Methodology Study for Sealing Technology of Robotic Implementation

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Utveckling av en metodik för provning av robottätningar

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Godkänt 2014-10-20	Examinator Ulf Sellgren	Handledare Sergei Glavatskih
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Sammanfattning

Detta examensarbete är baserat på ett så kallat STEP-projekt (Tätningsteknik – förstärkande egenskaper), inom ABB Corporate Research i Sverige, med syftet att studera tätningsteknik för robottillämpningar på ett vetenskapligt/systematiskt sätt.

I dagsläget används radiella läpptätningar inom många områden, såsom fordons-, flyg- och fartygsindustri. Under de senaste decennierna har den vidareutvecklats och är nu gjord av flera olika material. De flesta är utformade för konventionella tillämpningar, som exempelvis fordon. Där arbetar axeln vanligen imedkontinuerligt roterande rörelser, och vid sådana förhållanden kan läpptätningar normalt fungera väl. Men när det gäller robottillämpningar, där axeln typiskt arbetar i dubbelriktade och intermittenta rörelser, fungerar läpptätningen inte idealt och kan även ge oönskat läckage.

Detta examensarbete är fokuserat på att utveckla en experimentell metod för att studera läpptätningars prestanda med väl kontrollerade parametrar, såsom oljans egenskaper, temperatur, tryck, o.s.v. I arbetet ingår litteraturstudie av läpptätningar, specificering av testrigg, byggande av testrigg, utveckling av ett system för att detektera läckage, utförande av benchmark-tester, samt tätningsprov för olika robotrörelser.

Nyckelord: *läpptätning, robot, provrigg*

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Abstract

This thesis is based upon one project, STEP (Sealing Technology – Enhanced Properties), inside ABB Corporate Research, Sweden, which is aiming to study the sealing technology of robotic implementation by a scientific/systematic approach.

Nowadays the radial lip seal can be found in many fields such as automobiles, aero-planes, and marines, etc., and they have evolved into different designs and materials for the past several decades. Most of them are designed for conventional applications like cars, in which the shaft usually works in continuous rotary motions, and with such conditions lip seals could normally function well due to the sealing mechanism. However, regarding the robotic application, in which the shaft typically works in bi-directional and intermittent motions, the lip seal may not perform ideally and sometimes cause additional leakage.

Hence, this thesis is mainly focused on an experimental approach to study the lip seal performance with controlled parameters, especially the robotic motion, together with other parameters, such as oil, temperature, pressure, etc. The work includes literature survey of lip seals, specifying the test rig, building the test rig, developing a leakage detection system, carrying out benchmark tests and seal tests with different robotic motions.

Keywords: *lipseal*, *robot*, *test rig*

Acknowledgment

Hereby I would express my appreciation to my supervisor Shanghua Li at Insulation Material Technology (IMT) group of ABB Corporate Research (ABB SECRC), Västerås, and project member Arne Broberg at ABB Robotics, Västerås, you two guided me through the whole project and taught me lots of working experience, which makes it feel like more than a thesis work. I am also thankful for the comments and contribution given by my examiner Professor Sergei Glavatskih at department of Machine Design, School of Industrial Engineering and Management of the Royal Institute of Technology - KTH. Plus, here is my special thanks to Kun Wei, who works in Technology Support Center at ABB SECRC, and helped a lot regarding the post analysis of the seals.

Lastly I want to give my great thanks to all my friends and colleagues who accompanied me through the period, which made it a joyful and unforgettable time for me.

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1 INTRODUCTION

1.1 Problem definition

In the sealing system of robotics, there is always an expectation that the radial lip seal could withstand high load of working cycles and prevent minimum leakage for long term, especially now some customers have even higher demand regarding the sealing capability, for more and more robots are implemented in applications with critical hygienic standards, such as food and medical industries. Hence, there is a strong drive to understand how different working conditions/elements, such as temperature, pressure and robotic motions, etc., may affect the performance of the lip seal.

As mentioned above, for sealing conditions, the major difference between robotic and conventional applications is the shaft motion. In robotic ones, the typical shaft rotation is short-term, bi-directional and intermittent, while in other conventional ones, the shaft rotation is mostly long-term, unidirectional and consistent. Thus, there is a great interest to see how lip seals perform under robotic motions coupled with other test conditions.

1.2 Scope and structures

Since the purpose of the project is to study the sealing technology for robotics by a scientific/systematic approach, the prior step is to build up one test rig capable of doing seal tests with controlled parameters, so as to gather information of seal performance similar to real robots. Therefore, this thesis work is mainly focused on specifying and building such a test rig. The concept of test rig is derived from the ISO test rig standards, then combined with commercial robotic control units, which gives a design being able to test lip seals with any programmed robotic motions (3.1.2). In addition, a leakage detection system is developed to monitor the leakage in later test phases (3.1.6). Before tests, all the rigs are commissioned and validated according to ISO standards (3.1.7). A set of benchmark tests are carried out based on referenced seals and standard robot in-house test motions (3.2). These referenced seals have been tested and recorded on real robots. Based on the result of benchmark tests, a conclusion has been drawn that the test rig could reflect the real operating situation of general robots (4.1). After benchmark tests, seal tests with different robotic motions have been performed (3.2), which indicates that tests using small-degree oscillation motion yields more leakage for seals compared to the ones using standard robotic in-house test motion (4.2).

The structure of the report is shown below:

Chapter 1 gives the introduction for the problem definition, a scope for the thesis work and the structure of the report.

Chapter 2 gives the overall introduction for the radial lip seal, including basic designs, sealing mechanism, different seal material properties, seal specifications and general failures.

Chapter 3 gives the detailed methodology of studying the sealing application of robotics, which is divided into two parts, one is the test rig building-up, the other one is methods for conducting seal tests. In the part of test rig building-up, it introduces the design concept of rig, different functional units of the rig, and rig commissioning.

Chapter 4 gives the results for both benchmark seal tests and robotic motion seal tests.

Chapter 5 gives the preliminary evaluation of the tests and draws a general conclusion for all the study.

Chapter 6 gives the proposal for future work.

1.3 Review of previous experience

In this thesis, there are mainly two fields of experience to be reviewed, one is about lip seal and sealing tests, which gives a comprehensive view of lip seals and provides knowledge to set up test rigs; The other one is about AVR system development, which gives tutorials for programming the microchip system, as well as setting up peripheral components for the leakage detection system.

(Baart, 2008) has given a overall summary for the fundamental sealing theories for lip seals. It concluded that the theory of micro-elastohydrodynamic film and Non-symmetrical tangential deformations are considered to be the most acknowledged sealing mechanism. (R.K.Flitney, 2007) offered detailed introductions for all types of seals, including lip seals. It cataloged the sealing mechanism into both micro and macro pumping effect.

(Cheng, 2004) has summarized the design specifications for lip seals, which were considered to be important parameters for the sealing system design.

(Van Leeuwen, 1997) developed an experimental approach for revealing the tangential deformations. It also introduced one test rig being capable of measuring the distance between the shaft/seal contact.

(Jagger, 1957) developed a theory based on the surface tension of the oil film, which was considered to be related to sealing mechanism.

(Paige & Stephens, 2004) has given a study on the asperities presented on a specific seal design at a set different operating conditions. It also introduced one vertically placed test rig, of which the testing axis is perpendicular to the ground.

(Shore, et al., 2000) has given an introduction to a specifically designed test rig for testing seals under contaminated environment.

(S. Plath, 2005) has studied the frictional torque of a lip seal by both experimental and finite element method. It also introduced one vertically placed test rig.

(Camera, 2010) (Camera, 2007) (Camera, 2006) have introduced the use of AVR interrupts, timer, and LCD respectively.

(Jin, 2003) has given a overall introduction to the AVR system, as well as examples for programming.

1.4 Nomenclature

NBR	Nitrile
FKM	Fluoroelastomer
PTFE	Polytetrafluoroethylene
VMQ	Silicone
CR	Neoprene
ACM	Polyacrylate
EPDM	Ethylene Propylene
AEM	Ethylene Acrylic
EHL	Elastohydrodynamic Lubrication
AVR	Advanced Virtual RISC

2 Lip seals

2.1 Introduction of lip seals

Generally speaking, in most rotary applications, lip seals can be found as sealing devices. They usually serve as ‘bearing guards’, preventing leakage of lubricant while excluding aggressive dusts or fluid from working environment. Such applications cover many fields like automobiles, air-crafts, machine tools, etc. After decades of development, lip seals have evolved dramatically, which come into hundreds and thousands of designs, but basically range from single or double lip elastomer configuration to PTFE-based seals. Figure 2.1 shows the cross section exposure of a standard lip seal design.

Figure 2.1 Standard lip seal with cross section exposure (Parker, 2003)

The primary task of lip seals is to retain lubricants within certain oil vessels, and the secondary task is to protect lubricant system from outside contaminants. Beside these, lip seals are also used to separate different fluids, maintain the internal and external pressure. The maximum pressure rated by major manufacturers is 0.3 to 0.5 bar, further applied pressure would cause distortion of the lip, increasing the contact temperature which results in quick wear of the seal (R.K.Flitney, 2007).

2.2 Development of lip seals

Long ago seals were just leather strips tied on wheel axles to retain lubricants. Later during the industrial revolution, sealing system such as the bore on the wheel to hold packing was developed, followed by new designs of packing materials (Parker, 2003).

In 1929, Dr. Walther Simmer of Freudenberg group invented the first lip seal with beveled leather washers crimped in metal cases. In 1930s, such seals are widely put into production.

In 1940s, springs were introduced into leather lip seals. However, due to the temperature limitation of leather, new materials such as synthetic rubber were developed as lip seal material during World War II, and the technique of bonding rubber to metal cases by chemical coating processes was developed (Parker, 2003).

In 1960s, more reliable bonding techniques made it possible to directly mold rubber lips onto outer case, so as to eliminate the leakage coming from the seal assembly (Parker, 2003).

Nowadays, assembled seals made of rubber or leather is no longer popular because of high cost and internal leakage. Most seal producers start to focus on bonded designs for small diameter seals. In that case, advanced material like PTFE is implemented (Parker, 2003).

2.3 Basic designs

A cross-section exposure of typical rotary shaft seal is shown below. The seal is comprised of a rigid outer component and a flexible inner lip (Parker, 2003). See Figure 2.3.2.

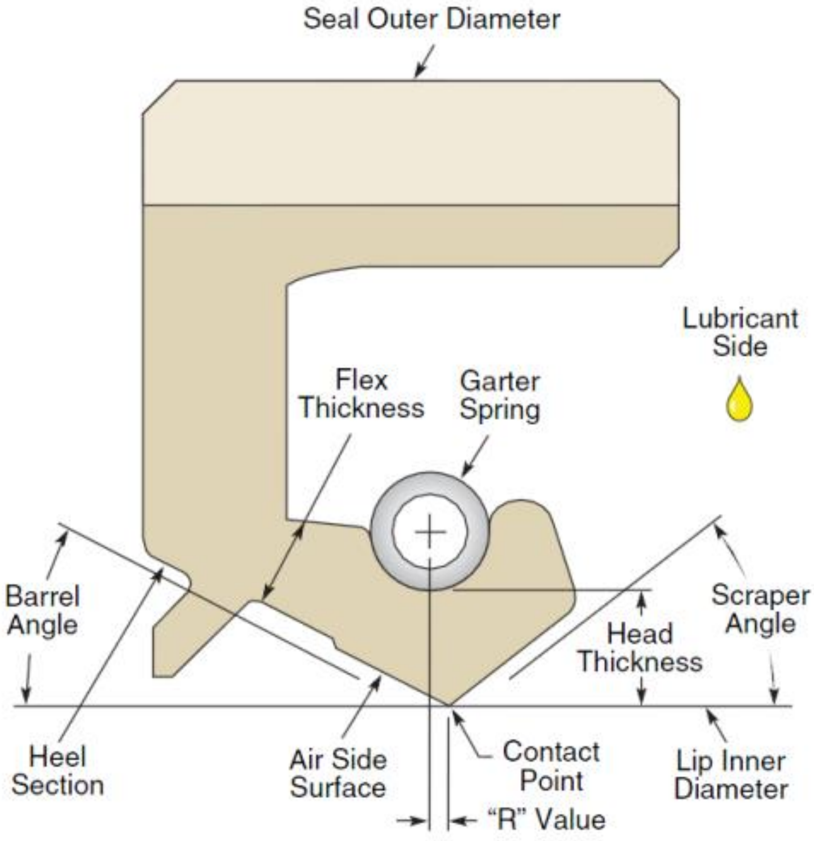


Figure 2.3.1 Basic seal design (Source: Parker)

The main purpose of the outer component is to keep the seal fitted in the housing after mounting, and the outer diameter of the seal shall be larger than the seal housing to create a press fit. This component is usually made from carbon steel, aluminum and stainless steel, even some nonmetallic composite. Another purpose of this component is to prevent leakage between the sealing outer surface and the housing (Parker, 2003).

The flexible seal lip component is bonded to the outer component by a molding press or mechanically crimp. It is directly contacting with the surface of working shaft (Parker, 2003).

Since the function of the seal is derived from its asymmetric lip shape, it is easy to see that the angle on the oil side of the seal is steeper than that on the air side. For a typical design, the angle of the oil side ranges from 35 to 55 degrees, and the air side a angle around 15 to 30 degrees. These angles determine the contact footprint of the lip on the shaft, which contributes to the sealing mechanism. Incorrect angles during mounting will result in an improper footprint, causing leakage later (R.K.Flitney, 2007).

In some cases, a spring-loaded design is implemented to provide a constant, uniform load upon the seal lip. The most popular spring is the garter spring, which applies a circumferential force to the seal lip, see Figure 2.3.2 (R.K.Flitney, 2007) (Parker, 2003).

Figure 2.3.2 Garter spring seal

2.4 Sealing mechanism

From various resources, it can be concluded that there are number of hypotheses describing the sealing mechanism, which can be further divided into primary sealing mechanism and secondary sealing mechanism (Baart, 2008).

The micro-elastohydrodynamic lubrication pump theory and the non-symmetrical tangential deformation theory are both acknowledged as the primary sealing mechanism (Baart, 2008). Here is a summary of such pumping mechanism based on micro-EHL theory. See Figure 2.4.1 Micro-pumping mechanism.

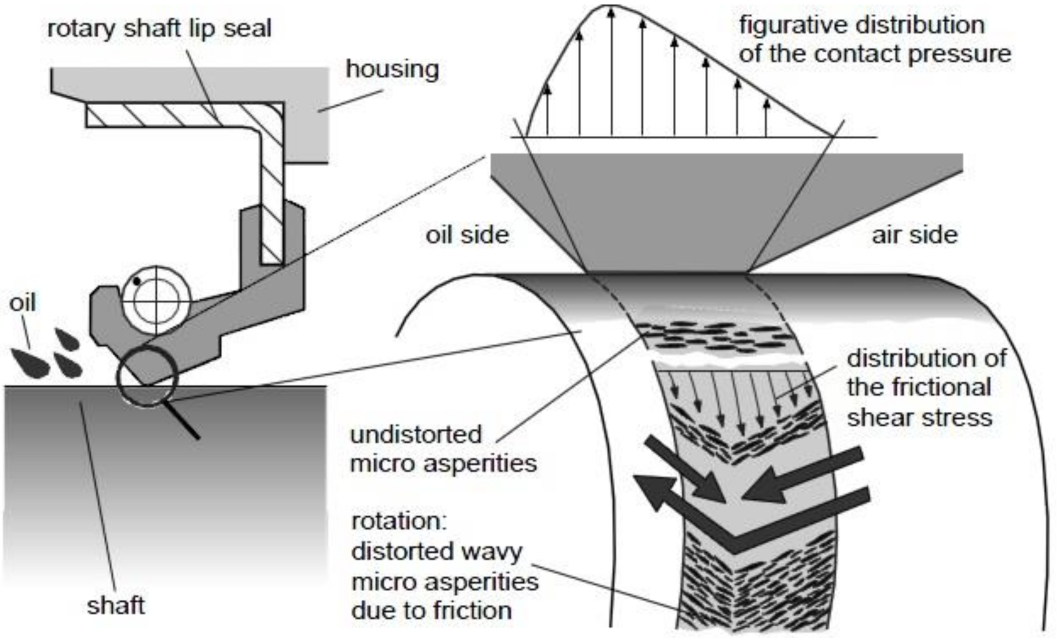


Figure 2.4.1 Micro-pumping mechanism (Bauer, 2010)

When the shaft stay still, the oil is retained by the pre-loaded elastomeric material of seal lip. Because the asymmetric design of seal lip angle, $\alpha > \beta$ (α is the oil-side angle, β is the air-side angle), it leads to an asymmetric contact pressure profile. When the shaft starts to rotate, the lip material will be distorted under the effect of friction shear stress, and the maximum distortion exactly happens at the place with the maximum contact pressure. To look into a microscopic view, there are many asperities existing due to the roughness of contact surface, these asperities will be therefore stretched along with the lip material, and skewed in the opposite direction at both sides of the peak contact pressure. Thus, these skewed micro asperities will deflect the circumferential shear flow toward the peak pressure line. Since this action happens in both side of the lip, it pumps the oil towards the lip center from both sides, but due to more extensive asperities existing at the air side, the pumping effect at the air side is much stronger than that at the oil side, which leads to a net pumping flow inwards the oil side. Hence, the lubricating film could be maintained within contacting area beneath the seal lip (R.K.Flitney, 2007) (Muller, 1998).

