Inspection Technique for Lubricant Condition Detection in Static Mechanisms

Thesis Submitted in Fulfillment of The Requirements for the Degree of Doctor of Philosophy

Marwan A. Ali
M.Sc. University Science of Malaysia
B.Sc. University of Technology-Baghdad

School of Engineering
College of Science Engineering and Health
RMIT University

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ABSTRACT

There are number of methods, already developed, used to monitor condition of lubricants in dynamic systems through the detection of the wide spectrum of sound, produced during the movements of mechanical parts. Generated sound, often, includes frequencies that can be detected by human ear. However, these methods are only applicable to moving, i.e. dynamic mechanical systems, and cannot be applied for static mechanical systems. They are designed to remain static, until they are required to respond to an external trigger. Some examples of the static systems, which have activation mechanism, are spring actuated high voltage circuit breakers, safety valves, latches and hooks with retracting springs. Dry up of lubricants, or grease, in such actuation mechanisms, will result in sluggish response. These static devices do not emit any acoustic signal. That makes it hard to monitor their condition with already developed sound processing methods. Thus, another, ultrasonic inspection approach is proposed to test such mechanisms. This research project reviews current technologies and introduces new, ultrasonic pulse-echo technique that can be applied in the inspection of lubricant in the static mechanical systems. Using this novel method, ultrasound waves are propagated through a specimen consisted of the high viscosity grease and metal pieces. Different impedances and thickness of the lubricant/grease can be measured, and its condition can be monitored. Ultrasonic inspection system is constructed to produce high frequency ultrasonic pulses and receive echo signals. Echo signals are acquired using digital Data Acquisition (DAQ) system. In the proposed method, wavelet transform was used to de-noise the signal and extract the features from sound samples. Features data, from different samples, were analyzed and used to develop a fuzzy inference system to define the lubricant condition. Classification system was then examined using grease samples with known conditions. The newness percentage of the samples was found from the fuzzy classification system and was compared to the known conditions. Using this approach, novel methodology in health monitoring of the static mechanical systems, was verified. Elements of this new system, as well as experimental results are already presented in several publications, including journals, book chapters and conference proceedings.
ACKNOWLEDGEMENT

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I acknowledge the support I have received for my research through the provision of an Australian Government Research Training Program Scholarship.

Please then type your name and date after the declaration.
DECLARATION

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and, ethics procedures and guidelines have been followed.

I acknowledge the support I have received for my research through the provision of an Australian Government Research Training Program Scholarship.

MARWAN A. ALI

08/10/2019

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R Reflection coefficient
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<th>Description</th>
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<tr>
<td>T</td>
<td>Transmission coefficient</td>
</tr>
<tr>
<td>A</td>
<td>Amplitude</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>Attenuation coefficient</td>
</tr>
<tr>
<td>(\eta)</td>
<td>Dynamic viscosity</td>
</tr>
<tr>
<td>(\omega)</td>
<td>Angular sound frequency</td>
</tr>
<tr>
<td>(\rho)</td>
<td>Density</td>
</tr>
<tr>
<td>c</td>
<td>Sound speed in material</td>
</tr>
<tr>
<td>D</td>
<td>Traveled distance</td>
</tr>
<tr>
<td>t</td>
<td>Time of flight</td>
</tr>
<tr>
<td>(\lambda)</td>
<td>Wavelength</td>
</tr>
<tr>
<td>f</td>
<td>Sound frequency</td>
</tr>
<tr>
<td>(\chi)</td>
<td>Thickness</td>
</tr>
<tr>
<td>Fa</td>
<td>Scale pseudo frequency</td>
</tr>
<tr>
<td>Fc</td>
<td>Center of frequency</td>
</tr>
<tr>
<td>a</td>
<td>Scale</td>
</tr>
<tr>
<td>(\Delta)</td>
<td>Sample period</td>
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CHAPTER I

INTRODUCTION

1. Overview

This chapter presents a general introduction of the topic investigated. The research background and problem statement are concisely discussed in the first section followed by the project objective and scope of the project, then finally thesis organization and outline.

