signal and a basic sampler.

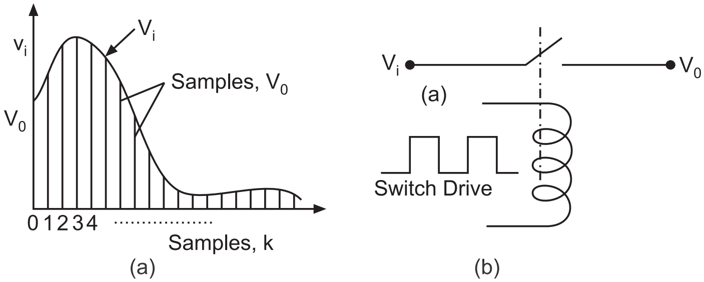


Fig. 8.40 Sampling Operation and Symbolic Sampler

As can be noticed very clearly, that the instantaneous samples would not be carrying any energy, therefore samples *i.e.* the ideal switch, is always followed by a hold circuit to prolong the sample for a finite time. In effect there is no absence of signal at any time.

And, during reconstruction from the samples available the hold effectively extends the sample up to the time the next sample is available, in a predefined manner. In effect, there is no absence of signal at any time. Actual signal type during inter-sampling instant is approximated and upon the type of hold circuit *i.e.* zero, first or second order. In Fig. 8.41 are shown different sample and hold circuit and the effect of hold actions-zero and first order types.

In the case of zero order hold operation the sampled value of signal is held constant during the inter-sampling interval and it changes immediately as the next sample value is available. First order hold circuits provide smoother reconstructed signal (shown by dotted line in Fig. 8.41(*d*), based on linear interpolation of samples during the inter-sampling interval. This and higher order samples are more accurate but make the process slow, therefore not popular. *ZOH* are commonly used and sampling rates up to a million samples per second are achievable. For details of mathematical description of sample and hold, see bibliography.

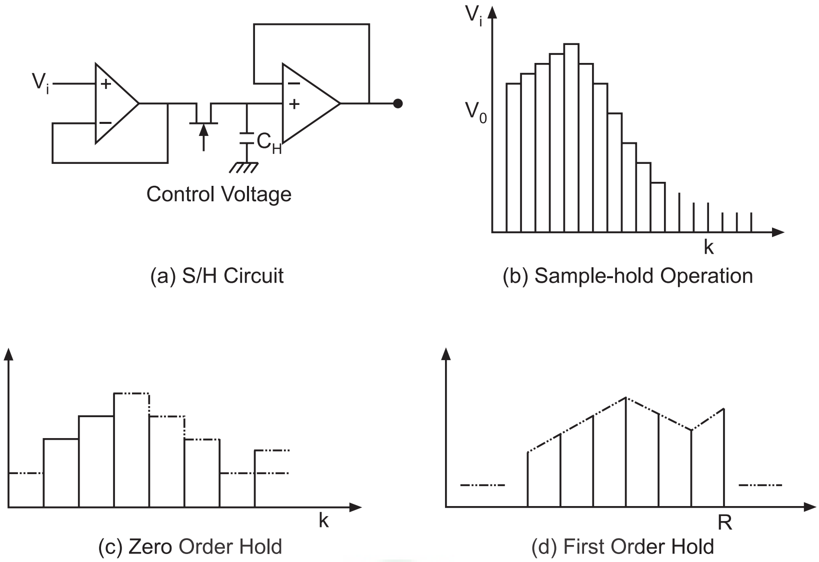


Fig. 8.41 Sample and Hold Operations

The Op-amps used with S/H circuits have high output current capability even with capacitive load. FET switches used are required to have, high $R_{DS\,(\mathrm{off})}/R_{DS(\mathrm{on})}$ ratio so that C_H can charge quickly to peak value with minimal droop during inter-sampling interval.

The characteristics of S/H devices are defined by:

(*a*) Acquisition time is the time required for the holding capacitor to charge up to a level close to the input voltage during the sampling time (Fig. 8.42) and this depends on:

(*i*) *RC*, the time constant, resulting from $R_{DS(\mathrm{on})}$ of *JEFT* switch and the holding capacitance C_H.

(*ii*) Maximum output current, which can be sunk from the first Op-amp

(*iii*) Slew-rate capability of the Op-amp.

(*b*) Aperture time, of an S/H circuit, is the time required for the switch to change the state and uncertainty in time in which this change of state occurs. During this time, the quantization and coding by the device (ADC) must complete. Use of S/H avoids the need for very fast ADCs.

(*c*) Holding time is the time for which an S/H circuit can hold the charge without dropping by more than a specified percentage.

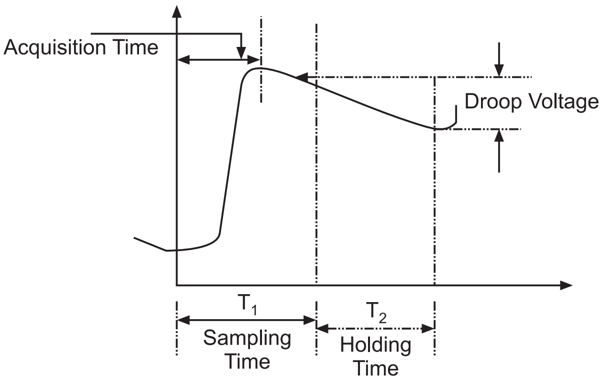


Fig. 8.42 Characteristics of S/H Device

Typical available S/H devices include LF 198/298/398 from National Semiconductors. Its specification is: Acquisition time = 4s for output voltage within 0.1% of 10 V step. Nett leakage current from holding capacitor of 1nF is about 30 pA with droop rate 30mV/s. For details refer bibliography.

EXAMPLE 8.12

Suppose, a sinusoidal signal is to be converted, maximum rate of change at zero crossing

$$\Delta V = \left[\frac{d}{dt}(V_m \sin\omega t)\right]_{t=t_a} = V_m.\omega.t_a$$

$$\therefore\ t_a = \frac{\Delta V}{\omega V_m}$$

i.e. for a 1 kHz signal of 1 V peak value, to have 0.01% resolution i.e. 10 bits data, acquisition time would be $t_a = 160$ *ns.*

Quantization error: This occurs due to abrupt changes in level of digital output as shown in Fig. 8.43, where corresponding to the changing analog level from 0 to 9, the digital values change from 0000 to 1001 in steps. But if the resolution isles than 1 unit (analog) and no corresponding digital output are available, the situation results in quantization error as shown in figure (lower part). This can be reduced by increasing the resolution with larger number of bits to represent the analog value in digital format.

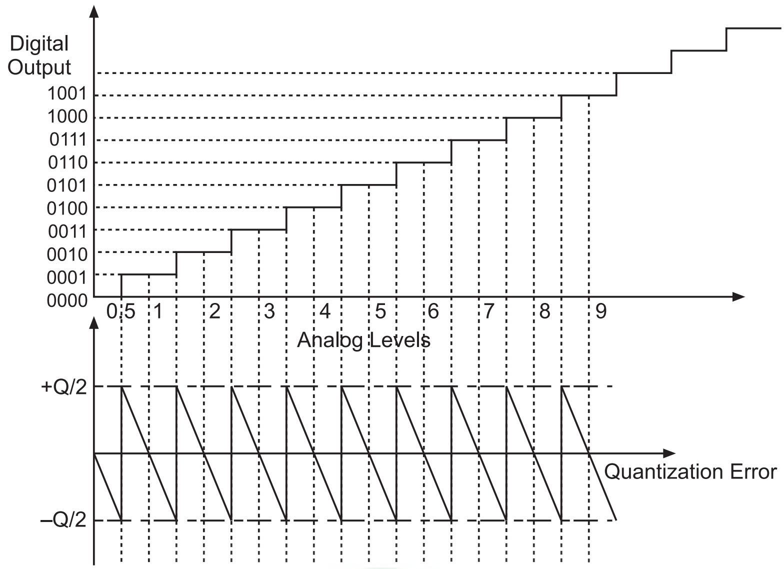


Fig. 8.43 Quantization Error for 1-Voice Quantization Level

8.7.2 Digital Data Format

Although the binary is most basic form of digital representation and used for hardware implementation, there are several other formats which at times are more convenient for data handling-display, recording, documentation etc.

Typically decimal for convenient manipulation to verify, hexadecimal for compact expression particularly with words of large bit size and binary coded decimal (BCD) for display especially convenient to human operators. The choice of the format therefore will be governed by the application, and conversion from one form to other must be understood. For details please refer to bibliography.

8.7.3 Data Conversion

Modern day instrumentation systems are involved with a large number of variables to be monitored, transmitted, recorded and processed. The task can be made simpler by embedding the computers in data handling. Since most of the system/process variables are analog in nature, a data conversion operation is necessary *viz.* from analog to digital and later from digital to analog. There are many approaches are currently available but a hardware conversion is preferable to software approach because of faster speed of conversion and after conversion computer is able to provide suitable processing and manipulation efficiently.

It is logical to discuss the analog to digital converters (ADC) first, but some of the ADC configurations make use of digital to analog converters (DAC) in their operation, it is considered necessary to discuss DACs before starting with the description of ADCs.

8.7.4 Digital to Analog Converters/Decoders

These are required to interface the digital computer with the analog systems/devices. The process of data conversion from digital-to-analog format requires 4 major elements:

1. Logic circuitry
2. Resistor network, according as the type of digital code.
3. Means of switching a reference voltage/current to proper input terminals as function of digital input values;
4. Reference voltage with a bidirectional output switch to bringing positive/negative reference voltage according as the sign of digital word.

A general layout with the above components is shown in Fig. 8.44 for a 4-bit D/A decoder having 3 magnitude bits and MSB as the sign bit and operating with parallel digital word as input. As will be noticed later that, it will be possible to extend this configuration to any number of bits operation.

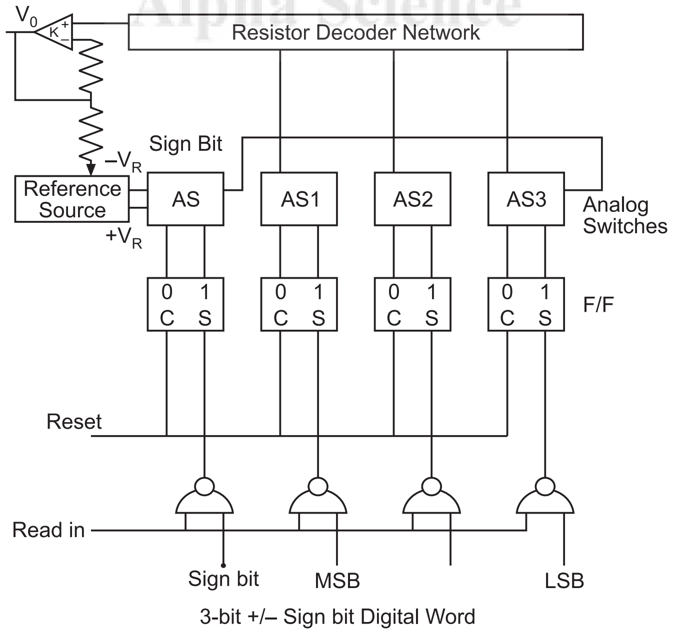


Fig. 8.44 Architecture of D/A Decoder

An R-2R ladder network is commonly used and shown in Fig. 8.45 and Table 8.7 provides the outcome for positive input for three significant bit values. The results for any other combination can be obtained using superposition principle.

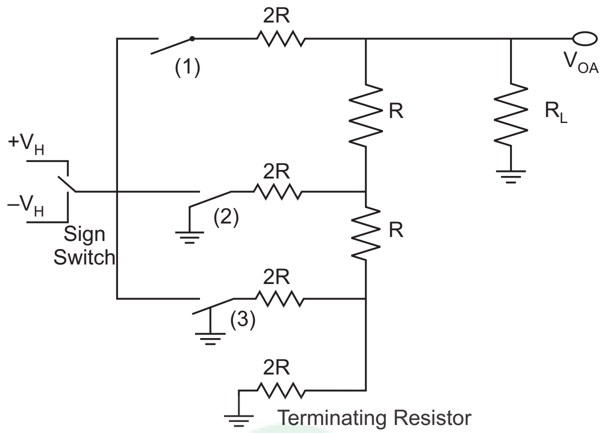


Fig. 8.45 Resistor Network for R/2R Type DAC

An increase in the number of bits of digital input data does not change the weights of bits starting from MSB but the resolution is altered as LSB is reduced by a factor of 2 for each bit added.

TABLE 8.7 Output of R-2R Type DAC (for Fig. 8.45)

Digital input	*Analog output*	*Internal resistance*
1 1 0 0	$\frac{V_R}{2}\left(\frac{R_L}{R+R_L}\right)$	R
1 0 1 0	$\frac{V_R}{4}\left(\frac{R_L}{R+R_L}\right)$	R
1 0 0 1	$\frac{V_R}{8}\left(\frac{R_L}{R+R_L}\right)$	R
1 1 1 1	$\frac{7V_R}{8}\left(\frac{R_L}{R+R_L}\right)$	R

For an '*n*'-bit digital data, it can be formalized that:

Quantization steps, $V_{OA} = \frac{V_R}{2^n}$ ...(8.88)

And, the number of quantization steps are $(2^n - 1)$ in going from all 0 to all 1s.

In general, $$V_{OFs} = (2^n - 1)\frac{V_R}{2^n} \quad ...(8.89)$$

For achieving a specified full-scale output V_{oFS} the required reference voltage can be calculated as:

$$V_R = \frac{2^n V_{OFs}}{(2^n - 1)} \quad ...(8.90)$$

And the equivalent output for '*n*'-bit digital data can be expressed as

$$V_{OA} = \left[\frac{1}{2}D_1 + \frac{1}{4}D_2 + \frac{1}{8}D_3 + ... + \frac{1}{2^n}Dn\right]V_R\left(\frac{R_L}{R + R_L}\right) \quad ...(8.91)$$

where D_1 represents *MSB* and D_n the *LSB*;

D_i, i = 1, 2,………, n can have values 0 or 1.

EXAMPLE 8.13

Find the analog output of an unsigned 10-bit DAC with reference voltage of 12 volts, if the digital input is (i) B5H (ii) 20FH. Neglect loading effect.

SOLUTION:

(*i*) B5H = $00\ 1011\ 0101_2$

$$\therefore\ V_{OA} = \left(\frac{1}{2^3} + \frac{1}{2^5} + \frac{1}{2^6} + \frac{1}{2^8} + \frac{1}{2^{10}}\right) V_R = 2.121082317 \text{ V}$$

(*ii*) 20FH = $10\ 0000\ 1111_2$

$$\therefore V_{OA} = \left(\frac{1}{2} + \frac{1}{2^7} + \frac{1}{2^8} + \frac{1}{2^9} + \frac{1}{2^{10}}\right) V_R = 0.514648437 \times 12 \text{ V}$$

= 6.175781244 volts = 6.1758 Volts.

EXAMPLE 8.14

Find full-scale analog output for a 10-bit DAC and its resolution, if V_R = 12 V

SOLUTION:

Full-scale analog output

$$V_{OFs} = \frac{(2^{10} - 1)V_R}{2^{10}} = \frac{1023}{1024} \times 12 = 11.9882 \text{ V}$$

$$\text{Resolution} = \text{Value of LSB} = \frac{V_R}{2^n} = \frac{12}{2^{10}} = 0.011718 \text{ volt}$$

$$= 11.72 \text{ mV}$$

EXAMPLE 8.15

Find the number of bits required to provide output increment of 1mV or better if reference voltage V_R is known to be 10 V.

SOLUTION:

Since, resolution $\Delta V = \dfrac{V_R}{2^n}$

$$\therefore \quad 2^n = \frac{V_R}{\Delta R} = \frac{10}{1 \times 10^{-3}} = 1000$$

$$\therefore \quad n \log 2 = 4$$

$$\therefore \quad n = \frac{4}{\log 2} = \frac{4}{0.30103} = 13.28 \cong 14\text{-bits}$$

(Always an integer value is to be taken and on the higher so that actual performance shall be better than the specified)

Actual increment achieved shall be

$$= \Delta V' = V_r / 2^{14} = 6.1035 \times 10^{-4}$$

$$= 610.35 \ \mu\text{V}$$

With $n = 13$, increment : L.S.B. value = 1.22 mV !!

An alternate approach is to evaluate the analog output is by finding decimal equivalent of digital data given and expressing it as a fraction of total counting states possible with n-bits used.

With this $V_{oa} = \dfrac{V_{10}}{2^n} V_R$

EXAMPLE 8.16

For an 8-bit digital input B5H (or 1011 0101 $_2$), with V_R=12 V, N = 181 will provide DAC output

$$V_{oa} = \frac{181}{2^8} V_R = \frac{181}{256} \times 12 = 8.4843 \text{ volts}$$

Other D/A decoder types

(*a*) Single valued current D/A decoder: The components used to implement this are similar as in the previous case of binary digital to analog decoder using R/2R type network. The difference is in the use of current sources instead of voltage reference source and the R/2R network arranged little differently as shown in Fig. 8.47.

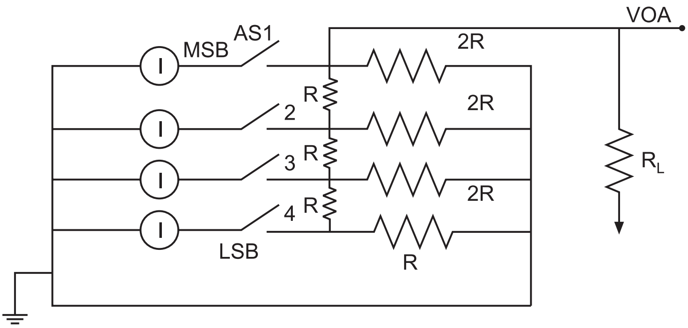


Fig. 8.47 Resistive Network for Single Valued Current D/A Decoder

Current sources are of same magnitude for each bit in 1 state regardless of the significance, and have much greater resistance than 2R.

Output V_{OA} for *ON* state of various bits for a 4-bit input to *DAC* is presented in Table 8.8.

The general equation for the analog output can be arrived at:

$$V_{OA} = \left[\frac{2}{3}D_1 + \frac{1}{3}D_2 + \frac{1}{6}D_3 + ... + \frac{2/3}{2^{n-1}}D_n\right] I_R \left(\frac{R_L}{R_O + R_L}\right) \qquad ...(8.92)$$

where $R_O = \dfrac{2R}{3}$ for each case.

TABLE 8.8 Performance of Current D/A Decoder

Digital input	***Analog output***		***Ro***
	No load V_{OA}	***V_{OA} on load***	
1000	$\frac{2}{3}IR$	$\frac{2}{3}IR\left(\frac{R_L}{R_O+R_L}\right)$	$\frac{2}{3}R$
0100	$\frac{1}{3}IR$	$\frac{1}{3}IR\left(\frac{R_L}{R_O+R_L}\right)$	$\frac{2}{3}R$
0010	$\frac{1}{6}IR$	$\frac{1}{6}IR\left(\frac{R_L}{R_O+R_L}\right)$	$\frac{2}{3}R$
0001	$\frac{1}{12}IR$	$\frac{1}{12}IR\left(\frac{R_L}{R_O+R_L}\right)$	$\frac{2}{3}R$
1111	$\Sigma = \frac{5}{4}IR$	$\frac{5}{4}IR\left(\frac{R_L}{R_O+R_L}\right)$	$\frac{2}{3}R$

(*b*) BCD to analog decoder: Figure 8.48 shows the resistor network for an 8-bit *BCD* to analog decoder with different weights assigned to each digital bit by associated resistance in relation with the weights.

The calculation of output for different input digital words is produced for a few sample values in Table 8.9. It can be observed that:

A '1' in LSB corresponds to $V_{OA} = \frac{1}{165} V_R \left(\frac{R_L}{R_O + R_L} \right)$ ...(8.93)

and, a '1' in MSB corresponds to its weight of 80 as:

$$V_{OA} = \frac{80}{165} V_R \left(\frac{R_L}{R_O + R_L} \right) \quad ...(8.94)$$

A full-scale input of 99 can, provide an output

$$V_O A_{F.S} = \left(\frac{80}{165} + \frac{10}{165} + \frac{8}{165} + \frac{1}{165} \right) V_R \left(\frac{R_L}{R_O + R_L} \right)$$

$$= \left(\frac{99}{165} \right) V_R \left(\frac{R_L}{R_O + R_L} \right) \text{ volts}$$

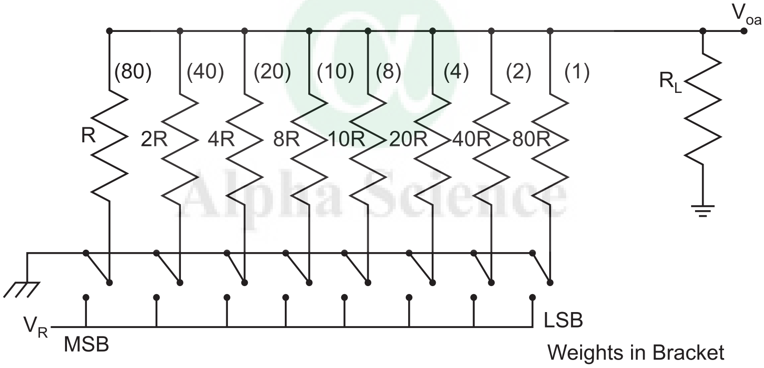


Fig. 8.48 8-bit BCD to Analog Decoder

TABLE 8.9 Input-output Relations of an 8-Bit-BCD D/A Decoder (Sample)

WeightsBCD input	***80***	***40***	***20***	***10***	***8***	***4***	***2***	***1***	***Analog equivalent***
00	0	0	0	0	0	0	0	0	0
06	0	0	0	0	0	1	1	0	6
15	0	0	0	1	0	1	0	1	15
79	0	1	1	1	1	0	0	1	79
99	1	0	0	1	1	0	0	1	99
X	1	1	1	1	1	1	1	1	165

8.7.5 Analog to Digital Converters

This is one of the most important devices for interfacing the system/plant/process with computer. The functional diagram of an ADC is shown in Fig. 8.49 and its functioning is complimentary to DAC discussed earlier.

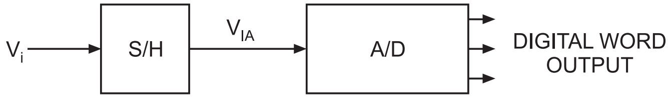


Fig. 8.49 Representation A-D Converter with Sample Hold

There are various types of ADCs available and these can be classified in different ways, such as:

(*i*) **Programmed,** for which the conversion from analog to digital occurs in a fixed number of steps, each clocked to fixed time interval.

or, Non-programmed, for which conversion of data occurs as a sequence of events, not in fixed-time steps. The time taken for each step depends on response time of (circuit) elements involved.

(*ii*) **Open-loop type,** where analog input is compared with a reference input and the result of comparison is digital word equivalent to analog input.

Or, feedback (closed-loop) type, in which data conversion is used for comparison of digital output with the input (analog) to be converted, until both become equal.

(*iii*) **Based on hardware configuration, according as**

Capacitor charging type, using the principle of digital encoding of time to charge a capacitor to a reference value/analog input. The examples include:

- Voltage-to-frequency type A/D converter
- Pulse Width Modulator(PWM) type A/D converter
- Dual slope integration type A/D converter

and **Discrete Voltage Comparison Type,** wherein discrete voltage levels are generated to result in a digital word, by comparison of discrete voltage against input analog type to find equivalent digital (value) combination. The process can be sequential, simultaneous or a combination of both. The examples of this class include:

- Counter ramp type

- Successive approximation type
- Flash (or simultaneous) type
- In the present text, it has been preferred to use the last type of classification for discussion about the each type of ADC.

8.7.5.1 Capacitor charging type ADCs

These are generally low priced, slow in operation and modestly accurate.

(*i*) *V*/*f* conversion type ADC: Configuration of this type of *ADC* is shown in Fig. 8.50. The analog input voltage V_{IA} to be converted into digital format is first converted into an analog current signal, which is integrated using an integrating–directly coupled amplifier. The integrated output voltage is compared with a reference V_R (of same polarity). Only one of the analog comparators will be active and provide a window action for the counter to allow a clock signal from the 'programmer' (/decision making unit) to produce a digital word out put continues to increase until the recently active analog comparator achieves a balance of inputs *i.e.* comparator output is zero, to close the window. At this stage the word output does not change further and it is calibrated to read out the analog input voltage V_{IA}, due to which the actions started. The process takes a very small time even for a 16-bit conversion (≅ 20 μ second with a 1 MHz clock) and the reading is intended to be updated at regular (pre decided) intervals, with output of counter from the programmer and the current integrator.

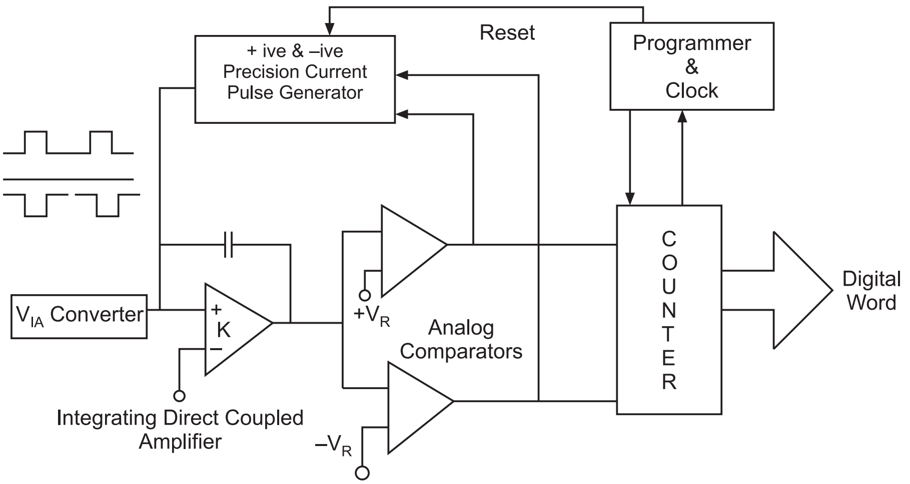
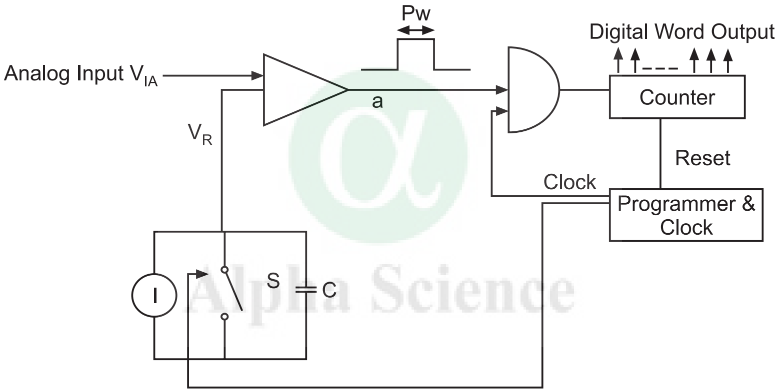


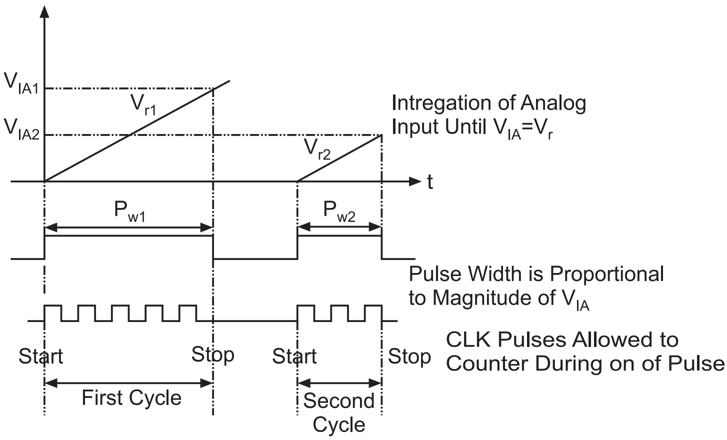
Fig. 8.50 V/f Conversion Type ADC

The integration process is reset by providing a precision current pulse at the integrator input terminal of reverse polarity, from a current pulse generator, to exactly cancel the integrator input (and, the output too with a small response time) and the process of A to D conversion resets. The process goes on. The number of clock pulses allowed into the counter has inverse relationship with the magnitude of analog input voltage *i.e.* with larger input voltage the time taken to reach the fixed ± *ve* will be smaller and therefore the number of pulses shall also be small and vice versa.

(*ii*) Pulse width modulator type ADC: In this configuration as shown in Fig. 8.51, the analog signal input V_{IA} is converted to a pulse with its width/ON-time proportional to magnitude of V_{IA}, by using a comparator. To provide a comparison reference to the comparator, a constant current source is used to charge capacitance *C* by opening the switch S through a programmed action.



(a) Configuration



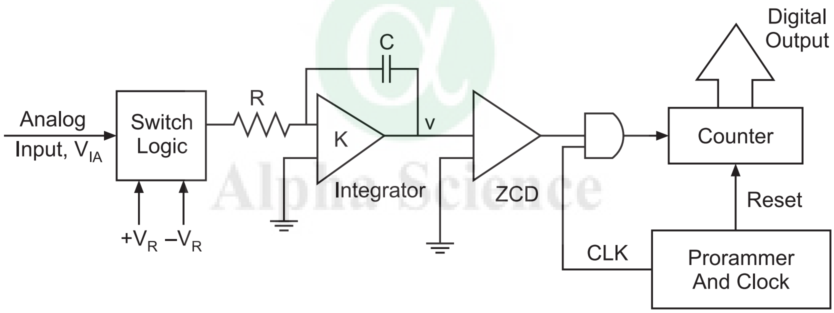
(b) Conversion Process for 2 Values of Input-analog Signal, V_{IA1},(first cycle) and V_{IA2}(2nd cycle)

Fig. 8.51 PWM type of AD converter

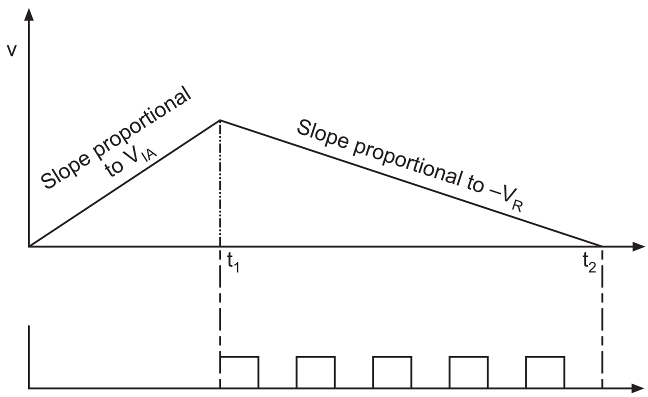
Output of comparator will be available as long as V_r is smaller than V_{IA} and longer the pulse width or output (*a*) available, AND gate will allow the clock pulses available from programmer unit, to be transmitted to increment the counter providing digital output.

As soon as the two comparator inputs become equal, comparator out put is (*a*) is not available and clock pulses are no more allowed through the gate. The counter output is freeze and the current counter out put is a measure of pulse width and hence of. The process is shown in Fig. 8.51 (*b*) for input analog values and. Calibration of system is obtained for known current source, *C* and clock pulse rate. Updation at regular intervals as programmed is available by closing the switch *S* and initializing the counter at desired rate of updation usually in milliseconds. This is sometimes also referred as single slope integration type of *ADC*.

(*iii*) Dual slope integration type ADC: The arrangement for this type of ADC as shown in the Fig. 8.52 is an improvement over the previous one, that the chosen input analog voltage is integrated over a



(a) Configuration of Dual-Slope Integration Type ADC



(b) Operation and Timing Diagram

Fig. 8.52 Dual Slope Integrator Type ADC prefixed interval of time t_1 through an integrator. The end of this interval the input signal is removed and a fixed reference voltage of opposite polarity is switched, so that a reverse integration starts, through the same integrator. The integrator output starts reducing and a comparator acting as Zero Crossing Detector, provides output to the AND gate, as long it takes the zero crossing to be detected. During this period, T_2 only the clock pulses are allowed through the AND gate into the counter to increase the digital output.

Thus the digital output attained over the period T_2 is a measure of the input voltage V_{iA}.

It can be seen that, during the integration over time 't_1'

$$v_1 = \frac{1}{RC}\int_0^{t_1} V_{iA}dt = \frac{V_{iA}t_1}{RC} \quad \text{...(8.95)}$$

During reverse integration beyond 't_1' over the interval '$t_2 - t_1$'

$$v' = v_1 - \frac{1}{RC}\int_{t_1}^{t_2} V_R dt = v_1 - \frac{V_R}{RC}(t_2 - t_1) = 0$$

$$\therefore \quad v_1 = \frac{V_{iA}t_1}{RC} = \frac{V_R}{RC}(t_2 - t_1)$$

$$\therefore \quad V_{iA} = V_R\frac{(t_2 - t_1)}{t_1} = \frac{V_R NT}{2^N T} = \frac{V_R N}{2^N} \quad \text{...(8.96)}$$

where $t_1 = 2^N T$; T being clock pulse period;

N = number of clock pulse allowed during $t_2 - t_1$ = digital count

$= N \times T$

Since t_1 is fixed V_{iA} is directly proportional to number of clock pulses allowed during the interval $(t_2 - t_1)$. As can be easily observed that for desired accuracy $|V_R|$ and clock rate should be appropriately chosen. These are also known as up-down integrating type *ADC*.

The process of conversion is slow from updation point of view as it involves integration, converted value represents the average value of input and therefore not suitable for dc or low frequency input signals. It can be used for signals with larger time constant where rate of updating is not very important such as for digital panel meters, digital multi-meters and weighting scales.