Another micro pumping action is caused by the lead created by conventional cylindrical grinding or other process during shaft machining. Such leads are similar to screw threads, see Figure 2.4.2, pumping the oil just like an auger feeding machine, see Figure 2.4.3.

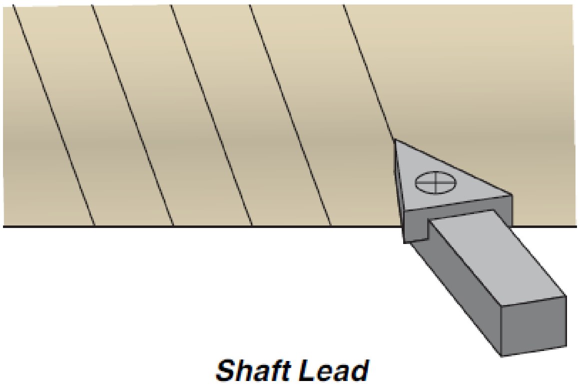


Figure 2.4.2 Shaft lead

Figure 2.4.3 Auger feeding component

It will either pump oil out of the seal lip to air side, or pump oil back to the oil sump, depending on which direction the shaft rotates. Hence, this pumping effect will either causes leakage problem, or help to retain the lubricants. Smart seal design would usually take advantage of this feature (R.K.Flitney, 2007).

Some of the secondary sealing mechanism is known as macro pumping mechanism. One of such mechanism is called cocking [5], which is caused by misalignment of the seal. When a shaft rotates, it will create a wiping action on the area of shaft, which will retain small amount of leaked lubricants back to the chamber. Now some seal designs (wave seals) have utilized such a feature by modifying the shape of seal lip to aid the pumping effect (R.K.Flitney, 2007).

2.5 Different materials and features

Now there are a huge range of materials used to manufacture lip seals, the most popular ones are: Nitrile (NBR), Fluoroelastomer (FKM), PTFE (Polytetrafluoroethylene), Silicone (VMQ), Neoprene (CR), Polyacrylate (ACM), Ethylene Propylene (EPDM), and Ethylene Acrylic (AEM). Here are some summaries from Parker seal handbook.

NBR offers excellent resistance to petroleum-based hydraulic fluids and hydrocarbon solvents, though it has poor resistance to ozone, steam or hot water. It is recommended for operating at temperatures ranging from -20 to +250 °F (-29 to +121 °C) (Parker, 2003).

FKM provides excellent resistance to oils, fuels and hydraulic fluids at higher temperature than NBR. It also has very good resistance to flame and excellent impermeability to gases and vapors. FKM is recommended for operating at temperatures ranging from -40 to +400 °F (-40 to +204 °C) (Parker, 2003).

PTFE is acknowledged to be used with virtually any fluid. Its advantages includes: extremely low friction, high temperature tolerance, and dry running capabilities. In addition, excellent mechanical properties could be achieved when PTFE is used with fillers such as glass, bronze, carbon fiber, mineral and others (Parker, 2003).

VMQ is generally recommended for high temperature, low friction applications. Silicone is resistant to weather, ozone, water, bases and alcohols, while it has poor abrasion resistance. VMQ is recommended for operating at temperatures ranging from -90 to +400 °F (-67 to +204 °C) (Parker, 2003).

CR offers very good resistance to weather, ozone and moderate resistance to oil and gasoline. It is recommended for operating at temperatures ranging from -45 to +250 °F (-43 to +121 °C) (Parker, 2003).

ACM is often used in high temperature environment and applications where extreme pressure lubricants are used. It is recommended for operating at temperatures ranging between -13 to +302 °F (-25 to +150 °C) (Parker, 2003).

EPDM has good resistance to alkalis, acids, and oxygenated solvents, it also offers good flexibility at low temperatures. EPDM is recommended for operating at temperatures ranging from -60 to +300 °F (-51 to +149°C) (Parker, 2003).

AEM is often used in low temperature transmission applications. It has good dry running capabilities and good abrasion resistance. AEM is recommended for operating at temperatures ranging from -40 to +350 °F (-40 to +177 °C) (Parker, 2003).

2.6 Design specifications

It is important to select a right lip seal for certain applications, so knowing the seal design specifications is of great interest. Below some technique experiences are taken from mechanical handbooks regarding the seal and sealing system design (Cheng, 2004).

- The amount of interference between the seal lip and the shaft shall be moderate. Generally speaking, when the diameter of shaft is less than 20 mm, the pressed lip value shall be around 1mm; otherwise, it shall be around 2mm.

- The circumferential force applied by seal spring shall be moderate. When linear velocity of the shaft v<=4m/s, the force shall be around 1.5-2N/m, otherwise it shall be controlled around 1-1.5N/m.
- The roughness of shaft surfaces shall be settled wisely, too coarse surface will result in excessive wear of the seal lip, while too smooth surface will result in the failure of lubricant film, making lubricants squeezed out of the seal lip, which overheats and wears off the seal.
- Vibration of the rotary shaft shall be controlled.
- The eccentricity of seals mounting on shafts would cause potential leakage in long term running.
- Limited shaft speed shall be considered according to different seal materials.
- Different thermal expansion rate of the seal outer frame and the housing shall be taken into account. Different swelling rate would cause the housing diameter be either large or small to the seal, which could result in leakage.
- The Young's' modulus of elastomer changes with temperature, too low temperature will make elastomer harder, and too high temperature will make elastomer softer, both cases make the elastomer seal lose elasticity, causing potential leakage.
- Lubricants shall be properly selected, for some lubricants will be incompatible with certain seal materials.

3 METHODOLOGY

3.1 Test rig for lip seal tests

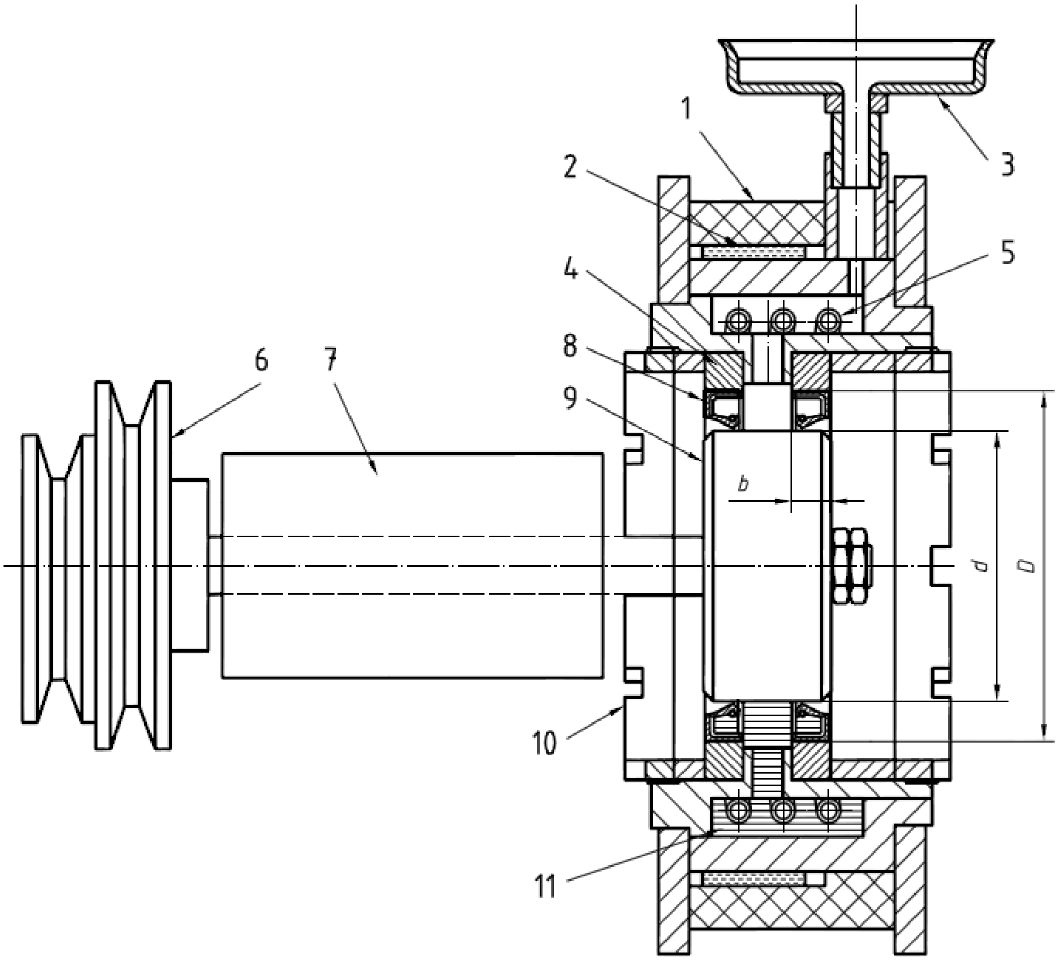
In this part, it focuses on details of the test rig building, including test rig specifications, design concepts, and all functional units on the rig. Regarding the part of leakage detection system, it covers the general description of hardware design and software programming.

3.1.1 Test rig specifications

In order to carry out seal tests with controllable parameters, a test rig is required. Here are specifications according to both ISO standards and robotics application.

Test rig standards are listed in ISO 6194-4 Rotary shaft lip type seals — Part 4: Performance test procedures.

Standard test rig structure is shown in Figure 3.1.1 Schematic drawing of seal test apparatus.



Key

1 Insulation
2 Heater band
3 Filler tray
4 Seal housing
5 Cooling coils
6 Drive from prime mover
7 Test head support
8 Test seal
9 Test shaft
10 Locking ring
11 Test fluid

Figure 3.1.1 Schematic drawing of seal test apparatus (ISO, 1999)

The test apparatus shall also conform to some additional requirements mentioned in document ISO 6194-4, which is mainly used as criterion for validating the test rig, for example: (ISO, 1999)

“...

c) The test head shall be designed and constructed so as to maintain the housing bore alignment relative to the test shaft axis within 0.03 mm throughout the operating temperature range.

...”

In addition, according to robotics application, some more specifications are required as below:

a) Arbitrary rotary movements of the shaft in both directions at predefined angles.

b) Be able to test seals ranging from 20 – 210 mm in diameter.

c) Working in a temperature range from -20 ... +150°C.

d) Automatic leakage detection by means of optical methods.

e) Measurement of oil temperature as well as the temperature on the seal’s lip

f) Detection or feedback of rotational speed, torque, etc.

3.1.2 Design concepts

The project is aiming to study and understand how seals perform under robotic motions, here the robotic motion is defined as a movement which can do rapid directional change with high acceleration or deceleration, so it is very important to reproduce such motion on one test rig design.

Nowadays there are some manufacturers building standard test rigs for conventional seal tests, but these rigs are only capable of testing seals at a relatively constant speed without too many changes of direction due to simple control system and low-end actuators. However, a commercial ABB robot control unit, plus the servo motor system, can be programmed to do whatever motion robots perform in reality, so here comes the idea to combine the mechanical part of one standard test rig with one set of robot actuation system (robot motor, gearbox and control unit). With such configuration, the standard test rig could easily run seal tests in robotic mode.

In order to transmit the power and motion from the output shaft of robot gearbox to test rig input shaft, a timing belt is used to connect these two separate systems. See figure 3.1.2 concept drawing for transmission chain.

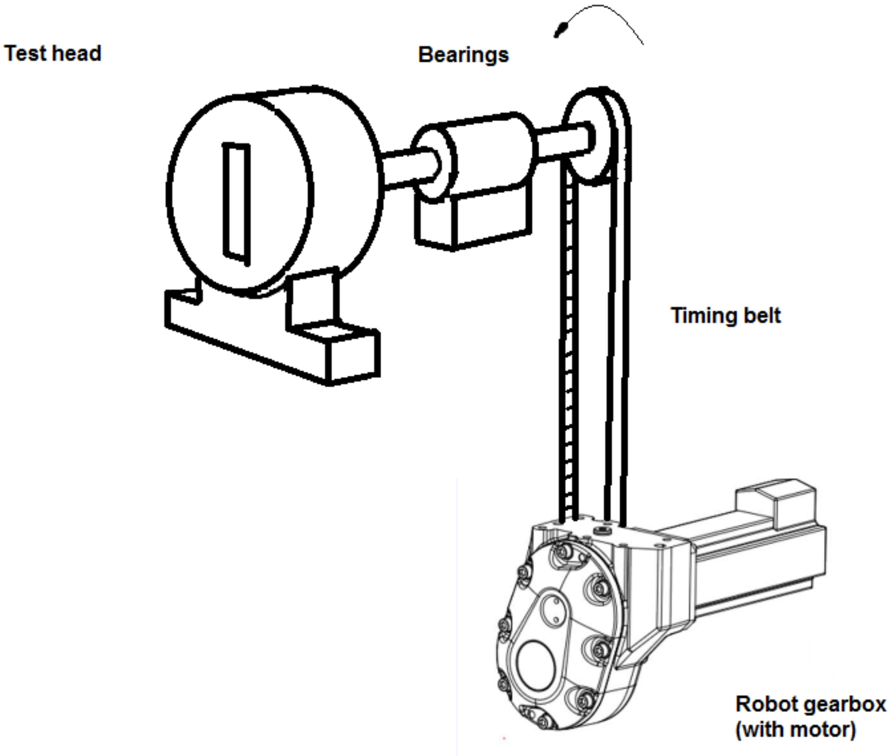


Figure 3.1.2 Concept drawing of transmission chain

3.1.3 Mechanical components

3.1.3.1 Test frame

The main mechanical structures of our test rig, including machine rack, test heads, etc. were directly purchased from Mingzhu Testing Machine Co. Ltd., China, and they are parts of the standard lip seal test machine - MZ4005B, as shown in Figure 3.1.3 Test rig appearance (a) and 3.1.3 Test rig appearance (b)

Figure 3.1.3 Test rig appearance (a)

Figure 3.1.3 Test rig appearance (b)

The main mechanical feature of the MZ-4005B is shown below:

Bi-directional rotation available

Main shaft allowable maximum speed: 8000 rpm

Seal size range: ф7mm - ф200mm

Total size: 1300mm×1000mm×1500mm

Pressure range: 0 – 0.03 MPa

Weight: 420 kg

Each test rig consists of 2 test heads, 2 sets of belt transmission systems, 2 sets of heating elements, tapped spindles and test shafts. More details will be explained in the following chapters.

3.1.3.2 Test head

On each of the test rig, there are two test heads, as shown in Figure 3.1.3 Test rig appearance (a), which means two lip seals can be tested simultaneously on one test rig.

The test head is a vessel filled up with oil when it is running a seal test, as shown in Figure 3.1.4 Test head front view and Figure 3.1.5 Test head back view. The detailed head structure is shown in Figure 3.1.6 Test head structure. On the bore plate, the hole is the place where lip seal sits.