1.1 Research Background

In some heavy manufacturing productions, the financial losses caused by maintenance and downtime are as high as 50% of the operating costs [1-5]. Review data from Shell of the United States [2, 9], show that about 35% of diesel engine operation failures and 38.5% of gear failures are due to wear. Almost 40% of rolling bearing failures are owing to improper lubrication. The degree of wear and tear of the mechanical components can be inferred by the particle size and composition of the particles in the lubricant used. If we could better control lubricant conditions and consequently the wear rate, that would extend the service life of the tools, and evade disastrous accidents. Lubricant quality analysis has become one of the significant means for the diagnosis and healthiness assessment of powered equipment. Individuals are continually striving to find more accurate techniques, mainly for various power mechanical systems that need a long-term nonstop operation. The traditional method of lubricating grease testing is laboratory analysis after sampling.
Laboratory analysis can provide inclusive information on the wear of equipment components. Experiment results have a certain degree of precision despite advanced technology. Strict environment, and long testing time, are susceptible to uncertainties, even for an experienced industrial analyst. Test results are still reasonably discrete. Offline laboratory test cannot provide real-time information on the condition of the device equipment. Delay in laboratory testing information has amplified the risk of coincidences in operating equipment [10]. Therefore, solid particles with a particle size of 1–60μm suspended in lubricating grease become the focus of observation [11-14].

Certain online lubricating procedures and lubricant monitoring devices were developed, so that real-time diagnosis of mechanical equipment becomes possible. Hager [15], Flanagan et al. [16], Wu et al. [17], and Martin et al. [18] used acoustic emission detection techniques to judge the quality of lubricants by reflecting the amplitude changes of sound waves. This method is susceptible to automated background noise and lube oil temperature changes. Khandaker et al. [19], Keller and Saba [20], and Flanagan et al. [21] used a capacitive sensor to detect changes in the dielectric constant of lubricating oils. In this scenario, test results were often affected by changes in lubricant properties and lubricant ambient temperatures. It becomes very complex, and the measurement of the dielectric constant cannot determine the size and concentration of the particles.

Flynn and Whittington [22] further improved the resistive capacitive sensing method, which can detect not only iron particles, but nonferrous metal particles, as well. However, only particles with diameter greater than 100μm can be detected. In 1995, Liu et al. [23] established that scatter counting optical methods can detect particles in lubricating oil, but the accuracy of the measurement is affected by the optical properties of the particles. Reintles et al. [24] studied the relationship between
lubricating oil and particles’ vibration and judged the wear status of the device by comparing with the vibration spectrum. The finding result depends on the vibration spectrum of the previous study. Meanwhile, Peng et al. [25] used the real-time measurement of lubricant wear debris for measurable valuation of wear. Peng developed an online particle counter to quantitatively assess equipment wear. Also, he considered the total amount of debris as the quality loss of the exam sample during the assessment process yet ignoring the contaminants and combustion products in the lubricant exaggerated the degree of wear.

Iwai et al. [26] used a series of expansion methods to separate out 9.9μm particles, absorbed only on fluids, with flow rates which are slower than 200 mL/min. Yilmaz and Morton [27] used lubricant fragment magnetic field sensors with seven channels, arranged in parallel, to screen metal fragments in greases and positively separated particles with particle sizes of 75μm–105μm and 125μm–150μm in diverse flow rates. Du and Zhe [28] offered a new asymmetric sharpening edge method to monitor high-flux particle concentration. This technique has low sensitivity to lubricant movement and can separate particles of 9.94 μm. The technique needs to arrange a series of sharp corners, and the monitoring structure is more complicated. Fan et al. [29] used frequency division multiplexing techniques which utilize multiple channel impedance-pulsed sensor shunts, but every frequency must correspond to a single channel.

In recent years, there is emergence of the use of ultrasonic standing wave particle separation techniques to monitor lubricants [29-33]. Those techniques utilize ultrasound standing wave field to move the transverse acoustic radiation created by the suspended particles in fluids.
Zhe et al. [34-37] haveprimary applied ultrasonic separation technology to the suspended particles in lubricating lubricant separation and online monitoring. Ren et al. [38] utilize a curved interdigital transducer to produce a stronger and more concentrated surface acoustic wave, reducing the wave energy loss during propagation. At the same time, this technique has accomplished experimental success in the separation of polystyrene particles/polyamide (about 5μm) [39] and cells in the blood (10-100μm) [40] in fluids, but the effect of viscous on acoustic radiation is neglected, and only two particle sizes need to be separated. Some research teams have also begun to study the role of aerosol particles in the microfluidic channels, between the acoustic radiation force and the particles [41-44]. Zhu et al. [45] deliberate a single attribute sensor, such as a wear sensor and a monitoring sensor [46], for online lubricating oil condition monitoring. A variety of special function lubricant sensors provided the conditions for comprehensive monitoring.