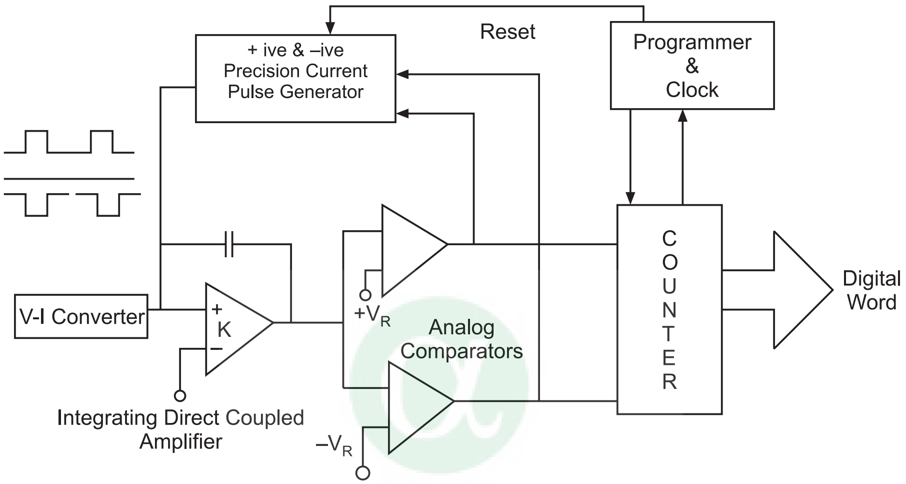
With the availability of high quality clock sources, the conversion accuracy to 20-bits and more is possible. This makes it ideal for instrumentation.

Additional advantage is that, the accuracy of integrating elements and nonlinearity of integration process gets cancelled due to forward and reverse integrations through same elements.

EXAMPLE 8.17

For a voltage to frequency converter providing frequency output over a range of 4.6 kHz to 37 kHz (with the change of input voltage) suggest an ADC and evaluate the time taken to show the maximum values in the counter and the counter value for minimum frequency output.

SOLUTION:



$$f_{min} = 4.6 \text{ kHz}$$
$$f_{max} = 37 \text{ kHz}$$

Sensor output maximum for maximum input

For n-bit counter count = $2^n - 1$

$\therefore$ for count time $T_c = \dfrac{2^n - 1}{f_{\max}}$

For any other frequency, $N = f.T_c$

10-bit counter has maximum output $2^{10} - 1 = 1023$

$\therefore$ For maximum frequency count time must allow counter to reach full 1023 *i.e.* $(1\ 111\ 111\ 111)_2$

$$\therefore \qquad T_c = \frac{2^{10} - 1}{37 \times 10^3} = \frac{1023}{37} = 27.64 \text{ m sec.}$$

For 4.6 kHz frequency input (minimum), count = $N = 4.6 \times 10^3 \times T_c$

$= 4.6 \times 27.64 = 127.1837 \cong 127$ (only integer value admissible).

8.7.5.2 Discrete voltage comparison type ADCs

(*i*) Counter Ramp type has a feedback configuration as shown in the Fig. 8.53. The analog value of signal to be converted into digital format generally obtained by sample and hold operation performed on the input ac signal, is compared in the input comparator with an analog equivalent signal of the current digital output (zero at the start.). Thus the output of comparator is high at the start and therefore the AND gate allows clock pulses into the counter providing a digital output. For this digital output, analog equivalent is obtained using a DAC (as discussed earlier), and provides a feedback at the input comparator. As long as the two analog signals do not become equal, counter will continue to receive clock pulses and the digital out-put is incremented monotonically.

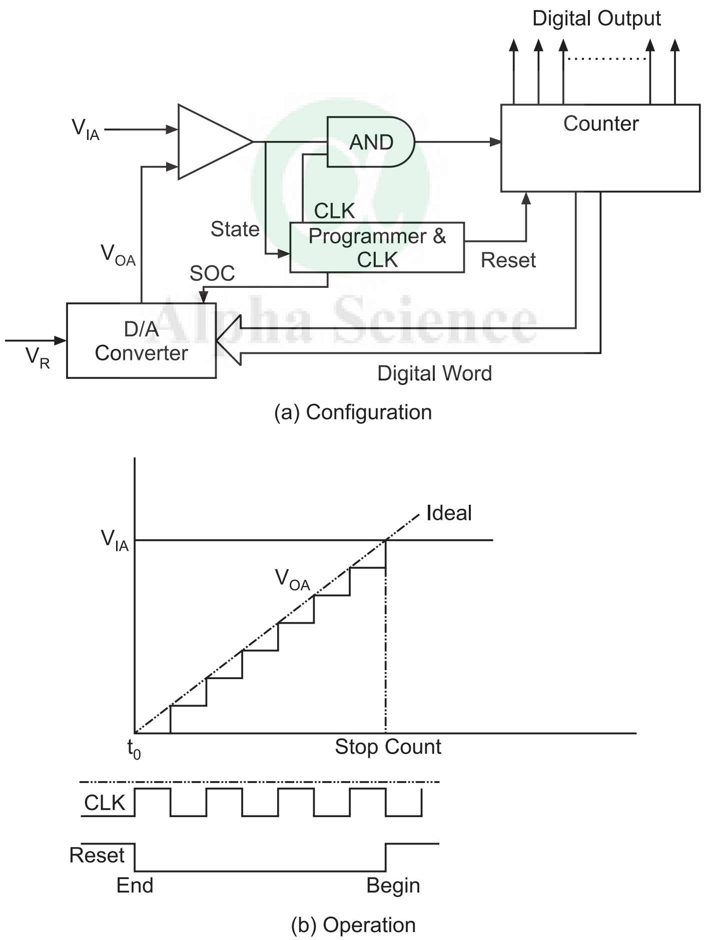


Fig. 8.53 Counter Ramp Type ADC

The moment comparator output becomes zero, the counter out-put shows up the desired digital equivalent of analog signal at the out-put. The counter is not incremented any more. The process is shown in Fig. 8.53(*b*).

The conversion is repeated by resulting the counter by a programmed (clockwise) reset pulse.

This ADC is asynchronous in operation and the time taken for conversion is dependent on the magnitude of input analog signal whose digital equivalent is to be found.

The time taken for an *n*-bit digital signal to reach full-scale display would be $(2^n - 1) \times$ (clock pulse period), and is considered slow for most of the computer enabled systems though used commonly with DVMs and DMMs due to simplicity and economy.

(*ii*) Successive approximation type ADCs has smaller conversion time. The Fig. 8.54(*a*) shows the typical logic of comparisons being made in this ADC, for a 3-bit example.

A trial and error procedure is implemented with the help of a programmer which starts by providing a reference digital out-put with '1' in MSB and all other bits as '0'. This digital signal converted to analog by the DAC. is compared with the input analog signal in the successively in the manner as shown below:

I Comparison: If $V_{IA} \geq V_{OA_1}$ TRUE then compare with

$V_{OA_2} = 110$

If FALSE then compare with $V'_{OA_2} = 010$

II Comparison: (*i*) If $V_{IA} \geq V_{OA_2}$ TRUE then compare with

$V_{OA_3} = 111$

FALSE then compare with $V'_{OA_3} = 101$

or, (*ii*) If $V_{IA} \geq V'_{OA_2}$ TRUE then compare with

$V_{OA_4} = 011$

FALSE then compare with $V'_{OA_4} = 001$

III Comparison:

(*i*) If $V_{IA} \geq V_{OA_3}$	True then	Output = 111
	False then	Output = 110
(*ii*) If $V_{IA}(> V_{OA_2}) \geq V'_{OA_3}$	True then	Output = 101
	False then	Output = 100
(*iii*) If $V_{IA}(< V_{OA_2}) \geq V_{OA_4}$	True then	Output = 011
	False then	Output = 010

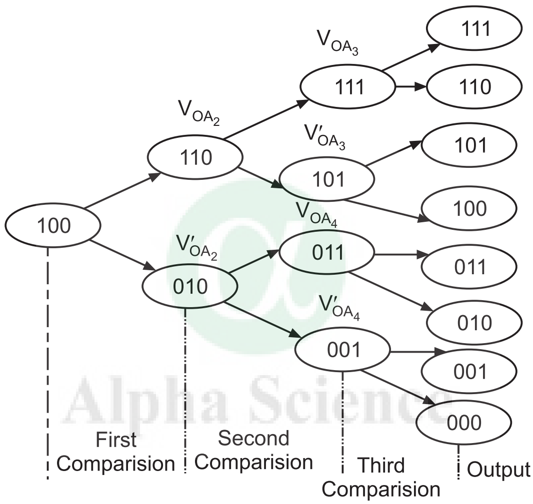
(*iv*) If $V_{IA}(< V_{OA_2}) \geq V'_{OA_4}$ True then Output = 001

False then Output = 000

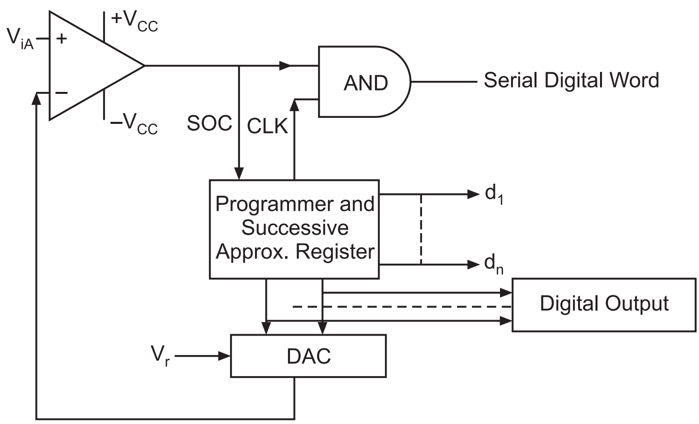
The above process of logical comparison is shown in Fig. 8.54 (*a*) and is extendable to any number of bits system. It is to be noticed that for a 3-bit ADC it took 3 comparison steps.

As can be seen, the member of comparisons required to reach the full scale *i.e.* '*n*'-bit equivalence, will be '*n*', same as the number of bits.

To implement the above logic of comparison a programmer and a set of successive resisters (SAR) will be needed. A hardware configuration is shown in Fig. 8.54(*b*), is general.



(a) Operational Logic for a 3-bit Converter



(b) Hardware Configuration for Implementation of SA type ADC

Fig. 8.54 Successive Approximation Type A/D Converter

The successive approximation type ADC takes only 'n' steps of comparison to reach the full-scale display each and every time independent of the magnitude of input analog signal. It is therefore also referred as synchronous conversion, reduces conversion time from $(2^n - 1) \times$ (periods of clock pulse) for counter ramp type to $n \times$ (period of clock pulse), as each comparison can be affected during one clock pulse period.

(*iii*) Flash/Simultaneous *A-D* converters are the one shot converters and the result of conversion can be realized over one clockwise period by extending the voltage comparison method as discussed above.

This is achieved for an 'n'-bit converter by making $(2^n - 1)$ comparisons simultaneously as shown in Fig. 8.55 using as many reference voltages, logic circuit and an 'n'-bit priority encoder which encodes the out-put bits corresponding to the TRUE and FALSE conditions with $(2^n - 1)$ comparators.

This is the fastest *ADC* but the speed is realized at a much higher cost.

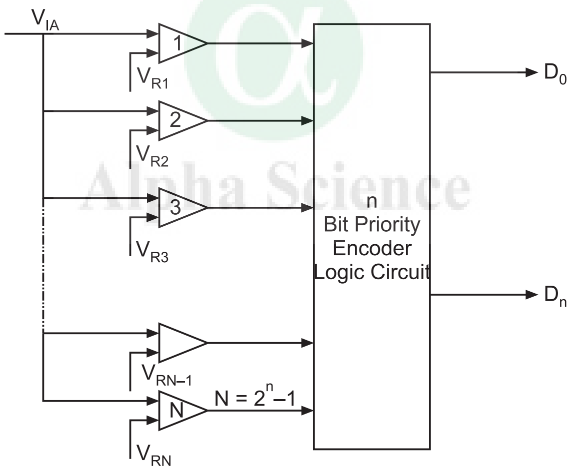


Fig. 8.55 Flash/Simultaneous Type ADC

EXAMPLE 8.18

An 8-bit 20 μs bipolar ADC with V_R = 5.0 V monitors a Sine signal with 3.00 V peak amplitude, What is the maximum frequency that can be tracked to 8-bit accuracy? (Concept: conversion time consequences)

SOLUTION:

In discrete voltage comparison type ADCs comparison of feedback value with input determines final converted values. Therefore If input changes during conversion then error will occur (by more than least count, ΔV, during τ_c)

$$\frac{dv_{in}}{dt} < \frac{\Delta V}{\tau_c} = \frac{V_R/2^n}{\tau_c}$$

From the given data

$$\frac{dv_{in}}{dt} \leq \frac{5/2^8}{20 \times 10^{-6}} \cong \frac{10^6 \times 5}{256 \times 20}$$

$$\cong 976.56 \text{ V/sec}$$

$$\cong 977 \text{ V/sec}$$

Let us consider, to what frequency it would be correspond to, if input is sine(wave) voltage

$$v_{in} = v_m \sin \omega t$$

$$\frac{dv_{in}}{dt} = \omega v_m \cos(\omega t) \leq \frac{\frac{v_R}{2^n}}{\tau_c} \quad \therefore \omega = \frac{v_R}{2^n \tau_c v_m}$$

$$\therefore \qquad f = \frac{v_R}{2\pi 2^n \tau_c v_m}$$

For use of full range, let $v_0 = v_R \therefore \omega < \dfrac{5}{2^8 \times 20 \times 10^{-6} \times 3} \leq 325.52$ rad/sec

$$\therefore \qquad f = 51.83 \text{ Hz}$$

$\therefore$ Note that a 20 μ sec converter can not find an 8-bit representation of oscillating signal > 51 Hz !

Flash converters are fastest type of ADC but the need of a large number of comparators, makes it very expensive in terms of area and power consumption with increase of the number of bits in digital word, n. The input buffer-needs to drive the capacitance of $2^n - 1$ comparators, increases the demand of power. These are therefore not recommended above 8-bits converters.

8.7.5.3 A new approach to get over this problem results in sub-ranging ADC

An improvement in flash type ADC as above is achieved in 2-step converter.

The principle is shown in Fig. 8.56, that the conversion process is split in two steps.

First step uses a flash converter to generate first 'm'-bits, followed by a DAC whose output is subtracted from the original signal (sampled and held).

In second step, the residue is amplified by 2^n and conversion applied to '$n - m$'-bits.

If $m = n/2$, the complexity is reduced by order of n (say 8, for an 8-bit ADC) with speed also reduced by 2. This feature of configuration can be helpful in a variety of applications.

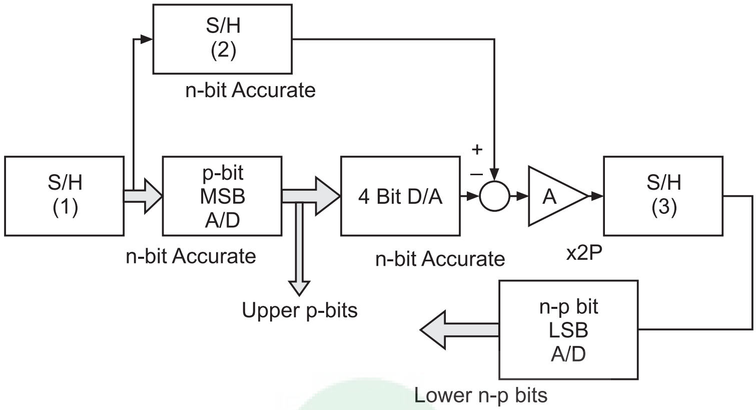


Fig. 8.56 n-bit Subranging A/D Converter

8.7.5.4 Properties of A-D converters

Resolution of a data converter is the smallest change that can be produced in the input (or output). Resolution of an 8-bit D/A converter, with $(2^n - 1)$=255 intervals between zero and full-scale value is given by,

$$\text{Resolution} = \frac{V_{FS}}{2^n - 1} = 1\ lsb\text{, in volts.}$$

It can be stated alternatively as:

For 8-bit *ADC*	For-16 bit *ADC*
1 part in 255	1 part in 64K
A resolution of 0.392% of full-scale	a resolution of 0.15% of full-scale
8-bit resolution	16-bit resolution

The resolution of an *ADC* is defined as the smallest change in analog input for a change of least significant bit in the output. For example, 8-bit converters can have 255 intervals in output and corresponding to the smallest interval in a 10 V range of input, resolution will be $\frac{10V}{255} = 39.22$ mV and for a 16-bit ADC it will be 0.15 mV. In Table 8.10, resolution is shown for various bit size of ADCs.

TABLE 8.10 Resolution of ADCs

Bits	*Intervals*	*lsb (% of F.S)*	*lsb (10V F.S)*
8	255	0.392%	39.2 mv
10	1023	0.0978%	9.72 mv
12	4095	0.0244%	2.44 mv
16	65535	0.0015%	0.15 mv

Linearity: In an ideal DAC, equal changes in digital input should produce equal changes in analog output and the transfer curve should be linear. However, in practice it may not be always true, as shown in Fig. 8.57 for a 3 magnitude bit *DAC*, linearity error is a measure of deviation δ from the best fitted line (to the measured output points) for a true change Δ and expressed in %.

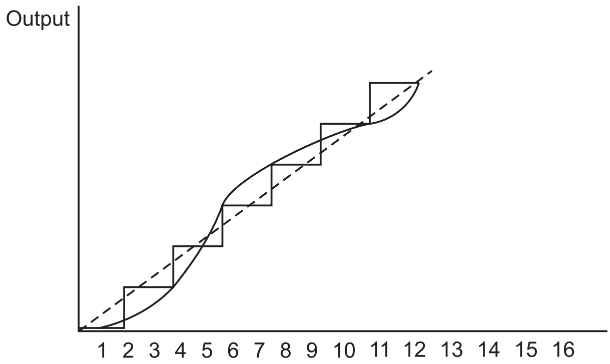
$$\text{Linearity error} = \frac{\frac{\delta}{\Delta}}{\text{full-scale voltage}} \times 100\ \% \,. \qquad \text{...(8.97)}$$

Accuracy: Absolute accuracy is defined as maximum deviation between actual and ideal converter outputs. Moreover it is more common to specify the relative accuracy as the maximum deviation noticed after compensating for gain and offset errors. It is expressed in terms of lsb increment or as the percentage of full-scale voltage.

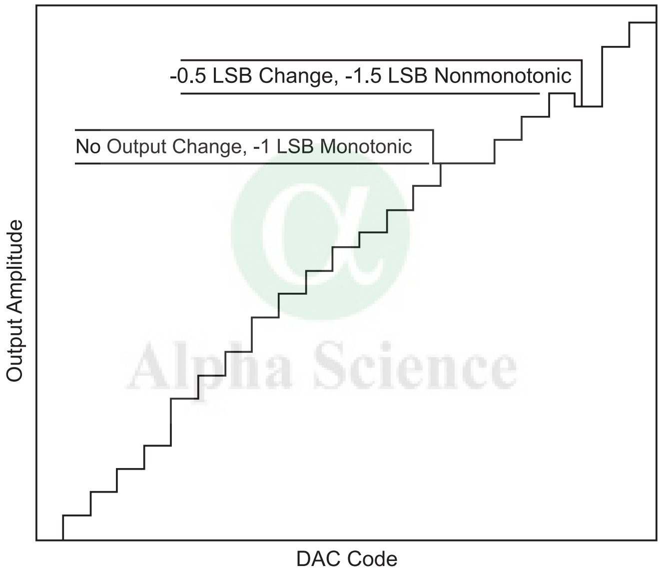
Monotonicity: An ADC is said to be monotonic if the analog output increases for every increase in digital input. This is essential in control applications to prevent occurrence of oscillations due to this nonlinear characteristic. To achieve monotonicity, linearity error must be less than $\pm\frac{1}{2}$ lsb at each output level.

Settling time: The time taken to complete the conversion for a full-scale change of input and settle within $\frac{1}{2}$ lsb of the final steady value is called settling time. Depending upon the word length, switching time of logic circuitry, resistive network and passive capacitance magnitudes, it may vary from 100 nsec to microseconds.

Stability: The stability of offset, gain, linearity can vary with temperature variation, passage of time (age) and variations in supply. These are specified over full temperature range.



(a) Input and Output Equivalent Relation for a 3-bit DC



(b) Example of Non-monotonous Conversion

Fig. 8.57 Linearity of 3-bit ADC

Remarks

Signal conditioning in both analog and digital formats is of interest in practical systems. Quite often the solution strategy may provide the best results with combination of both in different sections of the instrumentation channels. Now that, the signal has been converted into desired format, the next step would be to transfer it/telemeter it to control room where the decision is to be taken as to what is to be done with the information obtained.

Next discussion shall be on the telemetering and networking of information.

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Lam, K.F.-Active and digital filters-Design and realization (PH)

REVIEW PROBLEMS

(*i*) What is the purpose of signal conditioning? What processing operations the term includes?

(*ii*) Why the common 4-arm ac bridges can not be used with inductance or capacitance of transducer in one of the arms?

(*iii*) What is understood by the sensitivity adjust in a transducer bridge?

(*iv*) What is zero-adjust in dc bridges?

(*v*) Why are precision diodes needed in instrumentation applications?

(*vi*) Explain the operation and advantages of precision diodes.

(*vii*) What are chopper amplifiers and their role in transducer signal conditioning?

(*viii*) Explain the realization and operation of full-wave precision rectifier?

(*ix*) What are the typical applications of isolation amplifiers? Explain clearly.

(*x*) Compare the two common methods of providing isolation between input and output sides.

(*xi*) Explain the logical operations in the R-2R type of Digital-to-analog converters.

(*xii*) Explain the process of obtaining analog output from the configuration of R-2R type DAC corresponding to various digital input signals with examples.

(*xiii*) What type of ADC is commonly used in digital voltmeters?

(*xiv*) What is the major advantage of BCD code for displays?

(*xv*) What are the maximum values that can be displayed in a) 8-bit b) 12-bit c) 16-bit displays?

(*xvi*) Explain the conversion logic in a successive approximation type ADC for 4-magnitude bits input word. How the sign can be included?

PROBLEMS FOR EXERCISE

8.1 Explain the operation for sine input V_i in the circuit shown in Fig. Q. 8.1? What could be the possible application of this circuit?

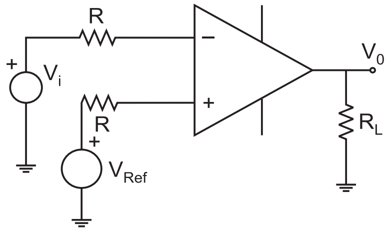


Fig. Q. 8.1

8.2 For the circuit shown in Fig. Q. 8.2, Calculate (a) V_0 for $V_1 = 5V$, $V_2 = 2V$.

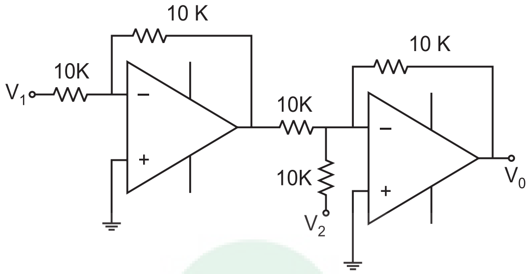


Fig. Q. 8.2

8.3 For the circuit shown in the Fig. Q. 8.3 calculate V_0

If (*a*) $V_1 = 0.1, V_2 = 0.2\ V_3 = -0.3$

$R_1 = 4K, R_2 = 3K, R_3 = 1K$

$R_f = 4.8K; R = 2.4K$

(*b*) $R_1 = R_2 = R_3 = 3R_f$

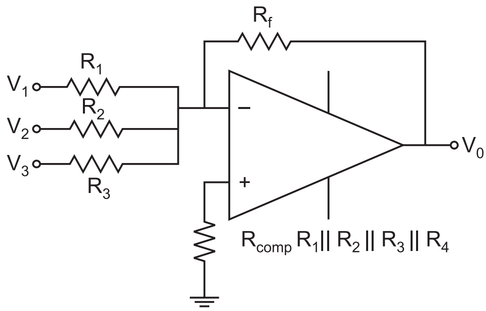


Fig. Q. 8.3

8.4 For the active network of Fig. Q. 8.4 calculate

(*a*) $V_{0,}$ If $R_1 = R_2 = R_3 = \dfrac{R_f}{2}$

(*b*) R_f, If $V_1 = V_2 = 1.5; V_3 = 3V$

$R_1 = R_2 = R_3\ R = 1.5K; V_0 = 5V$

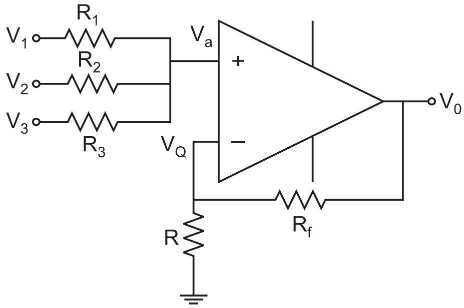


Fig. Q. 8.4

8.5 For the circuit given in Fig. Q. 8.5, show that $V_0 = a_1 V_1 + a_2 V_2 + a_3 V_3$ and find a_1, a_2, a_3. Also find, V_0 if (*i*) R_4 is short circuited. (*ii*) R_4 is removed. (*iii*) R_1 is short circuited.

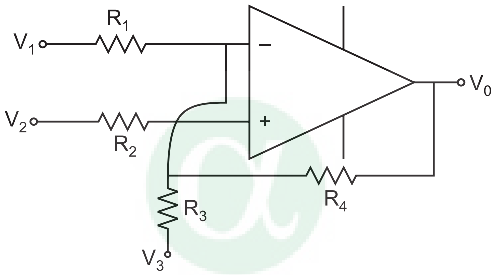


Fig. Q. 8.5

8.6 A practical integrator is shown in Fig. Q. 8.6. The parallel combination of R_f and C_f behaves like a practical (having losses) capacitor and R_f limits the low frequency gain to $\frac{R_f}{R_1}$ so as to provide dc stabilization.

(*a*) Evaluate the expression for gain $|A| = \left|\frac{V_0}{V_i}\right|$.

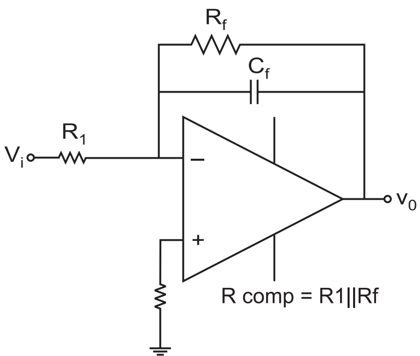


Fig. Q. 8.6

(*b*) Evaluate gain for $w = 0$, 1000 rad/s. If $R_f = 10K$, $R_1 = 1K$, $C_f = 0.01$ μ*f*.

(*c*) Find R_f and R_1, so that the peak gain is 20 dB and is 3 dB down from peak when $f = 10$ kHz, $C_f = 1$ *nf*.

8.7 For the 3 bridges shown in Fig. Q. 8.7 below:

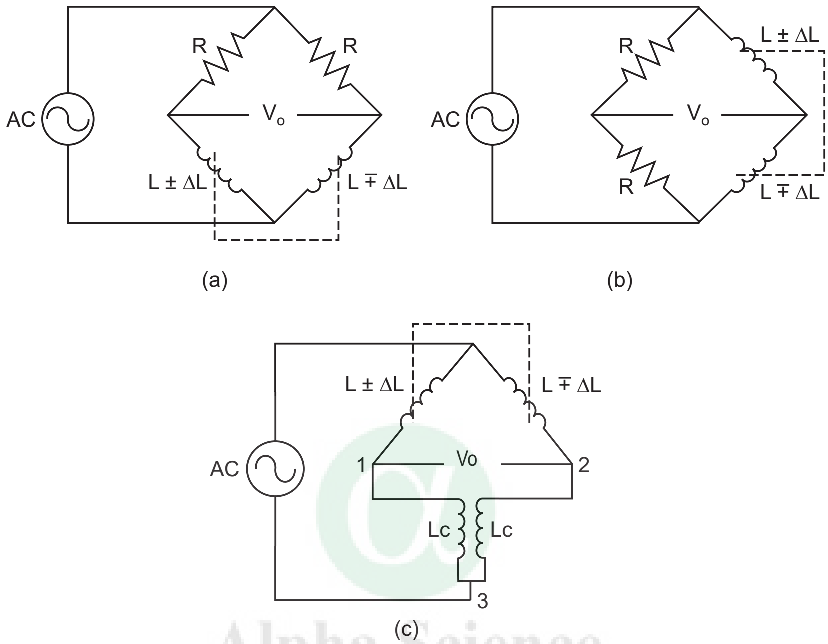


Fig. Q. 8.7

assume the transducer to have high *Q* and in a double coil push-pull form. In (*a*) & (*b*) balance is obtained by Resistance $R\,(= \omega L)$. In (*c*) balance is obtained by closely coupled ratio arms of mutual inductance *M*. Excitation source is V_s volts at ω rad/sec. and v_0 is output.

Derive bridge sensitivity $\left(\dfrac{v_0/v_s}{\Delta L/L}\right)$ for each bridge and compare their application, for inductive transducer.

8.8 A push-pull transducer of capacitive type is used with Blumlein bridge at 0.5 MHz. At balance the capacitance of each half (arm) is 300 pF. Determine

(*a*) Suitable values of inductance L_C, to have least sensitivity to change in L_C and bridge frequency of operation.

(*b*) Bridge output impedance at balance, unbalance.

8.9 Explain the operation of a grounded-load, OP-amp based V/I converter circuit.

8.10 How full-wave precision rectification is achieved? Draw a configuration, and explain the operation with details and necessary calculations.

8.11 Show the configuration of a 3-OP-amp standard instrumentation amplifier and derive its gain relation.

8.12 Calculate the CMRR required of an amplifier if the common mode error is to be kept within 0.1% with differential signal, common mode signals to be of the order of 1mV and 1V respectively.

8.13 What is the CM error of an amplifier experienced at the output if e_d and e_{cm} are of the order of 0.5 mV and 1V. CMRR of the amplifier is known to be 90dB.

8.14 Calculate the minimum differential signal into an amplifier that need be applied if the common mode error is to be limited to 0.1%, when the CM signal is about 2V and CMRR is 120 dB.

8.15 Calculate the desired CMRR of the amplifier if the common mode error is required to be within 0.001% with e_d about 1mv and e_{cm} about 5000 V, how can this much of CMRR be realized?

8.16 Design a filter using the Sallen-Key equal component low pass active filter to meet the following specifications:

(*a*) Roll-off rate : 40dB/decade

(*b*) Critical frequency : 2 kHz

(*c*) Pass band as flat as possible

(*d*) Gain of 5 at low frequencies *i.e.* dc gain

8.17 Design a filter using the Sallen-Key unity gain low pass active filter to meet the following specifications:

(*a*) Roll-off rate : 40 dB/decade

(*b*) Critical frequency : 1 kHz

(*c*) Pass band as flat as possible

(*d*) Gain of 5 at dc

8.18 Show the detailed architecture of R – 2R (decoder network) type of digital to analog converter with a neat sketch, indicating each block clearly.

Briefly discuss the conversion process.

8.19 For a DAC of this type, with 10 v reference, calculate the word length required to achieve output increment of 1 mV, the corresponding full scale analog output and output for a digital input of 24ABH.

8.20 Calculate the output of an 10-bit DAC with V_R = 10.0 V for input of

(*i*) 0A7H (*ii*) B5H (*iii*) 20FH find the output in each case.

How can you obtain an output of 6.50 V?

8.21 With the help of neat sketches, explain the operation of a dual slope *ADC*.

A dual-slope ADC has integrator components R = 100 KΩ and *C* = 0.1 μF. If the reference is 10V and the fixed integration time is 10 m sec, find the conversion time for a 7.8V analog input.

8.22 An analog voltage signal with highest significant frequency of 1 kHz is to be converted to an equivalent digital signal, with a resolution of 0.01%, covering a range of 0-10 V.

To avoid loss of information, find:

(*a*) Minimum sampling rate

(*b*) Minimum no. of bits in digital code

(*c*) Analog value of *LSB*

(*d*) RMS value of quantization noise

(*e*) Dynamic range of *ADC* in *dB*.

8.23 A dual slope ADC uses a 16 bit counter with a 5 MHz clock. The maximum input voltage is + 12V and maximum integrator output at 2^n count (after time t_1) is 9V. If *R* is chosen to be 1 MΩ find required value of capacitor in the integrator, to have desired performance.

8.24 If the above *ADC* has input analog voltage of 6.384 V, evaluate the corresponding digital output.

8.25 A 16-bit dual slope integrator type of *ADC* operates with a clock of 4 MHz and maximum input voltage, +10 V. If the maximum integrator output is limited to –8V, after the counter has cycled through 2^n count (fixed time) and *C* is 0.1 μ*F*, find the resistance required. Also calculate the output digital count and equivalent binary for analog input of 3.562 *V*?

8.26 Explain the principle of operation of a successive approximation type of *ADC*.

8.27 An analog input signal varies between-2 and +6 volts in an '*n*'-bit *A/D* converter. Calculate (*i*) quantization levels available (*ii*) resolution (*iii*) output for maximum and minimum magnitude inputs for number of bits taken to be 10 and repeat for 16-bits.

8.28 Temperature is measured by a sensor with an output of 0.02 V/°C. Determine the required *ADC* reference source voltage, and word size to measure 0°C to 100°C with 0.5° resolution.

CHAPTER 9

Telemetry and Networked Systems

Inside the Chapter

INTRODUCTION

The signals picked-up from the plant/process, by the transducer are conditioned – analog/and digitally, to bring into a format suitable for any or all of the three basic objectives – monitoring, control and analysis. Of these, monitoring is often local as well as in control room usually at a distance. Control action, almost always will require the conditioned signal to be transmitted to control room. Same is true for the analysis by recording and processingdevices for online as well as offline for various processes.

In this chapter the emphasis the is on the transmission of data – techniques and hardware, for various situations, which arise due to the remoteness, connectivity, medium of data flow, objectives to be met and special nature of the system.