Figure 3.1.4 Test head front view

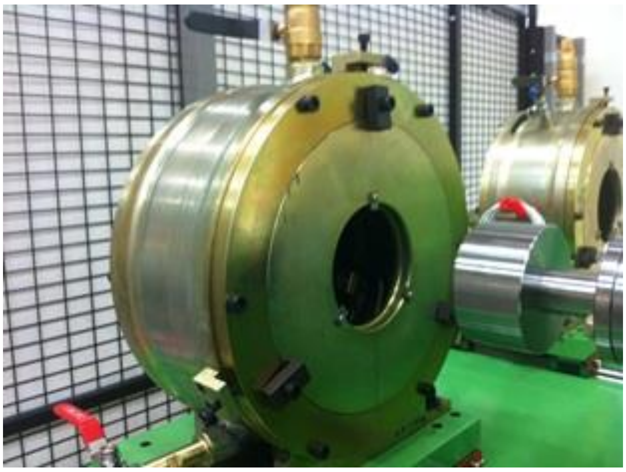
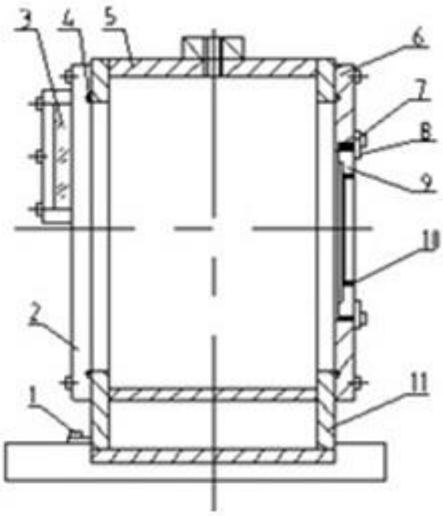


Figure 3.1.5 Test head back view



1. Gauge 2. Back cover 3. Chamber hatch 4. Oring 5. Test drum 6. Front cover
7. O ring 8. Small press board 9. Bore plate 10. Seal 11. Adjusting board

Figure 3.1.6 Test structure

3.1.3.3 Test shaft

Since the test shaft directly interacts with the seal, all of them are manufactured according to ABB robotics specification, which is shown below (ABB, 2009):

Seal surface: Plunge-cut grinded.

Helical-free surface.

Surface hardness: low speed shaft (peripheral speed <0.3 m/s) : >190 HB; other shafts: >45 HRC

Roughness: Rz 1 – 4 µm, Ra 0.2 – 0.8 µm, Rmax ≤ 6.3 µm

Protect surface after grinding.

The test shaft is mounted on one tapped spindle (Morse taper 4), and fastened by double-nuts at the end. See Figure 3.1.7 Concept drawing for the test shaft assembly and Figure 3.1.8 Test shaft assembly. Since one lip seal of size 95*128.56*8 is picked out to study, the shaft diameter is settled to be 95mm. The tapped spindle is specifically required from the manufacturer, so the test shaft can be easily mounted and dismounted. The drawing of test shaft and assembly are enclosed in the appendix.

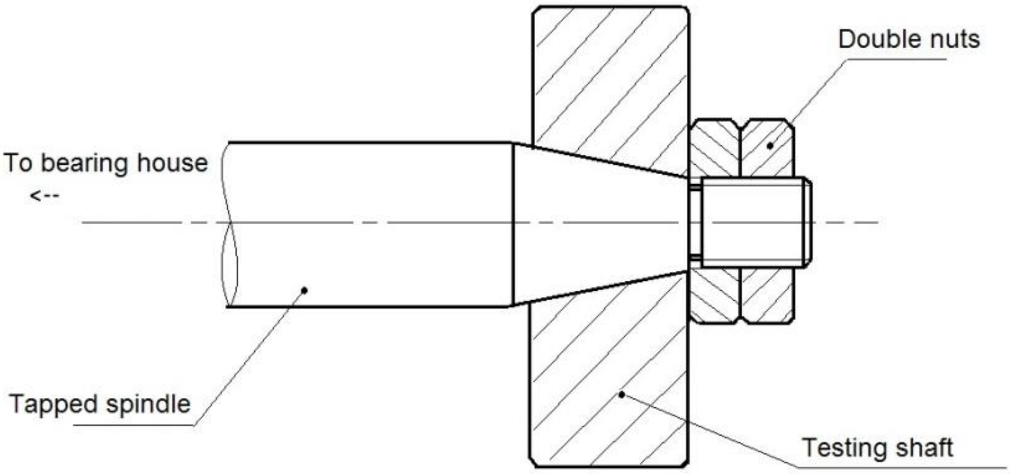


Figure 3.1.7 Concept drawing for the test shaft assembly

Figure 3.1.8 Test shaft assembly

3.1.3.4 Robot gearbox and motor

For each test head, there is one set of actuation system (gearbox with motor) behind, providing robotic motions to the main spindle via one timing belt. This actuation system is taken directly from ABB FlexPicker robot and integrated in our test rig, for it has relatively compact size among all other robot actuation systems. See figure 3.1.9 Actuation system.

The motor itself has a maximum speed of 3000 rpm and maximum torque of 2.85 N/m, together with the gearbox which has a reduction ratio of 11.5, the gearbox can provide the maximum speed of 260.87 and maximum torque of 32.78 N/m at the end of output shaft.

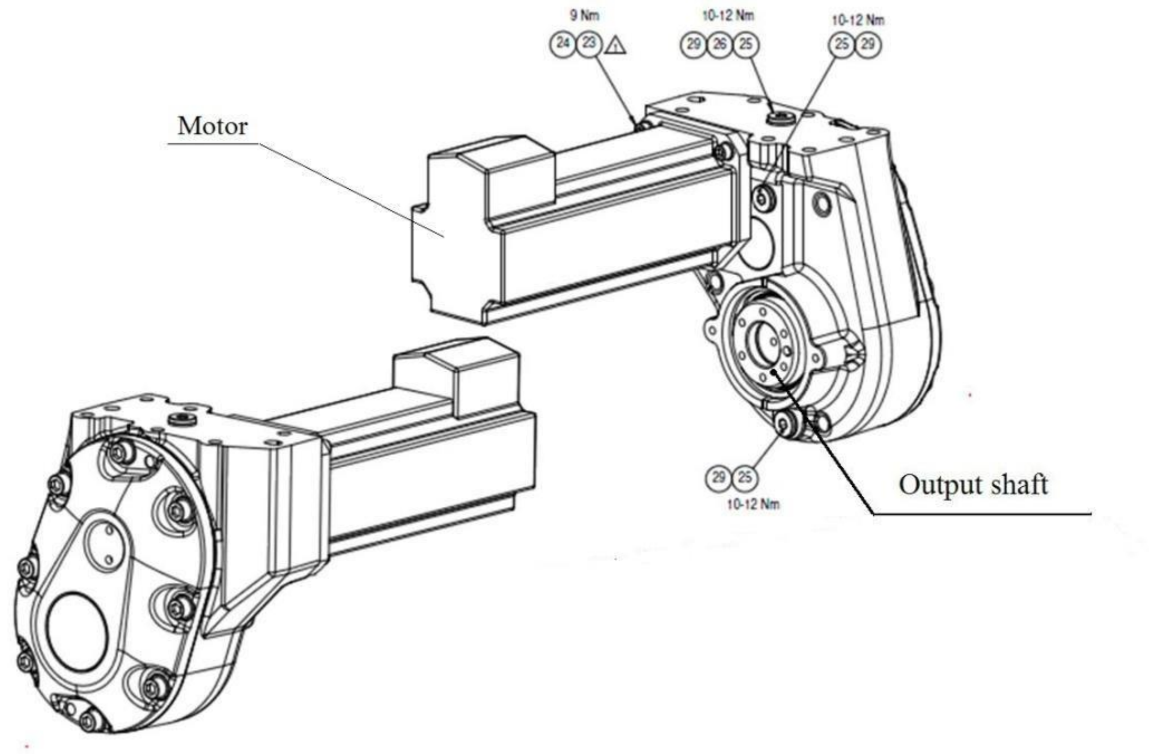


Figure 3.1.9 Actuation system

3.1.3.5 Motion transmission system

The motion transmission system consists of three major components, one is the timing belt pulley assembly, see Figure 3.1.10(a) and Figure 3.1.10(b), which is connected with the actuation system (see Figure 3.1.11), one is the timing belt, and the last one is another pulley assembly which is connected with the main spindle, see Figure 3.1.12 Transmission system.

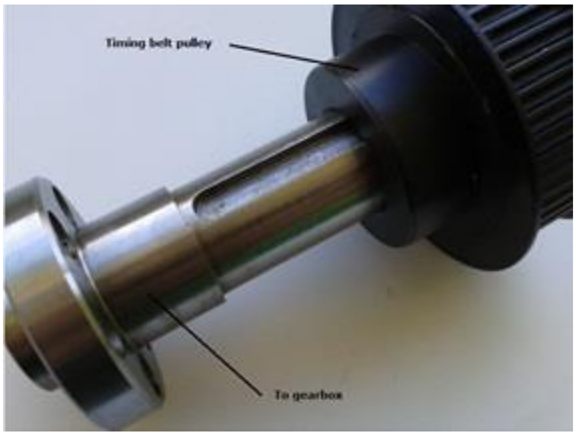


Figure 3.1.10(a) Pulley assembly

Figure 3.1.11 Pulley assembly to gearbox

Figure 3.1.10(b) Pulley assembly Figure 3.1.12 Transmission systems

3.1.3.6 Overall assembly

Drawings of the overall mechanical assembly are enclosed in appendix, which shows how the Flexpicker actuation system is integrated in the standard lip seal test machine. The design and manufacture is done by cooperation with the test rig manufacturer.

3.1.4 Actuation control system

The main idea using the robotic control unit is to provide a robust control for the actuation system, so as to fulfill the purpose of simulating real robotic motions. Since both control unit and actuation system are mature products of ABB, it only requires specific programs to make it work after all setups, which saves a lot of efforts and meanwhile guarantee the stability of the whole system in a long term running.

In the current configuration, the robotic control unit is in charge of 6 actuation systems, each actuation system is connected with one test head (2 heads/ test rig). Here is one concept drawing showing how actuations systems are connected with the control unit, see Figure 3.1.13 Control unit connections.

As shown in Figure 3.1.13, the control unit is connected with motors through 2 interface boxes, each interface box get power from the controller, and then distributes it to 3 motors; meanwhile it gathers feedback signals coming from the motor, establishing the communication.

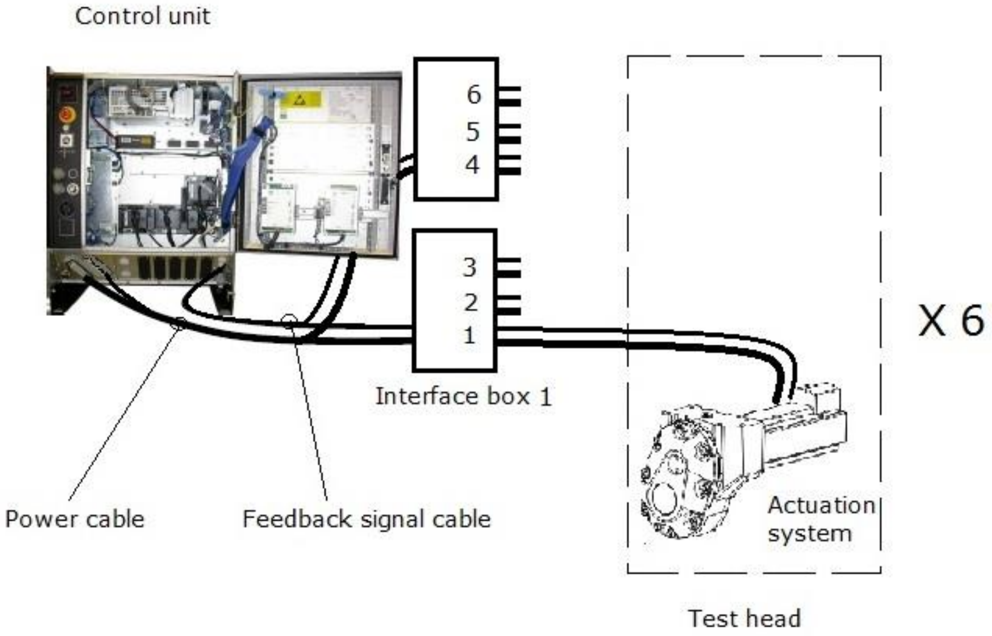


Figure 3.1.13 Control unit connections.

3.1.5 Oil heating system

Since the standard test rig was purchased without any control circuit, the whole oil heating system was built up in house. This system mainly consists of 2 components, one is the heating element, and the other one is the temperature regulator. The heating element is a simple resistance heater with rated power of 2000 w and rated voltage of 220 v, and it is attached to the front cover of test head. See Figure 3.1.14 Heating element.

Figure 3.1.14 Heating element

JUMO eTRON M is selected to be the temperature regulator, and the main features are shown below (JUMO, n.d.):

- 76 × 36 mm
- Three-digit back-lit LCD display with special characters
- Measuring input for RTD temperature probes, thermocouples, and current or voltage standard signals
- 1 x 10 A relay (changeover contact) or 2 x 5 A relays (normally open contact)
- Customer-specific linearization via tabular function
- Heating operation, cooling operation, or limit value monitoring

Besides, there is one temperature sensor PT100 used in each heating system, the probe of the sensor is inserted from the cylindrical surface of test head and the other end of the sensor is connected to the temperature regulator, so it can monitor the oil temperature and give feedback to the regulator.

The cable connection of oil heating system is shown in Figure 3.1.15 :

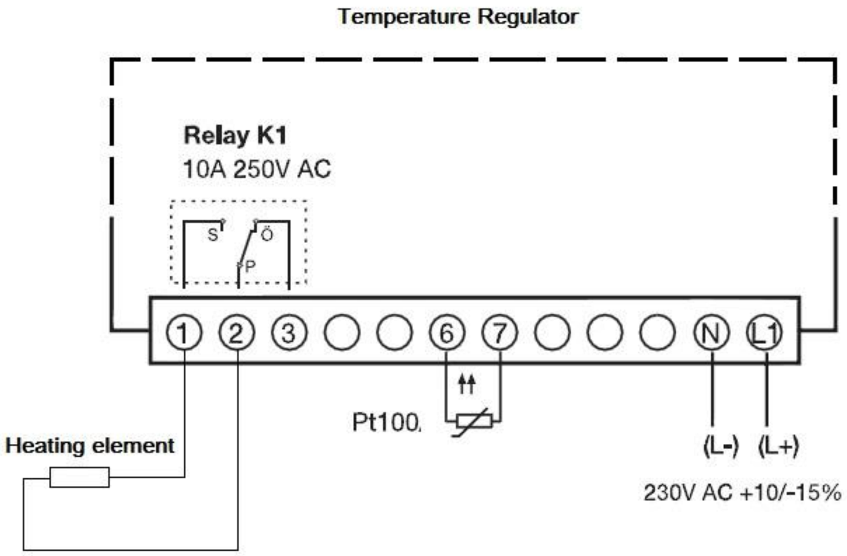


Figure 3.1.15 Oil heating system cabling

3.1.6 Leakage detection system

In order to easily check whether there is leakage occurring during the test, one part of the thesis work is defined to design and build such a leakage detection system. The following content explains how this system was developed and how it works.

The leakage detection system is basically a timer, instead of having a mechanical button to stop or pause, the system receives a signal to do so, and the signal is coming from an infrared sensor, which is the core sensor of this system.

The design concept is inspired by one phenomenon: when dropping a dip of oil on a paper (ordinary A4 printing paper), the dipped area will turn darker and somehow transparent, anyway the paper color will be changed when it touches oil. Hence, here comes the idea to utilize one sensor component named photoreflector, which can detect such change and turn it into current signals. See Figure 3.1.16 Photoreflector. It is an integrated component consists of both infrared emitter and receiver.