Lubricating oil is assigned the essential task of ensuring that moving parts, which interact within a machine system, are provided with the required level of contact separation. However, lubricants are mainly used to reduce friction and to prevent destructive wear. Even finely machined metals have microscopically rough surfaces that, when in contact, will cause some wear which is considered normal. The lubricant minimizes this wear by providing separation, cooling and surface protection. Without it, the systems would suffer from increased friction, heat and resultant damage such as local welding, scuffing, seizing and the unwanted transfer of metal debris [47-52].

Academic research has exposed that, up to 1% of the gross domestic product could be saved in terms of energy in western industrial countries, if current tribological knowledge, i.e. the science of friction, wear and lubrication, was applied just before lubricated processes [53].
Apart from important applications in internal combustion engines (ICE), vehicle, and engineering gearboxes, compressors turbines or hydraulic systems, there is a vast number of other systems which mostly require a detail tailored lubricant application. This is illustrated by the numerous types of greases, or the different lubricants, for chip-forming and chip-free metalworking operations, which are available. About 5000 – 10 000 different lubricant formulations are necessary to satisfy more than 90% of all lubricant applications [54 and 55].

In engineering, lubrication is usually divided into three regimes, fluid-film, mixed and boundary lubrication, as illustrated schematically in Figure 1.1. The tribological characteristics associated with each lubrication regime are listed below.

### 1.2 Lubrication Regimes

Lubrication regimes are basic contact conditions that predict the way the load is carried from one surface to another. Four main lubrication regimes are currently encountered as shown in Figure 1.1:

**Figure 1.1** Lubrication mechanisms in metal forming: (a) hydrodynamic lubrication; (b) mixed lubrication; (c) boundary lubrication; and (d) solid-film lubrication (film thicknesses are not to scale; they are much less in (b) and (c) than in (a) and (d)).

- Hydrodynamic lubrication: the tool and the workpiece are unglued by a liquid lubricant which is thick enough to prevent any direct contact between two surfaces. The load is carried by the pressurized lubricant.
- Mixed lubrication: the average lubricant film thickness between the tool and the workpiece is lower than the mean roughness of their surfaces. Direct contacts occur between asperities. The load is carried partly by the lubricant, partly by direct tool/workpiece contacts.

- Boundary lubrication. No liquid lubricant is used: the load is carried by direct tool/workpiece contacts at the level of the asperities. Surfaces have to be coated by solid lubricant in order to prevent direct metal-to-metal contact (such as zinc phosphate coating in cold forging).

- Solid-film lubrication: the tool and the workpiece are separated by a solid lubricant thick enough to avoid any contact between the tool and the workpiece. The load is carried by the lubricant.

In the case of mixed lubrication, the network of asperities forms valleys and plateaus where the lubricant can be trapped [57]. There are:

- The Micro Plasto Hydro Dynamic Lubrication (MPHDL),
- The Micro Plasto Hydro Static Lubrication (MPHSL).

The MPHDL occurs when the hydrodynamic pressure generated in the lubricant exceeds the tool pressure. The lubricant escapes from the valley in the direction opposite to the movement of the workpiece (backward escape). The MPHSL occurs when the hydrostatic pressure in the valley exceeds the die pressure. The fluid escapes in the workpiece moving direction (forward escape), Figure 1.2. These mechanisms are influenced by various factors, such as the relative sliding velocity, the viscosity of the lubricant, the initial lubricant film thickness at the plateaus, and obviously, the pocket geometry [58].
Figure 1.2 Principles of lubricant escape from a valley. (a) MPHDL, (b) MPHSL.

The alternate new measurement of lubrication is straight through parting techniques. The principle of the separation technique is based on the resistivity.

Figure 1.3 Typical friction factors and associated lubrication regimes [60].

Sound emissions, in high frequency range, cannot be detected by human ears but can be by the ultrasonic measuring system. Small amplitude changes in the narrow band of high frequencies of the ultrasound from friction, enable the monitoring of the applied lubricants’ properties [60].

The drawback is that this technique is only applicable to moving (dynamic) mechanical systems, but not to the mechanical systems that are static, such as compressed springs, designed to be activated in response to external trigger. Some examples are:

• High voltage circuit breakers with actuated springs
• Pressure relief/safety valves
• Latches and hooks with retracting springs.