The special nature of problems typical to the system can be grouped as:

- Manufacturing industry
- Process industry: chemicals and oil
- Transport services: aero, shipping, rail ways, road ways.

- Utilities: water, gas, electrical supply (transmission distribution).
- Aero-space and warfare industry: aircraft, missiles, rocket, satellites
- Marine (underwater) and mines (underground) operations.
- Biomedical: patient monitoring, telemedicine
- Ecology and environment.

Above indicate only the broad groups and call for very different techniques and hardware which shall have to be specially considered to meet the specifications of accuracy, speed of response,feasibility and economy.

The aggregate of various subsystem/hardware used to accomplish the task of transferring process variable/measurements between the control room and plant is commonly referred as data telemetry channel/system.

9.1 TYPES OF DATA TELEMETRY SYSTEMS

The two broad categories to classify telemetry systems are:

9.1.1 Mechanical System

Mechanical system,which include fluidic and pneumatic systems and can be used up to 300 meters.Fluid systems are typically used for high power actions, use highly viscous fire proof oil as medium which additionally provides lubrication. These systems use hydraulic pumps, relays, amplifiers and tubes/pipes for transmission.

Pneumatic systems use dry compressed clean air as the inexpensive medium and work over range of 20 to 100 KPa (3-15 psi) with supply pressure of 20 psi, implemented with the help of air pressure based motors, valves, amplifiers and comparators.

Both these systems can be used in systems where electrical methods are unsuitable due to possible fire hazards – as in case of oil industry and many of the chemical industries. These are imminently suitable for avoiding ionizing radiation, strong electromagnetic fields and are more reliable compared to electrical networks. Pneumatic systems are more economical, reliable and common yet these are being replaced gradually by electrical systems – compatible with computers. Here processing capability is lacking and complex computation based conditioning/operations are not possible with pneumatic systems.

9.1.2 Electrical Systems

Electrical systems are common for most operations other than in the field zone. These systems can operate in desired frequency range –

low frequency, radio frequency, microwave ranges and transfers through optical fibers including cables as well, thus practically eliminating any limitation on distance.

These systems offer large bandwidth and transmission speed. The available infrastructure can also be made use of (say) for example, telephone lines with limited bandwidth and speed, or paired transmission lines with microwave range of signals or a leased line. Electrical methods offer greatest flexibility and options by using communication systems technology with (wireless) RF and digital transmission techniques even for mobile stations sender or/and receiver.

Optical fiber cables for ground communications provide large bandwidth and high immunity to external interference.

9.1.3 Comparison of Wired and Wireless Data Transmission

Wired solutions are inexpensive compared to wireless solutions, on the sensor side. Copper wiring in general has very long life expectancy.

Quality of service is excellent as the wired connections eliminate the need for establishing the need for end-to-end connection every time.

Speed is a big advantage with wired connections, whereas wireless speed is not even close to that of wired ones.

Although wire is susceptible to interference due to noisy machinery – air-conditioners, motors etc. Shielded or armored cables are used to get over this problem in addition to protection against weather and other external factors.

The security of wired systems is open to tapping but only in case of open access. In case of wireless it is very vulnerable!

On the other hand, wired connections are realistic as broadband access may not be available all over.

Ethernet cables need boosting for almost every 100 meters. Therefore, special cables are needed to preserve signal strength, but with a cost.

Considerations in the selection of either mode-wired or wireless will therefore depend upon several factors-sensor node cost, hardware capabilities, data storage capacity, bandwidth and operation environment.

Use of protocols has made the systems more efficient to take care of security challenges, fault tolerance, alerts handling with either of the systems.

9.2 LAND LINE TELEMETRY

This type is in general economical, reliable and simplest with no restriction on size and weight as shown in schematics of Fig. 9.1. The performance is affected by distortions due to line frequency, thermo-emf, SNR and bandwidth limitations. Signal multiplexing is difficult and the quality of data is limited by the availability of proper hardware. Table 9.1 shows the performance of various electrical data telemetry methods.

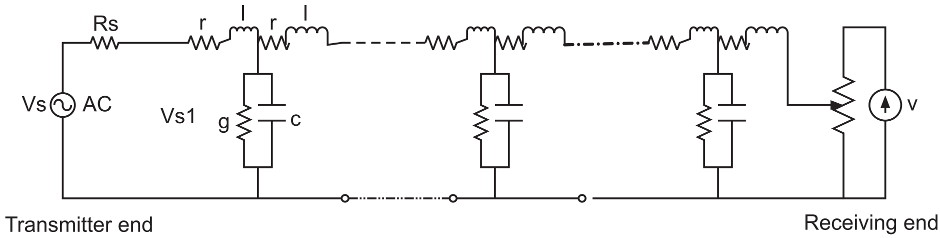


Fig. 9.1 Land Line Telemetry-General Configuration

Land line telemetry methods includes the use of voltage, current, frequency, position or pulses as the mode for data information. For small disturbances voltage signals can be transferred through cables providing direct point to point, secure connections. The cable with distributed parameters can be represented as shown in Fig. 9.2 which can be approximated for medium length by the lumped equivalent as in (*a*) or (*b*).

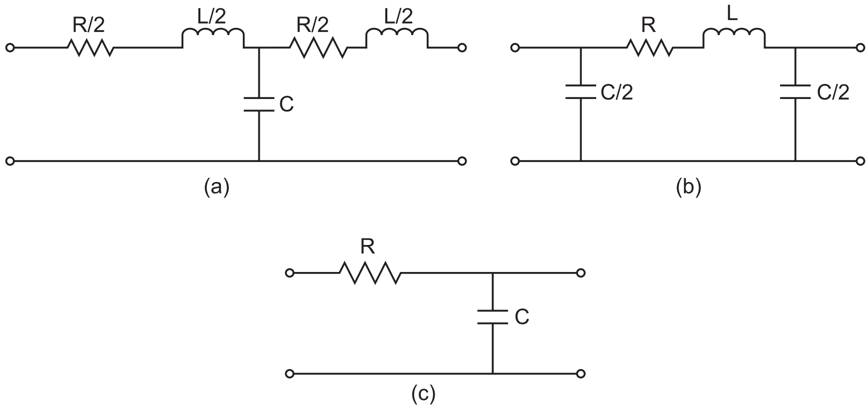


Fig. 9.2 Models of Cable

For short cables the effect of inductance can be neglected and the connecting cable can be approximated by the model as shown in Fig. 9.2(*c*). The cable parameters resistance and capacitance for acceptable performance are of the order 0.03 Ω/m. and 100 pf/m.

These parameters affect economy; wired telephony lines can also be used.The typical response of cable is shown in Fig. 9.3 with different values of terminating meter resistance R_v. To economise the high cost of cables, existing wired telephone network can also be made use of. However, the bandwidth of open conductor lines is limited and secrecy is low, it is preferable to use digital format as shown in the block diagram of Fig. 9.4 which results in higher accuracy of order 0.1% and noise immunity comparable to analog transmission over the same lines. The wave form of signals is really not important but the frequency response is low due to limitations of telephone line.

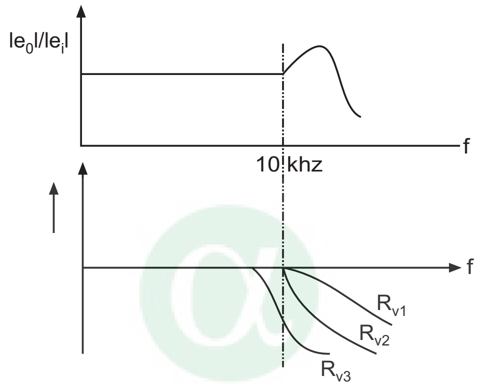


Fig. 9.3 Response of Cable Connectors

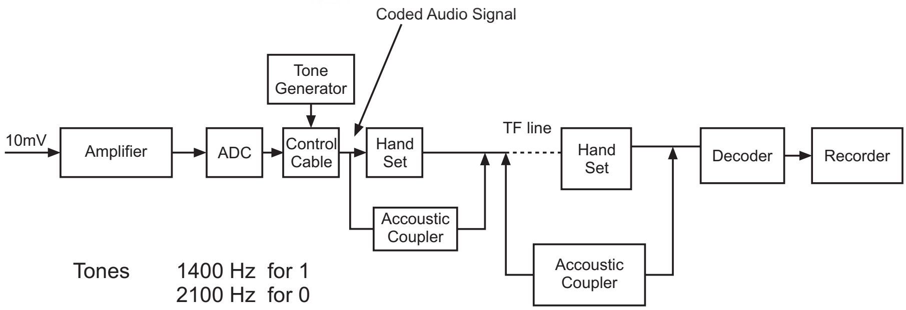


Fig. 9.4 Use of Telephone Line for Remote Data Sensing

Cable telemetry has limitations due to:

- Parasitic voltage due to loops formed by connecting wires.
- Power frequency interference.
- Thermo electric emf as noise
- Magnetic interference due to induced voltages but can be reduced by twisting the wires as pairs.

- Capacitance interference, which can be however be reduced by shielding the cable and connecting one of the ends to ground. For a source V_s, the cable length that can be allowed is given by

TABLE 9.1 Performance of Data Telemetry Methods

Method	Format	Distance	Speed	Remarks
Voltage Direct wire	Analog Voltage +1 to + 10V	30 M	1 MHz	Limited utility B.W. 10 Hz Accuracy 0.5%
Current Telemetry with V/I Converter	Analog 4-20 mA Current	300 M	10 kHz	Process control Standard
Frequency Telemetry With V/F and F/V converters	Recorded Analog 100 kHz to 10 MHz	1500 M	Variable	Assumes line drivers
Frequency Shift keying	Audio tones	15 km	1200 bps	Uses limited distance MOD Ems
Phase Shift Keying	Phase modulation	TF systems	2400 bps	Line conditioning needed
Radio telemetry	FSK	8 km	300 bps	11-meter bands used
Digital telemetry with line drives	Base band digital	150 M	600 bps	Economical

$$I_{\max} = \frac{V_s D_n}{f_n . e . N_i . R_e . C_f} \qquad \text{...(9.1)}$$

where D_n is distance from interfering source

f_n is identified highest significant frequency causing interference

e is desired frequency of transmission

N_i is strength of interfering source

R_e is equivalent resistance of circuit

C_f is coupling factor proportional to inverse of efficiency of cable shielding.

9.3 CURRENT TELEMETRY

If current signal is not available directly from the transducer then a V/I converter is used to obtain the signal in current format. The analog current standard for industry is 4-20 mA range with 100 mV and uses live zero concept as discussed earlier.

9.3.1 Types and Advantages

A schematic for electromechanical force instrumentation is shown in Fig. 9.5 as an example of 2-wire type current telemetry with the general layout as shown in Fig. 9.6.

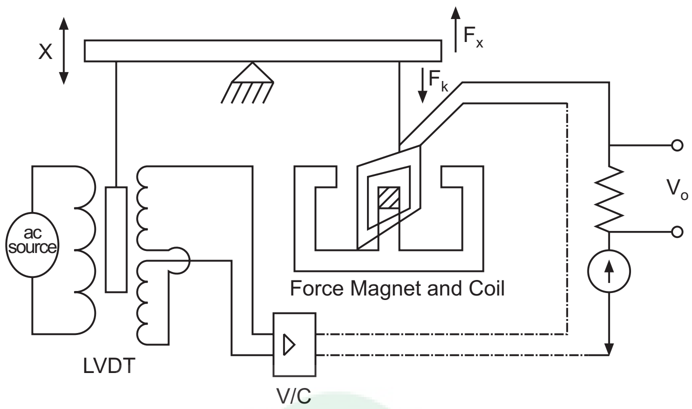


Fig. 9.5 Force/displacement Instrumentation with Current Telemetry

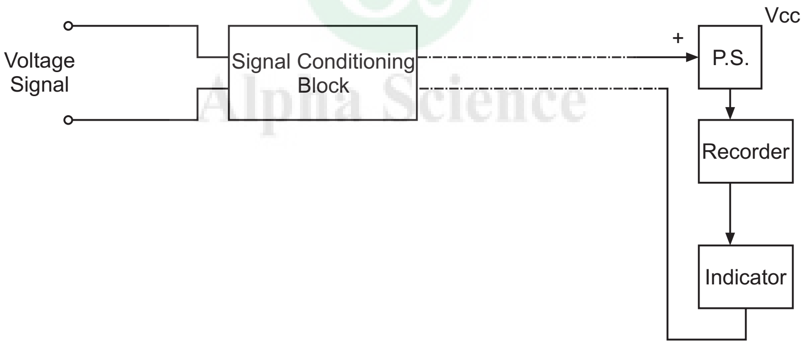


Fig. 9.6 2-wire Current Telemetry

Another option is to use 3-wire current telemetry with separate signal and power lines as shown in Fig. 9.7.

The current telemetry approach offers major advantages that

- there is no change in current amplitude with distance.
- thermo-emfs become ineffective
- magnetic coupling effect is greatly reduced
- it permits use of thinner and thereby economical wires.

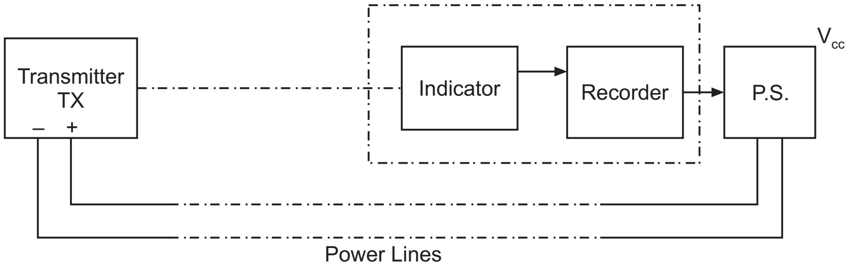


Fig. 9.7 3-Wire Current Telemetry

To keep the error due to capacitive coupling low, the receiver resistance is desired to be less than 250 Ω. The permitted cable length is given by

$$l_{max} = \frac{I_s D_n}{f_n . e . N_i . C_f} \tag{9.2}$$

where I_s the signal current in loop and other symbols have their usual meaning.

9.3.2 Anderson Current Loop

This is basically a recent current telemetry technique and had been developed by K.F. Anderson at NASA (1997) to overcome the limitations of earlier voltage telemetry arrangements based on Wheatstone bridge principle.

Wheatstone bridge arrangement has been in use for more than 150 years for determining unknown resistance by obtaining the balance at which the product of opposite arm resistances are equal. The methodology has been successfully used with variable resistance strain gauges as linear sensing element with infinite resolution. The use of dc coupled amplifier at the bridge output provides a simple effective signal conditioner. Yet for its applications as a transducer circuit topology has some limitations such as:

- half the signal from each element's impedance change is attenuated by adjacent bridge arms.
- out put signal is a nonlinear function of resistance change in individual bridge arm.
- multiple sensing resistances observed simultaneously provide only a single out put signal.
- lead wire and connector resistance changes typically add uncertainty although can be taken care in limited cases by using Muller Bridge.

- transfer function (including compensation) of bridge transducer get 'locked-in' after manufacturing and normally not adjustable.
- thermo-emf output are difficult to separate from change in resistance when using dc excitation.

These limitations have been overcome in the novel current loop measurement circuit topology offered by Anderson, utilizing a dual differential subtraction approach.

Dual-differential Subtraction

The subtractor as shown in Fig. 9.8, is a six terminal three port active analog electric circuit. It deals with floating inputs and may provide amplified ground or floating outputs. The common mode signal contribution in the out put is limited by the common mode rejection capability of the subtractor-amplifier.

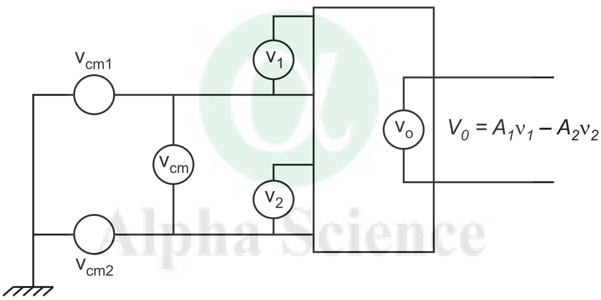


Fig. 9.8 Dual Differential Substractor

Current loop configuration is shown in Fig. 9.9. The voltage drops across lead wires Z_{w1}, Z_{w2} are simply avoided in the signals being processed. Voltage drop across lead wires Z_{w3} and Z_{w4} are negligible and therefore the system model is able to avoid the need for considering lead wire resistances.

When the reference impedance Z_{ref} is chosen equal to the initial resistance of sensing element as is generally possible in the case of strain gauge and *RTD* applications, and the subtractor inputs are processed with unity gain, the output would be

$$v_0 = i\ \Delta R$$

Thus the response is linear to changes in sensor element. And any variation in the excitation i appears in the output as reading error which can be taken care during calibration. Also, not only dc, any other form of excitation can be used for ratiometric measurements.

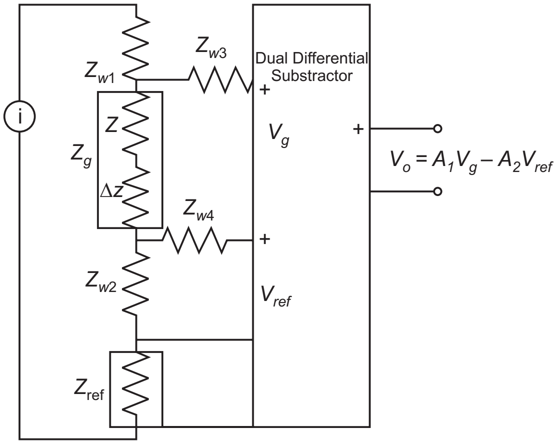


Fig. 9.9 New Current Loop Measurement Circuit Topology

Multiple Sensor Loops

In the Anderson Loop it is possible to include multiple sensors. Subtractor shall observe the drop across two sensors they may not be adjacent ones, to record the difference from reference, with or without amplification.

The simplest dual differential subtractor can be realized by using instrumentation amplifier (IA)ICs with acceptable linearity, CMRR and thermal stability (discuss in detail earlier). Figure 9.10 shows use of

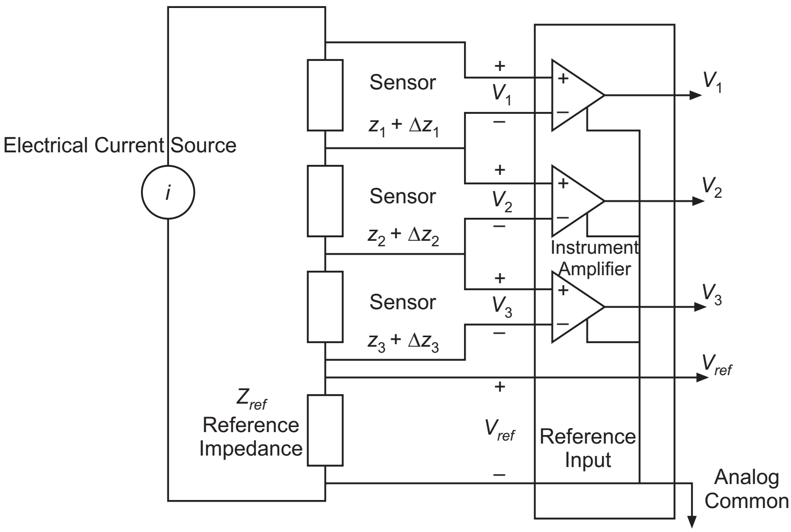


Fig. 9.10 Instrumentation Amplifiers used as New Current Loop Characteristic

IAs as differential half subtractor to get V_1, V_2.....and later each of these can be compared with any one of these or with a specified reference.

The configuration shown has sense lead-wire shared say for Z_1 and Z_2 and so on this arrangement requires total lead wires equal to number of impedance plus three only.

If the initial impedance of each sensors is same as reference element (commonly in strain gauge measurement) the following outputs result:

$$v_1 - v_{ref} = i.\Delta Z_1$$
$$v_2 - v_{ref} = i.\Delta Z_2$$
$$v_3 - v_{ref} = i.\Delta Z_3$$
$$v_4 - v_{ref} = i.\Delta Z_4$$

so that,
$$v_1 - v_2 = i.(\Delta Z_1 - \Delta Z_2)$$
$$v_1 - v_3 = i.(\Delta Z_1 - \Delta Z_3) \text{ etc.}$$

Advantages of Anderson Current Loop

As has been shown, the limitations of Wheatstone bridge are removed by using active subtraction and these can be listed as:

- large and linear outputs from each sensor
- power dissipation in sensor cut down due to reduced current.
- immunity from changes in lead wires without additional cost
- temperature compensation and calibration become simpler and implementable in signal conditioner
- out put sensitivity is twice of that in Wheatstone bridge
- number of sensors is variable
- some sensor can be used for measurement or compensation with any number of sensor outputs
- same excitation current can pass through several geometrically dispersed sensors with voltage drop carried to subtractor using Kelvin sensing. This offers accurate differences – particularly useful with RTDs in various locations
- inclusion of active element tends to improve the overall signal to noise level which is useful in industrial environment.

The current loop approach is as much, rather more fault tolerant than Wheatstone bridge, with provisions for bypassing the open sensors in the loop and this makes it more robust.

9.4 FREQUENCY TELEMETRY

This approach provides greatly improved noise immunity. In practice all voltage controlled oscillators (VCO's) are voltage to frequency converters (VFC's), but with limited variation range, *i.e.* 100 to 1 (maximum) say typical full-scale output frequency from 100 kHz to 10 MHz. With range variation of 1 to 10 K.

A schematic diagram for this technique is shown in Fig. 9.11, indicating necessary units, correspondingly a 13-bit resolution can be achieved.

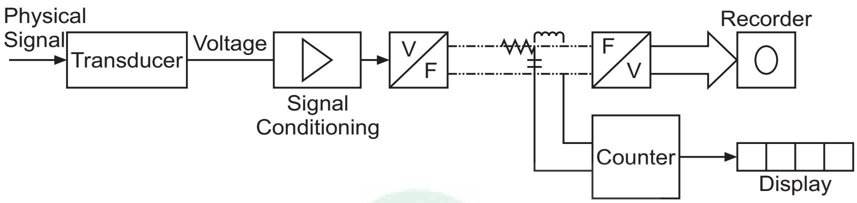


Fig. 9.11 Configuration of Frequency Telemetry

9.4.1 Voltage-to-Frequency Converter (VFC)

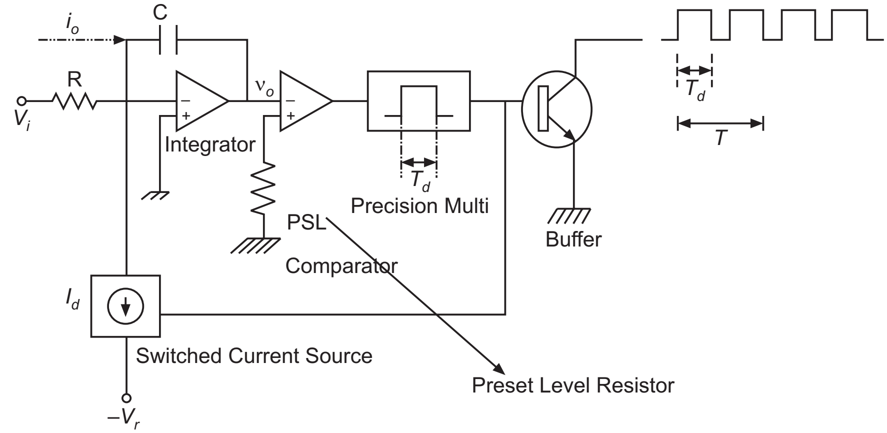
Modular/monolithic VFC's are available using charge balance principle. Referring to Fig. 9.12, the capacitor C charges for positive input, providing a negative slope for its output V_o to reach a preset level (PSL)and trigger a MONOSTABLE which provides precisely fixed amplitude of duration T_d. Digital buffer allows the pulse output to be sent over. Pulses from monostable also control the discharge of C, by switching a constant intensity current source Id(≈ 1 mA). This source provides a charge $I_d.T_d$ to which the input which compensates for the charge drained from capacitor.

A balance is maintained with

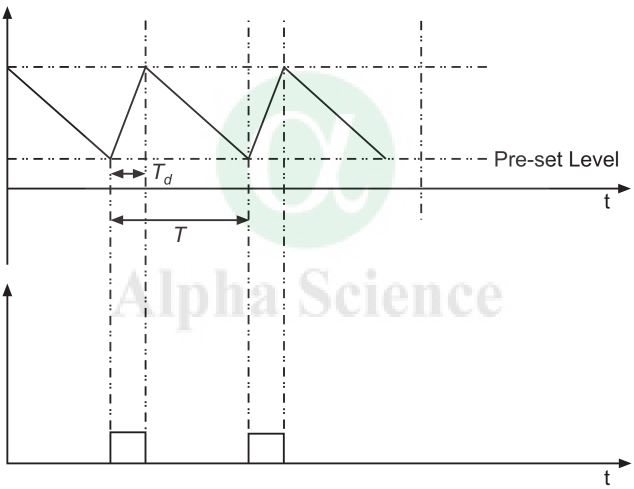
$$I.T = I_d.T_d$$

$$\therefore \qquad f = \frac{1}{T} = \frac{I}{I_d.T_d}$$

and, the output frequency is controllable by T_d and I_d. Flexibility can be attained, by adding a current I_0 at the summing point of input op-amp, to shift output range *i.e.* 0 Hz corresponding to 0 V and the out put frequency can be scaled by using a digital counter.



(a) Hardware Configuration of VFC



(b) Monostable Output

Fig. 9.12 V/F Telemetry

A symmetric square waveform, if desired can also be derived from converter pulse train,by giving the pulse to a bistable D-Flip-Flop as shown in Fig. 9.13.

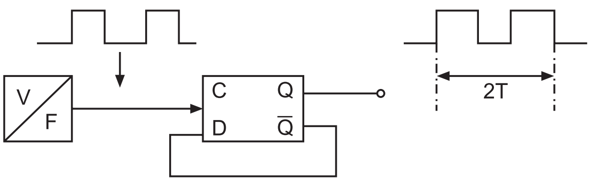


Fig. 9.13 Obtaining Symmetrical Square Wave Output

At times it may be desired, to have large output pulse for higher immunity to noise *i.e.* converting TTL out put to 0-12 V output. A possible circuit is shown in Fig. 9.14. Output of VFC being output to a digital counter is analogous to ADC operation; therefore the specifications of VFC are generally given relative to other ADC's.

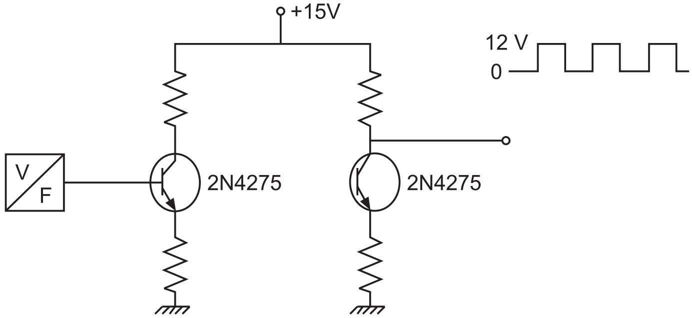


Fig. 9.14 Voltage to Voltage Conversion for TTL Signal Circuit

These are highly linear with nonlinearity ranging from 0.05% to 0.002% (lower for high output frequencies.), have high resolution and immunity to noise but slow operation in terms of conversion rate.

Normal mode rejection ratio, NMRR is defined as

$$NMRR = 20\log\left(\frac{\sin\left(\pi.f_{noise}.T_{counter}\right)}{\pi.f_{noise}.T_{counter}}\right)$$

which in a limiting case of $T_{counter} = n \times T_{\text{noise}}$ will provide *NMRR* tending to infinity.

Dynamic range, with usual inputs of 0 to 10V or 0-1 mAmp and threshold of 1 mV (due to offset etc.) is given by,

$$\text{Range} = \frac{\text{Max voltage}}{\text{Threshold}} = \frac{10v}{1mv} = 10^4 = 80\ \ dB$$

or 4 decades, and can go up to 6 decades, which is usually large enough and amplification may not be needed.

9.4.2 Frequency-to-voltage converters (FVC)

In Fig. 9.15 is shown a basic circuit of a frequency-to-voltage convertor (FVC). It has an input capacitor of very low value to block dc and the first stage is a differentiator, which limits the input pulses of duration less than a specified duration T. The bias network at the comparator sets a dc voltage level suitable for comparator. This comparator senses when an input level reaches a preset level (PSL), then it triggers the monostable. The monostable switches a current from the 'switched current source', to be integrated during interval T to provide output voltage V_0, which is also the average value of voltage drop in R. So that

$$I_{av} = I.f.T$$

$$\therefore \quad v_0 = f.I.R.T$$

Ripples in output voltage, $\delta v_0 = \frac{I.T}{C}$, so that C can be used for ripple scaling and R can be used for voltage amplitude scaling.

Thus the output voltage is proportional to frequency of input and as is easily noticeable 0-10 V output range shall not correspond to scale like 0-10 K rather 4K to 8K pulses/min.

These can be also used with frequency generating transducers.

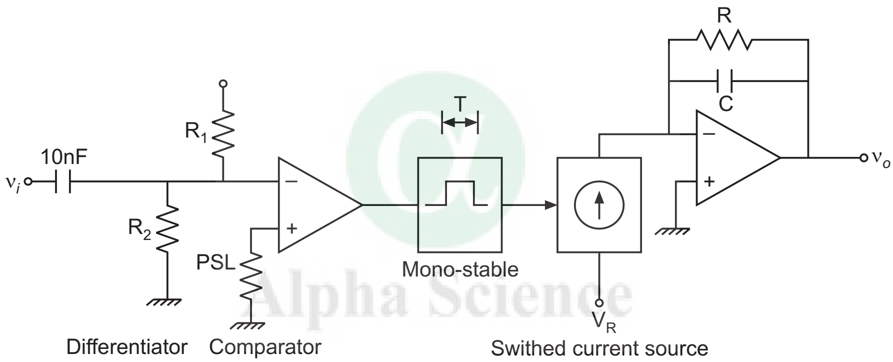


Fig. 9.15 A Basic Circuit for FVC

9.5 MULTIPLEXING OF SIGNALS

A general structure is shown in Fig. 9.16, including short, medium, long and large distance modes of transmission, using amplitude modulation typically for one or more sensors.

In case of large number of channels data to be telemetered, multiplexing of signals is essential and either TDM or FDM based radio telemetry techniques are used. Figure 9.17 shows the TDM based technique applicable for slow process variables, which can be extended to factory wide data sharing too via a data bus. In the Fig., is shown a data handling via TDM for N number of analog variables 1, 2, 3....N converted into digital data. Also shown is a digital channel which will be digitally multiplexed to output digital data corresponding to one channel out of (N + 1) at a time. For details of bus structures and protocol, bibliography may be referred. The number of largest number of analog data channels that can be attended is calculated as $N = \dfrac{f_c}{k.f_m}$ where f_c is maximal frequency for A_{mux}, f_m is maximal frequency of signals 1, 2,.....N and $k \geq 2$ to satisfy Shannon's theorem and provides the number of samples to be taken per cycle.

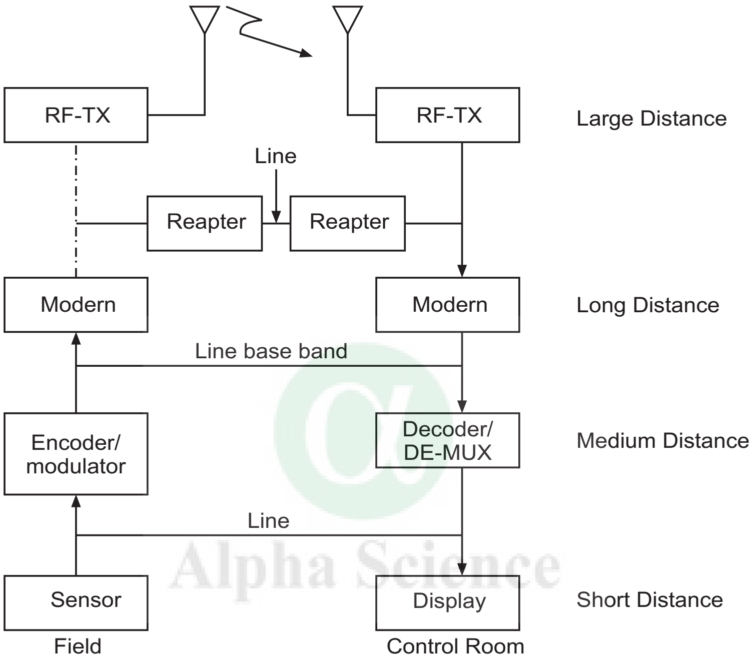


Fig. 9.16 General Structure of Telemetry

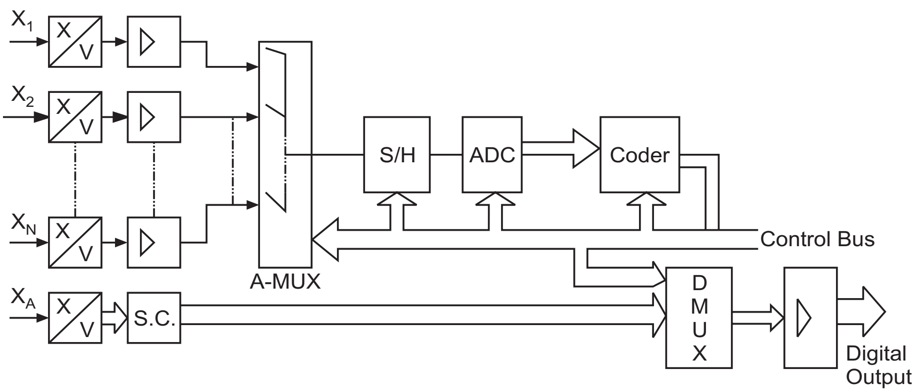


Fig. 9.17 Time Division Multiplexed Signals

In the case when signals are changing fast and the possible loss of information, as it may occur in *TDM* cannot be afforded, Frequency Division Multiplexing (FDM) techniques are preferred.