Figure 3.1.16 Photoreflector

The basic working mechanism of photoreflector is that the emitter emits infrared ray straight forward within a relative narrow angle, when there is any obstacle or surface blocking in front of the photoreflector, some of the infrared ray will be absorbed, while some will be bounced back and sensed by the infrared receiver inside photo-reflector. The lighter color the covering surface is, the larger amount of ray it reflects. Because the resistance of infrared receiver is inversely proportional to the amount of ray it receives, it allows larger current going through the receiver circuit when the photoreflector is facing at a lighter colored covering surface. This current signal is then interpreted into voltage signal by the resistor R2, noted as V4, see Figure 3.1.17 Circuit schematic drawing of working RPR220 [13]. Since V4 equals to the VCC (=5 v) minus the voltage drop on R2, so the larger the current, the smaller voltage potential at V4 will be. Hence, according the character of photoreflector, the brighter the covering surface is, the smaller V4 voltage will be (close to 0 v), and the darker the covering surface is, the bigger V4 voltage will be (close to VCC=5 v).

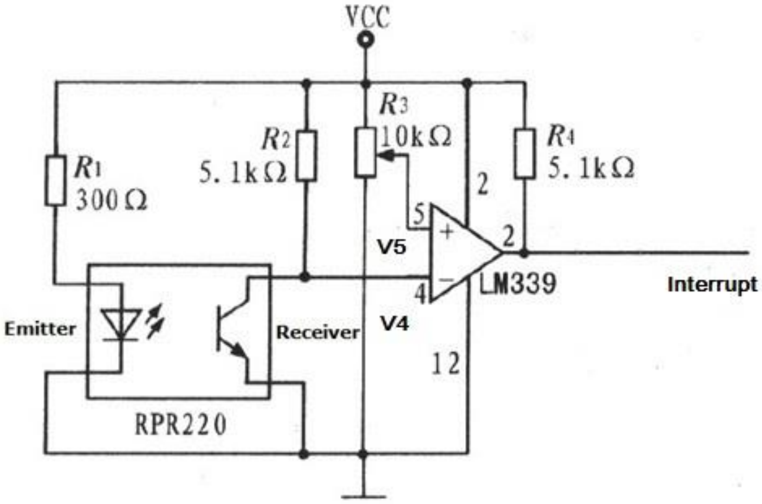


Figure 3.1.17 Circuit schematic drawing of working RPR220 (IOTer, 2011)

Therefore, in order to tell when it is “dark” or “bright”, a threshold value is needed, which is realized by one potential meter and one comparator. As shown in Figure 3.1.17, V5 and V4 are the input of the comparator LM339, the working principle is that when voltage potential at V5 is higher than V4, the output will be pull up to high level, which is equal to VCC=5v. Since the output signal is linked to the interrupt port of the micro-controller, this voltage level is continuously being checked by the interrupt event. The interrupt event triggering rule is the low level triggering, so that means as soon as the voltage at V5 is lower than V4, the voltage at output of comparator will be pull down to 0 v, and this sustained low level signal will trigger the interrupt, which is further programmed to stop the timer in the system.

Here is the routine showing how this detection system works: First adjust the system time according to real time. Then put the photoreflector facing to one clear test paper (A4 printing paper), using multi-meter to check the voltage value $V4^1$, then dip some oil on the paper and dry it a bit, when seeing the oil dipped area change color, put the photorefector onto that area, again measure and note down the voltage value $V4^2$. All the measurement are done with the shield wrapped on the sensor, which gets rid of the influence of environmental lighting, shown in Figure 3.1.19 Photoreflector attached to the test rig. Since $V4^1$ voltage is measured based on a clear paper, so it shall have lower voltage value than $V4^2$. Next, pick up an average number of these two values, which will be used as the threshold value. This threshold value V5 is then realized by setting up the potential meter R3 in Figure 3.1.17. In theory, when the test paper (A4 printing paper) is dyed by the leaked oil, the voltage value at V4 shall rise from $V4^1$ to $V4^2$, and it will be sure to bypass the threshold value V5. Thus, the input values of comparator are flipped, which will lead to a pull down voltage level to the output of the comparator.

On this detector system, there are 2 photoreflectors, after all of two sensors have been calibrated and mounted, one could start the timing process when the seal test starts, and the timer is counted by hours. As soon as the leakage happens, it will trigger the interrupt which will stop the timer.

In reality, one prototype system has been developed for this detection purpose, besides the sensor module (photon-reflector: RPR220), it also contains input module (4*4 button pad), output module (4 line LCD displayer), timing module (DS1302), and the minimum Atmega16 working board, see Figure 3.1.18 Detection system. The programmed is written in C and compiled via AVR studio, which is enclosed in appendix. Also, see Figure 3.1.19 Photo-reflector attached to the test rig, it shows how the sensor is attached to the test rig with one shield.

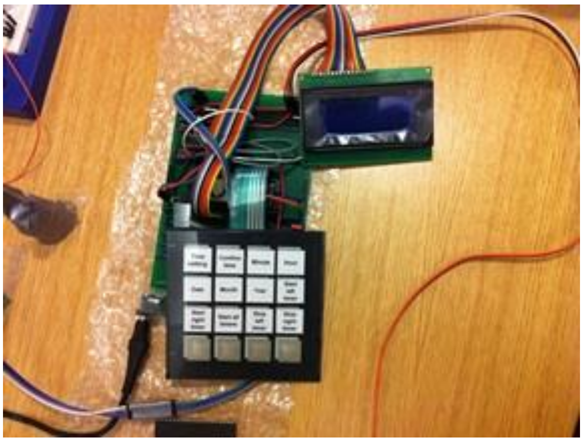


Figure 3.1.18 Detection system

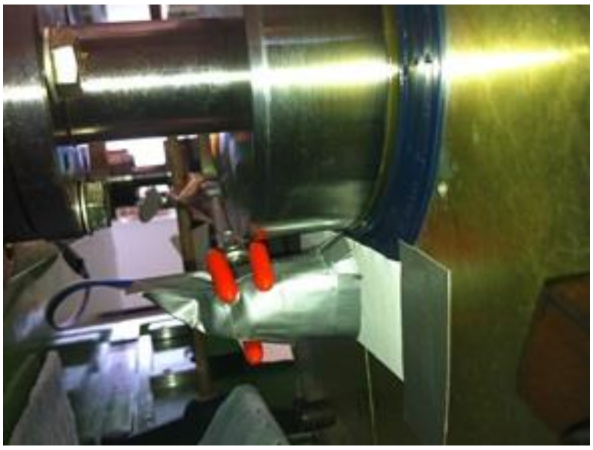


Figure 3.1.19 Photoreflector attached to the test rig

3.1.7 Test rig validation

3.1.7.1 Run-out validation

According to ISO 6194-4 (ISO, 1999), "... b) the shaft shall be capable of maintaining the specified test eccentricity under dynamic conditions to within ± 0. 03 mm throughout each test....", the run-out of each shaft was checked. As shown in Figure 3.1.20, the probe of dial indicator is laid against the shaft surface, and the base is fixed on the test rig frame. The run-out of shafts were observed as 0.015 ~ 0.020 mm, so they are validated for further tests.

Figure 3.1.20 Run-out validation

3.1.7.2 Eccentricity validation

According to the seal system design for ABB robotics, "Shaft to bore misalignment + shaft run-out < 0.25 mm." (ABB, 2009), which in fact covers the run-out criteria as mentioned above, the probe of dial gauge is laid against the housing bore surface instead of the test shaft surface, and the base is fixed on the shaft, which makes the dial gauge be available to rotate along with the shaft, see Figure 3.1.21 Gauge fixture. After a full clockwise rotation ordered from the control panel, the eccentricity between the test shaft and the bore can be read from the gauge, see Figure 3.1.22 Validation test view.

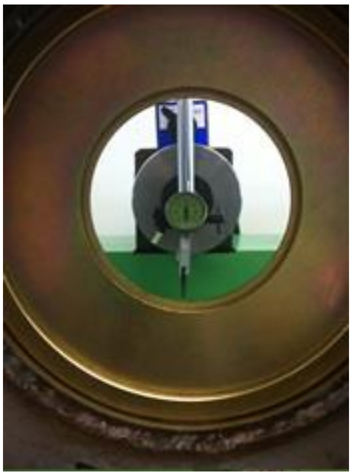


Figure 3.1.21 Gauge fixture

Figure 3.1.22 Validation test view

In order to manually adjust the alignment between the bore hole and the test shaft, there is a set of mechanism on the housing bore plate, which consists of 3 screws averagely distributed along the plate edge, see Figure 3.1.23 (a) and Figure 3.1.23 (b). By adjusting the set screws while watching the gauge indication, the bore plate could be finely aligned with the shaft, so the eccentricity is normally controlled within 0.2 mm to fulfill the criteria.

Figure 3.1.23 (a) Adjusting Mechanism

Figure 3.1.23 (b) Adjusting Mechanism

3.1.7.3 Shaft surface roughness validation

The shaft roughness was checked before being assembled to the test rig. The picked shaft is measured with 4 positions, averagely distributed along the shaft surface, and on each position, a path of 32 mm along the shaft axis has been measured. All main roughness parameters Ra (Arithmetical mean deviation), Rz (Ten point height of roughness profile), Rt (Maximum height of profile) have been recorded. See Table 3.1 Shaft roughness. The recorded surface profile at 0 degree is shown in Figure 3.1.24 Surface profile at position 1.

Parameter	Unit	Result				
		position 1	position 2	position 3	position 4	avg
		0 degree	90 degrees	180 degrees	270 degrees	
Ra	µm	0,281	0,321	0,297	0,289	0,297
Rz	µm	3,001	3,681	3,24	3,253	3,294
Rt	µm	4,239	5,989	4,55	5,828	5,152
Measured length along axis	mm	32				

Table 3.1 Shaft roughness

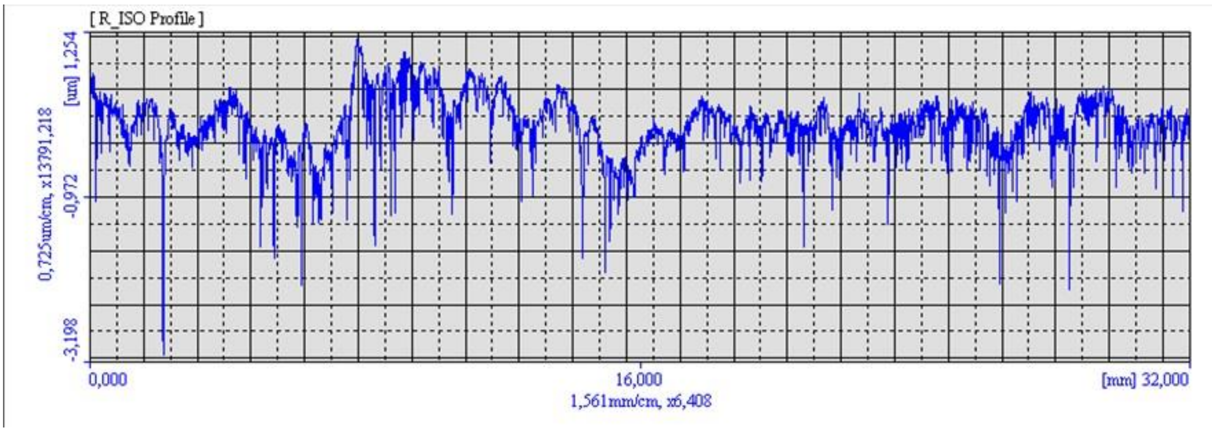


Figure 3.1.24 Surface profile at position 1

The criteria for the shaft roughness are “Rz 1 – 4 µm, Ra 0.2 – 0.8 µm, Rmax ≤ 6.3 µm” as mentioned in 3.1.3.3. Hence, the roughness is therefore validated and the shaft is ready to mount to test.

3.2 Methods for benchmark tests

3.2.1 Goal

The goal for benchmark test is to establish the relationship between the test rig and real robots. Since ABB Robotics has done several in-house tests regarding one specific lip seal, this seal then is selected for test purpose for the thesis work. Hence, by comparing the leakage results of test rigs with those results taken from in-house tests, it would tell whether the test rig is capable of imitating real robot condition, which will also be set as certain criteria for later stage tests.

3.2.2 Test setups

Seal: NBR seal (ABB internally tested), 95X128.56X8 mm

Oil: Mineral oil
Grease: lithium-based grease (for general lubrication purposes)

Motion: This motion is programmed according to "IRB XXX in-house standard test program", which is quite typical for leakage tests. The motor acceleration and deceleration speed is set as 20 rad/s^2, which is obtained by watching test records and tuning program on the test rig. Each of the motion step is defined as certain degrees of rotation in a polar coordination system. This reference system is marked according to the axis 2 of IRB XXX, shown in Figure 3.2.1.
In order to get an impression how fast the shaft rotates at certain point, the following calculations was carried out.

The whole loop of motion is mainly sets of 90° and 45° rotation in clockwise and counterclockwise respectively, and the loop itself repeats over and over. During one loop, there are also 5 interval stops of 3 s long each. One step time t_{one_step} can be calculated by:

$$t_{one\_step} = 2t_{acc} = 2t_{dec} \quad \text{(Eq 3.1)}$$

$$t_{acc} = t_{dec} = \sqrt{\frac{2\phi_{acc}}{\alpha_{acc}}} = \sqrt{\frac{2\phi_{dec}}{\alpha_{dec}}} \quad \text{(Eq 3.2)}$$

$$\phi_{one\_step} = 2\phi_{acc} = 2\phi_{dec} \quad \text{(Eq 3.3)}$$

For example, in the first step, $\phi_{one\_step} = 120°$, the t_{one_step} is calculated as 0.64s by equations shown above. All other motion steps are shown in Table 3.2.

The theoretical maximum speed can be obtained by:

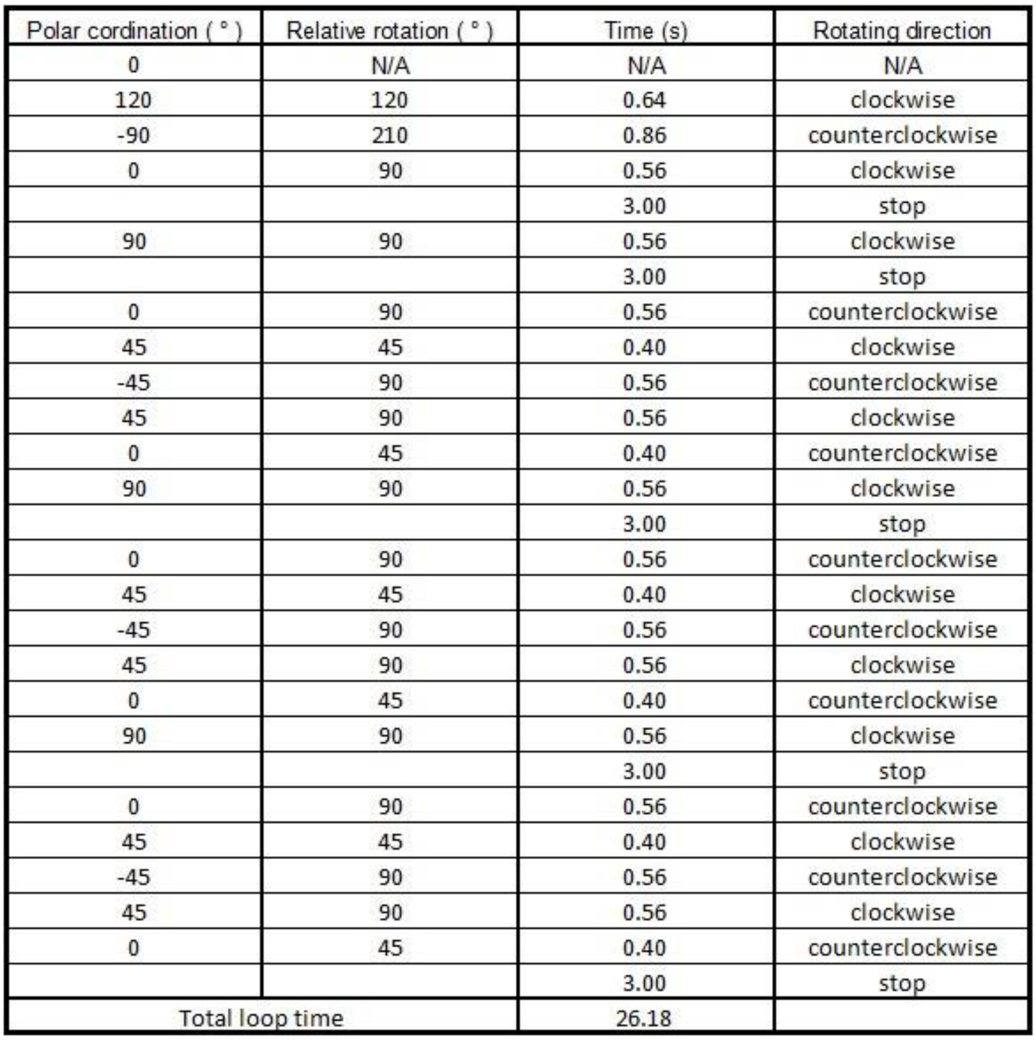
$$v_{\max} = \alpha_{acc} t_{acc} \quad \text{(Eq 3.4)}$$

$$v_{\max\_rpm} = \frac{60 v_{\max}}{2\pi} \quad \text{(Eq 3.5)}$$

The maximum speed for motions steps 120°, 210°, 90°, 45° are 192 rpm, 258 rpm, 168 rpm, 120 rpm respectively.