These devices must have adequate lubrication to all moving mechanical parts that will be actuated by stored spring energy, over long period of time, and are expected to perform the duty upon external triggering event. However, these devices that are intended to be statically active over a long period of time, may fail, or show sluggish response upon external triggering event, if the applied lubricant/grease is dried, or degraded. It is ultimately leading to the undesired event. These static devices do not emit any acoustic sound at rest, which makes it impossible to use the conventional ultrasonic detection technique to monitor the condition of the applied lubricant/grease. Hence, another ultrasonic inspection approach is required to test such mechanisms installed in industry.

1.3 The Problem Statement

Currently, run-to-failure maintenance is used as an approach to take care of machines [61-64]. Such strategy is generating high risk to workers, production and property. This is seen by the high rate of unscheduled events associated with breakdowns, emergencies, long working hours and high maintenance costs.

The oldest and most common maintenance and repair policy is known as “fix it when it breaks”. The appeal of this method is that no analysis or planning is required [65, 66]. Early detection of faults in the system is a key to avoid failure of equipment [67, 68]. Unlike dynamic mechanisms, the main problem challenges in static mechanisms mountainous as follow:
1.3.1 Insufficient Greasing

- Due to prolong static non-operation of some systems, such as spring actuated Circuit Breakers (CB), the lubricants/grease in the actuation mechanism dries up.

- Periodic lubrication of mechanical parts is required for smooth operation.

- Bad lubricant condition, such as in high voltage CB unit, may behave sluggish during the operation / servicing, or racking. Process can lead to ionizing arcs which can result in arc blast explosions, threatening the operators’ lives.

- Traditional methods of inspection are slow, cost time and can cause damages to the units.

1.2.2 Silent Nature of static mechanical systems

- No acoustic signals are available from static mechanical components and assemblies.

- In absence of acoustic signal, the detection of lubrication condition of mechanical assemblies is not possible

- Active Ultrasonic system can be used for transmission and detection of lubrication condition in these circumstances.

1.4 Research Objectives

The main objective of this research is to further investigate active testing techniques in ultrasonic evaluation methods and to develop novel methodology in static mechanisms inspection. In order to validate new approach, we will be using a static mechanical system, such as recoiling springs, in pressure relief valve, that resembles real life industry application. Various, mostly used, lubricants will be used
in our experiments. In addition to that, various arrangements of the layers are also going to be used by changing the shape and size of the metal constructions.

Desired objectives to be achieved from this research project can be summarized as following:

1. To investigate if fresh grease, and the grease used in static mechanical components, have different ultrasonic traces based on their absorptions and reflections, i.e. to investigate grease degradation.

2. To use ultrasonic system to perform data acquisition and following that determine the state of the lubrication in static mechanical components and assemblies.

3. To develop a fuzzy based procedure to monitor grease condition, using wavelet technique, based on features extracted from the ultrasonic pulse echo signals.

4. Develop safe, fast, accurate, remotely operated intelligent inspection system.

5. The novel inspection system should be user friendly in its operation.

1.5 Scope of the project

Lubricant in service is subjected to a wide range of conditions which can degrade its base oil and additive system [69]. Such factors include heat, entrained air, incompatible gases, moisture, internal or external contamination, process constituents, radiation and inadvertent mixing of different fluids [70,71]. Those harsh conditions might lead to an increase in oil oxidation and viscosity, varnish formation, sludge and sediment formation. On the other hand, the lubricant must also dissipate heat; this means the lubricant will sometimes be heated above its recommended stable temperature which might lead to thermal breakdown, thus increasing its viscosity [72].
The durability of machine elements such as gears, bearings and seals rely on the integrity of the lubricant film separating the contact surfaces. It is therefore critical that the lubricant continue to have inherent physical properties along its life span [73].

Movement of mechanical parts produces a wide spectrum of sound including low frequencies and audible sound, that can be detected by human ear. Other emissions, of high frequencies, above 20kHz, are inaudible to human ears, but can be detected by the ultrasonic measuring system. By focusing on this narrow band of high frequencies, known as ultrasound, small changes in their amplitude resulting from friction can be detected.

The scope of this research includes the development of a procedure which can be used to investigate the condition of lubricating grease film between two metal assemblies. The procedure was validated using different types of grease and metals’ assemblies.