This approach is also very useful in case of mobile communications. A basic configuration is shown in Fig. 9.18. the subcarrier frequencies have been standardized by Interrange instrumentation group (IRIG, USA) so that the equipments are compatible as also the interference from other important communication is avoided. The 25 channels in the band from 400 Hz (for channel 1) to 70 kHz (for 18 channels) are selected in the ratio of 1:1.3 *i.e.* 400, 560, 730 …. The percentage deviation allowed is 7.5 with modulation index between 1 and 5. This ensures frequency separation

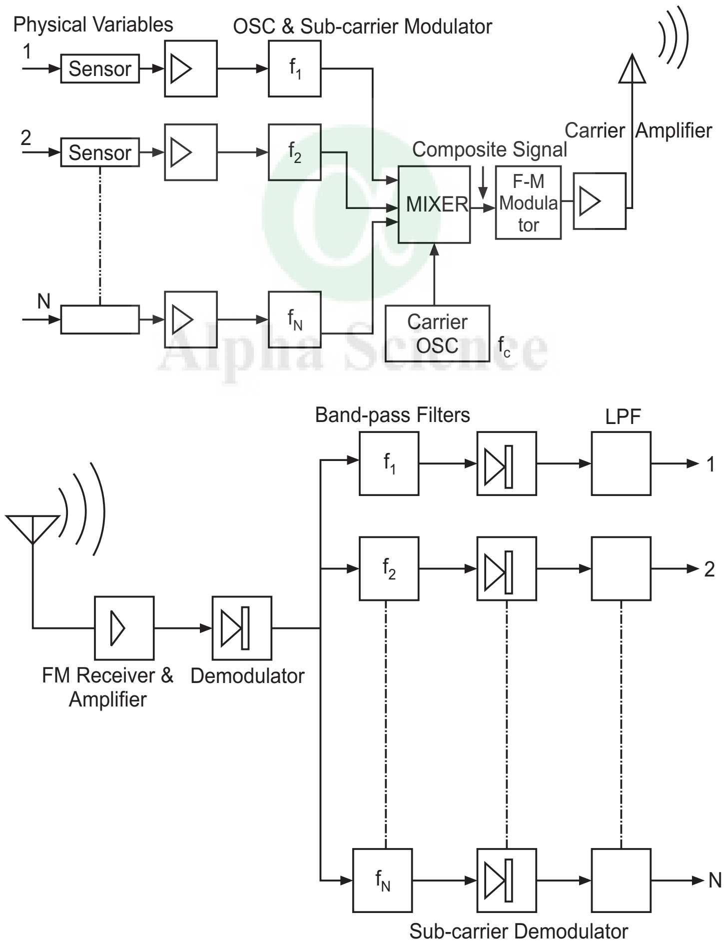


Fig. 9.18 Basic Configuration of a FDM Telemetry

without overlap and need of complex filters. It can be used over a range up to 640 kms with accuracy of ±2% of full-scale. The Table 9.2 shows the bands and corresponding frequency response.

Various techniques are available for increasing the range of transmission technique as shown in Fig. 9.19, with modulated frequencies up to 217.55/219.45 MHz.

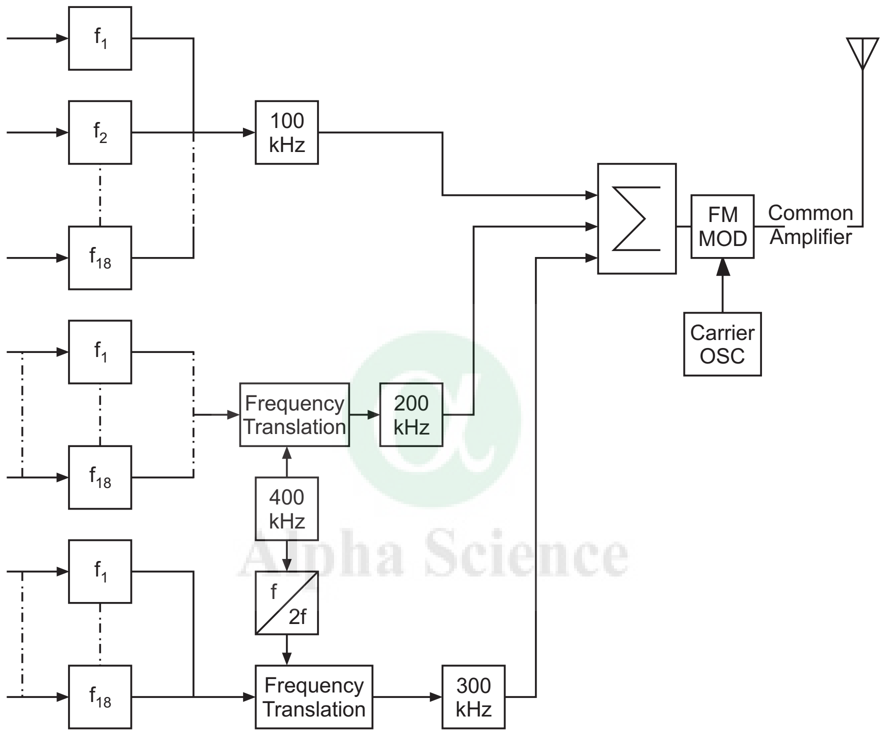


Fig. 9.19 RF-Telemetry using Frequency Translation

TABLE 9.2 F.M. Telemetry Bands

Band	*Central frequency, Hz*	*± frequency deviation % of F.S*	*Overall frequency response, dc to Hz*
1	***2***	***3***	***4***
1	400	7.5	6
2	560	’’	8.4
3	730	’’	11
4	960	’’	14

1	*2*	*3*	*4*
5	1300	,,	20
6	1700	,,	25
7	2300	,,	35
8	3000	,,	45
9	3900	,,	59
10	5400	,,	81
11	7300	,,	110
12	10500	,,	160
13	14500	,,	220
14	22000	,,	330
15	30000	,,	450
16	40000	,,	600
17	52500	,,	790
18	70000	,,	1050

9.6 DIGITAL DATA-TRANSMISSION

We have seen that the communication systems involve both analog and digital transmission. Only for a limited data flow cases and for remote logging serial communication may be used. The choice of scheme will depend on:

- distance
- noise and disturbances
- speed
- cost
- simplicity
- data security

For large data transfers, following are the options:

- serial or parallel
- synchronous or asynchronous
- local area network.

9.6.1 Serial Transmission

Serial transmission is used economically for long distance cable communication but it is slow as only bit-by-bit characters transmit at a time. It may be required to use serial – to parallel converters for interfacing the digital output with a line, called asynchronous communication interface adapter (ACIA) or universal asynchronous receive and transmit device (UART). The scheme may beas shown in Fig. 9.20.

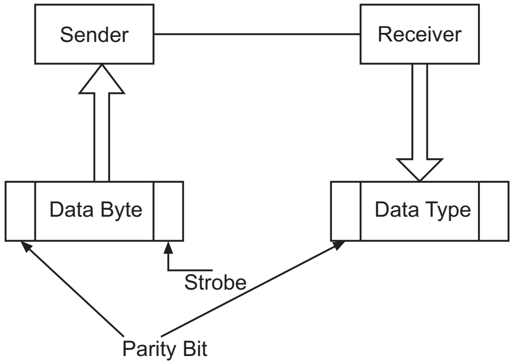


Fig. 9.20 Serial Transmission

9.6.2 Parallel Transmission

In this mode one bit per wire is transmitted along with two additional wires for parity check and clock signal. This shall be N times faster than serial transmission, where N is the number of bits in the data word, as shown in Fig. 9.21. Parallel interfacing requires a peripheral interface adapter (PIA) chip between ADC and the lines (or computer for logging) as shown in Fig. 9.22.

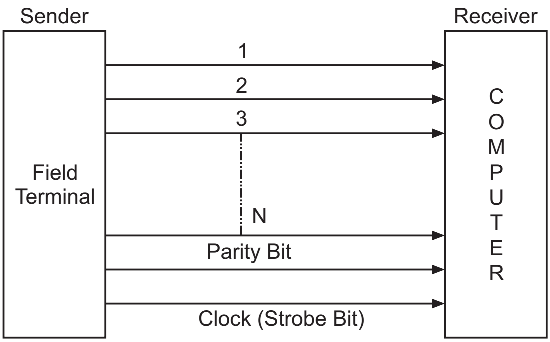


Fig. 9.21 Parallel Transmission

In case the distance between transducers (plant devices) and the control room (receivers) is large, analog techniques are inadequate due to need for high SNR in industrial environment and therefore limited. Parallel digital transmission provides high data rate but proves expensive due to cabling and interfacing devices, therefore used only for short distances requiring high speed of data transfer.

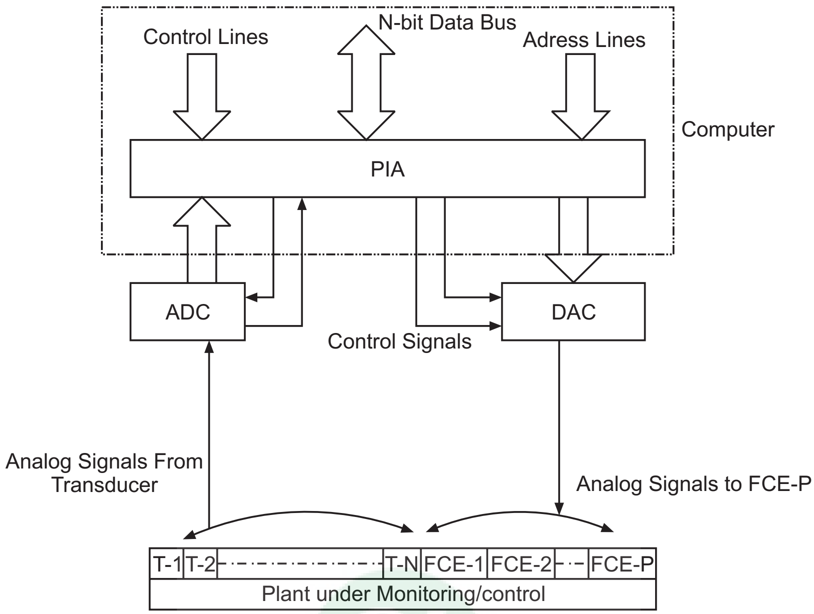


Fig. 9.22 Computer Interfacing with Plant

9.6.3 Synchronous and Asynchronous Transmission

Successful data transmission requires that the equipment at two ends – sending and receiving, must be synchronized to code and decode the information. No start or stop bits are used and a timing circuit should maintain them in step, over long durations.

Whereas in asynchronous scheme, the sender transmits the data whenever ready and the transmission intervals may not be uniform. In such a system, with large number of data (variables) there is need for proper identification, coding, synchronization as well as start-stop signals also called protocol.

The system is slower but less expensive and often used for connecting devices to computer.

9.6.4 Local Area Network (LAN)

In this approach of device interconnection, all communicating devices also called stations are connected to the main cable, called data HI way or backbone (or other medium). Every device connected (receivers) can see (and receive) every packet (group of data) and examine the destination address field of packet to decide to receive or not. LAN s are useful for small distances up to 5 kilometers at a high speed, say the control room of a plant with number of devices connected to the line-personal computers, peripherals–disks, printers, VDUs. These can make use of twisted pair cable, coaxial cable or fiber optic cable.

The LAN configurations also known as topology are in three basic types-bus, ring and star as shown in Fig. 9.23.

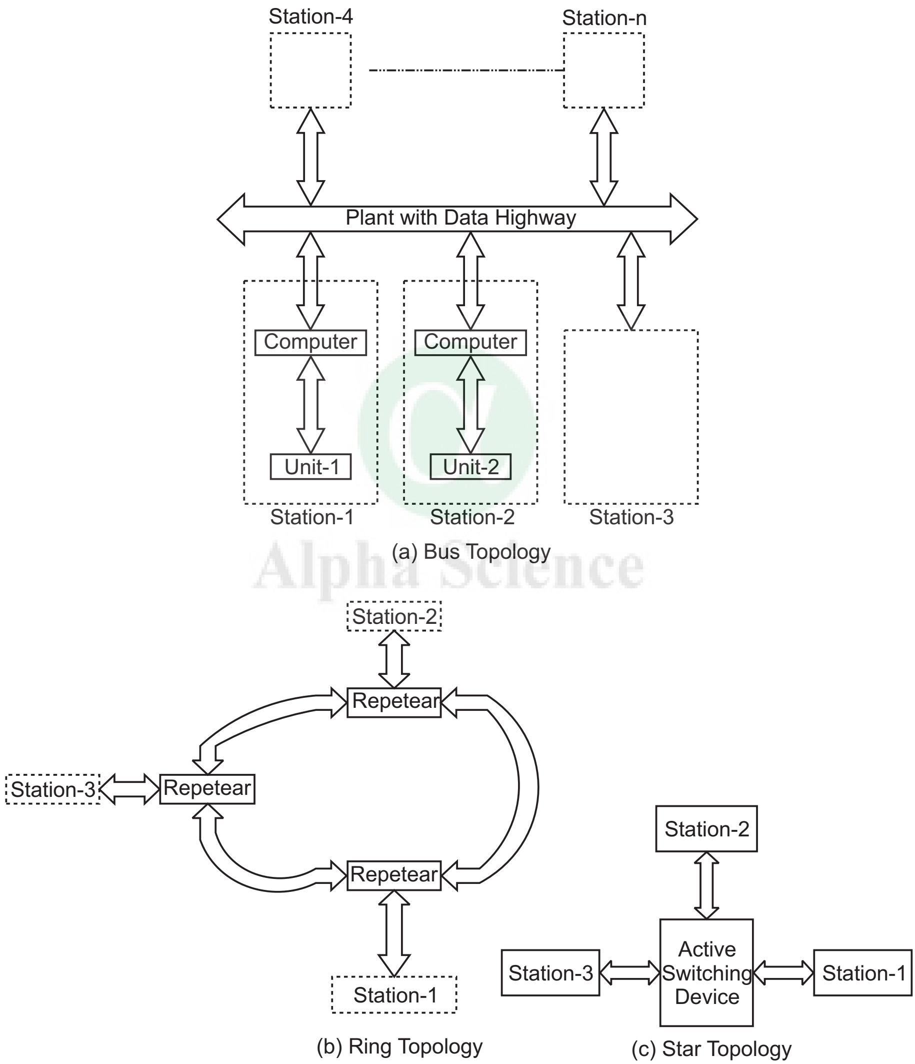


Fig. 9.23 LAN Topologies

Bus topology is simplest, normally passive with all devices plugged into common node of cable. This is reliable but has limitations of distance.

In ring topology, all the nodes are connected to the nearest ones in the notional ring. To communicate between nodes Ethernet is the common medium. Ethernet is a bus topology with branch connections and follows the IEEE 802.3 standard of specifications.

Ethernet consists of screened coaxial cable with taps for connection of peripherals. It supports communication at different speeds, as the connected units need to decode data/message directed to them only.

9.7 NETWORK REQUIREMENTS

At field level sensing and control, the network is frequently in use therefore the response time and the data strings have to be short.

At control level (level-2) and above demand is different and response time can be more. The requirements shall vary at each level considering the transmission rate, protocol and interfaces and have to be installed appropriately. Several networks could be found working in a large industry. To ensure clarity at each level of communication hierarchy and between devices standards have been evolved.

9.7.1 ISO Reference Model

International standards organization has developed and defined a reference model for communication in the network across different equipment and applications called open systems interconnections (OSI) model. The model applies to all communication systems at the administrative level to data exchange at field level. It is now considered the primary architectural model for inter computing and networking communications. It defines seven fundamental layers as shown in Fig. 9.24, which divides the task involved with transfer of information between networks into these seven smaller, more manageable task groups. A task is then assigned to each layer which are reasonably self-contained and can be implemented independently. The seven layers are:

- Application layer
- Presentation layer
- Session layer
- Transient layer
- Network layer
- Data link layer
- Physical layer

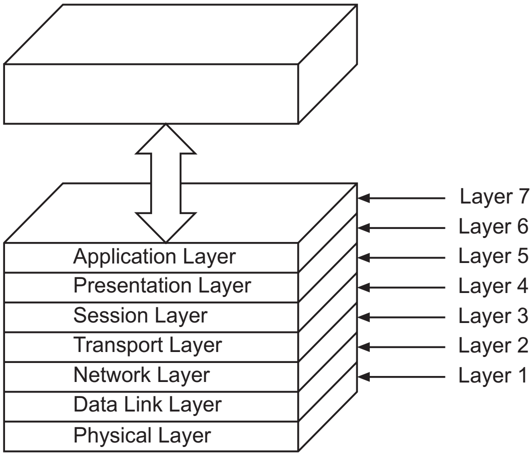


Fig. 9.24 OSI Model Architecture

Upper layers (7, 6 and 5) deal with application issues and are generally implemented in software. Application layer is the highest and closest to end user.

The lower layers (4, 3, 2 and 1) handle data transport issues and are implemented in hardware and software. The specific applications of each layer are defined as:

9.7.2 Role and options for the various layers

As each layer of OSI model has been assigned specific set of operations to be carried out at that level, satisfying a protocol, it helps to maintain a smooth flow of data with synchronism and reliability of communication.

Layer-1: Physical layer

The layer deals with the physical aspects of sending data over network devices by providing interface between conditioned signals (digital) obtained from the system (being monitored) and communication network medium. Also defines pin-outs, electrical characteristics, modulation and encoding of data bits on carrier signals. This ensures synchronization and plants the received binary pattern into receiver buffer. Once decoding of bit stream is complete the physical layer notifies the data link layer that a frame has been received and passes up. Example of specifications includes:

V.24, V.35, EIA/TIA-232, EIA/TIA-449, FDDI, 802.3, 802.5, Ethernet, RJ45, NRZ, NRZI.

Layer-2: Data link layer

In this layer appropriate physical protocol is assigned to data for operating communication link, according as the type of network and packet sequencing to be used. It also provides for flow control, quality of service with detection of errors.

Error check is performed using Frame Check Sequence (FCS) in the trailer and discards the frame, if an error is detected. It then looks at the addresses to see if it needs to process the rest of frame or to pass it on to another host. The data between header and trailer is passed to layer 3.

The MAC layer controls the access and determines the use of physical transmission as in the case of token ring protocol.

LLC shields the higher level layers from the problems of specific LAN implementation. The examples include:

—IEEE 802.2, 802.3, 802.5-Token ring; HDLC; Frame relay; FDDI; ATM; PPP.

This layer ensures the exchange of data between devices and governs not only network access and data format but also the data security. With several devices/stations connected an effective ambiguous control has to be established for transmission of data.

In principle access is controlled through either of the two methods – centralized and decentralized. In centralized bus control, a master station/device assigns the right to one station at a time. But if master fails the network breaksdown.

Therefore the decentralized control is preferable. In this scheme, the right to transmit is assigned to more than one station and the following three approaches are available:

(*a*) **CSMA/CD method:** In this (Carrier Sense Multiple Access with Collision Detection), all the transmitters are allowed to transmit and each station senses the bus. If the bus is free any station can transmit but if more than one are to transmit at the same time, a collision is detected and all have to withdraw. Then a random generator at each station determines the interval before it can try to transmit again.

This is not suitable for instrumentation systems with field-bus systems as the short response time (amust) for alarm systems can not be ensured.

(*b*) **Token passing method:** This provides for a token/right to transmit from one station to other(s), in a pre-specified sequence of priority, with fair enough time for each, so that it can transmit within that time. Frequency of polling of each member is determined from the time taken to pass the token over all the transmitting devices. This approach is suitable for field devices and control applications.

(*c*) **Master slave method:** This works on the principle of a Master device which addresses (or polls) the other devices in turn, sends to them (must be in a state to receive) and then instructs to send (say in case of sensor, receive in caseof controller, actuator). Method is suitable for sensors/actuators applications.

Layer 3: Network Layer

This layer is responsible for sending data to recipient device by using appropriate logical protocol, routing of packets according to unique network device address. This can be connection oriented or connection less and is independent of topology or the path of data packet.

Fragmentation of layer packets into smaller ones depending on MTU for different media is achieved. Once the data is received from layer 2; layer 3 examines the designation address and if it is own end station, it passes the data after layer 3 header to layer 4.

Examples of data 3 layer:

—IP, IPX, DEX net, Appletalk DDP

Layer 4:Transport layer

This layer maintains flow control of data and provides for error checking and recovery between devices. This includes checking for incoming data from one or more and packet fragmentation to integrate them into single stream. After error recovery and reordering the data port is passed to layer 5. Examples are: TCP; UDP; SPX.

Application set:

Layer 5: Session layer

The layer manages transmission sequencing and sometimes authorization by controlling the start and finish to data transfer session using appropriate protocol *e.g.* RPC, SQL, NET BIOS-, DEC net SCP, Appletalk ASP… , to start and termination of logic links between users in directional manner. In case of multiplicity of conversations, it helps to create notification if some message fails. Only after a completed conversation, the data will be passed to layer 6.

Layer 6: Presentation layer

This layer provides function call exchange between host operating systems and software layers. It masks the differences of data formats between dissimilar systems, by defining the format of data being sent and any encoding encryption and compression/detection of data that may be used, so that an architecture independent data transfer format is generated.

The services used include: MIDI, HTML, GIF, JPEG, ASCII, TIFF, and EDCDIC.

Layer 7: Application layer

It is employed in software packages which implement client-server software and defines the interface to user processes for communication and data transfer network. Through this only the user interactswith the OS or application – transfer files, read messages or network related activities. The header contains the parameters agreed between applications and this is sent only at the beginning of application operation.

Services related to this layer are: FTP, DNS, SNMP, Network file system (NFS), web browser, X.400. It provides standardized services *e.g.* Virtual; terminal, file and job transfer etc.

The OSI 7-layer model is defined by ISO in document 7498 and ITU document. Protocols are defined for different layers by ISO and can be looked into.

It is to be noticed that some protocols are useful for several layers. A major advantage of OSI 7-layer model is that, the software can be written using modular approach. Also each layer has its own header with information relevant to its own header with information relevant to its role. The header is passed down to lower layer which adds its own header until the physical layer adds the layer-2 information to next device which understands the information and then strip header of each layer in turn and convey the data to right location. Next we shall discuss the technique of data transfer using OSI model. However in industrial instrumentation systems only 03 layers are generally needed *viz.* physical, data link and application layers.

9.8 COMMUNICATION INTERFACE IN INDUSTRIAL SYSTEMS

As shown in Fig. 9.24 the data from the industrial system/field devices is interfaced through the field bus which are linked to sensors and actuators at the process level through signal conditioners and software (read intelligence) so that information system (and outflows there from). Devices which have built in intelligence include Programmable Logic Controllers (PLCs), distributed control system (DCS), intelligent controllers.

Field buses offer the following advantages:

- Bidirectional digital transmission
- Higher level of resolution of process variables
- Simple and expandable cabling
- Avoidance of cross cabling
- Simpler maintenance
- More safety

Three common buses types available are listed and compared are presented in Table 9.3 for MOD BUS, PROFIBUS and FIP BUS.

TABLE 9.3: Comparison of Data Buses

Features	*MOD-BUS*	*PROFI- BUS*	*FIP- BUS*
1	*2*	*3*	*4*
Definition	Protocol	Interface, protocol, application	Same
Cabling	Not specified	Shielded/Twisted pair/ coaxial	Twisted pair/glass fiber/coaxial bus
Topology	Bus	Bus	Bus
Length	Up to 15 m - RS 232C Up to 1200 m- RS422 Up to1000 m – 4-20 mA loop	≤ 1.2 km	≤ 2 km
Interface	RS 232, RS 422, 4-20 mA loop	RS-485	Proprietary
Transmission rate, in KB/s	0.6-19.2	Distance Dependent up to 500 m	Distance dependent up to 1000m
Connectable Devices	Master: Slave:: 1:247	Max.32/Bus hybrid central/decentralised, token passing, Master/slave	≥ 256 central
Bus access coding	Master-slave ASCII, RTU, Configurable	NRZ	Proprietary
Transmission mode	Not specified	½ Duplex, synchronous	Proprietary

MOD BUS

Offers a choice of medium from amongst RS-232 C; RS-422 or 4-20 mA current loops with appropriate transmission rates defined. It works on Master-Slave principle up to 247 devices and therefore slows but popular choice due to flexibility of transmission media and mode-RTU/ASCII and low communication errors.

PROFI BUS (Process Field Bus)

Uses 03 layers 1, 2, 7 protocols as per OSI model and offer high performance with flexibility to choose from centralised/decentralised/hybrid options combining centralised Master-slave system with decentralised token passing. Its higher level integrity makes it suitable for Manufacturing Automation Protocol (MAP) also.

Factory Information Protocol (FIP) Bus

Has specified protocol and interface with high transmission rates and works on hybrid broadcasting principle. It handles digital compatible instruments only and adopts international standards. Data security is highest and provides real time scanning options, polling management and error checking.

9.9 DATA ACQUISITION SYSTEMS(DAS)

As has been seen earlier that the various sensors, controllers, actuators, alarms, display devices and recorders can be interconnected with data, signal flow from the field instrumentation to control room and vice versa is possible through telemetry schemes.

9.9.1 SCADA

A system that collects the data at a factory, plant or some remote location and sends it to a central computer which manages and controls the data, is referred as SCADA, an acronym for Supervisory Control And Data Acquisition.

The parts of SCADA include

- Signal hardware (input-output)
- Controllers
- Networks
- User interface (Human-Machine Interface, HMI)
- Communication equipment
- Software

For the most part, the brain of SCADA is implemented by the Remote Terminal Unit (RTU). The RTU consists of programmable logic controller (PLC) and is set to specific requirements. However, most RTUs allow human intervention. For example, in a factory situation, RTU might control the setting of conveyor belt and the speed can be changed at any time by operator intervention.

In addition, any changes or errors are usually automatically logged and/or displayed. A SCADA system will monitor and make slight changes to function optimally. These are considered closed-loop systems and run with limited human intervention. One of the major features of SCADA is to monitor the system in real time. It can be considered as a system with many data points in the plant.

It is important to consider data acquisition system (DAS) from various points (nodes) in the plants, to be brought to central computer and the various configurations of DAS have significant impact on speed, accuracy and cost of the overall system.

9.9.2 DAS-1: with Multiplexed Signal Conditioning

The configuration of DAS-1 as shown in Fig. 9.25, each analog signal from the sensor group is provided with decentralized signal conditioning, multiplexed in the time-mode, sampled at an appropriate pre-programmed rate and converted to digital format and then made available on system bus with digital output interface (common to all *n*-sensor channels).

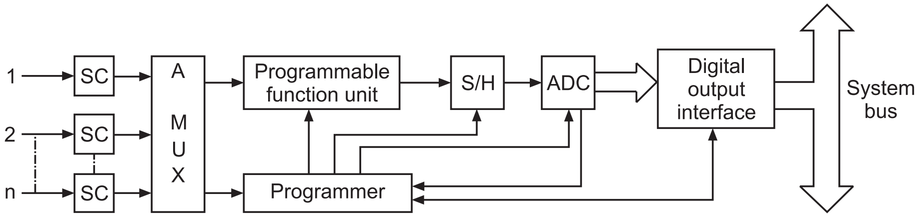


Fig. 9.25 DAS-1: with Multiplexed Signal Conditioning Operations

The arrangement is general and conditioning of each sensor output provides a faithful data logging into the computer connected to system bus.

9.9.3 DAS-2: with Multiplexed High Level Inputs

As shown in Fig. 9.26, DAS-2 configuration offers an economical preposition with individual signal conditioners for each channel avoided and a common instrumentation amplifier used. This would be applicable with the limitation that the sensor group should have all sensors with characteristics in a close range.

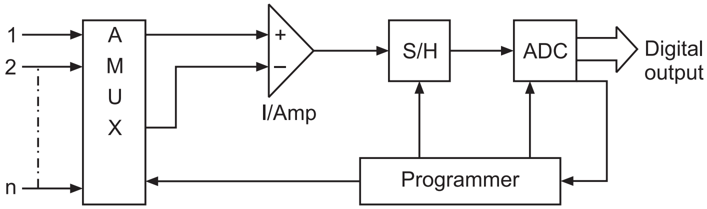


Fig. 9.26 DAS-2: with Multiplexed High Level Inputs

9.9.4 DAS-3: with Multiplexed Sample/Hold outputs

This configuration as shown in Fig. 9.27 includes Sample/Hold for each sensor channel over and above DAS-1, so that the data is more closely monitored for each channel and no abnormal variation is skipped during off periods of analog multiplexing. This is particularly useful in situations such as encountered in monitoring of (say) vibration, earthquake.

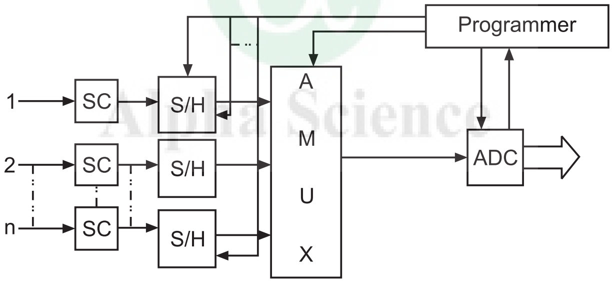


Fig. 9.27 DAS-3: with Multiplexed S/H Output

9.9.5 DAS-4: with Multiplexed Converter Outputs

The configuration uses least sharing of equipment, therefore expensive and multiplexes the digital signals obtained for different channels, as in Fig. 9.28.

Probably some other configurations of DAS are possible and at times these are specifically designed for the application. The hardware requirements shall vary in accordance with the speed of response desired which may be very high in case of auto-pilot of an aircraft compared to that of steel rolling process and so on. For individual plants/process information/design the case studies need to be looked into for arriving at the most suitable configuration.

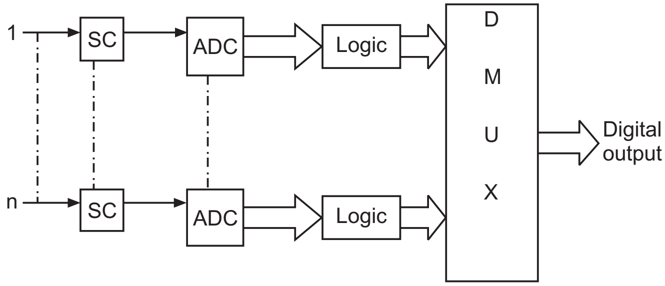


Fig. 9.28 DAS-4: with Multiplexed Converter Outputs

9.10 SENSOR NETWORK AND SMART TRANSDUCERS

The application of sensors everywhere has been discussed as used in variety of measurements and control applications, many of which touch our lives everyday, ranging from industrial automation to health care to intelligent transportation to home appliances and security to country's defense.

We have briefly discussed about embedding of computers in instrumentation but it has become very complex due to massive cabling that increases nonlinearity when number of sensors increase to thousands and need be communicating together. Networking of sensors of late has emerged as an effective solution for connectivity, much alike networking of PCs.

These smart sensor networks have been developed with features to such as:

- self-identification.
- plug and play module capability.
- wireless sensor network with ad-hoc configuration.
- networking capabilities.

Wireless sensors with ad-hoc networking feature shall free the sensors from often complex and cumbersome wiring. It shall be possible to share the sensor data over a large area among different users and applications with networking.

A large variety of existing sensor networks and the new ones to come; call for interoperability among heterogeneous and multi-vendor networks.

Standards have therefore been developed as framework to guide the developers and OEM towards building networks suitable for both wireless and wired networks, such that network presence can be detected, accessed and use sensor driven data. The framework provides for open sensor interfaces, standard data format for sensors, message standards so that integration, access, fusion, use and delivery of data is possible without conflict or ambiguity.

IEEE 1451 Smart transducer interface standard for sensor and actuators is the answer to many of these tasks and are in the various stages of development, implementation. It is hoped that, in the next decade there will be wide spread use in the new systems coming up and many of the existing instrumentation systems will change over to this technology, particularly in process systems. The smart transducers and the IEEE standard 1451 alongwith its variants are introduced next.

SMART TRANSDUCERS

It is integration of an analog or digital sensor (or actuator) element, a processing unit and a communication interface.

A smart transducer comprises a hardware or software device containing a sensor (and actuator) element, a microcontroller and the associated software for signal conditioning, calibration, diagnostics and communication.

Based on the above definitions, a smart transducer model can be considered as shown in Fig. 9.29. It consists of 4 parts:

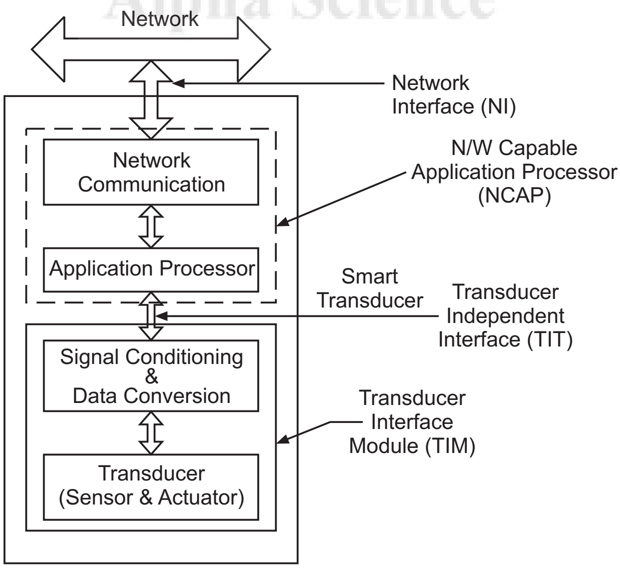


Fig. 9.29 Smart Transducer Model

- Transducer (sensor and actuator).
- Signal conditioning and data conversion.
- Application processor.
- Network communication.

The signal output of a sensor is conditioned, scaled (amplified), and converted to a digital format by an ADC. The digitised sensor signal can now be easily processed by a microprocessor using a digital application control algorithm. The measured parameters can now be passed-on to a host or monitoring system in a network, by means of network communication protocol. In a reverse path, an actuator command send from a host controller via network can be used to control an actuator.