Test time limit: 30 days.

Since the seal leakage test is heavily time-consuming and unpredictable, plus the tests are aiming for short-term leakage observation, 30 days is therefore decided to be a reasonable time to check the leakage status of tested seals, and any leakage within 30 days will be regarded as statistic element to evaluate. Some of the tests were running more than 30 days for other purposes, for example, to test how long one sealing case start to leak after the seal start getting wet (oil or grease appears at the contact area between the seal lip and the shaft, which is considered as early indication of leakage), so there were several leakage happened beyond 30 days, but they were not counted for the test case being studied.



Polar cordination (°)	Relative rotation (°)	Time (s)	Rotating direction
0	N/A	N/A	N/A
120	120	0.64	clockwise
-90	210	0.86	counterclockwise
0	90	0.56	clockwise
		3.00	stop
90	90	0.56	clockwise
		3.00	stop
0	90	0.56	counterclockwise
45	45	0.40	clockwise
-45	90	0.56	counterclockwise
45	90	0.56	clockwise
0	45	0.40	counterclockwise
90	90	0.56	clockwise
		3.00	stop
0	90	0.56	counterclockwise
45	45	0.40	clockwise
-45	90	0.56	counterclockwise
45	90	0.56	clockwise
0	45	0.40	counterclockwise
90	90	0.56	clockwise
		3.00	stop
0	90	0.56	counterclockwise
45	45	0.40	clockwise
-45	90	0.56	counterclockwise
45	90	0.56	clockwise
0	45	0.40	counterclockwise
		3.00	stop
Total loop time		26.18	

Table 3.2 Motion details for benchmark tests with problematic seals

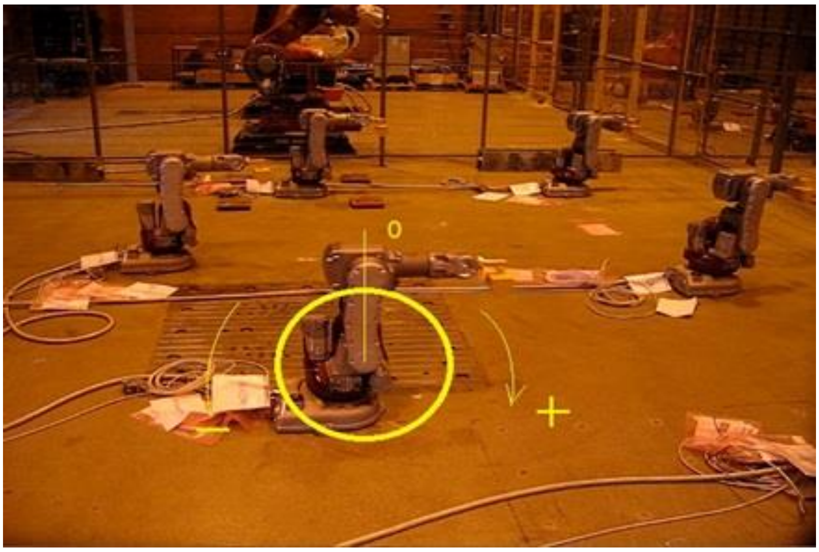


Figure 3.2.1 Reference coordination system on IRB XXX

Temperature: Based on typical robot working conditions, 55°C is set to be the oil temperature, so as to build up certain level of pressure inside test heads, details are listed in the following paragraph. This heating process is applied by the heating element and controlled by the temperature regulator.

Pressure: As one passive control parameter, the pressure varies when the temperature changes. It is observed to surge to around 0.1~0.2 bar immediately after heating process starts, when the temperature is set as 55°C. Since there is no active air pump, the pressure inside test heads is built up merely due to the heating. After half a day, the pressure usually drops to 0 due to the imperfect air-tightness of test head. This phenomenon is exactly as same as what observed on real robots.

3.3 Methods for studying effects of robotic motion

3.3.1 Goal

The goal for testing seals under different robotic motions is to find out which motion has stronger influence to the leakage. It has been highly appreciated and given high-priority because there is no established knowledge so far on how the robotic motion can affect the sealing performance. Another goal for studying effects of robotic motion is to find out a 'tough' robotic motion for acceleration tests in the future, which will not be included in this thesis. Here, 'tough' refers to more leakage observed by using certain robotic motions.

3.3.2 Test setups

Seal: NBR seal (ABB internally tested), 95X128.56X8 mm

Oil: Mineral oil

Grease: lithium-based grease (for general lubrication purposes)

Motion: This motion is programmed according to typical robotic movement suggested from robotics side . So far two different motions have been tested, as shown below:

Motion 1: +/-3° continuously, with 5s stop + 180° turn after each minute

Motion 2: +/-90° continuously, with 180° turn after each minute

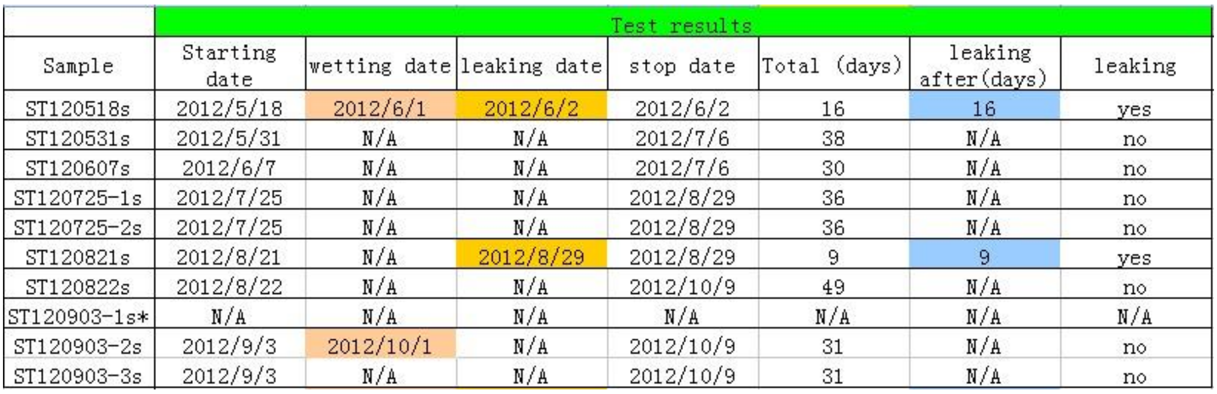
The basic idea to run motions described above is to get the seal work in a poor condition, especially the one like "+/-3° with 5s interval stops", which is believed to destroy the oil film between the lip seal and the shaft, causing sealing mechanism fail or insufficient lubricating. (one hypothesis).

Temperature and pressure conditions are as same as those set for benchmark test.

4 RESULTS AND DISSCUSSION

4.1 Results of benchmark test

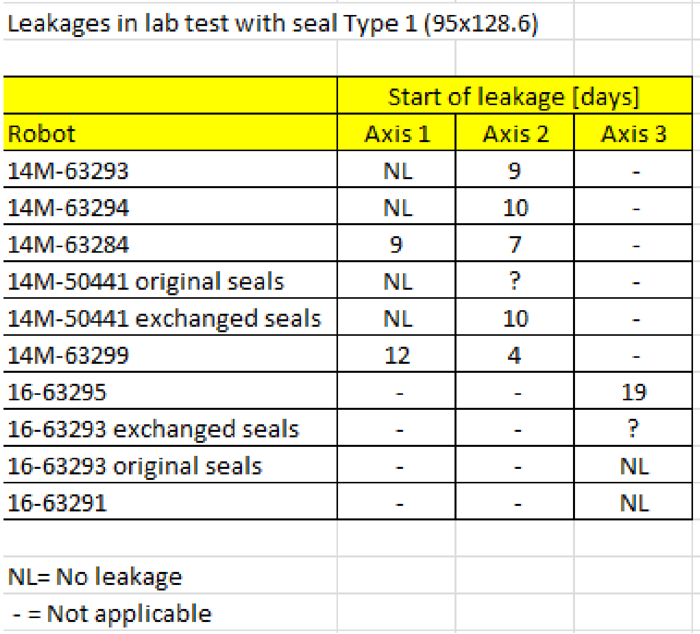
Benchmark tests with specified seals started in May 2012, and ended at the beginning of October 2012. Here is one table showing how leakage status is, see Table 4.1.



	Test results						
Sample	Starting date	wetting date	leaking date	stop date	Total (days)	leaking after(days)	leaking
ST120518s	2012/5/18	2012/6/1	2012/6/2	2012/6/2	16	16	yes
ST120531s	2012/5/31	N/A	N/A	2012/7/6	38	N/A	no
ST120607s	2012/6/7	N/A	N/A	2012/7/6	30	N/A	no
ST120725-1s	2012/7/25	N/A	N/A	2012/8/29	36	N/A	no
ST120725-2s	2012/7/25	N/A	N/A	2012/8/29	36	N/A	no
ST120821s	2012/8/21	N/A	2012/8/29	2012/8/29	9	9	yes
ST120822s	2012/8/22	N/A	N/A	2012/10/9	49	N/A	no
ST120903-1s*	N/A	N/A	N/A	N/A	N/A	N/A	N/A
ST120903-2s	2012/9/3	2012/10/1	N/A	2012/10/9	31	N/A	no
ST120903-3s	2012/9/3	N/A	N/A	2012/10/9	31	N/A	no

Table 4.1 Leakage status for benchmark tests with specified seals

Totally 10 tests were scheduled, but one test (ST120903-1s) was aborted due to test head pressure issue. 2 confirmed leakage (9 & 16 days) and 1 wetting case (28 days) out of 9 tests have been observed. In comparison to the leakage situation of the in-house testing of robot IRB XXX, where 8 confirmed leakage cases out of 16 tests have been observed (Table 4.2), it could be concluded that the testing conditions for the specified seals on the test rigs are at the border situation of real robot leakage. Thus, a conclusion can be drawn that the test rig could reflect the real situation of the general robot operation. The relationship between the test rig and the robot is therefore established.



Leakages in lab test with seal Type 1 (95x128.6)

	Start of leakage [days]		
Robot	Axis 1	Axis 2	Axis 3
14M-63293	NL	9	-
14M-63294	NL	10	-
14M-63284	9	7	-
14M-50441 original seals	NL	?	-
14M-50441 exchanged seals	NL	10	-
14M-63299	12	4	-
16-63295	-	-	19
16-63293 exchanged seals	-	-	?
16-63293 original seals	-	-	NL
16-63291	-	-	NL

NL= No leakage

- = Not applicable

Table 4.2 Leakage status for IRB XXX tests

4.2 Results of studying effects of robotic motion

Tests focused on different robotic motions started in November 2012. Totally 16 tests were carried out for 2 types of robotic motions, 4 tests per batch were done for these 2 types of motion respectively. The first and fourth batch of tests have been completed based on the 1st robotic motion defined in 3.3.2 (+/-3° continuously, with 5s stop + 180° turn after each minute). Given the 30 days limit, 1 confirmed leakage (15 days) and 5 wetting cases (10~14 days) out of 8 tests have been observed as shown in Table 4.3. The second and third batch of tests have been completed based on the 2nd robotic motion defined in 3.3.2 (+/-90° continuously, with 180° turn after each minute). Given the 30 days limitation, 2 confirmed leakage (6 days and 14 days) and 2 wetting cases (15~22 days) out of 8 tests have been observed as shown in Table 4.3. Despite that the 1st robotic motion yielded less leakage cases compared to the 2nd one, the first one gives out more wetting cases. As defined in previous chapters, 'wetting' means oil or grease appears at the contact area between the seal lip and the shaft, which is considered as early indication of leakage. Hence, it could indicate that the 1st robotic motion might be a bit 'tougher' than the 2nd one. Also, it indicates that both of the 2 robotic motions are 'tougher' than the IRB XXX in-house standard test program used in benchmark tests. However, further tests might be required to confirm this preliminary conclusion.

		Test results						
		Starting date	wetting date	leaking date	stop date	Total (days)	leaking after(days)	leaking
1	ST121102-1s	2012-11-2	2012-11-12	2012-11-26	2012-12-3	32	15	yes
	ST121102-2s	2012-11-2	2012-11-12	N/A	2012-12-3	32	N/A	no
	ST121102-3s	2012-11-2	2012-11-12	N/A	2012-12-3	32	N/A	no
	ST121102-4s	2012-11-2	2012-11-16	N/A	2012-12-3	32	N/A	no
2	ST121220s	2012-12-20	N/A	2012-12-25?	2012-12-27	8	6	yes
	ST121212-1s	2012-12-12	N/A	N/A	2012-1-25	45	N/A	no
	ST121212-2s	2012-12-12	2012-12-27	2013-1-24	2012-1-25	45	44	yes
	ST121212-3s	2012-12-12	N/A	N/A	2012-1-25	45	N/A	no
3	ST130225-1s	2013-2-25	2013-3-10	2013-3-14	2012-4-2	37	14	yes
	ST130225-2s	2013-2-25	N/A	N/A	2012-4-2	37	N/A	no
	ST130225-3s	2013-2-25	N/A	2013-4-2	2012-4-2	37	37	yes
	ST130225-4s	2013-2-25	N/A	N/A	2012-4-2	37	N/A	no
4	ST130408-1s	2013-4-8	N/A	N/A	2012-5-13	33	N/A	no
	ST130408-2s	2013-4-8	N/A	N/A	2012-5-13	33	N/A	no
	ST130408-3s	2013-4-8	2013-4-22	N/A	2012-5-13	33	N/A	no
	ST130408-4s	2013-4-8	2013-4-29	N/A	2012-5-13	33	N/A	no

Table 4.3 Leakage status for tests focused on robotic motions

4.3 Post analysis

Tested seals and oil were sent to the technology support personnel at CRC for further analysis, here are some important notes taken from the analysis.

4.3.1 Seal geometry

After the examination of both leaked seals and un-leaked seals taken from benchmark tests, it is noticed that the 2 leaked seals have relatively smaller inner diameter than the un-leaked ones after tests. 2 leaked seals have inner radius of 45.61 mm and 45.82 mm respectively, see Appendix 3.1 Leaked seal 1 and Appendix 3.2 Leaked seal 2, while 2 picked un-leaked seals have inner radius of 46.28 mm and approx 46.48 mm (irregular), see Appendix 3.3 Un-leaked seal 1 and Appendix 3.4 Un-leaked seal 2. Due to knocking seal off from the bore during dismounting, certain extent of distortion may have been done to the seal lip or structure, so the geometry change is not considered reliable for drawing further conclusions.

4.3.2 Seal lip

Also the seal lip has been examined under the optical microscope after benchmark tests, here are pictures taken from one leaked seal and one un-leaked seal respectively, see Figure 4.3.1 Enlarged view of leaked seal lip and Figure 4.3.2 Enlarged view of un-leaked seal lip.

There are two things to be noticed, the first is that the lip shows no obvious wear trace, even not for the leaked one. The reason might be due to the short term leakage, which does not give enough time for extensive wear-off. Hence, the reason for the leakage is not likely because of the wearing, instead it might be caused by other elements, such as the failure of sealing mechanism due to certain robotic motion. The second one to be noticed is that the leaked seal has barely any grease kept in the groove between sealing lip and dust lip, while the un-leaked one still have a lot of grease left in the groove. This phenomenon is also observed on the leaked seal from robotic motion tests. As practical experience, the usage of grease is not only being start-up lubricating, but also acts as sealants preventing ingress of external contaminations, so the grease is expected to be resistant to the oil in some extent. If it is easily dissolved in the oil, it may fail to protect the sealing lip, which may cause leakage after a while. However, why the grease disappeared so thoroughly in some of the leaking cases, how much it contributes to the leakage, and how much robotic motions has its influence on this phenomenon are still unclear, which needs further investigation.

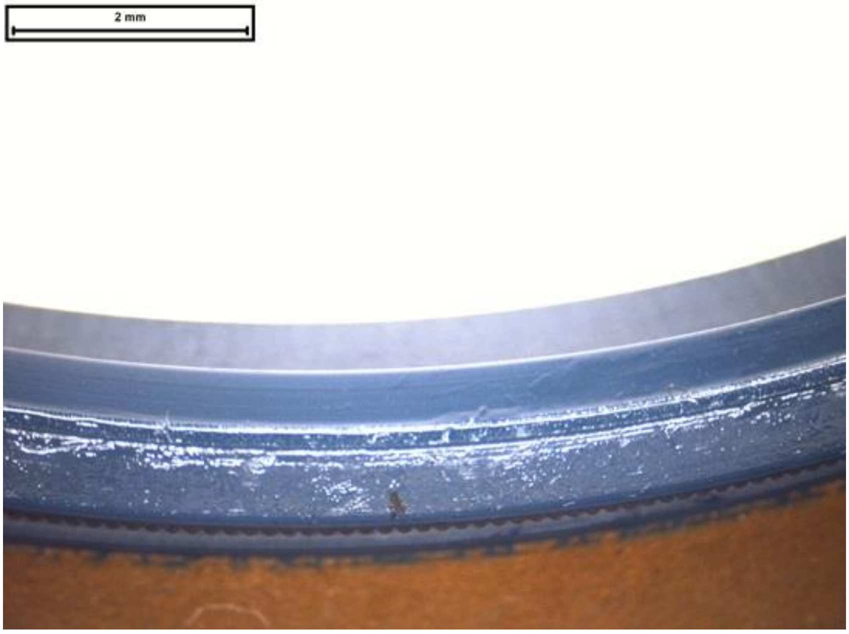


Figure 4.3.1 Enlarged view of leaked seal lip

Figure 4.3.2 Enlarged view of un-leaked seal lip

5 CONCLUSION

The following technical results have been achieved for the thesis work:

- Test rig specification has been defined according to ISO standards and ABB specifications.
- Test rigs specified in performing rotary lip seal tests under robotic motions have been built up in house.
- Test rigs commissioning and validation have been done, and test rigs are ready to run seal tests with robotic motions.
- Leakage detection system has been developed for the test rig, which is able to detect oil leakage automatically.
- Test plan to get a basic understanding of sealing technology for robotic application has been made, including benchmark tests with problematic seals, tests under robotic motions, tests focused on seals from different sources, etc.
- Benchmark tests with specified seals have been performed on the test rigs. A conclusion can be drawn that the test rig could reflect the real situation of the general robot operation, which means that future testing results on the test rigs can offer relative good reference for the equivalent operation on the robots.

- Preliminary seal tests for different robotic motions have been performed, which indicates that the defined motion (+/-3° continuously, with 5s stop + 180° turn after each minute) is ‘tougher’ for sealing compared to another motion (+/-90° continuously, with 180° turn after each minute) Also it indicates that all chosen robotic motions are ‘tougher’ for sealing compared to the standard test motion for in-house robots. Further tests might be required to confirm these conclusions.

Overall, during the thesis, the test rig has been built up, and a self-developed leakage detector has been designed and made into prototype. Benchmark tests have been performed to validate the use of the test rig, and 2 typical robotic motions have been tested for the sealing.

Due to the limitation of time, all studied cases have limited statics. Hence, further tests for interested parameters will be performed in larger scales in the future.

6 FUTURE WORK

The test rigs have been well-constructed in this project which will allow us to study more parameters in a controlled way. This hopefully can help us to get a good understanding of the general sealing technology for robotic application which can reduce or control the leakage problem of ABB robots.

- Seal-focused tests

After achieving the worst robotic motion, all tests would proceed to focus on seals from different suppliers, so as to find the possible different performance of seals coming from different sources.

- Seal design

Test lip seals with different types of dust excluder, for example, thermoplastic bonding, double excluder, etc., will be of great interest to inspect via tests on rigs.

- Sealing simulations

After batches of tests have been performed, it is motivated that how FEM simulations could be applied for studying seals, preferably to find a way to simulate sealing mechanism in a dynamic way, which would be a meaningful approach for studying sealing performance under robotic motions.

After all tests carried out as mentioned above, it is believed that certain extent of knowledge about “seal performance under robotic motions” would be obtained.

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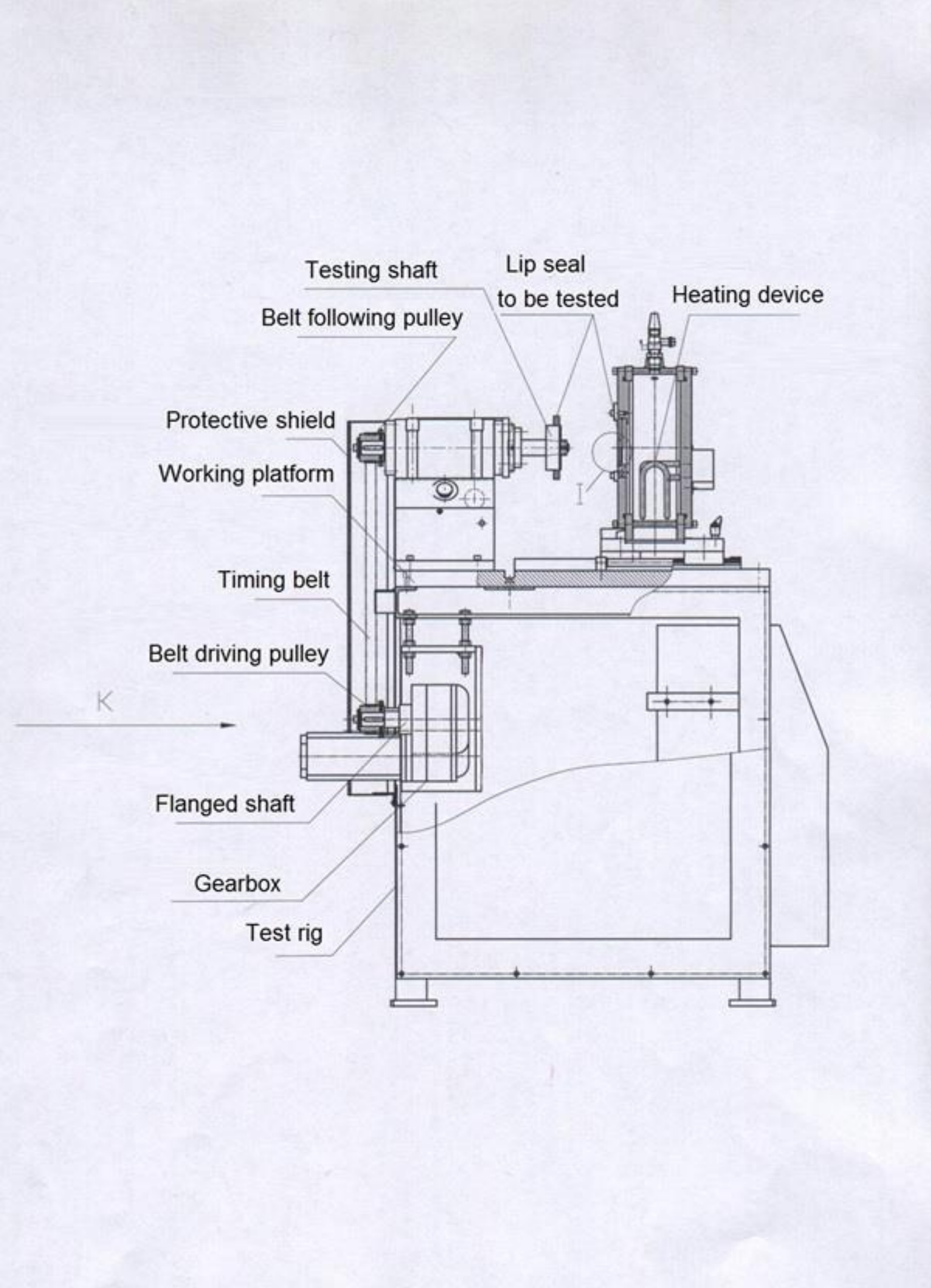
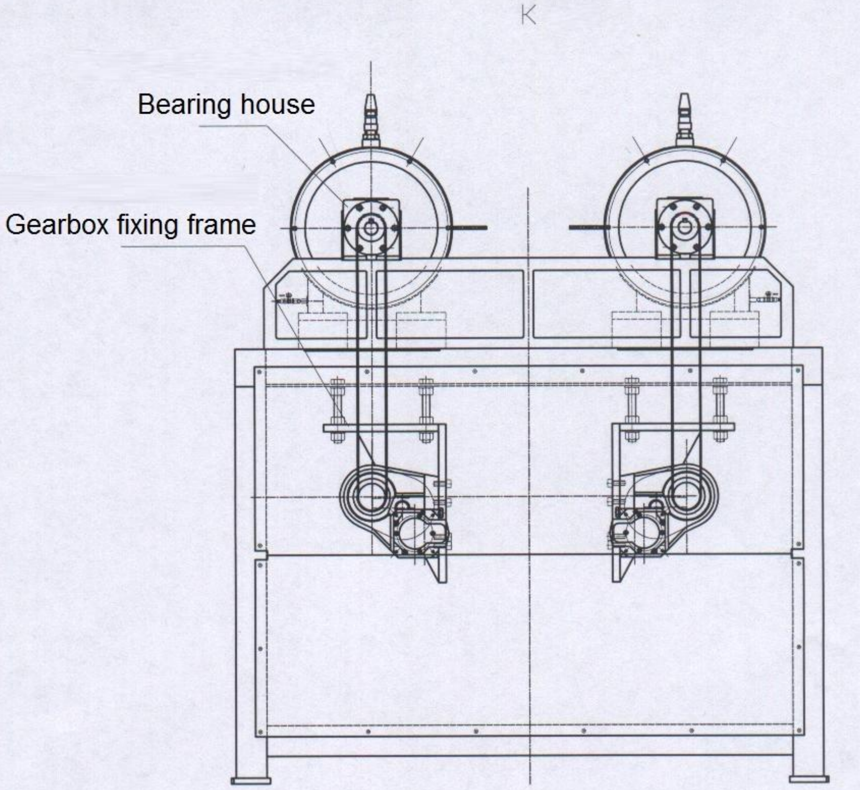
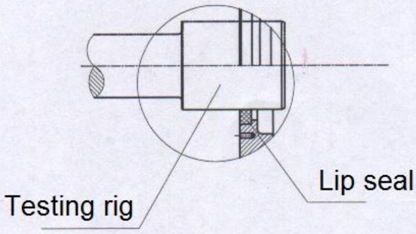
APPENDICES

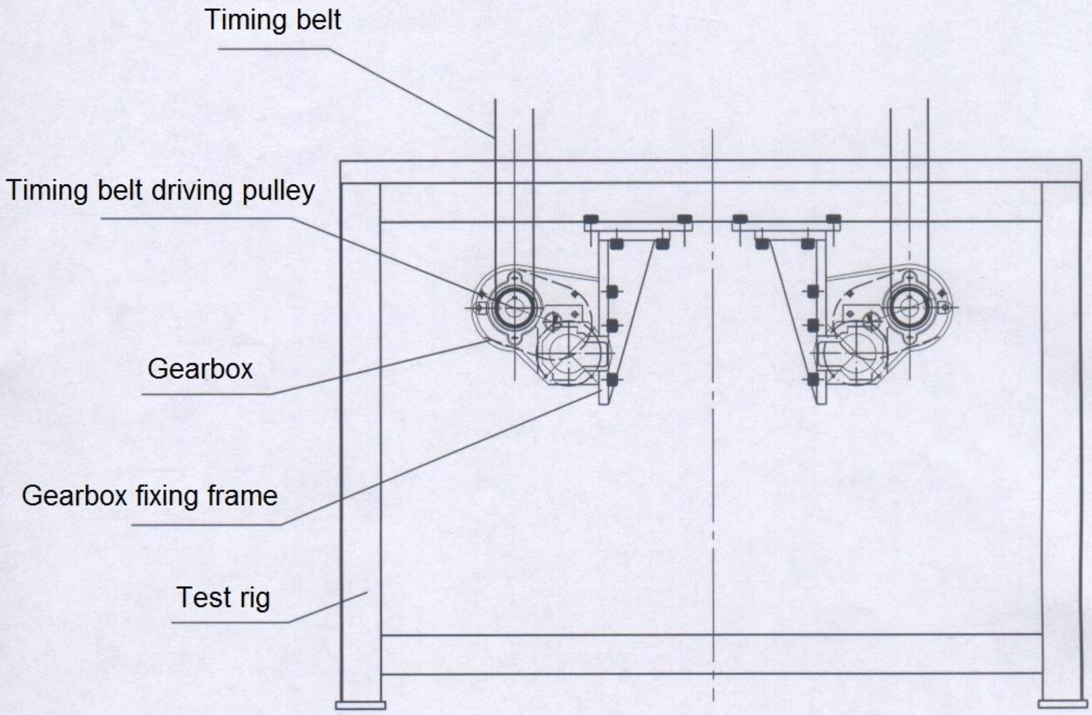
1 Test rig assembly (Mingzhu manufacturer)