To achieve the standardization required in the industry, IEEE 1451 smart transducer standard is developed. It defines smart transducer that provides functions beyond those necessary for generating a current representation of a sensed or controlled quantity.

This functionality simplifies the integration of transducers into application in a networked environment. Thus it provides for capabilities of self-identification, self-description, self-diagnosis, self-calibration, location-awareness, time-awareness, data processing, reasoning, data fusion, alert-notification and report, standards-based data formats and communication protocols.

In the architecture (Fig. 9.30), Transducer Electronics Data Sheets (TEDS) constitute important component of transducer interface model (TIM) detailed.

TEDS are like identification card containing all information viz. OEM, range, accuracy, calibration data, stored in EPROM.

Network Capable Application Processor (NCAP) is a network node that performs application processing and communication functions. Transducer Interface Module (TIM) consists of transducer signal conditioning, data converters, sensors and actuators with a combination up to 255 devices, for 8-bit architecture. This is useful for working with large sensor arrays *i.e.* mix of sensor and actuators, MEMS. The Transducer Independent Interface (TII) defines a communication medium and protocol for transfer of sensor information by providing operations such as- read, write of data, messages and responses. Network Interface (NI) defines a network communication protocol for NCAP communications to network.

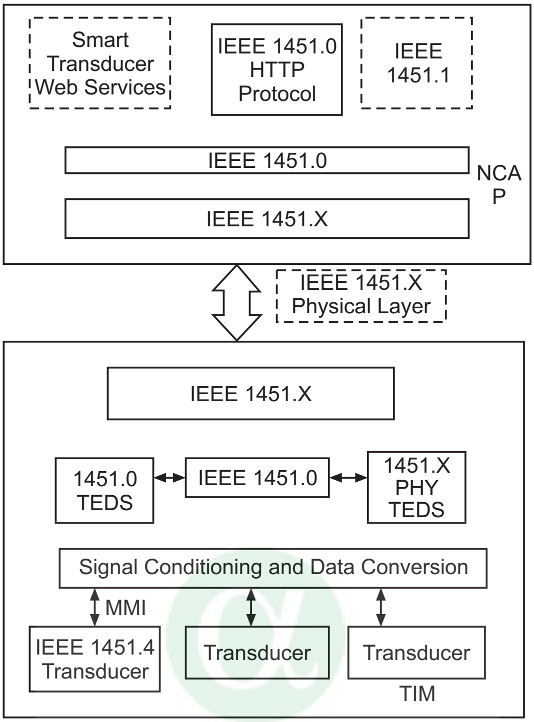


Fig. 9.30 Architecture of IEEE 1451 Standards

Architecture of IEEE 1451 Family of Standards

The standard defines a set of open, common, network independent communication interfaces for connecting transducers (sensors/actuators) to µPs, instrumentation systems, and control networks. Figure 9.31 shows the various components to establish communication between transducers(s) and network. These are listed as;

(*a*) Network Capable Application Processor (NCAP) provides interface between TIM and network by any one of the: IEEE 1451.1 / IEEE 1451.0 HTTP / Smart transducer web service

(*b*) Physical layer between NCAP and TIM includes

- Point-to-point interface to meet the standards 1451.2 – 1997.
- Distributed multi-drop interface that meets the standards of 1451.3, 2003.
- Wireless interface to meet the IEEE standard 1451.5 -2007(Wi-Fi, Bluetooth, Zigbee).

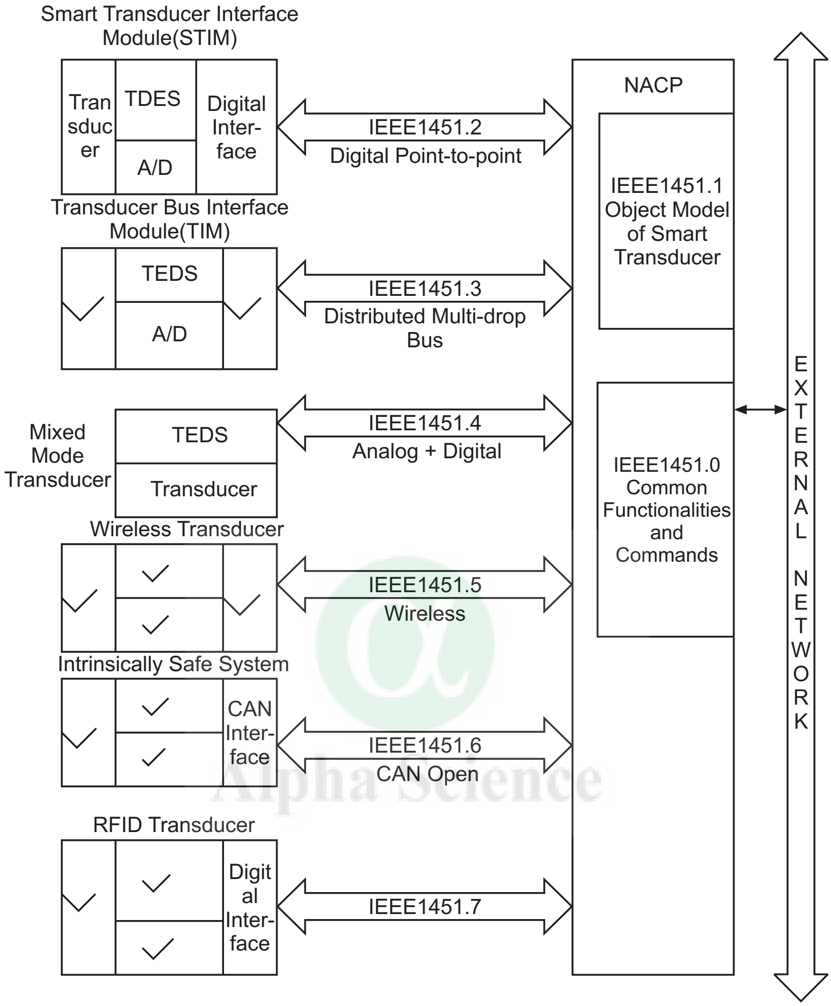


Fig. 9.31 IEEE 1451 Standard Family

- Can open interface that meets standard IEEE p. 1451.6.
- RFID interface that meets the standard IEEE p. 1451.7.

In general the interface between the units is not specified with the exception of IEEE1451.4 specifying low level, mixed mode interface for transducers. It also defines TEDS and deals with analog signals from transducers.

Elements of IEEE 1451 Standard

(*a*) IEEE 1451.0: Functioning of this is independent of physical communication media between transducer (TIM) and NCAP. It is capable of read/write to transducers, read-write TEDS and sends configuration, control, and operation commands to TIM. Its prime purpose is to achieve data level interoperability in a situation of many wired/wireless sensor networks connected in the system.

(*b*) IEEE 1451.1: It defines a common object model and interface specification for components of a networked smart transducer and applicable to distributed measurement and control applications. The software architecture is defined by any of the 03 models:

(*i*) A data model specifying the type and form of information communicated across 1451.1 the specified object interface for both local and remote communication.

(*ii*) An object model that specifies the software component types used for design and implementation of application system.

(*iii*) 02 communication models defining system type and semantics of the software interface between communication network and the application objects.

As can be noticed it focuses on communication between NCAPs, NCAPs and other nodes.

(*c*) IEEE 1451.2: This standard defines the communication layer:

Transducer-to-NCAP interface and, TEDs for point-to-point configurations. It allows a number of sensors built in a sensor module that provides signal conditioning, digitising etc.

It provides interface with IEEE 1451.0 and supports UART and Universal Serial Interface.

(*d*) IEEE 1451.3: This defines transducer-to-NCAP interface and TEDs using multi-drop communication protocol. With this, transducers are used as nodes in array on the multi-drop transducer network, sharing the common pair of wires as bus providing for power, timing and data connections.

(*e*) IEEE 1451.4: This is standard for mixed-mode interface for analog transducers with both analog and digital operating modes. It focusses on adding TEDs feature to legacy analog sensors, thus up dating them for current networked systems configuration. On powering the transducer, its TEDS is sent via one-wire digital interface, then interface is switched for analog operation and same interface is used to carry analog signal into the instrumentation system network.

(*f*) IEEE 1451.5: This is the standard for interfacing of transducer-to-NCAP and TEDs for wireless transducers. The specifications include radio-specific protocols for each of:

- Wi-Fi 802.11
- Bluetooth 802.15.1
- Zigbee 802.15.4

Figure 9.32 shows architecture of 1451.5 wireless sensor networks. In this the NCAP having multi-facility configuration can interact with each wireless transducer interface module (WTIM), using corresponding protocol and also interact with external network.

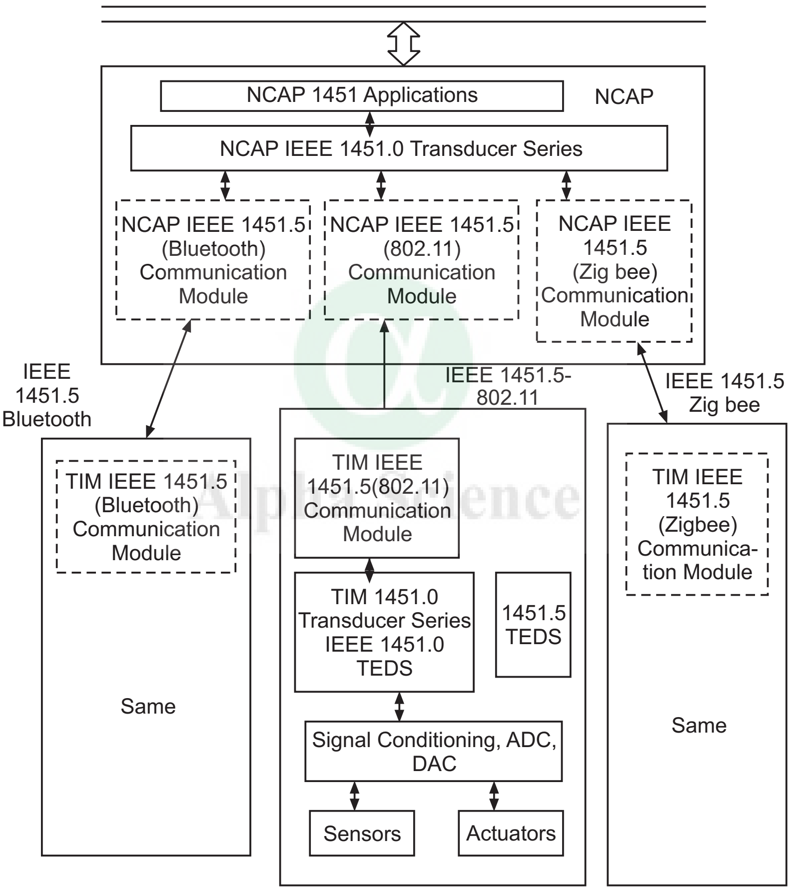


Fig. 9.32 Architecture of 1451.5

(*g*) IEEE 1451.6: This defines high speed CAN open network for transducer to NCAP interface and TEDS. It supports messages, process data, configuration parameters and diagnostic information.

(*h*) IEEE 1451.7: This defines the interface and protocol between transducers and RFID systems.

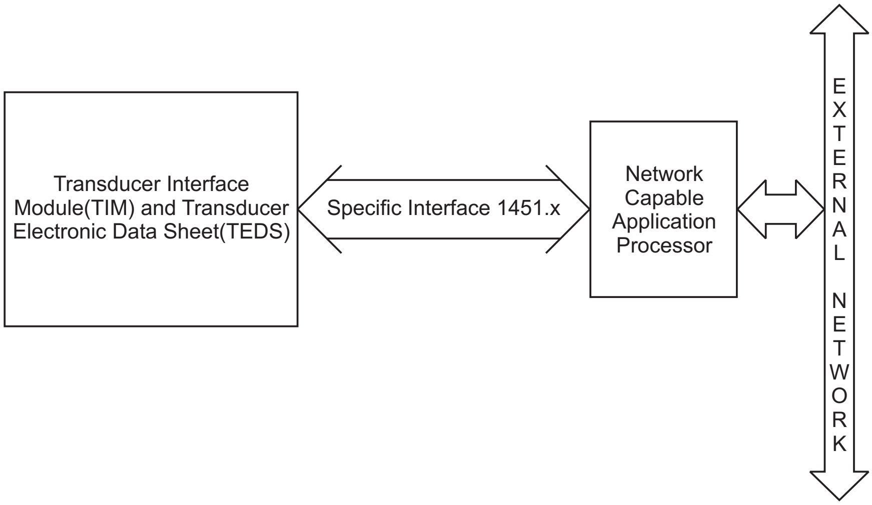


Fig. 9.33 IEEE 1451-Standard Architecture

Advantages of standard IEEE 1451

The main advantages with the inclusion of TEDS can be now listed as:

- Self identification of sensor/actuator.
- Information about location, technical details, maintenance record, and calibration updates readily available.
- Reduced human error and possibility of manipulation.
- Ease of installation, upgrade and maintenance contributing to reduce overall life cycle cost.
- Plugged module feature is available with adoption of standard for TIM and NCAP for physical communication activity, with sensor/actuator from different vendors, and applicable for all sensor/actuators. The sensor/actuators actually in use can be upgraded to work in a networked environment and also the addition of features becomes possible in future.
- The possibilities and confidence is enhanced for remote monitoring and activation with use of internet.
- Distributed measurement and control with better collaboration between these operations is achievable.
- A high degree of interoperability and possibility of including all smart sensors is achievable over factory wide or nation wide sensor network.

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APPENDIX A

Instrumentation Symbols

Instrumentation in any industry is for the purposes outlined in Chapter 1 and closely compatible with the equipment for which it is being used. Precise and elaborate details of industrial processes are thoroughly documented with the help of literature including Process and Instrumentation (P&I) diagrams drawn with the help of symbols and notations for equipment, instruments, accessories. To understand, monitor and control the process flows it is necessary to understand the process diagram.

How instrumentation systems are documented

- Equipment specifications and sizing
- Operating manuals
- Technical documentation of plant experiments and control equations

TABLE A.1 : Symbol Nomenclature *(as per ISA*)*

1st letter	Type of variable/instrument/device
A	Analyzer
T	Temperature
P	Pressure
L	Level
F	Flow rate
AC	Composition Analyzer
2nd letter	**Type of operation**
C	Control
T	Transmitter
I	Indicating (only)
Y	Any other

*Instrument Society of America.

- Process instrumentation diagrams
- Symbols—ISA (Instrument society of America)
- 1st letter in PI diagram with instrument symbol-variables
- 2nd letter indicates type of calculation.

TABLE A.2 : Detailed Nomenclature

Identification letters					
	First letter		Succesding letters		
	Measured or initiating variable	Modifier	Readout or passive function	Output function	Modifier
A	Analysis		Alarm		
B	Burner, combustion		User's choice	User's choice	User's choice
C	User's choice			Control	
D	User's choice	Differential			
E	Voltage		Sensor (primary element)		
F	Flow rate	Ration (fraction)			
G	User's choice		Glass, viewing device		
H	Hand				High
I	Current (electical)		Indication		
J	Power	Scan			
K	Time, time schedule	Time rate of change		Control station	
L	Level		Light		Low
M	User's choice	Momentary			Middle, intermediate
N	User's choice		User's choice	User's choice	User's choice
O	User's choice		Orifice, restinction		
P	Pressure, vaccum		Point (test connection)		
Q	Quantity	Integrate, totalizer			
R	Radiation		Record		
S	Speed, frequency	Safety		Switch	
T	Temperature			Transmit	
U	Multivariable		Multifunction	Multifunction	Multifunction
V	Vibration, mechanical analysis			Valve, damper, lower	
W	Weight, force		Well		
X	Unclassified	X axis	Unclassified	Unclassified	Unclassified
Y	Event, state, or pressure	Y axis		Relay,compute convert	
Z	Position, dimension	Z axis		Driver,actuater	
Source: Control Engineering with data from ISA 55 : standard					

PREFIXES

CW-cooling water

MU-makeup

FW-feed water

SE-Sewar

RX-reactor

UT-Utilities

CA—chemical addition

IA-Instrument air

ABBREVIATIONS

D-drum

C-column

CT-cooling tower

TK-tank

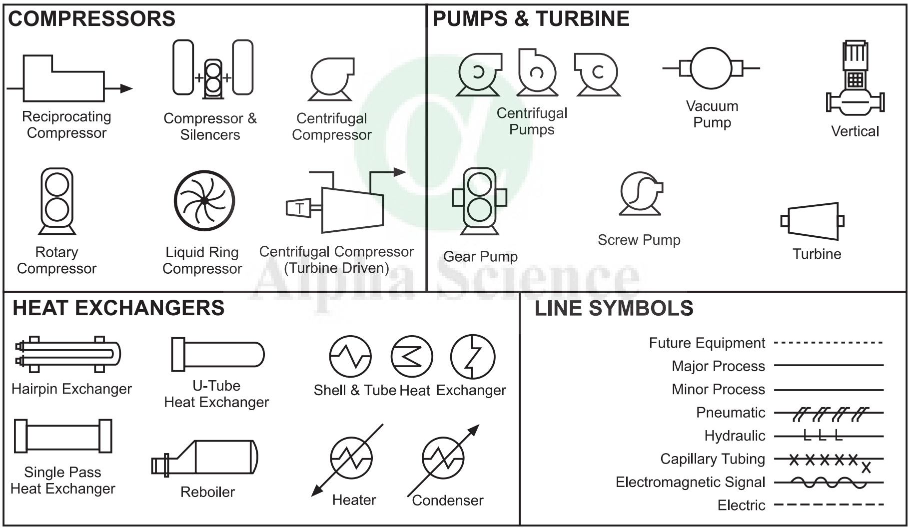
F-furace

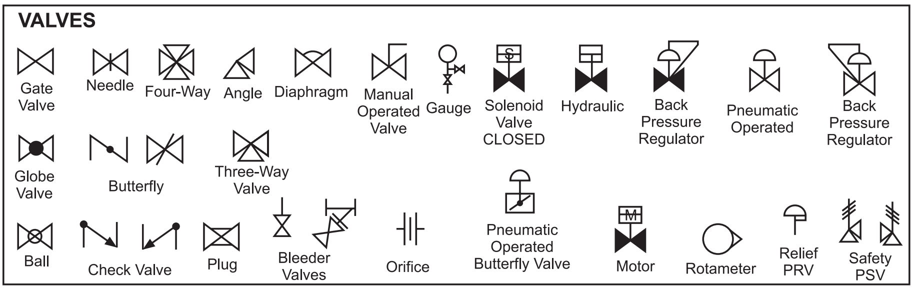
EX-exchanger

P-pump

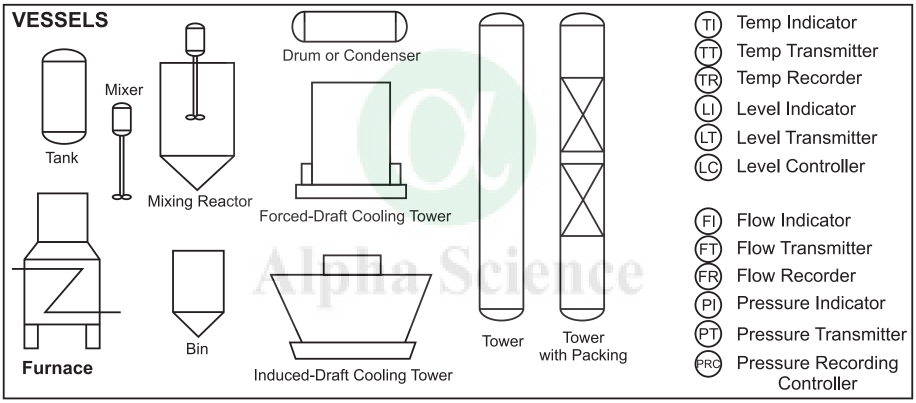
V-valve

TABLE A.3 : Symbols for Equipment





(M)	Motor	Fuse	MCC Motor Control Center
(V)	Voltmeter: measures voltage	V_S	Voltmeter Switch
(27)	Under Voltage Relay		Current Transformer: reduces high voltage to instrumentation.
(A)	Ammeter: measures electric current	A_S	Ammeter switch
(50)	Transformer Overcurrent Relay (Instantaneous)		Potential Transforming Symbol
(51)	Transformer Overcurrent Relay (Time delay)		Power Transformer: reduces high voltage
	Circuit Breaker: a protective device that interrupts current flow through an electric circuit	Switch	Motor Circuit Contacts



APPENDIX **B**

Compensation of Lead Resistance by Mueller's Method

The approach is general though explained here in context of RTDs and can be used for other devices too. Compensation of lead resistance in RTD circuits is considered for 2 cases as follows:

(a) Assuming that the lead resistance remains constant: Referring to Fig. B.1, under initial balance, obtained with adjustment of variable arm R_D to (say) R_{D1}, we have

$$R_1 = R_2$$

and, $$R_{D1} + R_C = R_X + R_T \qquad \text{...(B.1)}$$

where R_C, R_T are resistances of lead from sensor to bridge and arealmost equal.

R_X is the resistance of sensor at this condition.

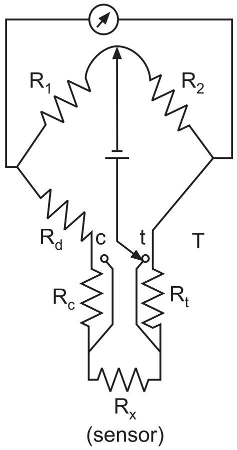


Fig. B.1 Muller's Bridge for Compensation of Leads

Commutating switch is operated to realize the position (*b*) with resistances switched as indicated in the figure. Balance is obtained again

$$R_{D2} + R_T = R_X + R_C \quad \text{...(B.2)}$$

By adding the equns B.1 and B.2

$$R_{D1} + R_{D2} + R_C + R_T = 2\, R_X + R_T + R_C$$

$$R_X = \frac{1}{2}\,(R_{D1} + R_{D2}). \quad \text{...(B.3)}$$

(*b*) If lead wire resistances are temperature dependent—

Then for the first position:

$$R_{D1} + R_{C1} = R_x + R_{T1}$$

and for second position :

$$R_{D2} + R_{T2} = R_X + R_{C2}$$

Then, $R_{D1} + R_{D2} + (R_{C1} - R_{T1}) - (R_{C2} - R_{T2}) = 2\, R_X$

$$R_X = \frac{1}{2}\,[(R_{D1} + R_{D2}) + \{(R_{C1} - R_{T1}) - (R_{C2} - R_{T2})\}] \quad \text{...(B.4)}$$

R_X is approximated by average of R_{D1} and R_{D2} as the measurement is almost independent of lead temperature, assuming lead resistances to be constant during the period of observation *i.e.* lead length, cross-sectional areas, temperature gradient along the lead wires to be constant, rather than trying for temperature of lead wires to be constant.

APPENDIX C

Basics of Operational Amplifiers (OP-amps)

Operational amplifier is an analog integrated circuit (IC) made by VLSI technique *i.e.* by packaging electronic circuit in a very compact form. It is a general purpose device available in 8-pin/14-pin packages as flat, metal dual-in-line in different forms. It is basically an amplifier which can be used for realizing many other common and special circuits such as summing, differencing, integrating, differentiating amplifier and voltage to current, current to voltage converter, etc by using additional external components. A few common applications of OP-**amps** are described briefly here.

Its behavior at low frequencies (dc) and at high frequencies (ac) is important to be understood, to utilize its potential.

C.1 REPRESENTATION OF AN IDEAL OP-AMP

Representation of an ideal OP-amp is symbolically shown in Fig. C.1 (*a*) with two inputs and one output terminal and Fig. C.1 (*b*) shows the

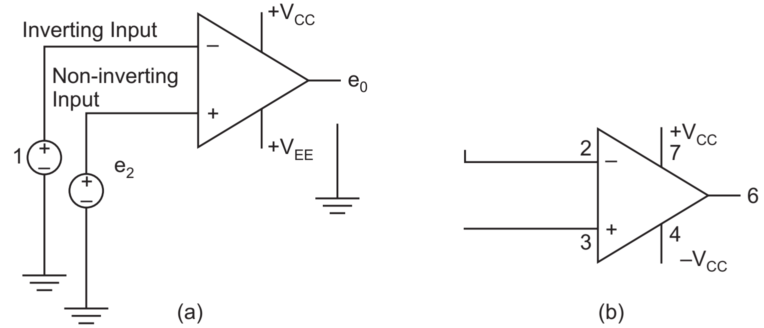


Fig. C.1

pin diagram for 8-pin types for electrical connections. The complete details can be looked into the manufacturer's data sheet.

C.2 DC CHARACTERISTICS

Ideal OP-amp draws no current from source, signal and provide infinite gain. But the non ideal dc characteristics that add error to dc output voltage involve:

Input bias current I_B^+ , I_B^-
Input offset current I_{OFS}
Input offset voltage V_{OFS}
Thermal drift

The basic specifications are shown in the Table C.1 below:

Table C.1

Parameter	***Ideal value***	***for typical op-amp (741C)***
Voltage gain, A_{OL}	∞	2×10^5
Output impedance, Z_0 0	75Ω	
Input impedance, Z_I ∞	2 MΩ	
Offset current, I_{OFS}0	20nA	
Off-set voltage, V_{OFS}	0	2 mV
Bandwidth, BW ∞	1 MHz	

Safety precautions to limit the short circuit current is built *i.e.* v_0 drops as Z_l drops (see Fig. C.2) in the data sheet average bias current is given, defined

$$I_B = \frac{I_B^+ + I_B^-}{2}, \leq 500 \text{ nA for } BJTs$$

$$\leq 50 \text{ pA for FETs}$$

A larger bias current may result in offset voltage, not acceptable in instrumentation, else, it needs to be compensated with built in compensation (74IC, LM318) may have to be externally compensated.

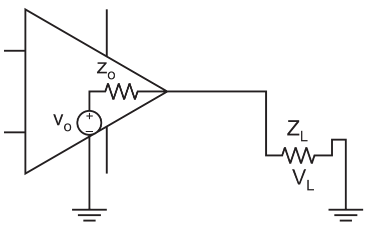


Fig. C.2

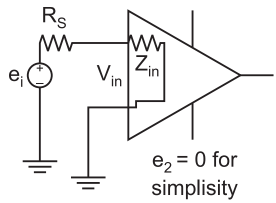


Fig. C.3

C.3 SUPPLY REQUIREMENTS

Two dc regulated stable supplies are needed with OP-amps (or one bipolar) called biasing operation and connected as shown in Fig. C.5 with the stipulations as follows.

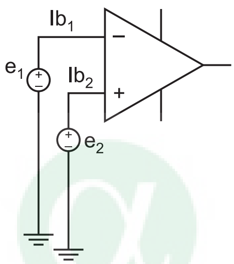


Fig. C.4 Input Bias Currents of OP-AMP

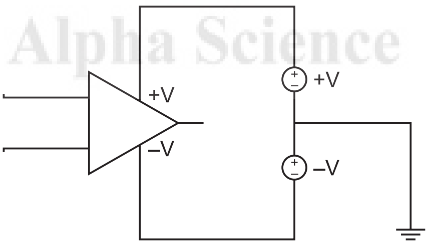


Fig. C.5 Biasing Suplies

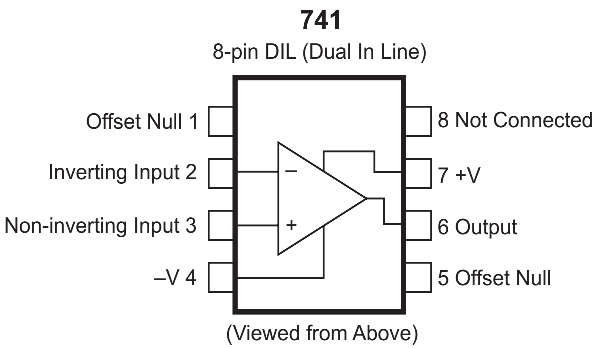


Fig. C.6 Pin Diagram of OP AMP 741

Input voltage amplitude $< v_{supply}$

Maximum output voltage = $(+/- v_{supply} - 2)$ volts

The pin diagram to identify the current terminals is shown in Fig. C.6.

C.4 AC CHARACTERISTICS

Frequency response: in ideal OP-amp would be infinite with constant gain over both audio and radio frequencies, for open-loop gain of about 80 db (with DC).

In practical OP-amps gain falls off at high frequencies. A h-f model of OP-amp is shown Fig. C-7 for which the output,

$$V_0 = \frac{-jX_C}{R_0 - jX_C}\left(A_{OL}.v_d\right)$$

$$A = \frac{v_0}{v_d} = \frac{A_{OL}}{1 + j2\pi f R_0 C}$$

$$= \frac{A_{OL}}{1 + j\left(\frac{f}{f_1}\right)} \text{ where, } f_1 \triangleq \frac{1}{2\pi R_0 C}$$

and,

$$\therefore |A| = \frac{A_{OL}}{\sqrt{1 + j\left(\frac{f}{f_1}\right)^2}}; \phi = -\tan^{-1}\left(\frac{f}{f_1}\right)$$

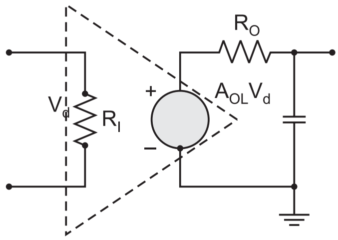


Fig. C.7 *h-f* Model of OP-amp

It can be deduced that

For $f << f_1$, $|A| = 20 \log A_{OL}$

(2) For $f = f_1$, $|A| = 20\log A_{OL}/2^5$

Referred to as 3db down frequency *i.e.* corner frequency

(1) For $f >> f_1, \frac{dA}{df} = -20$ dB/Decade = –6dB/Octave

The above result is shown in Fig. C.8.

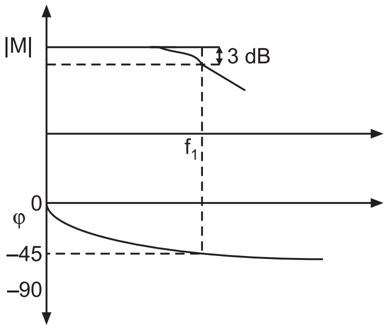


Fig. C.8 *h-f* Response of OP-amp

However a practical op-amp shows a magnitude response as:

$$A = \frac{A_{OL}}{\left(1+j\frac{f}{f_1}\right)\left(1+j\frac{f}{f_2}\right)\left(1+j\frac{f}{f_3}\right)}; 0 < f_1 < f_2 < f_3$$

and the transfer function would be

$$= \frac{A_{OL}w_1w_2w_3}{(s+w_1)(s+w_2)(s+w_3)}$$

where f_2, f_3 are the upper corner frequencies experienced due to parasitic capacitances effective at frequencies higher than f_1. The net result in Fig. C.9.

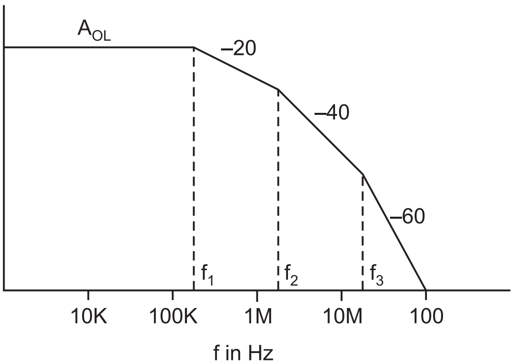


Fig. C.9 Response of OP-amp at High Frequencies

Slew rate: it is defined as the time of amplifier *i.e.* the time response to change from 10% to 90% for a step change in input; this should be more than the rate of change of input signals being given to the OP-amp so that the fidelity is maintained. Slew rate $\triangleq$ 0.35/BW (for small signals).

Often the limitation is self generated due to the capacitance connected (outside) in circuit to prevent oscillation (improving stability) and this restricts the rate of change.

Then $$\frac{dvc}{dt} = I_{MAX}/c$$

For example, in OP-amp 741 the maximum charging current ≤ 15 μA,

Therefore

$$\text{S.R.} = \left.\frac{dvc}{dt}\right|_{\max} = \frac{I_{MAX}}{C} = \frac{15\mu A}{30pF} = 0.5 \text{ V}/\mu\text{-sec.}$$

C.5 OP-AMP AS NEGATIVE FEEDBACK AMPLIFIER

The feedback configuration offers stable operation with noise reduction and faster response. The connection diagram is shown in Fig. C.10. The quantities are referred as

$$e_0 = A_{OL}\, e_d$$

$$e_f = \beta\, e_0$$

$$e_d = e_i . e_f$$

So $$A_{CL} = e_0/e_i = A_{OL}/(1+\beta) \therefore A_{OL} = 1/\beta \text{ as } \beta A_{OL} >> 1$$

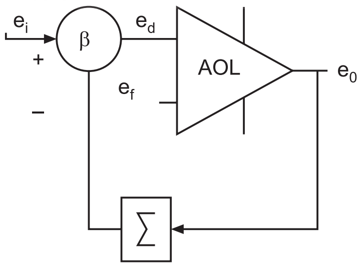


Fig. C.10 OP-amp as Negative Feedback Amplifier

C.6 OP-AMP AS INVERTING AMPLIFIER

This is realized as shown in Fig. C.11 wherein an R_f is a feedback resistor and input signal connected to

Inverting (or –ive) input terminal.

Here $$i_1 = e_s/R_i;\ i_1 = -I_f = -e_s/R_i = -e_0/R_f$$

So $$\frac{e_o}{e_i} = -\frac{R_f}{R_i} = A_{CL}$$

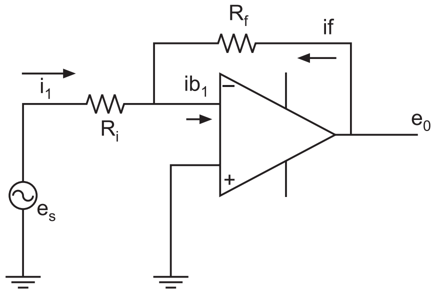


Fig. C.11 OP-amp as an Inverting Amplifier

R_i is kept ≤ 10 $K\Omega$ and gain is limited in value by the relation

$$\text{Gain} \times BW = 1\text{MHz}.$$

C.7 OP-AMP AS SUMMING AMPLIFIER

A very useful configuration for adding (or differencing) two signal, connected as shown in Fig. C.12.