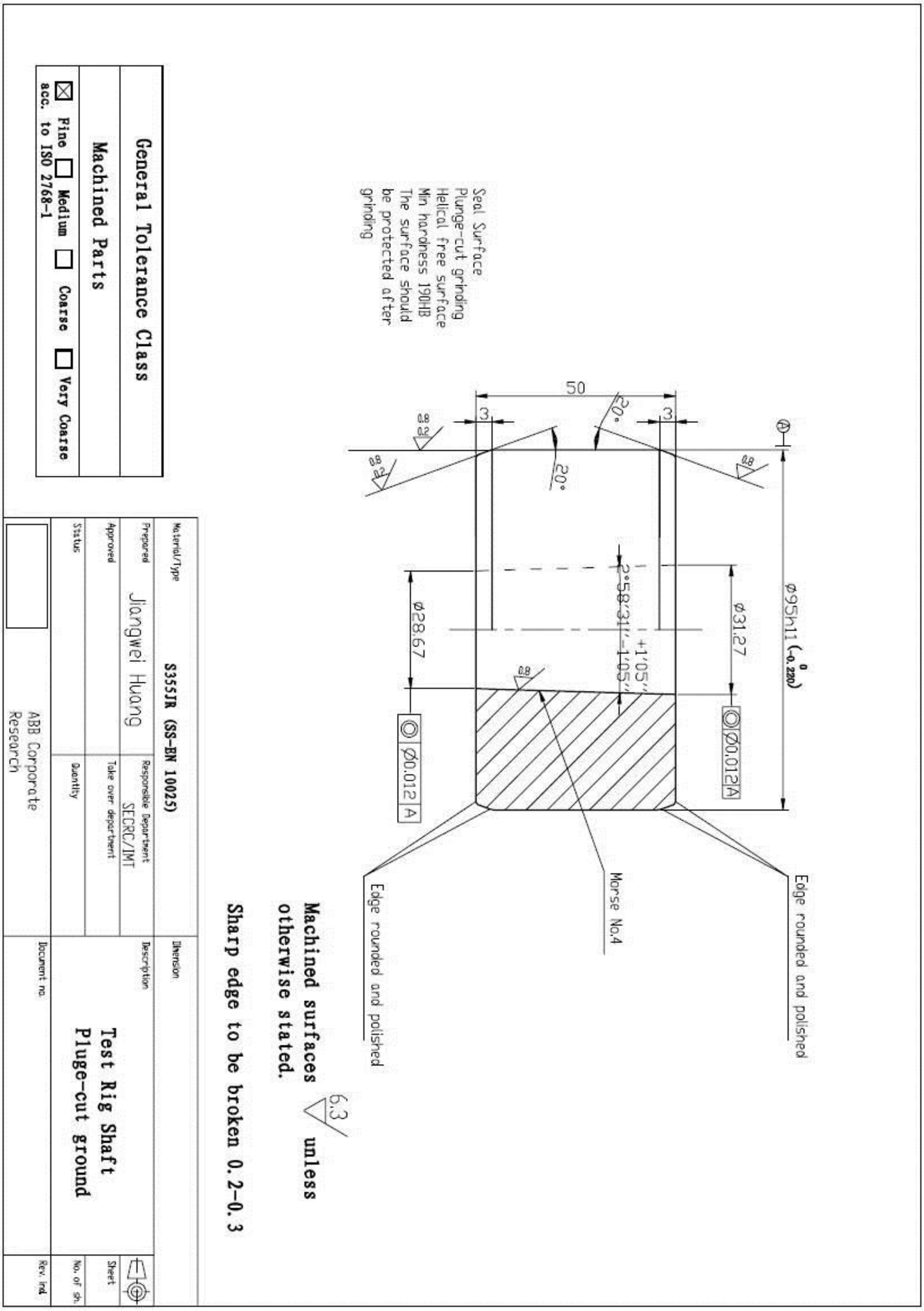


Ⅰ Amplification

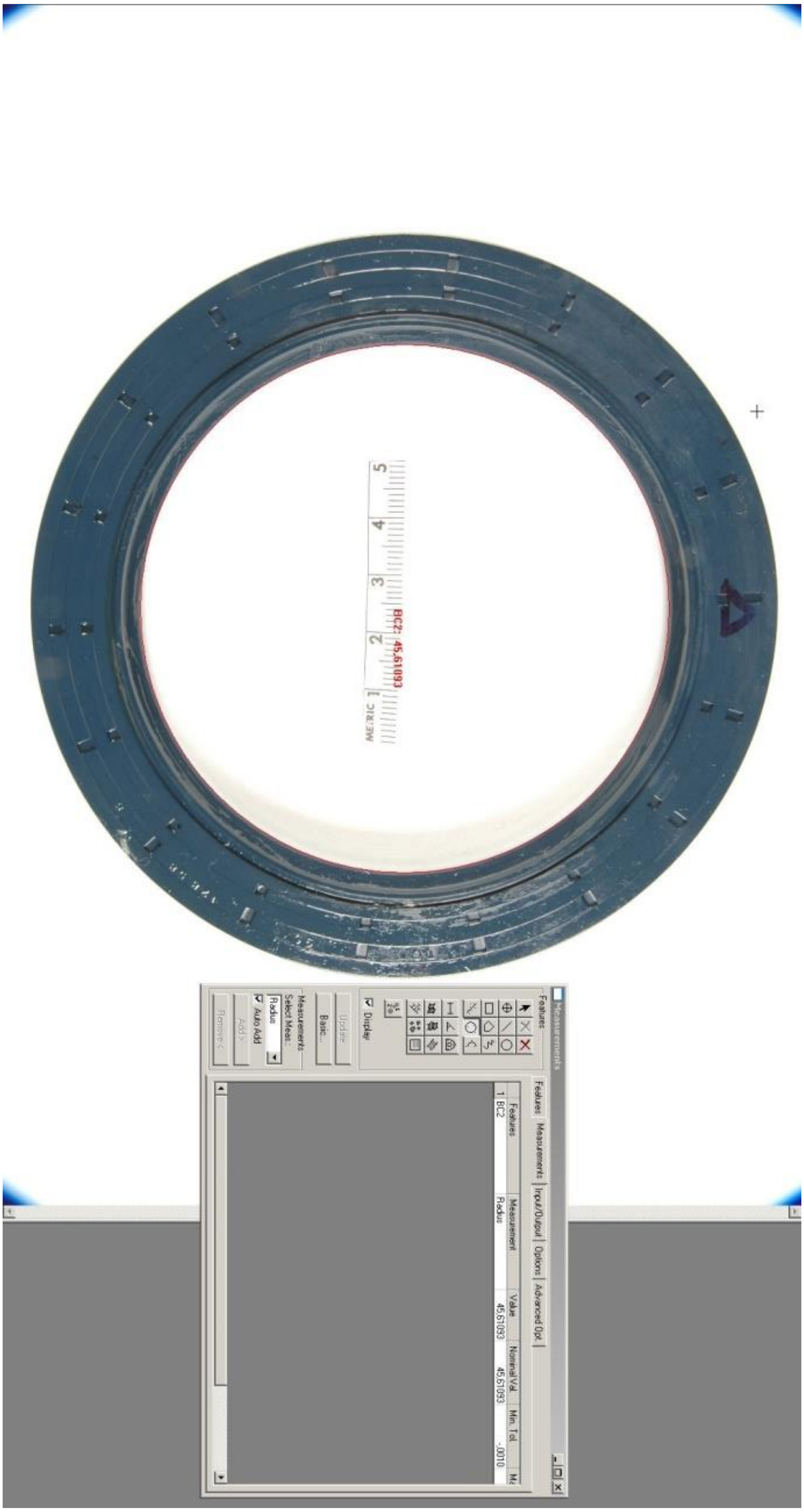



Timing belt
Timing belt driving pulley
Gearbox
Gearbox fixing frame
Test rig

2 Test shaft


Seal Surface
Plunge-cut grinding
Helical free surface
Min hardness 190HB
The surface should
be protected after
grinding
50
3
3
20°
20°
0.8
0.2
0.8
0.2
0.8
0.8
A
ø95h11 (0 / -0.220)
ø31.27
ø28.67
2°58'31'' +1'05'' -1'05''
◎ ø0.012 A
◎ ø0.012 A
Morse No.4
Edge rounded and polished
Edge rounded and polished
Machined surfaces 6.3 unless otherwise stated.
Sharp edge to be broken 0.2-0.3
General Tolerance Class
Machined Parts
☒ Fine ☐ Medium ☐ Coarse ☐ Very Coarse
acc. to ISO 2768-1
Material/Type
S355JR (SS-EN 10025)
Dimension
Prepared
Jiangwei Huang
Responsible Department
SECRC/IMT
Description
Test Rig Shaft
Pluge-cut ground
Approved
Take over department
Sheet
Status
Quantity
No. of sh.
ABB Corporate Research
Document no.
Rev. ind.

3.1 leaked seal 1



	Features	Measurement	Value	Nominal Val.	Min. Tol.
1	BC2	Radius	45.61093	45.61093	-.0010

3.2 leaked seal 2

	Center X Pos.	Center Y Pos.	Area	Length	Radius	Start X Pos.
1	104,9204	68,88225	6588,260	287,7334	45,79419	
2	104,9204	69,02112	6598,253	287,9516	45,82891	
3	104,9204	68,81281	6598,253	287,9516	45,82891	

3.3 Un-leaked seal 1

	Center X Pos.	Center Y Pos.	Area	Length	Radius	Start X Pos.
1	103.1845	70.82650	6728.859	290.7874	46.28026	

3.4 Un-leaked seal 2

	Center X Pos.	Center Y Pos.	Area	Length	Radius	Start X Pos.
1	103.1845	70.82650	6728.859	290.7874	46.28026	
2	102.9762	70.96538	6698.606	290.1330	46.15874	
3	103.0456	70.47931	6789.570	292.0963	46.48857	