Based on the assumption that the bias current is negligibly small, *KCL* at node '*a*' can be written as

$$I_1 + i_2 = i_3 = e_1/R_1 + e_2/R_2$$

So
$$e_0 = -i_3 R_3 = -\left(\frac{e_1}{R_1} + \frac{e_2}{R_2}\right) R_3$$

Gains or weights for both signals are adjustable with choice of R_1, R_2.

It can be extended for more than two signals also though the noise increases with each input.

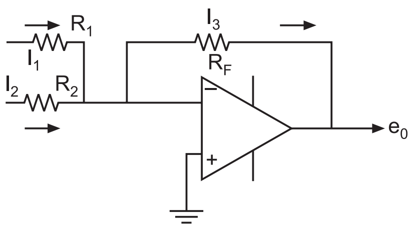


Fig. C.12 OP-amp as Summing Amplifier

C.8 NON-INVERTING AMPLIFIER

This configuration as shown in Fig. C.13 is very useful in instrumentation applications as it offers high input impedance and no phase (sign) change occurs from input to output. Note that, in this case the input signal is connected to non-inverting input terminal of OP-amp.

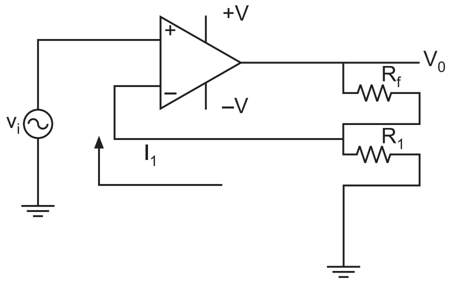


Fig. C.13

Again, as OP-amp does not draw any current from source/signal, voltage at node

$$-a,\ v_a = v_i = v_o R_1 / (R_1 + R_f)$$

So $$v_o/v_i = (R_1 + R_f)/R_1 = (1 + R_f/R_1) = A_{CL}$$

If $$R_f = R_1, \text{ closed-loop gain } = 2$$

And the gain shall always be greater than one.

C.9 VOLTAGE FOLLOWER

This configuration is helpful as a buffer between two stages, havingimpedances matching difficult to meet. It offers high input and low output impedance as shown in Fig. C.14. Feedback resistance is made zero.

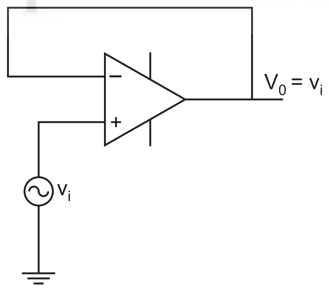


Fig. C.14

C.10 DIFFERENTIAL AMPLIFIER

This op-amp circuit configuration provides an amplified vector difference of two alternating signals connecting to the inverting and the non-inverting input terminals of the OP-amp through the input resistances R_1 and R_2. For the circuit shown in Fig. C.15.

At node–a applying KCL,

$$(V_3 - V_2)/R_1 + (V_3 - V_0)/R_2 = 0$$

So $V_3(1/R_1 + 1/R_2) - (V_2/R_1) = V_0/R_2$ ...(*a*)

and *KCL* at node *b* gives

$$(V_4 - V_1)/R_1 + V_4/R_2 = 0 \text{ and } V_4 = V_3$$

So $V_3(1/R_1 + 1/R_2) - V_1/R_1 = 0$ ...(*b*)

By taking difference of Eqn. a from *b*

$$(V_1/R_1 - V_2/R_2) = V_0/R_2 SO\ V_0 = (V_1 - V_2)R_2/R_1$$

This application is very useful in instrumentation and differential measurements in general.

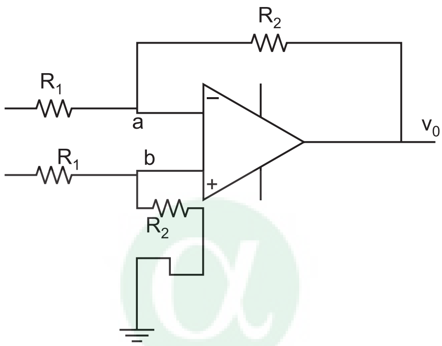


Fig. C.15 OP-amp as Differential Amplifier

APPENDIX D

Units and Conversions

Dimensions and Units

QuantityUnit	*Symbol*	*Unit definition*
Fundamental units:		
Length	meter, m	l
Mass	kilogram, kg	M
Electric current	Ampere, A	I
Time	second, s	t
Thermodynamic temperature	degree Kelvin, °K	T
Luminous intensity	candela, Cd	E
Supplementary units:		
Plane angle	radian	rad
Solid angle	steradian	Sr
Special derived units:		
Frequency	Hertz	f sec^{-1}
Force	Newton	F Kgm/s^2
Pressure, stress	Pascal	Pa / N/m^2
Work, energy, heat quantity	Joule	J Nm.
Power, heat flow rate	Watt	P J/s
Electric charge	Coulomb	Q As
Electric potential difference	volt	V W/A
Electrical resistance	Ohm, Ω	R V/A
Electrical conductance	Siemens, S	G A/V
Electrical capacitance	Farad, F	C As/V
Magnetic flux	Weber, wb	Õ Vs
Inductance	Henry, H	L, M Vs/A
Luminous flux	lumen, ln	Õ CdSr
Illumination	lux, lx	lm/m^2

Fractions and Multiples

Fraction	***prefix***	***symbol***	***multiple***	***prefix***	***symbol***
10^{-1}	deci	d	10	deca	da
10^{-2}	centi	c	10^{2}	hecto	h
10^{-3}	milli	m	10^{3}	kilo	K
10^{-6}	micro	μ	10^{6}	mega	M
10^{-9}	nano	n	10^{9}	giga	G
10^{-12}	pico	p	10^{12}	tera	T
10^{-15}	femto	f			
10^{-18}	alto	a			

In dealing with computers the prefix have a different meaning i.e. 1K = 210 = 1024; 1M = 220 = 1,048,576; 1G = 230 = 1,073,741,824

Generally Si units are used but CGS, FPS and other units are encountered at times, therefore some conversion factors are listed for convenience of ready reference:

	Imperial unit	***SI Unit***
Length	1 in.,	= 2.540 cms
	1 ft.,	= 0.3048 m
Area	1 mile,	= 1.609 km
	1 in^2	= 6.452 cm^2
Volume	1 in^3	= 0.0929 m^2
	1 ft^3	= 0.0832 m^3
Mass	1 lbm	= 0.4536 kg
	1 slug	= 14.59 kg
Force	1 lbf	= 4.448 N
Pressure	1 lbf/in^2 (in p.s.i.)	= 6.895 kPa
	1 in H_2O	= 24.91 Pa
	1 in Hg	= 3.386 kPa
Energy	1 ft lbf	= 1.356 J
	1 BTU	= 1.055 kJ
Power	1 HP	= 745.7 W
	CGS Unit	SI Unit
Magnetic field strength	1 Oe (Oersted)	= $(10^3/4\pi)$ A/m
Magnetic field	1 Mx (Maxwell)	= 10^{-3} wb
Magnetic flux density	1 Gauss	= 10^{-4} T.

APPENDIX E

Thermocouple Tables

The TC Tables for various types of industrial thermocouples have been collected and presented here for ready reference, as these would give an idea about the difference in the sensitivities and also shall be useful in working out the numerical examples included in chapter 06.

These are presented next for the TCs of the types: E, J, K, R.

TABLE E.1 : Type E Thermocouple—Thermoelectric Voltage as a Function of Temperature (°C); Reference Junctions at 0°C

°C	0	1	2	3	4	5	6	7	8	9	10	°C
						Thermoelectric Voltage in Millivolts						
0	0.000	-0.059	-0.117	-0.176	-0.234	-0.292	-0.350	-0.408	-0.466	-0.524	-0.582	0
0	0.000	0.059	0.118	0.176	0.235	0.294	0.354	0.413	0.472	0.532	0.591	0
10	0.591	0.651	0.711	0.770	0.830	0.890	0.950	1.010	1.071	1.131	1.192	10
20	1.192	1.252	1.313	1.373	1.434	1.495	1.556	1.617	1.678	1.740	1.801	20
30	1.801	1.862	1.924	1.986	2.047	2.109	2.171	2.233	2.295	2.357	2.420	30
40	2.420	2.482	2.545	2.607	2.670	2.733	2.795	2.858	2.921	2.984	3.048	40
50	3.048	3.111	3.174	3.238	3.301	3.365	3.429	3.492	3.556	3.620	3.685	50
60	3.685	3.749	3.813	3.877	3.942	4.006	4.071	4.136	4.200	4.265	4.330	60
70	4.330	4.395	4.460	4.526	4.591	4.656	4.722	4.788	4.853	4.919	4.985	70
80	4.985	5.051	5.117	5.183	5.249	5.315	5.382	5.448	5.514	5.581	5.648	80
90	5.648	5.714	5.781	5.848	5.915	5.982	6.049	6.117	6.184	6.251	6.319	90
100	6.319	6.386	6.454	6.522	6.590	6.658	6.725	6.794	6.862	6.930	6.998	100
110	6.998	7.066	7.135	7.203	7.272	7.341	7.409	7.478	7.547	7.616	7.685	110
120	7.685	7.754	7.823	7.892	7.962	8.031	8.101	8.170	8.240	8.309	8.379	120
130	8.379	8.449	8.519	8.589	8.659	8.729	8.799	8.869	8.940	9.010	9.081	130
140	9.081	9.151	9.222	9.292	9.363	9.434	9.505	9.576	9.647	9.718	9.789	140

°C	0	1	2	3	4	5	6	7	8	9	10	°C
150	9.789	9.860	9.931	10.003	10.074	10.145	10.217	10.288	10.360	10.432	10.503	150
160	10.503	10.575	10.647	10.719	10.791	10.863	10.935	11.007	11.080	11.152	11.224	160
170	11.224	11.297	11.369	11.442	11.514	11.587	11.660	11.733	11.805	11.878	11.951	170
180	11.951	12.024	12.097	12.170	12.243	12.317	12.390	12.463	12.537	12.610	12.684	180
190	12.684	12.757	12.831	12.904	12.978	13.052	13.126	13.199	13.273	13.347	13.421	190
200	13.421	13.495	13.569	13.644	13.718	13.792	13.866	13.941	14.015	14.090	14.164	200
210	14.164	14.239	14.313	14.388	14.463	14.537	14.612	14.687	14.762	14.837	14.912	210
220	14.912	14.987	15.062	15.137	15.212	15.287	15.362	15.438	15.513	15.588	15.664	220
230	15.664	15.739	15.815	15.890	15.966	16.041	16.117	16.193	16.269	16.344	16.420	230
240	16.420	16.496	16.572	16.648	16.724	16.800	16.876	16.952	17.028	17.104	17.181	240
250	17.181	17.257	17.333	17.409	17.486	17.562	17.639	17.715	17.792	17.868	17.945	250
260	17.945	18.021	18.098	18.175	18.252	18.328	18.405	18.482	18.559	18.636	18.713	260
270	18.713	18.790	18.867	18.944	19.021	19.098	19.175	19.252	19.330	19.407	19.484	270
280	19.484	19.561	19.639	19.716	19.794	19.871	19.948	20.026	20.103	20.181	20.259	280
290	20.259	20.336	20.414	20.492	20.569	20.647	20.725	20.803	20.880	20.958	21.036	290
300	21.036	21.114	21.192	21.270	21.348	21.426	21.504	21.582	21.660	21.739	21.817	300
310	21.817	21.895	21.973	22.051	22.130	22.208	22.286	22.365	22.443	22.522	22.600	310
320	22.600	22.678	22.757	22.835	22.914	22.993	23.071	23.150	23.228	23.307	23.386	320
330	23.386	23.464	23.543	23.622	23.701	23.780	23.858	23.937	24.016	24.095	24.174	330
340	24.174	24.253	24.332	24.411	24.490	24.569	24.648	24.727	24.806	24.885	24.964	340
350	24.964	25.044	25.123	25.202	25.281	25.360	25.440	25.519	25.598	25.678	25.757	350
360	25.757	25.836	25.916	25.995	26.075	26.154	26.233	26.313	26.392	26.472	26.552	360
370	26.552	26.631	26.711	26.790	26.870	26.950	27.029	27.109	27.189	27.268	27.348	370
380	27.348	27.428	27.507	27.587	27.667	27.747	27.827	27.907	27.986	28.066	28.146	380
390	28.146	28.226	28.306	28.386	28.466	28.546	28.626	28.706	28.786	28.866	28.946	390
400	28.946	29.026	29.106	29.186	29.266	29.346	29.427	29.507	29.587	29.667	29.747	400
410	29.747	29.827	29.908	29.988	30.068	30.148	30.229	30.309	30.389	30.470	30.550	410
420	30.550	30.630	30.711	30.791	30.871	30.952	31.032	31.112	31.193	31.273	31.354	420
430	31.354	31.434	31.515	31.595	31.676	31.756	31.837	31.917	31.998	32.078	32.159	430
440	32.159	32.239	32.320	32.400	32.481	32.562	32.642	32.723	32.803	32.884	32.965	440
450	32.965	33.045	33.126	33.207	33.287	33.368	33.449	33.529	33.610	33.691	33.772	450
460	33.772	33.852	33.933	34.014	34.095	34.175	34.256	34.337	34.418	34.498	34.579	460
470	34.579	34.660	34.741	34.822	34.902	34.983	35.064	35.145	35.226	35.307	35.387	470
480	35.387	35.468	35.549	35.630	35.711	35.792	35.873	35.954	36.034	36.115	36.196	480
490	36.196	36.277	36.358	36.439	36.520	36.601	36.682	36.763	36.843	36.924	37.005	490

°C	0	1	2	3	4	5	6	7	8	9	10	°C
500	37.005	37.086	37.167	37.248	37.329	37.410	37.491	37.572	37.653	37.734	37.815	500
510	37.815	37.896	37.977	38.058	38.139	38.220	38.300	38.381	38.462	38.543	38.624	510
520	38.624	38.705	38.786	38.867	38.948	39.029	39.110	39.191	39.272	39.353	39.434	520
530	39.434	39.515	39.596	39.677	39.758	39.839	39.920	40.001	40.082	40.163	40.243	530
540	40.243	40.324	40.405	40.486	40.567	40.648	40.729	40.810	40.891	40.972	41.053	540
550	41.053	41.134	41.215	41.296	41.377	41.457	41.538	41.619	41.700	41.781	41.862	550
560	41.862	41.943	42.024	42.105	42.185	42.266	42.347	42.428	42.509	42.590	42.671	560
570	42.671	42.751	42.832	42.913	42.994	43.075	43.156	43.236	43.317	43.398	43.479	570
580	43.479	43.560	43.640	43.721	43.802	43.883	43.963	44.044	44.125	44.206	44.286	580
590	44.286	44.367	44.448	44.529	44.609	44.690	44.771	44.851	44.932	45.013	45.093	590
600	45.093	45.174	45.255	45.335	45.416	45.497	45.577	45.658	45.738	45.819	45.900	600
610	45.900	45.980	46.061	46.141	46.222	46.302	46.383	46.463	46.544	46.624	46.705	610
620	46.705	46.785	46.866	46.946	47.027	47.107	47.188	47.268	47.349	47.429	47.509	620
630	47.509	47.590	47.670	47.751	47.831	47.911	47.992	48.072	48.152	48.233	48.313	630
640	48.313	48.393	48.474	48.554	48.634	48.715	48.795	48.875	48.955	49.035	49.116	640
650	49.116	49.196	49.276	49.356	49.436	49.517	49.597	49.677	49.757	49.837	49.917	650
660	49.917	49.997	50.077	50.157	50.238	50.318	50.398	50.478	50.558	50.638	50.718	660
670	50.718	50.798	50.878	50.958	51.038	51.118	51.197	51.277	51.357	51.437	51.517	670
680	51.517	51.597	51.677	51.757	51.837	51.916	51.996	52.076	52.156	52.236	52.315	680
690	52.315	52.395	52.475	52.555	52.634	52.714	52.794	52.873	52.953	53.033	53.112	690
700	53.112	53.192	53.272	53.351	53.431	53.510	53.590	53.670	53.749	53.829	53.908	700
710	53.908	53.988	54.067	54.147	54.226	54.306	54.385	54.465	54.544	54.624	54.703	710
720	54.703	54.782	54.862	54.941	55.021	55.100	55.179	55.259	55.338	55.417	55.497	720
730	55.497	55.576	55.655	55.734	55.814	55.893	55.972	56.051	56.131	56.210	56.289	730
740	56.289	56.368	56.447	56.526	56.606	56.685	56.764	56.843	56.922	57.001	57.080	740
750	57.080	57.159	57.238	57.317	57.396	57.475	57.554	57.633	57.712	57.791	57.870	750
760	57.870	57.949	58.028	58.107	58.186	58.265	58.343	58.422	58.501	58.580	58.659	760
770	58.659	58.738	58.816	58.895	58.974	59.053	59.131	59.210	59.289	59.367	59.446	770
780	59.446	59.525	59.604	59.682	59.761	59.839	59.918	59.997	60.075	60.154	60.232	780
790	60.232	60.311	60.390	60.468	60.547	60.625	60.704	60.782	60.860	60.939	61.017	790

TABLE E.2 : Type J Thermocouple—Thermoelectric Voltage as a Function of Temperature (°c); Reference Junctions at 0°C

°C	0	1	2	3	4	5	6	7	8	9	10	°C
						Thermoelectric Voltage in Millivolts						
0	0.000	-0.050	-0.101	-0.151	-0.201	-0.251	-0.301	-0.351	-0.401	-0.451	-0.501	0
0	0.000	0.050	0.101	0.151	0.202	0.253	0.303	0.354	0.405	0.456	0.507	0
10	0.507	0.558	0.609	0.660	0.711	0.762	0.814	0.865	0.916	0.968	1.019	10
20	1.019	1.071	1.122	1.174	1.226	1.277	1.329	1.381	1.433	1.485	1.537	20
30	1.537	1.589	1.641	1.693	1.745	1.797	1.849	1.902	1.954	2.006	2.059	30
40	2.059	2.111	2.164	2.216	2.269	2.322	2.374	2.427	2.480	2.532	2.585	40
50	2.585	2.638	2.691	2.744	2.797	2.850	2.903	2.956	3.009	3.062	3.116	50
60	3.116	3.169	3.222	3.275	3.329	3.382	3.436	3.489	3.543	3.596	3.650	60
70	3.650	3.703	3.757	3.810	3.864	3.918	3.971	4.025	4.079	4.133	4.187	70
80	4.187	4.240	4.294	4.348	4.402	4.456	4.510	4.564	4.618	4.672	4.726	80
90	4.726	4.781	4.835	4.889	4.943	4.997	5.052	5.106	5.160	5.215	5.269	90
100	5.269	5.323	5.378	5.432	5.487	5.541	5.595	5.650	5.705	5.759	5.814	100
110	5.814	5.868	5.923	5.977	6.032	6.087	6.141	6.196	6.251	6.306	6.360	110
120	6.360	6.415	6.470	6.525	6.579	6.634	6.689	6.744	6.799	6.854	6.909	120
130	6.909	6.964	7.019	7.074	7.129	7.184	7.239	7.294	7.349	7.404	7.459	130
140	7.459	7.514	7.569	7.624	7.679	7.734	7.789	7.844	7.900	7.955	8.010	140
150	8.010	8.065	8.120	8.175	8.231	8.286	8.341	8.396	8.452	8.507	8.562	150
160	8.562	8.618	8.673	8.728	8.783	8.839	8.894	8.949	9.005	9.060	9.115	160
170	9.115	9.171	9.226	9.282	9.337	9.392	9.448	9.503	9.559	9.614	9.669	170
180	9.669	9.725	9.780	9.836	9.891	9.947	10.002	10.057	10.113	10.168	10.224	180
190	10.224	10.279	10.335	10.390	10.446	10.501	10.557	10.612	10.668	10.723	10.779	190
200	10.779	10.834	10.890	10.945	11.001	11.056	11.112	11.167	11.223	11.278	11.334	200
210	11.334	11.389	11.445	11.501	11.556	11.612	11.667	11.723	11.778	11.834	11.889	210
220	11.889	11.945	12.000	12.056	12.111	12.167	12.222	12.278	12.334	12.389	12.445	220
230	12.445	12.500	12.556	12.611	12.667	12.722	12.778	12.833	12.889	12.944	13.000	230
240	13.000	13.056	13.111	13.167	13.222	13.278	13.333	13.389	13.444	13.500	13.555	240
250	13.555	13.611	13.666	13.722	13.777	13.833	13.888	13.944	13.999	14.055	14.110	250
260	14.110	14.166	14.221	14.277	14.332	14.388	14.443	14.499	14.554	14.609	14.665	260
270	14.665	14.720	14.776	14.831	14.887	14.942	14.998	15.053	15.109	15.164	15.219	270
280	15.219	15.275	15.330	15.386	15.441	15.496	15.552	15.607	15.663	15.718	15.773	280
290	15.773	15.829	15.884	15.940	15.995	16.050	16.106	16.161	16.216	16.272	16.327	290

°C	0	1	2	3	4	5	6	7	8	9	10	°C
300	16.327	16.383	16.438	16.493	16.549	16.604	16.659	16.715	16.770	16.825	16.881	300
310	16.881	16.936	16.991	17.046	17.102	17.157	17.212	17.268	17.323	17.378	17.434	310
320	17.434	17.489	17.544	17.599	17.655	17.710	17.765	17.820	17.876	17.931	17.986	320
330	17.986	18.041	18.097	18.152	18.207	18.262	18.318	18.373	18.428	18.483	18.538	330
340	18.538	18.594	18.649	18.704	18.759	18.814	18.870	18.925	18.980	19.035	19.090	340
350	19.090	19.146	19.201	19.256	19.311	19.366	19.422	19.477	19.532	19.587	19.642	350
360	19.642	19.697	19.753	19.808	19.863	19.918	19.973	20.028	20.083	20.139	20.194	360
370	20.194	20.249	20.304	20.359	20.414	20.469	20.525	20.580	20.635	20.690	20.745	370
380	20.745	20.800	20.855	20.911	20.966	21.021	21.076	21.131	21.186	21.241	21.297	380
390	21.297	21.352	21.407	21.462	21.517	21.572	21.627	21.683	21.738	21.793	21.848	390
400	21.848	21.903	21.958	22.014	22.069	22.124	22.179	22.234	22.289	22.345	22.400	400
410	22.400	22.455	22.510	22.565	22.620	22.676	22.731	22.786	22.841	22.896	22.952	410
420	22.952	23.007	23.062	23.117	23.172	23.228	23.283	23.338	23.393	23.449	23.504	420
430	23.504	23.559	23.614	23.670	23.725	23.780	23.835	23.891	23.946	24.001	24.057	430
440	24.057	24.112	24.167	24.223	24.278	24.333	24.389	24.444	24.499	24.555	24.610	440
450	24.610	24.665	24.721	24.776	24.832	24.887	24.943	24.998	25.053	25.109	25.164	450
460	25.164	25.220	25.275	25.331	25.386	25.442	25.497	25.553	25.608	25.664	25.720	460
470	25.720	25.775	25.831	25.886	25.942	25.998	26.053	26.109	26.165	26.220	26.276	470
480	26.276	26.332	26.387	26.443	26.499	26.555	26.610	26.666	26.722	26.778	26.834	480
490	26.834	26.889	26.945	27.001	27.057	27.113	27.169	27.225	27.281	27.337	27.393	490
500	27.393	27.449	27.505	27.561	27.617	27.673	27.729	27.785	27.841	27.897	27.953	500
510	27.953	28.010	28.066	28.122	28.178	28.234	28.291	28.347	28.403	28.460	28.516	510
520	28.516	28.572	28.629	28.685	28.741	28.798	28.854	28.911	28.967	29.024	29.080	520
530	29.080	29.137	29.194	29.250	29.307	29.363	29.420	29.477	29.534	29.590	29.647	530
540	29.647	29.704	29.761	29.818	29.874	29.931	29.988	30.045	30.102	30.159	30.216	540
550	30.216	30.273	30.330	30.387	30.444	30.502	30.559	30.616	30.673	30.730	30.788	550
560	30.788	30.845	30.902	30.960	31.017	31.074	31.132	31.189	31.247	31.304	31.362	560
570	31.362	31.419	31.477	31.535	31.592	31.650	31.708	31.766	31.823	31.881	31.939	570
580	31.939	31.997	32.055	32.113	32.171	32.229	32.287	32.345	32.403	32.461	32.519	580
590	32.519	32.577	32.636	32.694	32.752	32.810	32.869	32.927	32.985	33.044	33.102	590
600	33.102	33.161	33.219	33.278	33.337	33.395	33.454	33.513	33.571	33.630	33.689	600
610	33.689	33.748	33.807	33.866	33.925	33.984	34.043	34.102	34.161	34.220	34.279	610
620	34.279	34.338	34.397	34.457	34.516	34.575	34.635	34.694	34.754	34.813	34.873	620
630	34.873	34.932	34.992	35.051	35.111	35.171	35.230	35.290	35.350	35.410	35.470	630
640	35.470	35.530	35.590	35.650	35.710	35.770	35.830	35.890	35.950	36.010	36.071	640

°C	0	1	2	3	4	5	6	7	8	9	10	°C
650	36.071	36.131	36.191	36.252	36.312	36.373	36.433	36.494	36.554	36.615	36.675	650
660	36.675	36.736	36.797	36.858	36.918	36.979	37.040	37.101	37.162	37.223	37.284	660
670	37.284	37.345	37.406	37.467	37.528	37.590	37.651	37.712	37.773	37.835	37.896	670
680	37.896	37.958	38.019	38.081	38.142	38.204	38.265	38.327	38.389	38.450	38.512	680
690	38.512	38.574	38.636	38.698	38.760	38.822	38.884	38.946	39.008	39.070	39.132	690
700	39.132	39.194	39.256	39.318	39.381	39.443	39.505	39.568	39.630	39.693	39.755	700
710	39.755	39.818	39.880	39.943	40.005	40.068	40.131	40.193	40.256	40.319	40.382	710
720	40.382	40.445	40.508	40.570	40.633	40.696	40.759	40.822	40.886	40.949	41.012	720
730	41.012	41.075	41.138	41.201	41.265	41.328	41.391	41.455	41.518	41.581	41.645	730
740	41.645	41.708	41.772	41.835	41.899	41.962	42.026	42.090	42.153	42.217	42.281	740
750	42.281	42.344	42.408	42.472	42.536	42.599	42.663	42.727	42.791	42.855	42.919	750

TABLE E.3 : Type K Thermocouple—Thermoelectric Voltage as a Function of Temperature (°c); Reference Junctions at 0°C

°C	0	1	2	3	4	5	6	7	8	9	10	°C
					Thermoelectric Voltage in Millivolts							
0	0.000	-0.039	-0.079	-0.118	-0.157	-0.197	-0.236	-0.275	-0.314	-0.353	-0.392	0
0	0.000	0.039	0.079	0.119	0.158	0.198	0.238	0.277	0.317	0.357	0.397	0
10	0.397	0.437	0.477	0.517	0.557	0.597	0.637	0.677	0.718	0.758	0.798	10
20	0.798	0.838	0.879	0.919	0.960	1.000	1.041	1.081	1.122	1.163	1.203	20
30	1.203	1.244	1.285	1.326	1.366	1.407	1.448	1.489	1.530	1.571	1.612	30
40	1.612	1.653	1.694	1.735	1.776	1.817	1.858	1.899	1.941	1.982	2.023	40
50	2.023	2.064	2.106	2.147	2.188	2.230	2.271	2.312	2.354	2.395	2.436	50
60	2.436	2.478	2.519	2.561	2.602	2.644	2.685	2.727	2.768	2.810	2.851	60
70	2.851	2.893	2.934	2.976	3.017	3.059	3.100	3.142	3.184	3.225	3.267	70
80	3.267	3.308	3.350	3.391	3.433	3.474	3.516	3.557	3.599	3.640	3.682	80
90	3.682	3.723	3.765	3.806	3.848	3.889	3.931	3.972	4.013	4.055	4.096	90
100	4.096	4.138	4.179	4.220	4.262	4.303	4.344	4.385	4.427	4.468	4.509	100
110	4.509	4.550	4.591	4.633	4.674	4.715	4.756	4.797	4.838	4.879	4.920	110
120	4.920	4.961	5.002	5.043	5.084	5.124	5.165	5.206	5.247	5.288	5.328	120
130	5.328	5.369	5.410	5.450	5.491	5.532	5.572	5.613	5.653	5.694	5.735	130
140	5.735	5.775	5.815	5.856	5.896	5.937	5.977	6.017	6.058	6.098	6.138	140
150	6.138	6.179	6.219	6.259	6.299	6.339	6.380	6.420	6.460	6.500	6.540	150
160	6.540	6.580	6.620	6.660	6.701	6.741	6.781	6.821	6.861	6.901	6.941	160
170	6.941	6.981	7.021	7.060	7.100	7.140	7.180	7.220	7.260	7.300	7.340	170
180	7.340	7.380	7.420	7.460	7.500	7.540	7.579	7.619	7.659	7.699	7.739	180
190	7.739	7.779	7.819	7.859	7.899	7.939	7.979	8.019	8.059	8.099	8.138	190
200	8.138	8.178	8.218	8.258	8.298	8.338	8.378	8.418	8.458	8.499	8.539	200
210	8.539	8.579	8.619	8.659	8.699	8.739	8.779	8.819	8.860	8.900	8.940	210
220	8.940	8.980	9.020	9.061	9.101	9.141	9.181	9.222	9.262	9.302	9.343	220
230	9.343	9.383	9.423	9.464	9.504	9.545	9.585	9.626	9.666	9.707	9.747	230
240	9.747	9.788	9.828	9.869	9.909	9.950	9.991	10.031	10.072	10.113	10.153	240
250	10.153	10.194	10.235	10.276	10.316	10.357	10.398	10.439	10.480	10.520	10.561	250
260	10.561	10.602	10.643	10.684	10.725	10.766	10.807	10.848	10.889	10.930	10.971	260
270	10.971	11.012	11.053	11.094	11.135	11.176	11.217	11.259	11.300	11.341	11.382	270
280	11.382	11.423	11.465	11.506	11.547	11.588	11.630	11.671	11.712	11.753	11.795	280
290	11.795	11.836	11.877	11.919	11.960	12.001	12.043	12.084	12.126	12.167	12.209	290
300	12.209	12.250	12.291	12.333	12.374	12.416	12.457	12.499	12.540	12.582	12.624	300
310	12.624	12.665	12.707	12.748	12.790	12.831	12.873	12.915	12.956	12.998	13.040	310
320	13.040	13.081	13.123	13.165	13.206	13.248	13.290	13.331	13.373	13.415	13.457	320

°C	0	1	2	3	4	5	6	7	8	9	10	°C
330	13.457	13.498	13.540	13.582	13.624	13.665	13.707	13.749	13.791	13.833	13.874	330
340	13.874	13.916	13.958	14.000	14.042	14.084	14.126	14.167	14.209	14.251	14.293	340
350	14.293	14.335	14.377	14.419	14.461	14.503	14.545	14.587	14.629	14.671	14.713	350
360	14.713	14.755	14.797	14.839	14.881	14.923	14.965	15.007	15.049	15.091	15.133	360
370	15.133	15.175	15.217	15.259	15.301	15.343	15.385	15.427	15.469	15.511	15.554	370
380	15.554	15.596	15.638	15.680	15.722	15.764	15.806	15.849	15.891	15.933	15.975	380
390	15.975	16.017	16.059	16.102	16.144	16.186	16.228	16.270	16.313	16.355	16.397	390
400	16.397	16.439	16.482	16.524	16.566	16.608	16.651	16.693	16.735	16.778	16.820	400
410	16.820	16.862	16.904	16.947	16.989	17.031	17.074	17.116	17.158	17.201	17.243	410
420	17.243	17.285	17.328	17.370	17.413	17.455	17.497	17.540	17.582	17.624	17.667	420
430	17.667	17.709	17.752	17.794	17.837	17.879	17.921	17.964	18.006	18.049	18.091	430
440	18.091	18.134	18.176	18.218	18.261	18.303	18.346	18.388	18.431	18.473	18.516	440
450	18.516	18.558	18.601	18.643	18.686	18.728	18.771	18.813	18.856	18.898	18.941	450
460	18.941	18.983	19.026	19.068	19.111	19.154	19.196	19.239	19.281	19.324	19.366	460
470	19.366	19.409	19.451	19.494	19.537	19.579	19.622	19.664	19.707	19.750	19.792	470
480	19.792	19.835	19.877	19.920	19.962	20.005	20.048	20.090	20.133	20.175	20.218	480
490	20.218	20.261	20.303	20.346	20.389	20.431	20.474	20.516	20.559	20.602	20.644	490
500	20.644	20.687	20.730	20.772	20.815	20.857	20.900	20.943	20.985	21.028	21.071	500
510	21.071	21.113	21.156	21.199	21.241	21.284	21.326	21.369	21.412	21.454	21.497	510
520	21.497	21.540	21.582	21.625	21.668	21.710	21.753	21.796	21.838	21.881	21.924	520
530	21.924	21.966	22.009	22.052	22.094	22.137	22.179	22.222	22.265	22.307	22.350	530
540	22.350	22.393	22.435	22.478	22.521	22.563	22.606	22.649	22.691	22.734	22.776	540
550	22.776	22.819	22.862	22.904	22.947	22.990	23.032	23.075	23.117	23.160	23.203	550
560	23.203	23.245	23.288	23.331	23.373	23.416	23.458	23.501	23.544	23.586	23.629	560
570	23.629	23.671	23.714	23.757	23.799	23.842	23.884	23.927	23.970	24.012	24.055	570
580	24.055	24.097	24.140	24.182	24.225	24.267	24.310	24.353	24.395	24.438	24.480	580
590	24.480	24.523	24.565	24.608	24.650	24.693	24.735	24.778	24.820	24.863	24.905	590
600	24.905	24.948	24.990	25.033	25.075	25.118	25.160	25.203	25.245	25.288	25.330	600
610	25.330	25.373	25.415	25.458	25.500	25.543	25.585	25.627	25.670	25.712	25.755	610
620	25.755	25.797	25.840	25.882	25.924	25.967	26.009	26.052	26.094	26.136	26.179	620
630	26.179	26.221	26.263	26.306	26.348	26.390	26.433	26.475	26.517	26.560	26.602	630
640	26.602	26.644	26.687	26.729	26.771	26.814	26.856	26.898	26.940	26.983	27.025	640
650	27.025	27.067	27.109	27.152	27.194	27.236	27.278	27.320	27.363	27.405	27.447	650
660	27.447	27.489	27.531	27.574	27.616	27.658	27.700	27.742	27.784	27.826	27.869	660
670	27.869	27.911	27.953	27.995	28.037	28.079	28.121	28.163	28.205	28.247	28.289	670
680	28.289	28.332	28.374	28.416	28.458	28.500	28.542	28.584	28.626	28.668	28.710	680
690	28.710	28.752	28.794	28.835	28.877	28.919	28.961	29.003	29.045	29.087	29.129	690

°C	0	1	2	3	4	5	6	7	8	9	10	°C
700	29.129	29.171	29.213	29.255	29.297	29.338	29.380	29.422	29.464	29.506	29.548	700
710	29.548	29.589	29.631	29.673	29.715	29.757	29.798	29.840	29.882	29.924	29.965	710
720	29.965	30.007	30.049	30.090	30.132	30.174	30.216	30.257	30.299	30.341	30.382	720
730	30.382	30.424	30.466	30.507	30.549	30.590	30.632	30.674	30.715	30.757	30.798	730
740	30.798	30.840	30.881	30.923	30.964	31.006	31.047	31.089	31.130	31.172	31.213	740
750	31.213	31.255	31.296	31.338	31.379	31.421	31.462	31.504	31.545	31.586	31.628	750
760	31.628	31.669	31.710	31.752	31.793	31.834	31.876	31.917	31.958	32.000	32.041	760
770	32.041	32.082	32.124	32.165	32.206	32.247	32.289	32.330	32.371	32.412	32.453	770
780	32.453	32.495	32.536	32.577	32.618	32.659	32.700	32.742	32.783	32.824	32.865	780
790	32.865	32.906	32.947	32.988	33.029	33.070	33.111	33.152	33.193	33.234	33.275	790
800	33.275	33.316	33.357	33.398	33.439	33.480	33.521	33.562	33.603	33.644	33.685	800
810	33.685	33.726	33.767	33.808	33.848	33.889	33.930	33.971	34.012	34.053	34.093	810
820	34.093	34.134	34.175	34.216	34.257	34.297	34.338	34.379	34.420	34.460	34.501	820
830	34.501	34.542	34.582	34.623	34.664	34.704	34.745	34.786	34.826	34.867	34.908	830
840	34.908	34.948	34.989	35.029	35.070	35.110	35.151	35.192	35.232	35.273	35.313	840
850	35.313	35.354	35.394	35.435	35.475	35.516	35.556	35.596	35.637	35.677	35.718	850
860	35.718	35.758	35.798	35.839	35.879	35.920	35.960	36.000	36.041	36.081	36.121	860
870	36.121	36.162	36.202	36.242	36.282	36.323	36.363	36.403	36.443	36.484	36.524	870
880	36.524	36.564	36.604	36.644	36.685	36.725	36.765	36.805	36.845	36.885	36.925	880
890	36.925	36.965	37.006	37.046	37.086	37.126	37.166	37.206	37.246	37.286	37.326	890
900	37.326	37.366	37.406	37.446	37.486	37.526	37.566	37.606	37.646	37.686	37.725	900
910	37.725	37.765	37.805	37.845	37.885	37.925	37.965	38.005	38.044	38.084	38.124	910
920	38.124	38.164	38.204	38.243	38.283	38.323	38.363	38.402	38.442	38.482	38.522	920
930	38.522	38.561	38.601	38.641	38.680	38.720	38.760	38.799	38.839	38.878	38.918	930
940	38.918	38.958	38.997	39.037	39.076	39.116	39.155	39.195	39.235	39.274	39.314	940
950	39.314	39.353	39.393	39.432	39.471	39.511	39.550	39.590	39.629	39.669	39.708	950
960	39.708	39.747	39.787	39.826	39.866	39.905	39.944	39.984	40.023	40.062	40.101	960
970	40.101	40.141	40.180	40.219	40.259	40.298	40.337	40.376	40.415	40.455	40.494	970
980	40.494	40.533	40.572	40.611	40.651	40.690	40.729	40.768	40.807	40.846	40.885	980
990	40.885	40.924	40.963	41.002	41.042	41.081	41.120	41.159	41.198	41.237	41.276	990
1000	41.276	41.315	41.354	41.393	41.431	41.470	41.509	41.548	41.587	41.626	41.665	1000
1010	41.665	41.704	41.743	41.781	41.820	41.859	41.898	41.937	41.976	42.014	42.053	1010
1020	42.053	42.092	42.131	42.169	42.208	42.247	42.286	42.324	42.363	42.402	42.440	1020
1030	42.440	42.479	42.518	42.556	42.595	42.633	42.672	42.711	42.749	42.788	42.826	1030
1040	42.826	42.865	42.903	42.942	42.980	43.019	43.057	43.096	43.134	43.173	43.211	1040
1050	43.211	43.250	43.288	43.327	43.365	43.403	43.442	43.480	43.518	43.557	43.595	1050
1060	43.595	43.633	43.672	43.710	43.748	43.787	43.825	43.863	43.901	43.940	43.978	1060

°C	0	1	2	3	4	5	6	7	8	9	10	°C
1070	43.978	44.016	44.054	44.092	44.130	44.169	44.207	44.245	44.283	44.321	44.359	1070
1080	44.359	44.397	44.435	44.473	44.512	44.550	44.588	44.626	44.664	44.702	44.740	1080
1090	44.740	44.778	44.816	44.853	44.891	44.929	44.967	45.005	45.043	45.081	45.119	1090
1100	45.119	45.157	45.194	45.232	45.270	45.308	45.346	45.383	45.421	45.459	45.497	1100
1110	45.497	45.534	45.572	45.610	45.647	45.685	45.723	45.760	45.798	45.836	45.873	1110
1120	45.873	45.911	45.948	45.986	46.024	46.061	46.099	46.136	46.174	46.211	46.249	1120
1130	46.249	46.286	46.324	46.361	46.398	46.436	46.473	46.511	46.548	46.585	46.623	1130
1140	46.623	46.660	46.697	46.735	46.772	46.809	46.847	46.884	46.921	46.958	46.995	1140
1150	46.995	47.033	47.070	47.107	47.144	47.181	47.218	47.256	47.293	47.330	47.367	1150
1160	47.367	47.404	47.441	47.478	47.515	47.552	47.589	47.626	47.663	47.700	47.737	1160
1170	47.737	47.774	47.811	47.848	47.884	47.921	47.958	47.995	48.032	48.069	48.105	1170
1180	48.105	48.142	48.179	48.216	48.252	48.289	48.326	48.363	48.399	48.436	48.473	1180
1190	48.473	48.509	48.546	48.582	48.619	48.656	48.692	48.729	48.765	48.802	48.838	1190

TABLE E.4 : Type R Thermocouple—Thermoelectric Voltage as a Function of Temperature (°c); Reference Junctions at 0°C

°C	0	1	2	3	4	5	6	7	8	9	10	°C
						Thermoelectric Voltage in Millivolts						
0	0.000	-0.005	-0.011	-0.016	-0.021	-0.026	-0.031	-0.036	-0.041	-0.046	-0.051	0
0	0.000	0.005	0.011	0.016	0.021	0.027	0.032	0.038	0.043	0.049	0.054	0
10	0.054	0.060	0.065	0.071	0.077	0.082	0.088	0.094	0.100	0.105	0.111	10
20	0.111	0.117	0.123	0.129	0.135	0.141	0.147	0.153	0.159	0.165	0.171	20
30	0.171	0.177	0.183	0.189	0.195	0.201	0.207	0.214	0.220	0.226	0.232	30
40	0.232	0.239	0.245	0.251	0.258	0.264	0.271	0.277	0.284	0.290	0.296	40
50	0.296	0.303	0.310	0.316	0.323	0.329	0.336	0.343	0.349	0.356	0.363	50
60	0.363	0.369	0.376	0.383	0.390	0.397	0.403	0.410	0.417	0.424	0.431	60
70	0.431	0.438	0.445	0.452	0.459	0.466	0.473	0.480	0.487	0.494	0.501	70
80	0.501	0.508	0.516	0.523	0.530	0.537	0.544	0.552	0.559	0.566	0.573	80
90	0.573	0.581	0.588	0.595	0.603	0.610	0.618	0.625	0.632	0.640	0.647	90
100	0.647	0.655	0.662	0.670	0.677	0.685	0.693	0.700	0.708	0.715	0.723	100
110	0.723	0.731	0.738	0.746	0.754	0.761	0.769	0.777	0.785	0.792	0.800	110
120	0.800	0.808	0.816	0.824	0.832	0.839	0.847	0.855	0.863	0.871	0.879	120
130	0.879	0.887	0.895	0.903	0.911	0.919	0.927	0.935	0.943	0.951	0.959	130
140	0.959	0.967	0.976	0.984	0.992	1.000	1.008	1.016	1.025	1.033	1.041	140
150	1.041	1.049	1.058	1.066	1.074	1.082	1.091	1.099	1.107	1.116	1.124	150
160	1.124	1.132	1.141	1.149	1.158	1.166	1.175	1.183	1.191	1.200	1.208	160
170	1.208	1.217	1.225	1.234	1.242	1.251	1.260	1.268	1.277	1.285	1.294	170
180	1.294	1.303	1.311	1.320	1.329	1.337	1.346	1.355	1.363	1.372	1.381	180
190	1.381	1.389	1.398	1.407	1.416	1.425	1.433	1.442	1.451	1.460	1.469	190
200	1.469	1.477	1.486	1.495	1.504	1.513	1.522	1.531	1.540	1.549	1.558	200
210	1.558	1.567	1.575	1.584	1.593	1.602	1.611	1.620	1.629	1.639	1.648	210
220	1.648	1.657	1.666	1.675	1.684	1.693	1.702	1.711	1.720	1.729	1.739	220
230	1.739	1.748	1.757	1.766	1.775	1.784	1.794	1.803	1.812	1.821	1.831	230
240	1.831	1.840	1.849	1.858	1.868	1.877	1.886	1.895	1.905	1.914	1.923	240
250	1.923	1.933	1.942	1.951	1.961	1.970	1.980	1.989	1.998	2.008	2.017	250
260	2.017	2.027	2.036	2.046	2.055	2.064	2.074	2.083	2.093	2.102	2.112	260
270	2.112	2.121	2.131	2.140	2.150	2.159	2.169	2.179	2.188	2.198	2.207	270
280	2.207	2.217	2.226	2.236	2.246	2.255	2.265	2.275	2.284	2.294	2.304	280
290	2.304	2.313	2.323	2.333	2.342	2.352	2.362	2.371	2.381	2.391	2.401	290
300	2.401	2.410	2.420	2.430	2.440	2.449	2.459	2.469	2.479	2.488	2.498	300
310	2.498	2.508	2.518	2.528	2.538	2.547	2.557	2.567	2.577	2.587	2.597	310
320	2.597	2.607	2.617	2.626	2.636	2.646	2.656	2.666	2.676	2.686	2.696	320
330	2.696	2.706	2.716	2.726	2.736	2.746	2.756	2.766	2.776	2.786	2.796	330
340	2.796	2.806	2.816	2.826	2.836	2.846	2.856	2.866	2.876	2.886	2.896	340

°C	0	1	2	3	4	5	6	7	8	9	10	°C
350	2.896	2.906	2.916	2.926	2.937	2.947	2.957	2.967	2.977	2.987	2.997	350
360	2.997	3.007	3.018	3.028	3.038	3.048	3.058	3.068	3.079	3.089	3.099	360
370	3.099	3.109	3.119	3.130	3.140	3.150	3.160	3.171	3.181	3.191	3.201	370
380	3.201	3.212	3.222	3.232	3.242	3.253	3.263	3.273	3.284	3.294	3.304	380
390	3.304	3.315	3.325	3.335	3.346	3.356	3.366	3.377	3.387	3.397	3.408	390
400	3.408	3.418	3.428	3.439	3.449	3.460	3.470	3.480	3.491	3.501	3.512	400
410	3.512	3.522	3.533	3.543	3.553	3.564	3.574	3.585	3.595	3.606	3.616	410
420	3.616	3.627	3.637	3.648	3.658	3.669	3.679	3.690	3.700	3.711	3.721	420
430	3.721	3.732	3.742	3.753	3.764	3.774	3.785	3.795	3.806	3.816	3.827	430
440	3.827	3.838	3.848	3.859	3.869	3.880	3.891	3.901	3.912	3.922	3.933	440
450	3.933	3.944	3.954	3.965	3.976	3.986	3.997	4.008	4.018	4.029	4.040	450
460	4.040	4.050	4.061	4.072	4.083	4.093	4.104	4.115	4.125	4.136	4.147	460
470	4.147	4.158	4.168	4.179	4.190	4.201	4.211	4.222	4.233	4.244	4.255	470
480	4.255	4.265	4.276	4.287	4.298	4.309	4.319	4.330	4.341	4.352	4.363	480
490	4.363	4.373	4.384	4.395	4.406	4.417	4.428	4.439	4.449	4.460	4.471	490
500	4.471	4.482	4.493	4.504	4.515	4.526	4.537	4.548	4.558	4.569	4.580	500
510	4.580	4.591	4.602	4.613	4.624	4.635	4.646	4.657	4.668	4.679	4.690	510
520	4.690	4.701	4.712	4.723	4.734	4.745	4.756	4.767	4.778	4.789	4.800	520
530	4.800	4.811	4.822	4.833	4.844	4.855	4.866	4.877	4.888	4.899	4.910	530
540	4.910	4.922	4.933	4.944	4.955	4.966	4.977	4.988	4.999	5.010	5.021	540
550	5.021	5.033	5.044	5.055	5.066	5.077	5.088	5.099	5.111	5.122	5.133	550
560	5.133	5.144	5.155	5.166	5.178	5.189	5.200	5.211	5.222	5.234	5.245	560
570	5.245	5.256	5.267	5.279	5.290	5.301	5.312	5.323	5.335	5.346	5.357	570
580	5.357	5.369	5.380	5.391	5.402	5.414	5.425	5.436	5.448	5.459	5.470	580
590	5.470	5.481	5.493	5.504	5.515	5.527	5.538	5.549	5.561	5.572	5.583	590
600	5.583	5.595	5.606	5.618	5.629	5.640	5.652	5.663	5.674	5.686	5.697	600
610	5.697	5.709	5.720	5.731	5.743	5.754	5.766	5.777	5.789	5.800	5.812	610
620	5.812	5.823	5.834	5.846	5.857	5.869	5.880	5.892	5.903	5.915	5.926	620
630	5.926	5.938	5.949	5.961	5.972	5.984	5.995	6.007	6.018	6.030	6.041	630
640	6.041	6.053	6.065	6.076	6.088	6.099	6.111	6.122	6.134	6.146	6.157	640
650	6.157	6.169	6.180	6.192	6.204	6.215	6.227	6.238	6.250	6.262	6.273	650
660	6.273	6.285	6.297	6.308	6.320	6.332	6.343	6.355	6.367	6.378	6.390	660
670	6.390	6.402	6.413	6.425	6.437	6.448	6.460	6.472	6.484	6.495	6.507	670
680	6.507	6.519	6.531	6.542	6.554	6.566	6.578	6.589	6.601	6.613	6.625	680
690	6.625	6.636	6.648	6.660	6.672	6.684	6.695	6.707	6.719	6.731	6.743	690
700	6.743	6.755	6.766	6.778	6.790	6.802	6.814	6.826	6.838	6.849	6.861	700
710	6.861	6.873	6.885	6.897	6.909	6.921	6.933	6.945	6.956	6.968	6.980	710

°C	0	1	2	3	4	5	6	7	8	9	10	°C
720	6.980	6.992	7.004	7.016	7.028	7.040	7.052	7.064	7.076	7.088	7.100	720
730	7.100	7.112	7.124	7.136	7.148	7.160	7.172	7.184	7.196	7.208	7.220	730
740	7.220	7.232	7.244	7.256	7.268	7.280	7.292	7.304	7.316	7.328	7.340	740
750	7.340	7.352	7.364	7.376	7.389	7.401	7.413	7.425	7.437	7.449	7.461	750
760	7.461	7.473	7.485	7.498	7.510	7.522	7.534	7.546	7.558	7.570	7.583	760
770	7.583	7.595	7.607	7.619	7.631	7.644	7.656	7.668	7.680	7.692	7.705	770
780	7.705	7.717	7.729	7.741	7.753	7.766	7.778	7.790	7.802	7.815	7.827	780
790	7.827	7.839	7.851	7.864	7.876	7.888	7.901	7.913	7.925	7.938	7.950	790
800	7.950	7.962	7.974	7.987	7.999	8.011	8.024	8.036	8.048	8.061	8.073	800
810	8.073	8.086	8.098	8.110	8.123	8.135	8.147	8.160	8.172	8.185	8.197	810
820	8.197	8.209	8.222	8.234	8.247	8.259	8.272	8.284	8.296	8.309	8.321	820
830	8.321	8.334	8.346	8.359	8.371	8.384	8.396	8.409	8.421	8.434	8.446	830
840	8.446	8.459	8.471	8.484	8.496	8.509	8.521	8.534	8.546	8.559	8.571	840
850	8.571	8.584	8.597	8.609	8.622	8.634	8.647	8.659	8.672	8.685	8.697	850
860	8.697	8.710	8.722	8.735	8.748	8.760	8.773	8.785	8.798	8.811	8.823	860
870	8.823	8.836	8.849	8.861	8.874	8.887	8.899	8.912	8.925	8.937	8.950	870
880	8.950	8.963	8.975	8.988	9.001	9.014	9.026	9.039	9.052	9.065	9.077	880
890	9.077	9.090	9.103	9.115	9.128	9.141	9.154	9.167	9.179	9.192	9.205	890
900	9.205	9.218	9.230	9.243	9.256	9.269	9.282	9.294	9.307	9.320	9.333	900
910	9.333	9.346	9.359	9.371	9.384	9.397	9.410	9.423	9.436	9.449	9.461	910
920	9.461	9.474	9.487	9.500	9.513	9.526	9.539	9.552	9.565	9.578	9.590	920
930	9.590	9.603	9.616	9.629	9.642	9.655	9.668	9.681	9.694	9.707	9.720	930
940	9.720	9.733	9.746	9.759	9.772	9.785	9.798	9.811	9.824	9.837	9.850	940
950	9.850	9.863	9.876	9.889	9.902	9.915	9.928	9.941	9.954	9.967	9.980	950
960	9.980	9.993	10.006	10.019	10.032	10.046	10.059	10.072	10.085	10.098	10.111	960
970	10.111	10.124	10.137	10.150	10.163	10.177	10.190	10.203	10.216	10.229	10.242	970
980	10.242	10.255	10.268	10.282	10.295	10.308	10.321	10.334	10.347	10.361	10.374	980
990	10.374	10.387	10.400	10.413	10.427	10.440	10.453	10.466	10.480	10.493	10.506	990
1000	10.506	10.519	10.532	10.546	10.559	10.572	10.585	10.599	10.612	10.625	10.638	1000
1010	10.638	10.652	10.665	10.678	10.692	10.705	10.718	10.731	10.745	10.758	10.771	1010
1020	10.771	10.785	10.798	10.811	10.825	10.838	10.851	10.865	10.878	10.891	10.905	1020
1030	10.905	10.918	10.932	10.945	10.958	10.972	10.985	10.998	11.012	11.025	11.039	1030
1040	11.039	11.052	11.065	11.079	11.092	11.106	11.119	11.132	11.146	11.159	11.173	1040
1050	11.173	11.186	11.200	11.213	11.227	11.240	11.253	11.267	11.280	11.294	11.307	1050
1060	11.307	11.321	11.334	11.348	11.361	11.375	11.388	11.402	11.415	11.429	11.442	1060
1070	11.442	11.456	11.469	11.483	11.496	11.510	11.524	11.537	11.551	11.564	11.578	1070
1080	11.578	11.591	11.605	11.618	11.632	11.646	11.659	11.673	11.686	11.700	11.714	1080
1090	11.714	11.727	11.741	11.754	11.768	11.782	11.795	11.809	11.822	11.836	11.850	1090

°C	0	1	2	3	4	5	6	7	8	9	10	°C
1100	11.850	11.863	11.877	11.891	11.904	11.918	11.931	11.945	11.959	11.972	11.986	1100
1110	11.986	12.000	12.013	12.027	12.041	12.054	12.068	12.082	12.096	12.109	12.123	1110
1120	12.123	12.137	12.150	12.164	12.178	12.191	12.205	12.219	12.233	12.246	12.260	1120
1130	12.260	12.274	12.288	12.301	12.315	12.329	12.342	12.356	12.370	12.384	12.397	1130
1140	12.397	12.411	12.425	12.439	12.453	12.466	12.480	12.494	12.508	12.521	12.535	1140
1150	12.535	12.549	12.563	12.577	12.590	12.604	12.618	12.632	12.646	12.659	12.673	1150
1160	12.673	12.687	12.701	12.715	12.729	12.742	12.756	12.770	12.784	12.798	12.812	1160
1170	12.812	12.825	12.839	12.853	12.867	12.881	12.895	12.909	12.922	12.936	12.950	1170
1180	12.950	12.964	12.978	12.992	13.006	13.019	13.033	13.047	13.061	13.075	13.089	1180
1190	13.089	13.103	13.117	13.131	13.145	13.158	13.172	13.186	13.200	13.214	13.228	1190
1200	13.228	13.242	13.256	13.270	13.284	13.298	13.311	13.325	13.339	13.353	13.367	1200
1210	13.367	13.381	13.395	13.409	13.423	13.437	13.451	13.465	13.479	13.493	13.507	1210
1220	13.507	13.521	13.535	13.549	13.563	13.577	13.590	13.604	13.618	13.632	13.646	1220
1230	13.646	13.660	13.674	13.688	13.702	13.716	13.730	13.744	13.758	13.772	13.786	1230
1240	13.786	13.800	13.814	13.828	13.842	13.856	13.870	13.884	13.898	13.912	13.926	1240
1250	13.926	13.940	13.954	13.968	13.982	13.996	14.010	14.024	14.038	14.052	14.066	1250
1260	14.066	14.081	14.095	14.109	14.123	14.137	14.151	14.165	14.179	14.193	14.207	1260
1270	14.207	14.221	14.235	14.249	14.263	14.277	14.291	14.305	14.319	14.333	14.347	1270
1280	14.347	14.361	14.375	14.390	14.404	14.418	14.432	14.446	14.460	14.474	14.488	1280
1290	14.488	14.502	14.516	14.530	14.544	14.558	14.572	14.586	14.601	14.615	14.629	1290
1300	14.629	14.643	14.657	14.671	14.685	14.699	14.713	14.727	14.741	14.755	14.770	1300
1310	14.770	14.784	14.798	14.812	14.826	14.840	14.854	14.868	14.882	14.896	14.911	1310
1320	14.911	14.925	14.939	14.953	14.967	14.981	14.995	15.009	15.023	15.037	15.052	1320
1330	15.052	15.066	15.080	15.094	15.108	15.122	15.136	15.150	15.164	15.179	15.193	1330
1340	15.193	15.207	15.221	15.235	15.249	15.263	15.277	15.291	15.306	15.320	15.334	1340
1350	15.334	15.348	15.362	15.376	15.390	15.404	15.419	15.433	15.447	15.461	15.475	1350
1360	15.475	15.489	15.503	15.517	15.531	15.546	15.560	15.574	15.588	15.602	15.616	1360
1370	15.616	15.630	15.645	15.659	15.673	15.687	15.701	15.715	15.729	15.743	15.758	1370
1380	15.758	15.772	15.786	15.800	15.814	15.828	15.842	15.856	15.871	15.885	15.899	1380
1390	15.899	15.913	15.927	15.941	15.955	15.969	15.984	15.998	16.012	16.026	16.040	1390
1400	16.040	16.054	16.068	16.082	16.097	16.111	16.125	16.139	16.153	16.167	16.181	1400
1410	16.181	16.196	16.210	16.224	16.238	16.252	16.266	16.280	16.294	16.309	16.323	1410
1420	16.323	16.337	16.351	16.365	16.379	16.393	16.407	16.422	16.436	16.450	16.464	1420

APPENDIX F

Journals in Instrumentation Engineering

1. IEEE Transaction on Instrumentation and Measurement
2. IEEE Instrumentation and Measurement magazine
3. Instrumentation Society of America (ISA) Transaction
4. IEEE Sensors journal
5. Sensors and Instrumentation (ISA)
6. Journal of the Instrumentation Society of India

APPENDIX G

Websites for Data Sheets, Component Manufacturers and Technical Information

Manufacturer	Web site	Product/Sensors for
Alpha Sensors	www.alphasensors.com	Temperature
Analog Devices	www.analogdevices.com	Signal Conditioning
Avery Ltd.	www.averyindia.co.in	Load-cell, weighing scales
Vishay Precision Group	www.blh.de	Strain gauges
Capacitec	www.capacitec.com	Non-contact capacitive Displacement sensors, gap sensors
Codel Corporation	www.codel.com	Ultrasonic Flowmeters (fms)
Columbia Research Laboratory	www.crlsensors.com	Dynamic Pressure sensors, strain gauges
Conax Technologies	www.conaxtechnology.com	Temperature
CTS Corporation		Electronic Throttle Control
Cyber Search	www.cyberresearch.com	Motion Controllers
Globalspec	www.designinfo.com	Flowmeters
Dynasonics Inc.	www.dynasonics.com	Ultrasonic fms
Dallas Semiconductors maxim	www.maxim-ic.com	D-to-Analog Converters, Touch-interface and Haptics
Flexim Inc	www.flexsim.co	Ultrasonic fms
GE Sensing and Inspection Technologies	www.gesensing.com	Ultrasonic fms
Heraeus	www.heraeus-sensor-technology.de	Temperature Sensors
Hoentzch Corporation	www.hoentzch.com	Thermal Sensors, gas and mass flowmeters

Hoffer Flow Controls Inc	www.hofferflow.com	Flowmeters
Honeywell corp	www.Honeywell.com	Smart position sensor
Hottinger baldwin mess technik Gmbh	www.hbm.com	Strain gauges, load cells, sensors, transducers, DAQ systems
IEEE	www. ieee.org	Journals, standards, misc
Jumo GMBH & Co KG	www.jumo.net	Temperature Sensors
Kavilco	www.kavilco.com	Pressure
Kimo Instruments	www.kimo.fr	Air-flow Pitot tube
Kistler Instruments	www.kistler.com	Pressure Sensors
Kulite Semiconductors products Inc	www.kulite.com	Pressure Transducers
Linear Technologies	www.linear.com	Data Converters
Macro Sensors	www.macrosensors.com	LVDT
Magtrol	www.magtrol.com	Torque Flange Sensors
Micro-Epsilon	www.micro-epsilon.com	Displacement sensors, temperature Sensors
Minco-Inc	www.mincoitc.com	Thermal Sensors
National Semiconductors	www.national.com	Precision amplifiers , High speed amplifiers , Instrumentation Amplifiers
Novasina A.G.	www.novasina.com	Flowmeters
Omega Electronics	www.omega.com	Temperature, misc
Pankaj potentiometers Pvt. Ltd.	www.pankaj.com	**Potentiometer**
Peak sensors	www.peaksensors.co.in	**Thermocouples**
PerkinElmer corp	www.perkinelmer.com	Atomic Spectroscopy
MTS Sensors	www.mtssensors.com	Liquid Level Transmitter
Pavan Industries (Pankaj Potentimeters)	www.potsndials.com	Potentiometers
Ramsey	www.ramseyelectronics.com	Communications service Monitor
Sensorex	www.sensorex.com	pH meters
Setra Systems Inc	www.setra.com	Humidity, Pressure, Current sensors
Tanaka Electronic Industries	www.tanaka.com	Bonding Wire
Taylor Instruments	www.taylorusa.com	Safeguards for Vibration, moisture
Teledyne ISCO	www.teledyneisco.com	Ultrasonic fms
Texas Instruments Inc	www.ti.com	Amplifier, comparators,
Thermo-electra Measurement & Control	www.thermo-elecra.com	TCs, RTDs

Tokyo Keiki Inc	www.tokyo-keiki.co.jp	Radar level sensors for calm liquid surface 0-20 M, density, pressure, temperature for power plants, water works, food process storage, sticky oil storage, vapor rich steel coolant
Trans-Tek Inc	www.transtekinc.com	LVDT
Wintron	www.wintron.com	Pyrometers
ADS Transicoil		
Alpha Sensors	www.alphasensors.com	Temperature
Analog Devices	www.analogdevices.com	Signal conditioning
ASM		
Avery Ltd	www.blh.de	Strain gauges
Cahn Instruments		
Capacitec		
Codel Corporation	www.codel.com	Ultrasonic fms
Columbia research Laboratory		
Conax Technologies	www.conaxtechnology.com	Temperature
CTS Corporation	www.ctscorp.com	
Cyber Search	www.cyberresearch.com	
	www.designinfo.com	Flowmeters
Dynasonics Inc	www.dynasonics.com	Ultrasonic f.ms
Dallas semiconductors maxim		
Dimetix Corporation	www.entran.com	Pressure
Fagor Automation		
Flexim Inc	www.flexim.com	Ultrasonic f.ms
GE Sensing and Inspection Technologies	www.gesensing.com	Ultrasonic Fms.
Heraeus	www.heraeus-sensor-technology.de	Temperature sensors
Hoentzsch Corporation	www.hoentzch.com	Thermal Sensors; gas and mass flow meters
Hoffer Flow Controls Inc	www.hofferflow.com	Flowmeters
Honeywell Corporation	www.honeywell.com	
Hottinger Baldwin Mess Technik Gmbh		
IEEE	www.ieee.org	journals, standards,misc.
Jumo GMBH & Co KG	www.jumo.net	temperature Sensors
	www.kavilco.com	pressure
Kimo Instruments	www.kimo.fr	Air-flow Pitot Tube
Kistler Instruments		
Kulite Semiconductors products Inc		
Linear Technologies	www.linear.com	
	www.macrosensors.com	LVDT

Magtrol		
Measurand International		
Microepsilon		
Minco Inc	www.minco.com	Thermal sensors
Motorola Corporation	www.mot-sps.com	
MTS Sensors		
National Semiconductors	www.national.com	
Novasina A.G.	www.novasina.com	Flowmeters
Novatech Measurement Ltd.		
Omega Electronics	www.omega.com	Temperature, miscellaneous
Pankaj Potentiometers Pvt. Ltd.	www.pankaj.com	
Peak Sensors	www.peaksensors.co.uk/	
Perkin Elmer Corp		
Phillips Gmbh		
Pye Unicam		
All Electronic	www.allelectronics.com	
Corporation	allcorp@allcorp.com	
MTS Sensors		
Pavan Industries (Pankaj Potentiometers Pvt. Ltd.)		
Ramsey		
Sensorex		
Setra Systems Inc		
Systec Controls	www.systec-controls.de	dp/fms
Tanaka Electronic Industries		
Taylor Instruments		
Teledyne ISCO	www.teledyneisco.com	Ultrasonic fms
	www.temperatureworld.com	
Texas Instruments Inc		
Thermo-electra Measurement & Control		
Technics	www.thermo-electra.com	
Tokyo Keiki Inc	www.tokyo-keiki.co.jp	Radar level sensors, for calm liquid surfaces 0- 20 M, density, pressure, temperature for power plants, water works, sanitary food process storage, sticky oil storage, vapor rich steel coolant
Trans-Tek Inc.		
Transducer Inc		
Wintron	www.wintron.com	Pyrometers

APPENDIX H

Answers to Selected Problems for Exercise

CHAPTER 3

3.1 47.3, 127

3.2 $k > 1/4V$

3.4 1.4816V, ± 0.18%

3.5 866 (if 0.1Ω is s.d.)

3.6 120 ± Ω

3.9 0.98Ω

P3.9 $R = R_0 + R_0\alpha\, T - 25\, R_0\alpha$

Since the terms are not independent, special case of addition is not applicable.

Therefore, first find partial derivatives

$$\frac{\partial R}{\partial \alpha} = 1 + \alpha\,(T - 25)$$

$$\therefore \qquad \left(\frac{\partial R}{\partial R_0}\right)_{\text{mean}} = 1 + 0.004\,(60 - 25) = 1.140$$

$$\frac{\partial R}{\partial \alpha} = R_0\,(T - 25)$$

$$\left(\frac{\partial R}{\partial \alpha}\right)_{\text{mean}} = 200\,(60 - 25) = 7000$$

$$\frac{\partial R}{\partial T} = R_0\alpha\left(\frac{\partial R}{\partial T}\right)_{\text{mean}} = 200 \times 0.004 = 0.8$$

This time we have sum of three variables,

$$\sigma_R^2 = (1.140\ \sigma_{R0})^2 + (7000\sigma_\alpha)^2 + (0.8\sigma_T)^2$$

Converting percentage error in s.d.

$$\sigma_{R_0} = 0.3\% \approx 200 \times 0.003 = 0.6;\ \sigma_a = 0.004 \times 0.01$$
$$= 4 \times 10^{-5}$$
$$\sigma_T = 1°C$$

By substitution

$$\sigma_R^2 = (1.14 \times 0.6)^2 + (7 \times 10^3 \times 4 \times 10^{-5})^2 + (0.8 \times 1)^2$$
$$= 0.468 + 0.078 + 0.64 = 1.1846$$

∴ Mean value of R at 60°C

$$R_{60} = 200\ (1 + 0.004\ (60 - 25) = 228\Omega$$
$$(\sigma_R = 1.089)$$

∴ $$R_{60} = 228 \pm 1.09\Omega = 228 \pm 0.54\%\Omega$$

3.10 0.98Ω

P3.11 (*a*) R_x (nominal) = (520 × 610)/100 = 3172Ω.