4 Program for Atmaga16 control system

```
#include <avr/io.h>
#include <avr/interrupt.h>
#define F_CPU 8000000UL
#include <util/delay.h>
#include <avr/eeprom.h>

/*DS1302 Reset*/
#define RST_CLR         PORTD &= ~(1 << PD7)  /*set low*/
#define RST_SET         PORTD |= (1 << PD7)   /*set high*/
#define RST_IN          DDRD &= ~(1 << PD7)   /*input*/
#define RST_OUT         DDRD |= (1 << PD7)    /*output*/

/*DS1302 IO*/
#define IO_CLR          PORTD &= ~(1 << PD6)  /*set low*/
#define IO_SET          PORTD |= (1 << PD6)   /*set high*/
#define IO_RPIND & (1 << PD6)     /*read pin*/
#define IO_IN           DDRD &= ~(1 << PD6)   /*input*/
#define IO_OUT          DDRD |= (1 << PD6)    /*output*/

/*DS1302 Clock*/
#define SCK_CLR         PORTD &= ~(1 << PD5)  /*set low*/
#define SCK_SET         PORTD |= (1 << PD5)   /*set high*/
#define SCK_IN          DDRD &= ~(1 << PD5)   /*input*/
#define SCK_OUT         DDRD |= (1 << PD5)    /*output*/

/*DS1302 Register Address*/
#define ds1302_sec_add                  0x80            //second
#define ds1302_min_add                  0x82            //minute
#define ds1302_hr_add                   0x84            //hour
#define ds1302_date_add                 0x86            //date
#define ds1302_month_add                0x88            //month
#define ds1302_day_add                  0x8a            //week day
#define ds1302_year_add                 0x8c            //year
#define ds1302_control_add              0x8e            //write protection
#define ds1302_charger_add              0x90            //battery charger

#define ds1302_clkburst_add             0xbe    //burst mode

/*LCD PORTS*/
#define RS_CLR PORTA &= ~(1 << PA5)
```

```
#define RS_SET PORTA |= (1 << PA5)
#define RW_CLR PORTA &= ~(1 << PA6)
#define RW_SET PORTA |= (1 << PA6)
#define EN_CLR PORTA &= ~(1 << PA7)
#define EN_SET PORTA |= (1 << PA7)



/*Button defination*/
unsigned char Key_flag=0;
unsigned char volatile timing_flag_L=0;
unsigned char volatile timing_flag_R=0;



/*Time initializing*/
unsigned char time_buf[8] = {0x20,0x12,0x01,0x25,0x18,0x04,0x00,0x03};

/*Timer value initializing*/
unsigned char L_hr=0;  //note down time hr and min part.
unsigned char L_dig=0;
unsigned char L_ref_min;
unsigned char R_hr=0;
unsigned char R_dig=0;
unsigned char R_ref_min;

/*Timer pause*/
unsigned char pause_flag_L=0;
unsigned char pause_mark_L=0;
unsigned char L_hr_store=0;
unsigned char L_dig_store=0;

unsigned char pause_flag_R=0;
unsigned char pause_mark_R=0;
unsigned char R_hr_store=0;
unsigned char R_dig_store=0;

/*EEPROM value*/
unsigned char volatile EEMEM eep_L_hr=0;
unsigned char volatile EEMEM eep_L_dig=0;
unsigned char volatile EEMEM eep_R_hr=0;
unsigned char volatile EEMEM eep_R_dig=0;
```

```
/*Write one byte to DS1302*/
void ds1302_write_byte(unsigned char addr, unsigned char d)
{
 unsigned char i;

 RST_SET;                                                        /*Start DS1302*/

 IO_OUT;
 addr = addr & 0xFE;        /*Set the lowest bit as low-writing*/

 for (i = 0; i < 8; i ++)
 {
   if (addr & 0x01)
   { IO_SET; }
   else
   { IO_CLR; }

              SCK_SET;
              SCK_CLR;
              addr = addr >> 1;
  }

 /*Write data d*/
 IO_OUT;
 for (i = 0; i < 8; i ++)
 {
   if (d & 0x01)
              {IO_SET;}
              else
              {IO_CLR;}

              SCK_SET;
              SCK_CLR;
              d = d >> 1;
  }
              RST_CLR;                                                   /*Stop DS1302*/
}
```

```
/*Read one byte from DS1302*/
unsigned char ds1302_read_byte(unsigned char addr)
{
  unsigned char i;
  unsigned char temp=0;

  RST_SET;                                                        /*Start DS1302*/

  IO_OUT;
  addr = addr | 0x01;      /*Set the lowest bit as high-reading*/

  for (i = 0; i < 8; i ++)
  {
    if (addr & 0x01)
                  {IO_SET;}
                  else
                  {IO_CLR;}

                  SCK_SET;
                  SCK_CLR;
                  addr = addr >> 1;
   }

                 /*Get data to temp*/
   IO_IN;

   for (i = 0; i < 8; i ++)
   {
                   temp = temp >> 1;

                   if (IO_R)
                   {temp |= 0x80;}
                   else
                   {temp &= 0x7F;}

      SCK_SET;
                   SCK_CLR;
                 }
                 RST_CLR;                                                   /*Stop DS1302*/
                 return temp;
}
```

```
/*Write time into DS1302*/
void ds1302_write_time(void)
{
            ds1302_write_byte(ds1302_control_add,0x00);                              //clear
protection
            ds1302_write_byte(ds1302_sec_add,0x80);
            //Halt timer
            ds1302_write_byte(ds1302_charger_add,0xa9);                              //Charging
            ds1302_write_byte(ds1302_year_add,time_buf[1]);              //year
            ds1302_write_byte(ds1302_month_add,time_buf[2]);  //month
            ds1302_write_byte(ds1302_date_add,time_buf[3]);              //date
            ds1302_write_byte(ds1302_hr_add,time_buf[4]);                //hour
            ds1302_write_byte(ds1302_min_add,time_buf[5]);               //minute
            ds1302_write_byte(ds1302_sec_add,time_buf[6]);               //second
            ds1302_write_byte(ds1302_day_add,time_buf[7]);               //week day
            ds1302_write_byte(ds1302_control_add,0x80);                              //set
protection
}


/*Read time from DS1302*/
void ds1302_read_time(void)
{
   time_buf[1]=ds1302_read_byte(ds1302_year_add+1);                      //year
            time_buf[2]=ds1302_read_byte(ds1302_month_add+1);                        //month
            time_buf[3]=ds1302_read_byte(ds1302_date_add+1);             //date
            time_buf[4]=ds1302_read_byte(ds1302_hr_add+1);               //hour
            time_buf[5]=ds1302_read_byte(ds1302_min_add+1); //minute
            time_buf[6]=ds1302_read_byte(ds1302_sec_add+1); //second
            time_buf[7]=ds1302_read_byte(ds1302_day_add+1);              //week day
}

/*DS302 initializing*/
void ds1302_init(void)
{
            RST_CLR;                            /*RST set low*/
            SCK_CLR;                            /*SCK set low*/
            RST_OUT;                            /*RST pin set output*/
            SCK_OUT;                            /*SCK pin set output*/
}
```

```
/*LCD write command*/
void LCD_write_com(unsigned char com)
{
 RS_CLR;
 RW_CLR;
 EN_SET;
 PORTB = com;
 _delay_ms(5);
 EN_CLR;
}

/*LCD write data*/
void LCD_write_data(unsigned char data)
{
 RS_SET;
 RW_CLR;
 EN_SET;
 PORTB = data;
 _delay_ms(5);
 EN_CLR;
}

/*LCD write string*/
void LCD_write_str(unsigned char x,unsigned char y,unsigned char *s)
{
 if (y == 0)
 {
  LCD_write_com(0x80 + x);
 }
 else if(y==1)
 {
  LCD_write_com(0xC0 + x);
 }
 else if(y==2)
 {
  LCD_write_com(0x90 + x);
 }
 else if(y==3)
 {
  LCD_write_com(0xD0 + x);
 }
```

```
 while (*s)
 {
  LCD_write_data(*s++);
 }
}

/*LCD write char*/
void LCD_write_char(unsigned char x,unsigned char y,unsigned char data)
{
 if (y == 0)
 {
  LCD_write_com(0x80 + x);
 }
 else if(y==1)
 {
  LCD_write_com(0xC0 + x);
 }
 else if(y==2)
 {
  LCD_write_com(0x90 + x);
 }
 else if(y==3)
 {
  LCD_write_com(0xD0 + x);
 }
 LCD_write_data(data);
}

/*LCD initializing*/
void LCD_init()
{
 DDRB=0xFF;
 DDRA |= (1 << PA5) | (1 << PA6) | (1 << PA7);
 LCD_write_com(0x38);  /*display mode*/
 _delay_ms(5);
 LCD_write_com(0x08);  /*display on*/
 _delay_ms(5);
 LCD_write_com(0x01);  /*clear*/
 _delay_ms(5);
 LCD_write_com(0x06);  /*cursor shift*/
 _delay_ms(5);
```

```
 LCD_write_com(0x0C);  /*entry mode*/
 _delay_ms(5);
}

unsigned char key_scan()
{
 unsigned char static cord_r,cord_c;
 DDRC=0xF0;
 PORTC=0x0F;
 _delay_us(10);
 if(PINC!=0x0F)
 {
  _delay_ms(10);
  if(PINC!=0x0F)
  {
   cord_r=PINC&0x0F;
   DDRC=0x0F;
   PORTC=0xF0;
   _delay_us(10);
   cord_c=PINC&0xF0;
   return (cord_r+cord_c);
  }
 }
 return 0xFF;
}


void key_process()
{
    unsigned char minute;
                     unsigned char hour;
                     unsigned char date;
                     unsigned char month;
                     unsigned char year;
                     unsigned char temp;
                     ds1302_write_byte(ds1302_control_add,0x00);                                              //clear
protection
                     ds1302_write_byte(ds1302_sec_add,0x80);
                     //Halt timer
                     LCD_write_str(1,1,"Time on Setting");                        //Set mark

    switch(key_scan())
```

```
{

case 0xdb:while(key_scan()==0xdb);
        ds1302_write_byte(ds1302_sec_add,0x00);             //restart timing
                                ds1302_write_byte(ds1302_control_add,0x80);         //set protection
                                                  LCD_write_str(0,1,"                ");              //Clear mark
                                Key_flag=0;                                 //clear flag
        break;                  //K1 is comfirming button

case 0xdd:while(key_scan()==0xdd);
        temp=(time_buf[5]>>4)*10+(time_buf[5]&0x0F);
                                temp=temp+1;
                                if(temp==60) temp=0;

        minute=temp/10*16+temp%10;       //decade to hex
                                ds1302_write_byte(ds1302_min_add,minute);      //write to DS1302

        break;                  //2 Use Key2 to adjust minute

case 0xde:while(key_scan()==0xde);
        temp=(time_buf[4]>>4)*10+(time_buf[4]&0x0F);
        temp=temp+1;
                                if(temp==24) temp=0;

                                hour=temp/10*16+temp%10;        //decade to hex
                                ds1302_write_byte(ds1302_hr_add,hour);      //write to DS1302

        break;                  //2 Use Key3 to adjust hour

case 0xe7:while(key_scan()==0xe7);
         temp=(time_buf[3]>>4)*10+(time_buf[3]&0x0F);
                                 temp=temp+1;
                                 if(temp==32) temp=1;

                    date=temp/10*16+temp%10;        //decade to hex
                                 ds1302_write_byte(ds1302_date_add,date);      //write to DS1302

         break;                  //4 Use Key4 to adjust date

case 0xeb:while(key_scan()==0xeb);
        temp=(time_buf[2]>>4)*10+(time_buf[2]&0x0F);
```

```
                                temp=temp+1;
                                if(temp==13) temp=1;

                                month=temp/10*16+temp%10;         //decade to hex
                                ds1302_write_byte(ds1302_month_add,month);        //write to DS1302
            break;                   //5 Use Key5 to adjust month

    case 0xed:while(key_scan()==0xed);
            temp=(time_buf[1]>>4)*10+(time_buf[1]&0x0F);
                    temp=temp+1;
                                if(temp==100) temp=0;

                                year=temp/10*16+temp%10;         //decade to hex
                                ds1302_write_byte(ds1302_year_add,year);        //write to DS1302
            break;                   //6 Use Key6 to adjust year

  }

}

void timer_L()
{

 unsigned char temp;

 ds1302_read_time();
 switch (timing_flag_L)
 {
  case 0: break;
  case 1: L_ref_min=(time_buf[5]>>4)*10+(time_buf[5]&0x0F);timing_flag_L=2;break;
  case 2: temp=(time_buf[5]>>4)*10+(time_buf[5]&0x0F);
         if(((temp-L_ref_min+60+L_dig_store)%60)!=0)
                                 timing_flag_L=3;
                                 break;
  case 3: temp=(time_buf[5]>>4)*10+(time_buf[5]&0x0F);
         L_dig=(temp-L_ref_min+60+L_dig_store)%60;

         if(L_dig==0)
                                 {
                                  L_hr++;
```

```
                                          if(L_hr%24==0)
                                          {
                                           eeprom_write_byte(&eep_L_hr, L_hr);
                                           eeprom_write_byte(&eep_L_dig, L_dig);
                                          }

                                          timing_flag_L=2;
                                         }
                                         break;
 }



  LCD_write_char(0,1,'L');

  temp=((L_hr+L_hr_store)/1000%10)+'0';
  LCD_write_char(1,1,temp);
  temp=((L_hr+L_hr_store)/100%10)+'0';
  LCD_write_char(2,1,temp);
  temp=((L_hr+L_hr_store)/10%10)+'0';
  LCD_write_char(3,1,temp);
  temp=((L_hr+L_hr_store)%10)+'0';
  LCD_write_char(4,1,temp);

  LCD_write_char(5,1,'.');

  temp=L_dig/6+'0';
  LCD_write_char(6,1,temp);

}

void timer_R()
{

 unsigned char temp;

 ds1302_read_time();
 switch (timing_flag_R)
 {
  case 0: break;
  case 1: R_ref_min=(time_buf[5]>>4)*10+(time_buf[5]&0x0F);timing_flag_R=2;break;
```

```
  case 2: temp=(time_buf[5]>>4)*10+(time_buf[5]&0x0F);
          if(((temp-R_ref_min+60+R_dig_store)%60)!=0)
                                          timing_flag_R=3;
                                          break;
  case 3: temp=(time_buf[5]>>4)*10+(time_buf[5]&0x0F);
          R_dig=(temp-R_ref_min+60+R_dig_store)%60;
          if(R_dig==0)

                                          {
                                           R_hr++;

                                           if(R_hr%24==0)
                                           {
                                            eeprom_write_byte(&eep_R_hr, R_hr|0x80);
                                            eeprom_write_byte(&eep_R_dig, R_dig|0x80);
                                           }

                                           timing_flag_R=2;
                                          }
                                          break;
 }

  LCD_write_char(9,1,'R');

  temp=((R_hr+R_hr_store)/1000%10)+'0';
  LCD_write_char(10,1,temp);
  temp=((R_hr+R_hr_store)/100%10)+'0';
  LCD_write_char(11,1,temp);
  temp=((R_hr+R_hr_store)/10%10)+'0';
  LCD_write_char(12,1,temp);
  temp=((R_hr+R_hr_store)%10)+'0';
  LCD_write_char(13,1,temp);

  LCD_write_char(14,1,'.');

  temp=R_dig/6+'0';
  LCD_write_char(15,1,temp);
}

ISR(INT0_vect)
{
```

```
  GICR &=~(1 << INT0);
  timing_flag_L=0;
  LCD_write_str(0,2,"Stopped");
  LCD_write_str(0,3,"Leaking");

}

ISR(INT1_vect)
{
  GICR &=~(1 << INT1);
  timing_flag_R=0;
  LCD_write_str(9,2,"Stopped");
  LCD_write_str(9,3,"Leaking");

}



int main()
{
 unsigned char temp;

 _delay_ms(100);
 LCD_init();
 ds1302_init();
 _delay_ms(10);
// ds1302_write_time();

 DDRC&=0x00;   //Define buttons
 PORTC|=0xFF;

 DDRD &=~(1<<2); //Define interrupt int0
 PORTD|=(1<<2);



 DDRD &=~(1<<3); //Define interrupt int1
 PORTD|=(1<<3);

// MCUCR set to be 0 for int0 and int1 low level detection for left and right test head

 GIFR |=(1 << INTF0);              // clear int0 flag
 GIFR |=(1 << INTF1);              // clear int1 flag
```

```
sei();


while(1)
{
 ds1302_read_time();

 temp=(time_buf[0]>>4)+'0';
 LCD_write_char(0,0,temp);
 temp=(time_buf[0]&0x0F)+'0';
 LCD_write_char(1,0,temp);

 temp=(time_buf[1]>>4)+'0';
 LCD_write_char(2,0,temp);
 temp=(time_buf[1]&0x0F)+'0';
 LCD_write_char(3,0,temp);

 LCD_write_char(4,0,'-');

 temp=(time_buf[2]>>4)+'0';
 LCD_write_char(5,0,temp);
 temp=(time_buf[2]&0x0F)+'0';
 LCD_write_char(6,0,temp);

 LCD_write_char(7,0,'-');

 temp=(time_buf[3]>>4)+'0';
 LCD_write_char(8,0,temp);
 temp=(time_buf[3]&0x0F)+'0';
 LCD_write_char(9,0,temp);

 temp=(time_buf[4]>>4)+'0';
 LCD_write_char(11,0,temp);
 temp=(time_buf[4]&0x0F)+'0';
 LCD_write_char(12,0,temp);

 LCD_write_char(13,0,':');

 temp=(time_buf[5]>>4)+'0';
 LCD_write_char(14,0,temp);
 temp=(time_buf[5]&0x0F)+'0';
```

```
  LCD_write_char(15,0,temp);




 // LCD_write_char(13,1,':');

 // temp=(time_buf[6]>>4)+'0';
 // LCD_write_char(14,1,temp);
 // temp=(time_buf[6]&0x0F)+'0';
 // LCD_write_char(15,1,temp);

switch(key_scan())
  {

   case 0xd7: while(key_scan()==0xd7);
             if(timing_flag_L!=0||timing_flag_R!=0)
                             {

                                                                              LCD_write_str(0,2,"Operation   Denied");         //report
error if in timing mode
                                                                             _delay_ms(1000);
                                                                             _delay_ms(1000);
                                                                              LCD_write_str(0,2,"                ");
                                        }
                                        else
                                                            Key_flag=1;
                                                            break;//0 set flag on, entering time setting mode
   case 0xee: while(key_scan()==0xee);
             if(Key_flag==1)
                             {

                                                                              LCD_write_str(0,2,"Operation   Denied");         //report
error in time-adjusting mode
                                                                             _delay_ms(1000);
                                                                             _delay_ms(1000);
                                                                              LCD_write_str(0,2,"                ");
                                        }
                                                            else if(timing_flag_L!=0)
                                                            {
                                                             LCD_write_str(0,2," Stop it");
                                                             LCD_write_str(0,3,"  first ");
              _delay_ms(1000);
```

```
                                        _delay_ms(1000);
                                        LCD_write_str(0,2,"        ");
                                        LCD_write_str(0,3,"        ");
                                       }
                           else
                                       {
                    timing_flag_L=1;                //7 set left timing flag on
                                        GICR |=(1 << INT0);          // enable int0
                                        LCD_write_str(0,1,"        "); //clear screen
                                        LCD_write_str(0,2,"        ");
                                        LCD_write_str(0,3,"        ");
                                       }
        break;
             case 0xb7: while(key_scan()==0xb7);
        if(Key_flag==1)
                   {

                                                   LCD_write_str(0,2,"Operation   Denied");         //report error in time-adjusting mode
                                                  _delay_ms(1000);
                                                  _delay_ms(1000);
                                                   LCD_write_str(0,2,"                ");
                           }
                                       else if(timing_flag_R!=0)
                                       {
                                        LCD_write_str(9,2,"Stop it");
                                        LCD_write_str(9,3," first ");
                                        _delay_ms(1000);
                                        _delay_ms(1000);
                                        LCD_write_str(9,2,"       ");
                                        LCD_write_str(9,3,"       ");
                                       }
                           else
                   {
                    timing_flag_R=1;                //7 set left timing flag on
                                        GICR |=(1 << INT1);          // enable int1
                                        LCD_write_str(9,1,"        "); //clear screen
                                        LCD_write_str(9,2,"        ");
                                        LCD_write_str(9,3,"        ");
                                       }
        break;
             case 0xbb: while(key_scan()==0xbb);
```

```
         if(Key_flag==1)
                    {

                                                       LCD_write_str(0,2,"Operation   Denied");        //report
error in time-adjusting mode
                                                      _delay_ms(1000);
                                                      _delay_ms(1000);
                                                       LCD_write_str(0,2,"                ");
                            }
                                           else if(timing_flag_L!=0||timing_flag_R!=0)
                                           {
                                            LCD_write_str(0,3,"Stop all timers");
                                                       _delay_ms(1000);
                                                      _delay_ms(1000);
                                                       LCD_write_str(0,3,"                ");
                                           }
                            else
                    {

                                            timing_flag_L=1;
                                                      timing_flag_R=1;
                                                      GICR |=(1 << INT0);              // enable int0
                                                      GICR |=(1 << INT1);              // enable int1
                                                      LCD_write_str(0,1,"                "); //clear screen
                                            LCD_write_str(0,2,"                ");
                                                      LCD_write_str(0,3,"                ");
                                           }                   //9 set ALL flags on, start all timers
         break;
             case 0xbd: while(key_scan()==0xbd);
                                            if(timing_flag_L!=0)
                                                      {
                                                       timing_flag_L=0;

                                                       eeprom_write_byte(&eep_L_hr, L_hr);
                                  eeprom_write_byte(&eep_L_dig, L_dig);

                                                       L_hr=0;  //clear hr and min part.
          L_dig=0;

                                             LCD_write_str(0,2,"Stopped");           //10 stop left timers


                                                      }
```

```
                                           else
                                           {
                                            LCD_write_str(0,2,"Inactive");
                                            _delay_ms(1000);
                                            _delay_ms(1000);
                                            LCD_write_str(0,2,"        ");
                                           }
     break;
 case 0xbe: while(key_scan()==0xbe);
                                  if(timing_flag_R!=0)
                                           {
                                            timing_flag_R=0;

                                            eeprom_write_byte(&eep_R_hr, R_hr|0x80);
                          eeprom_write_byte(&eep_R_dig, R_dig|0x80);

                                            R_hr=0;  //clear hr and min part.
       R_dig=0;

                                   LCD_write_str(8,2,"Stopped");      //11 stop right timers

                                           }
                                           else
                                           {
                                            LCD_write_str(8,2,"Inactive");
                                            _delay_ms(1000);
                                           _delay_ms(1000);
                                            LCD_write_str(8,2,"        ");
                                           }
     break;
 case 0x77: while(key_scan()==0x77);
              pause_flag_L^=(1<<0);          //12 Pause and restart left the timer
     break;

 case 0x7b: while(key_scan()==0x7b);
              pause_flag_R^=(1<<0);          //13 Pause and restart Right the timer
     break;


}
```

```
  if((Key_flag==0)&&(timing_flag_L!=0))timer_L();        //key 7 on, then do left timing

  if((Key_flag==0)&&(timing_flag_R!=0))timer_R();        //key 8 on, then do right timing

  if((pause_flag_L==0)&&(timing_flag_L==0)&&(pause_mark_L==1))             //key 12 push once, then pause
left timing, push twice, then resume left timing
   {
                GICR |=(1 << INT0);
                timing_flag_L=1;
                pause_mark_L=0;
                LCD_write_str(0,2,"Resume");
                _delay_ms(1000);
                _delay_ms(1000);
                LCD_write_str(0,2,"       ");
               }
  else if((pause_flag_L==1)&&(timing_flag_L!=0))           //
   {
                GICR &=~(1 << INT0);
                timing_flag_L=0;
                pause_mark_L=1;
                L_hr_store=L_hr;
     L_dig_store=L_dig;
     L_hr=0;
                LCD_write_str(0,2,"Paused");

               }

  if((pause_flag_R==0)&&(timing_flag_R==0)&&(pause_mark_R==1))                  //key 13 push once, then
pause right timing, push twice, then resume right timing
   {
                GICR |=(1 << INT1);
                timing_flag_R=1;
                pause_mark_R=0;
                LCD_write_str(8,2,"Resume");
                _delay_ms(1000);
                _delay_ms(1000);
                LCD_write_str(8,2,"       ");
               }
  else if((pause_flag_R==1)&&(timing_flag_R!=0))           //
   {
                GICR &=~(1 << INT1);
                timing_flag_R=0;
```

```
                        pause_mark_R=1;
                        R_hr_store=R_hr;
        R_dig_store=R_dig;
        R_hr=0;
                        LCD_write_str(8,2,"Paused");

                       }
  if(Key_flag==1)key_process();          //key 0 on, then do adjustion

 }
}
```