(*b*) $R_x = R_1R_2/R_3$ = {(520 ± 5.2) × (610 ± 6.1)}/(100±0.5)

∴ R_x(max) = (525.2 × 616.1)/99.5 = 3252.017Ω

R_x(min) = (514.8 × 603.9)/100.5 = 3093.41Ω

∴ (Max) limiting error = (R_x(max)–R_x(nominal))/R_x (nominal) × 100% = ±2.52%.

CHAPTER 5

P5.3 ∴ $$dR = GF.R$$

∴ $$\text{Strain} = \frac{dR}{GF.R} = \frac{1.2}{2.2 \times 120} = 4.545 \times 10^{-3}$$

= 4545 micro strain

∴ Stress = Young's modulus, E × strain

$$= 2 \times 10^8 \times 4.545 \times 10^{-3}$$
$$= 9.09 \times 10^5\ \text{Kgf/m}^2.$$

P5.10 From Eqn.

$$R_t = R_o(1 + \Delta T)$$

From the measurement data available, it is possible to set up:

∴ $$R_1 = 200.5;\ R_2 = 368;\ T_1 = 150;\ T_2 = 400$$

$\therefore$ $$368 = R_o(1 + \alpha(400 - 0))$$

and $$200.5 = R_o(1 + \alpha(150 - 0))$$

$\therefore$ by solving for the unknown,

$$\alpha = \frac{R_2 - R_1}{R_1T_2 - R_2T_1}$$

$$= 0.0067\ \Omega/\Omega/°C.$$

P5.13 Maximum current allowed in the *RTD*

$$\sqrt{\frac{10\,mW}{400}} = \sqrt{\frac{10 \times 10^{-3}}{400}} = \frac{10^{-1}}{20} = 5mA$$

$\therefore$ $$E_i = 2 \times 400 \times (5 \times 10^{-3}) = 4V.$$

$\therefore$ Maximum output.

$$E_0 = \frac{E_i}{4R} \times \Delta R$$

$$= \frac{4}{4 \times 400}(400 \times 2 \times 10^{-3} \times (630 - 35))$$

$$= 2 \times 10^{-3} \times 595 = 1.190\text{ V}$$

$\therefore$ Amplication of output voltage signal appears necessary.

P5.14. Using the resistance temperature relation, from Eqn. (5.14),

$$R = e^{\frac{\beta}{T}}$$

at 75°C

$$R_{75}\,°C = 0.02 \exp \frac{4000}{(75 + 273.15)}\,\Omega$$

$$= 0.02 \times 433952.8736 = 8679.05\ \Omega \times h$$

and

$$R_{200}\alpha = 0.02 \exp \frac{4000}{(200+273.15)}$$

$$= 93.87\Omega.$$

P5.17 From the given data,

Resistance at 27°C, 2000 = $Ro \times e^{\beta/300}$

and at 90°C, $400 = R_o \times e^{-\beta/363}$

$\therefore \quad 2000/400 = 5\ (e^{\beta/300}/e^{\beta/363})$

$= e^{\beta(1/300\ -\ 1/363)}$

or, $\ln 5 = \beta[1/300 - 1/363]$

Therefore, $\beta = 2775/°k$

and $R_o = 2000/e^{\beta/300} = 4.968\ \text{K}\Omega$

$R_{60} = R_o \times \exp.\ [\{(1/333) - (1/273)\}\ 2775]$

$= 795.77\ \Omega$

and, $R_{30} = R_o \times \exp.\ \{(1/303) - (1/273)\ 2775\}$

$= 1815.98\ \Omega$

$R_{80} = R_o \times \exp.\ \{(1/3530 - (1/273)\ 2775\}$

$= 498\ \Omega$

$\therefore \quad R_{30} - R_{80} = 1317\ \Omega.$

CHAPTER 6

P6.3 {**Ans.** 12.21 mV; 10.61 mV; 17.5 mV; 23.71 mV; 34.93 mV}

P6.4 Sensitivity of the TC, $K = 20.7/400 = 0.05175$ mV/°C

(*a*) Temperature corresponding to 8.92 mV = 8.96 × 0.05175 = 171.98°C.

(*b*) $E = e_a + \Delta e = e_a + K\,(T - T_{\text{ref}})$

$= 20.7 - 0.05175\ (25 - 0) = 18.726$ mV

Therefore, correction at maximum temperature = 20.7 – 18.726 = 1.094 mV.

P6.6 From the TC Table for K-type TC

Output-voltage corresponding to reference temperature = 1.4 mV

Voltage output for hot junction temperature,

$$y = 45.26 + 1.4$$

$$= 46.66 \text{ mV}$$

From the table, temperature corresponding to y volts is 1140 = Hot junction temperature.

P6.8. We have the relation $E_0 = g.t.p.$ ...(6.8a)

where, g is the voltage sensitivity of the crystal, t is the thickness of the crystal, and p is the pressure applied on the crystal.

From Eqn. 6.8(*a*) We have

$$p = \frac{E_0}{gt} \qquad ...(6.8b)$$

$$p = \frac{100}{0.055 \times 1.5 \times 10^{-3}} \text{ N/m}^2 = 1.2 \text{ MN/m}^2$$

Force, $F = p \times A = 1.2 \times 10^6 \times 5 \times 5 \times 10^{-6} = 30\text{N}$.

P6.9 The leakage resistance of the transducer is very large as compared with the resistance of the measuring system R = 1MΩ =10^6Ω. The capacitance of the system is

$$C = C_P + C_C + C_A = 2000 + 500 = 2500 \text{ pF}.$$

The time constant of the circuit is $\tau = RC = 106 \times 2500 \times 10^{-12}$ = 2.5 ms.

Voltage across the load

$$e_L = \frac{dF}{C}\exp\left(-\frac{t}{\tau}\right) = \frac{100 \times 10^{-12}}{2500 \times 10^{-11}} \times 0.1 \text{ exp } \left(\frac{-t}{2.5 \times 10^{-3}}\right)$$

$$= 4 \times 10^{-3} \text{ exp } (-400t) \text{ for } 0 < t < 2\text{ms}$$

At t = 2ms 4×10^{-3} exp $(-400 \times 2 \times 10^{-3}) = 1.8 \times 10^{-3}$ V

This is the voltage just before 2 ms.

The output voltage just after 2 ms:

$$e_L = \frac{dF}{C}\left[\exp\left(-\frac{t}{T}\right) - 1\right]$$

$$= \frac{100 \times 10^{-12} \times .1}{2500 \times 10^{-22}}\left[\exp\left(\left(\frac{-2 \times 10^{-3}}{2.5 \times 10^{9}}\right)^{-1}\right)\right]$$

$$= -2.2 \text{ mV}$$

The voltage output beyond 2 seconds is given by:

$$e_L = \frac{dF}{C}\left[\exp\left(\frac{-t}{\tau - 1}\right)\right]\left[\exp-\left(t - \frac{T}{\tau}\right)\right]$$

$$= -2.2 \times 10^{-3} \times \exp(-400t - .8) \text{ for } 2\text{ms} < t < \infty.$$

Voltage after 10 ms of application of pulse:

$$= -2.2 \times 10^{-3} \times \exp[-400 \times 10 \times 10^{-3} - 0.8]$$

$= -0.09$ mV.

P6.10 Area of plates

$$A = 5 \times 5 \times 10^{-6} = 25 \times 10^{-6} \text{ m}^2$$

Pressure $P = \dfrac{5}{25 \times 10^{-6}}$ N/m²

Voltage sensitivity $g = \dfrac{d}{e_o \in_r} = \dfrac{150 \times 10^{-12}}{12.5 \times 10^{-9}} = 12 \times 10^{-3}$ Vm/N

Voltage generated $E_o = gtp = 12 \times 10^{-3} \times 1.25 \times 10^{-3} \times 0.2 \times 10^{-6}$

Strain $\in \; = \; \Delta t = \dfrac{\text{Stress}}{\text{Young's modulus}} = \dfrac{0.2 \times 10^6}{12 \times 10^6} = 0.0167$

Charge $Q = dF = 150 \times 10^{-12} \times 5 = 750$ pc

Capacitance $C_p = \dfrac{Q}{E_0} = \dfrac{750 \times 10^{-12}}{3} = 250 \text{ pF}$.

CHAPTER 7

(iii) What is equivalent noise source? How is it determined for any device?

In a system with a pure signal applied, the minimum amplitude of detectable signal can be determined from noise characteristic. A noise source (random signal generator) is connected to the sensor/transducer to produce output equal to the output in the first case. Then the minimum detectable signal is the effective equivalent noise source.

P7.2 (*a*) Pressure at the depth of 40 meters = ph = 1000 × 40 kg/m² = 4 kg/cm² and in terms of mercury column

$$= \frac{40 \times 10^3}{13.54} = 2954.2 \text{ m of Hg}$$

(*b*) Absolute pressure

= gauge pressure + atmosphere pressure

= 4 kg/cm² + 1.03 kg/cm² = 5.03 kg/cm²

= 2954.2 + 0.76 = 2954.96 kg/cm²

P7.3 Bourdon is likely to force additional pressure due to water head of 30 meters, alongwith water line pressure of 5 kg/cm².

∴ pressure head at the bourdon = 5 kg/cm² + 30 m of Hg = 5 + 3 = 8 kg/cm²

NB: a pipe line going at the height shall have lower pressure.

P7.4 velocity = $\sqrt{2gh}$ = 19.8 m/sec

(assuming 1 kg/cm^2 = 10m of water head)

$\therefore$ volumetric flow rate, $Q = AV$ = 1.38 m^3/sec.

P7.5 Flow rate Q = 2 litres/min = 2000cm^3/min

Area of cross section of pipe, $A = \dfrac{\pi d^2}{4} = \dfrac{\pi 2.5^2}{4} = 4.9087$ cm^2

$\therefore$ flow rate = $\dfrac{2000}{60 \times 4.9087}$ = 6.79 cm/sec

Induced emf, $e = B.d.v$ = 60 × (2.5 × 10^{-2}) × 6.79 = 10.455 mV.

P7.6 $\therefore\ e = Bdv$

$$\therefore B = \frac{e}{dv} = \frac{1 \times 10^{-3}}{20 \times 10^{-2} \times 0.01} = \frac{1}{20} \times 10^{-3} = 0.05 \text{ mWb/M}^2.$$

P7.7 Volume of the float, $V_f = \dfrac{\pi \times 1.5^2 \times 10^{-4}}{4} \times 3.5 \times 10^{-2}$

$= 6.18 \times 10^{-6}$ M^3

Corresponding to lowest position of float,

$$q_{min} = \frac{D_{p\min}{}^2 - D_f^2}{D_f}\sqrt{\frac{\pi g V_f (p_f - p)}{2p}}$$

$$= \left\{\frac{2^2 \times 10^{-4} - 1.5^2 \times 10^{-4}}{1.5 \times 10^{-2}}\right\}\sqrt{\frac{\pi \times 9.8 \times (6.18 \times 10^{-6}) \times (3 - 0.6) \times 10^3}{2 \times 0.6 \times 10^3}}$$

$= 22.757 \times 10^{-5}$ M^3/Sec

$D_{p\min} = 2$ cm

Corresponding to highest position of float,

$$q_{\max} = \frac{D_{p\max}{}^2 - D_f^2}{D_f}\sqrt{\frac{\pi g V_f (p_f - p)}{2p}}$$

$= 438.91410^{-5}$ M^3/sec ; D_{pmax} = 6 cm.

CHAPTER 8

P8.8 A push-pull transducer of capacitive type is used with Blumlein Bridge is shown in Fig. P8.8.

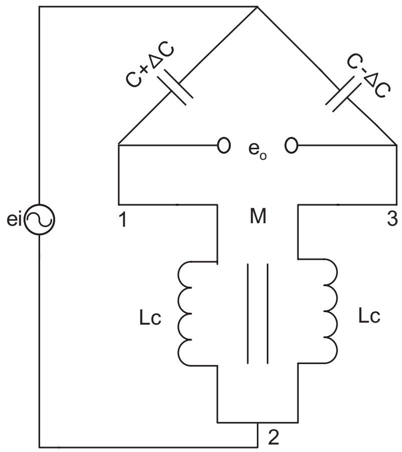


Fig. P8.8 Capacitive Type Blumlein Bridge

(a) Sensitivity, SB = $\dfrac{e_o}{e_i\left(\dfrac{\Delta C}{C}\right)} = \dfrac{4w^2L_cC}{2w^2L_CC-1}$

The sensitivity is independent of the variations in inductor and frequency if

$w^2 L_cC >> 1$. Let $w^2 LcC = 10$.

$$L_C = \frac{10}{w^2C} = \frac{10}{4\times 3.14^2 \times 0.5^2 \times 10^{12} \times 300 \times 10^{-12}}$$

$$\boxed{L_c = 3.38 \text{ mH.}}$$

(b) Output Impedance of bridge under balance condition is zero. Output impedance of bridge under unbalanced conditions of impedance 4jwLc and 2/(jwC) in parallel. However, 4wLc is very large as compared with 2/wC and hence the output impedance is approximately equal to 2/wC.

$$Zo = \frac{2}{wC} = \frac{2}{2\times 3.14 \times 0.5 \times 10^6 \times 300 \times 10^{-12}}$$

$$\boxed{Zo = 2.12 K\Omega.}$$

P8.12 *For a given amplifier we know that:*

$$E_0 = e_dA_d = e_{cm}A_{cm} = e_dA_d\left[1+\frac{\varepsilon_{cm}}{\varepsilon_d}\frac{A_{cm}}{A_d}\right] = e_dA_d\left[1+\frac{1}{CMRR}\frac{\varepsilon_{cm}}{\varepsilon_d}\right]$$

$\therefore$ error = $\dfrac{1}{CMRR}\dfrac{\varepsilon_{cm}}{\varepsilon_d}$ and

$$CMRR = \frac{1}{error} \times \frac{\varepsilon_{cm}}{\varepsilon_d} = \frac{100}{1} \times \frac{1}{10^{-1}} = 10^6$$

In dB, $CMRR = 20\ (\log_{10}(10^6)\} = 120$dB.

P8.13 Since CMRR is given in dB so, first we will express this into the numerical value

$\therefore$ $20\ \{\log_{10}(CMRR)\} = 90$dB

$$CMRR = 10^{\frac{90}{20}} = 31622.7766$$

Now as in above problem,

$$\text{error} = \frac{1}{31622.7766} \times \frac{e_{cm}}{e_d} = \frac{1}{31622.7766} \times \frac{1}{0.5 \times 10^{-3}} = 0.06324$$

$\therefore$ % error = 6.324%.

P8.14 Since CM error $\le$ 0.1% so,

$$\therefore \quad \frac{1}{CMRR} \times \frac{e_{cm}}{e_d} \le \frac{0.1}{100}$$

Numerical value of $CMRR$ can be found as in above problem as,

$$CMRR = 10^{\frac{120}{20}} = 1000000$$

$$\therefore \quad e_d \ge \frac{1}{1000000} \times \frac{2}{\frac{0.1}{100}} = 2 \text{ mV}$$

Therefore, the differential signal should be more than 2 mV.

P8.15 *Since CM error $\le 0.001\%$ so,*

$$\therefore \quad \frac{1}{CMRR} \times \frac{\epsilon_{cm}}{\epsilon_d} \le \frac{0.001}{100}$$

Taking limiting case for e_d and e_{cm} we have,

$$CMRR \ge \frac{5000}{1 \times 10^{-3}} \times \frac{100}{0.001} = 5 \times 10^{11}.$$

In dB, $CMRR \ge 20\ \{\log_{10}(5 \times 10^{11})\} = 233.979$ dB

Such a large *CMRR* can be realized with isolation amplifier, typically using optical isolation between input and output, discussed in the chapter

P8.16 We know that,

$$A_o = 1 + \frac{R_f}{R_i} \qquad 8.16(a)$$

Where A_o is gain, R_f is feedback resistance and R_i is input resistance.

Substituting given values $A_o = 5$ in Eqn., 8.16(*a*).

$$\frac{R_f}{R_i} = 4 \times \frac{10K}{1K}$$

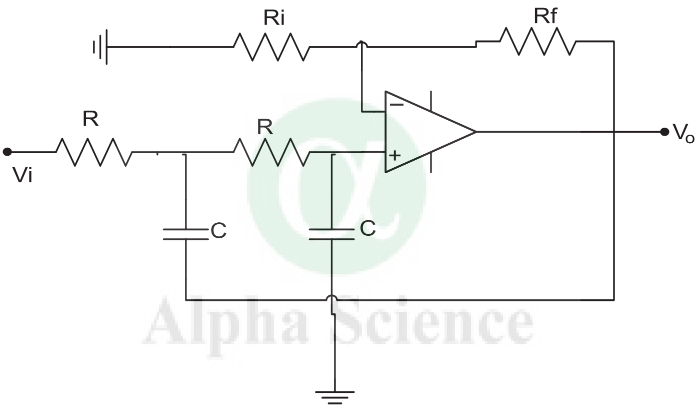


Fig. P8.16 : Sallen Key Filter (General Second Order)

From this relation $R_f = 4K\Omega$ and $R_i = 1\ K\Omega$.

For Sallen key configuration (Second Order Low-pass Filter).

Minimum *DC* offset, $R_i \parallel R_f = 2R$.

i.e. $$\left(R_i \times R_f\right)\frac{1}{R_i + R_f} = 2 \times \text{R}$$

$$R = 400\Omega.$$

since $$fc = 2\text{ KHz},$$

and $$fc = \frac{1}{2\pi RC}, \qquad ...[8.16(b)]$$

Substituting $R = 400\ \Omega$ in Eqn. 8.16(*b*).

$$C = 0.199\ \mu\text{F}.$$

P8.17

$$A_o = 1 + \frac{R_f}{R_i} \qquad ...[8.17(a)]$$

where A_o is gain, R_f is feedback resistance and R_i is input resistance. Since here, it's a unity gain specification.

Substituting given values $A_o = 1$ in Eqn., [8.16(*a*)].

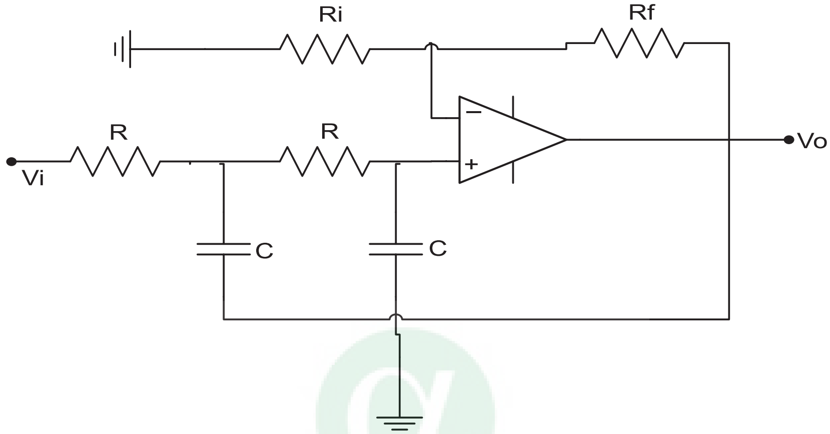


Fig. P8.17 Sallen Key Filter (General Second Order)

P8.20 Calculate the output of an 10-bit *DAC* with $V_R = 10.0$ V for input of

(*i*) 0A7H (*ii*) B5H (*iii*) 20 FH, find the output in each case.

How can you obtain an output of 6.50 V?

Ans. ***v*,** 1.767578 *v*, 5.14648 *v*, by adjusting V_R.

P8.22 (*a*) Highest significant frequency $f_m = 1$ kHz

Minimum sampling rate= $2 \times f_m = 2000$ samples/sec

(*b*) Given resolution = 0.01% = $\frac{100}{2^n - 1}$

$$2n = 10001$$

Therefore, minimum no. of bits in sampling $n = 14$

(*c*) Analog value of *LSB* = $\frac{\text{Full scale value}}{2^n - 1}$

$$= \frac{10}{2^{14} - 1} = 0.6103 \text{ mV}$$

(*d*) RMS value of quantization noise = $\frac{\text{step size}}{\sqrt{12}} = \frac{0.6103 \text{ mV}}{\sqrt{12}} =$ 0.176mV

(*e*) Absolute minimum value that a system can measure = $\frac{1}{2^{14}-1}$ = 0.061mV.

Dynamic range of *ADC* = 20 log (0.061 mV) = –84.287dB.

P8.23

$$t_1 = \frac{2^n}{\text{clock frequency}}$$

$$= \frac{2^{16}}{5 \times 10^6} = 13.1 \text{ m sec}$$

$$V_{\text{ramp}} = \frac{V_{in}}{RC} \times t_1$$

$$9 = \frac{12}{10^6 \times C} \times 13.1 \text{ m sec}$$

$$C = \frac{12}{9 \times 10^6} \times 13.1 \text{ m sec}$$

$$C = 0.017 \text{ μF.}$$

P8.24 For analog voltage of 6.384 V corresponding output = $\frac{6.384}{12} \times (12^{16} - 1)$ = 34865.15 = $(1000\ 1000\ 0011\ 0010)_2$.

P8.25

$$t1 = \frac{2^n}{\text{clock frequency}}$$

$$= \frac{2^{16}}{4 \times 10^6} = 16.38 \text{ m sec}$$

$$V_{\text{ramp}} = \frac{V_{in}}{RC} \times t_1$$

$$-8 = \frac{-10}{R \times 0.1 \times 10^{-6}} \times 16.38 \text{ m sec}$$

$$R = \frac{10}{8 \times 0.1 \times 10^{-6}} \times 16.38 \text{ m sec}$$

$$R = 0.204 \text{ M}\Omega.$$

For analog voltage of 3.562V corresponding output

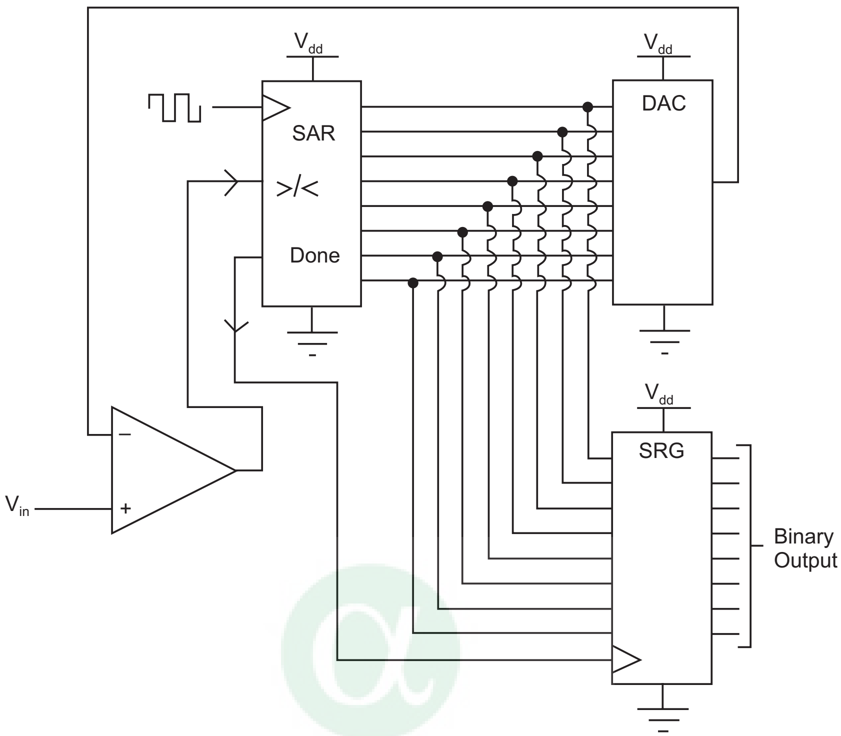
$$= \frac{3.562}{10} \times \left(2^{16} - 1\right)$$

$$= 23343.92 = (0101\ 1011\ 0011\ 0000)_2$$

P8.26 Principle of operation: In this type of conversion, the conversion time is constant and proportional to the number of bits in the digital output. The basic principle of this A/D converter is that the unknown analog input voltage has been approximated with an *n*-bit digital value. Instead of counting up in binary sequence, this register counts by trying all values of bits starting with the most-significant bit and finishing at the least-significant bit. This type of ADC operates by successively dividing the voltage range by half, as explained in the following steps:

1. The ring counter is initially reset to '0' which is a part of successive approximation register (SAR).
2. The MSB is initially set to '1' and the digital equivalent is compared with the unknown analog input voltage.
3. If the analog input voltage is higher than the digital equivalent, the MSB is retained as '1' and the second MSB is set to '1'. Otherwise the MSB is reset to '0' and the second MSB is set to '1'.
4. Comparison is made as given in step 2 to decide whether to retain or reset the second MSB and then the third MSB is set to '1'.
5. The above process is repeated down to LSB and by this time the converted digital value is available in SAR.

The basic block diagram is shown above. It is constructed using *n*-bit successive approximation register (SAR) whose output is given to an n-bit DAC. The output of DAC acts as the variable reference of the comparator while the another input of the comparator is connected with the unknown analog input voltage. The output is taken from SRG (Self Resetting Gate) which is just a latch, that keeps the binary value while the DAC is working on another conversion.



P8.27 For $n = 10$

(i) Quantization levels available $= 2^n - 1$

$$= 2^{10} - 1 = 1023$$

(ii) $$\text{Resolution} = \frac{\text{Full-scale value}}{2^n - 1}$$

$$= \frac{6-(-2)}{2^{10}-1} = 7.82 \text{ mV.}$$

(iii) output for maximum magnitude inputs *i.e.* + 6V = $(11\ 1111\ 1111)_2$

output for minimum magnitude inputs *i.e.* –2V = $(00\ 0000\ 0000)_2$

For $n = 16$

(i) Quantization levels available $= 2^n - 1$

$$= 2^{16} - 1 = 65535$$

(ii) $$\text{Resolution} = \frac{\text{Full scale value}}{2^n - 1} = \frac{6-(-2)}{2^{16}-1} = 0.122 \text{ mV.}$$

(*iii*) Output for maximum magnitude inputs *i.e.* + 6V = $(11\ 1111\ 1111)_2$

Output for minimum magnitude inputs *i.e.* –2V = $(00\ 0000\ 0000)_2$

P8.28

$$\text{Resolution} = \frac{\text{Full-scale value}}{2^n - 1}$$

$$0.5 = \frac{100}{2^n - 1}$$

Therefore, Word size $n = 8$

Resolution at output side = 0.02 × 0.5 = 0.01V

Reference voltage = (28 – 1) × 0.01 = 2.55V

APPENDIX

Glossary of Common Terms

A

Actuator—Part of the final control element, which translates control signal into action of the final control element/device.

Accelerometer—a sensor that measures the acceleration of the object to which it is attached.

ADC—Analog to digital converter that converts the analog voltage signal into a proportional digital signal.

Active transducer—A transducer that does not need external energy for its operation.

Analog signal—A quantity whose value is represented by a continuous variable.

B

Bellows–A pressure sensing element that converts pressure into linear displacement.

Binary—A number representation system of base (radix) 2 with only two symbols-0 and 1.

Bourdon tube—A pressure sensor that converts large gaseous pressure into displacement.

Block diagram—A pictorial and functional representation of a system.

Bandwidth—Part of the frequency spectrum within which component frequencies of a signal can pass through without attenuation.

C

Common mode rejection—The ability of the device to reduce the effect of a common signal at both input points.

Common mode signal—A signal simultaneously applied to both inputs of a differential amplifier.

Correlation—A study of simultaneous variation of two or more variables.

Cut-off frequency—The frequency at which gain reduces by a specified value.

D

DAC—Digital to analog converter performs the conversion of digital signals (*i.e.* from computer) into proportional analog signal.

DAS—A data acquisition system that interfaces many analog signals, called channels, to a computer. All switches, controls and the ADC are included in the system.

DP Cell—A pressure sensor that responds to the difference between two pressures. Most often used to measure flow by the pressure difference across a restriction in the flow line.

Damping—A characteristic of some systems which prevents rapid or excessive variations in response.

Digital signal—A quantity that can have only digitally coded values.

Dynamic variable—Process variable that changes in time domain.

Differential mode signal—A signal applied between two ungrounded terminals of a balanced three terminal system.

Dynamic characteristic—The characteristic of a system under normal working condition.

E

Error—The algebraic difference between expected and the measured value.

Equivalent noise source—In a system with a pure signal applied, the minimum amplitude of detectable signal can be determined from noise characteristic. A noise source (random signal generator) is connected to the sensor/transducer to produce output equal to the output in the first case. Then the minimum detectable signal is the effective equivalent noise source.

F

Filter—A device that discriminates between frequencies, usually to suppress a specified range of frequencies.

Frequency domain—Observations, measurements and mathematical operations performed with consideration of frequency as the variable.

Frequency response—The magnitude and phase shift of a system for a range of sinusoidal frequency input with the same input voltage applied at each frequency.

G

Gain—The ratio of the amplitudes of output and input signals.

H

Hardware—When used in the context of computer or electric equipment refers to physical equipment or components such as ICs, printed circuit boards, resistors etc.

Hysteresis–The tendency of an instrument/device to give a different output when the input is increased or decreased.

I

Impulse response—The output response of a system/network to a unit impulse at the input.

I to P converter—A device that converts electric current into gas pressure usually 4-20 mA signal into 3-15 p.s.i.

L

Laminar flow—Fluid flow in which adjacent layers do not mix.

Linearity—The closeness to which the curve between two variables approximates a straight line.

Load cell—A sensor for measurement of force or weight.

LVDT—A linear variable differential transformer is a device used to measure displacement in terms of output voltage.

M

Measurand—The physical quantity or property being measured.

Microcomputer—A computer based on the use of microprocessor or IC, often fitted on a printed circuit board and works with 8/16/32-bits of data.

Microprocessor—A large scale integrated circuit having all the function of a computer except memory and input/output devices.This IC includes ALU, registers, instruction set, control function.

Modulation—The modification of a carrier waveform in response to the information to be transmitted.

Multiplexing—The process of sharing a single data transfer channel for more than one input data.

N

Nozzle–A particular type of restriction used in flow systems to facilitate flow measurement by pressure drop across a restriction.

O

Open loop gain—The gain around the loop of a system employing feedback.

Operational amplifier—A high gain DC amplifier used with external feedback path.

Orifice plate—A type of restriction used in flow systems to facilitate flow measurement by pressure drop across a restriction.

P

Passive transducer—An energy modulating type of transducer that needs auxillary energy source for its operation.

Photo-diode—A sensor in which *p-n* junction diode when exposed to light intensity, causes variation in the diode reverse bias current.

Photovoltaic cell—A sensor that converts the intensity of EM radiation, usually in the IR or visible bands, into a voltage.

Pneumatic—systems that employs gas (usually air), as medium of signal transfer.

Power gain—The ratio of power density spectrum at the output to that at the input.

Primary sensing element—A device at the input of a measuring system that changes the measurand into another non electrical medium.

Push-pull transducer—As the input signal varies, the change in one half of the transducer increases while in the other half it decreases.

Pyrometer—A temperature sensor that measures temperature by taking into account the effect of electromagnetic radiation emitted by a hot body, which is a function of temperature.

R

Range—The region between the limits within which the variable is to be measured.

Resolution—The minimum detectable change of a variable in a measurement system.

Rise time—Time for a pulse signal in a system to rise from 10 to 90% of the maximum amplitude.

Rotameter—A flow measuring device placed in a flow system, arranged vertically, where the proportionality of rise of float is a linear function of the rate of flow.

RTD—Resistance temperature detector provides a measure of temperature with the change in resistance due to thermal properties.

S

Sensitivity—For a measuring device it is the ratio of change in output magnitude to the change in input magnitude, under steady state conditions.

Sensor—Used interchangeably with transducer that converts analog physical measurand into electrical signal.

Set point—The desired value of a controlled variable in a process loop, also called reference input.

Signal conditioning—Includes a variety of operations performed on electrical signal to bring it into the desired format.

Signal recovery—The process of obtaining the information in required format usually embedded in noise and may require a set of operations.

Signal to noise ratio—The ratio of power associated with noise to signal power in a terminated circuit, desired to be high.

Span—The algebraic difference between the upper and lower range values of a measuring device.

Stability—A property of systems which helps the system to recover equilibrium state after a disturbance.

Static characteristic—Relationship between two variables in a specified range when input variable is not varying in time.

Strain gauge—A resistance sensor that converts the strain developed due to force/load into change in resistance.

T

Thermistor—A temperature sensor constructed from semiconductor material, very sensitive to the temperature. The relationship has a negative slope and is highly nonlinear.

Thermocouple—A temperature sensor in which a voltage is produced nearly linear with the difference in temperature to be measured and a known reference.

Time constant—A number characterizing the time required for the output of a first order device to reach approximately 63% of the final value, following a step change of its input.

Time domain—Observations, measurements and mathematical operations performed with time considered as variable are said to be in time domain.

Telemetry—Transmission of measured quantities over a distance.

Transducer—A device that converts analog physical variable into an electrical quantity.

Transfer function—A mathematical expression relating output of a system to the input usually written as a function of complex variable.

Transient response—The output of a system after application of change/disturbance, until steady-state condition is reached.

V

Venturi—A particular type of restriction used in flow systems to facilitate flow measurement by pressure drop across a restriction.

Z

Zero crossing detector—An OP-AMP configured to sense the occurrence of zero value of difference between its 2 inputs.

APPENDIX J

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