1.6 Contribution and Benefits of This Thesis

In industry, lubrication condition plays an important role in the maintenance of complex devices [74, 75]. In recent years, condition monitoring of lubrication has become an important research topic in collaboration between academia and industry [76]. Major effort has been set into lubricant diagnostic and prognostic system development, as well as, in the research. In comparison with vibration based dynamic machine fitness monitoring techniques, lubrication condition monitoring using ultrasound, provides approximately 10 times earlier warnings for machine malfunction and failure as stated by Poley [77]. The determination of most research is, by means of monitoring the lubricant degradation processing in the real time, to provide early warning of machine failure. [78- 82].
For online lubrication analysis and condition monitoring information is gathered by sensors that are integrated in the lubricant circulation system. The gathered data is analyzed by special developed techniques and the result and proper maintenance suggestions are presented in the real time. At present, industry mostly uses offsite lubrication inspection.

As one can imagine, if many unexpected failures occur, monetary lost will be considerable. The employment of online lubrication monitoring will reduce the unnecessary costs. In the current schedule-based maintenance, most of the lubricant is dumped, well before it reaches its end of life. The cost of one change is enormous. Industry needs the tax incentives from federal government in order to survive [83, 84]. The high cost of maintenance is emerging as the warranties from the manufactures expire. An excessive quota of the maintenance bill is coming from unscheduled maintenance.

The proposed pulse-echo technique will make it possible to inspect the lubrication condition of static mechanisms. This method assists technicians to shift away from traditional methods. The research findings are the first steps in developing inspection systems that could enable operators of machines, with static mechanisms, to monitor grease condition instantly and regularly. New diagnostic systems will allow machine operators to maintain the machine in optimum operating condition, through regular inspections, or even can be attached permanently to provide a continuous online indication of the grease condition in remotely located machines.

1.7 Research Methodology

In order to achieve project objective a set of research methodologies were extensively used that included initial comprehensive literature review, hypothesis
definition, experimental part, data analysis methodology establishment, the use and finally verification of the novel system. More details are given here:

- Selection of ultrasonic equipment to be used in the experimental stage and in the final product.
- Studying and investigating the properties of grease and the effects of aging on those properties.
- Studying and investigating ultrasonic method.
- Selection of the best data analysis method by comparing Fourier transform and Wavelet transform approach.
- Wavelet analysis of ultrasonic echoes.
- Features extraction using wavelet transform technique.
- Using Fuzzy logic approach for the quality of lubricant classification.

1.8 Overview of Thesis structure

- **Chapter 1:** gives a general review of the lubricant applications, their degradations and the usage of ultrasound in their inspection.
- **Chapter 2:** is a comprehensive literature review on previous methods on ultrasonic inspection of lubricants. The common methods currently in use have been discussed along with the summary of related papers.
- **Chapter 3:** discusses the procedures and methods followed to develop the inspection system.
- **Chapter 4:** presents experimental results together with discussions on signal processing of those results.
- **Chapter 5:** Conclusions and recommendations for further work are drawn.
- **References** list key information sources used in the thesis.
- **Appendix A** lists the data and presents software codes
1.9 Chapter Summary

The problem statement is specified clearly in the beginning of the chapter, together with research background. Main objectives and scope of the project are also given. Finally, the last section gives the thesis outline which consists of a short description on the content of the following chapters.

Following chapter delivers fundamental information on various aspects of lubrication, ultrasonic inspection and presents a brief of related papers.
CHAPTER II

LITERATURE REVIEW

This chapter consists of five sections discussing lubrication and the basic principles of ultrasonic inspection. The first section provides an overview of the functionality of lubricants and the causes of their degradation. The following section describes the basic greases and their properties. The third section presents common methods of grease inspection. The fourth section discusses pulse echo inspection technique. Finally, the last section summarizes all relevant previous research findings.

2. Overview

It is estimated that one-half to one-third of the world’s energy is consumed by friction and wear. Lubrication aims to effectively reduce friction, sluggish, wear and energy consumption [85-90]. However, conventional lubricants are limited by their service life and dependence on contact conditions [91-96]. Therefore, researches have continuously sought for high-performance and environmentally friendly lubricants [97-101].

Lubricants are essential to provide separation between different mechanical parts, to prevent wear and damage in the parts that are subject to friction. Different kind of lubricants are used in various mechanical systems to reduce wear, noise, corrosion and malfunctions, and to ensure the functionality of the systems. It is important to monitor and maintain quality of the applied lubricants. Scheduled maintenance service is essential in order to ensure the functionality of the system and prolong its lifetime [102, 103].
Lubricants are normally subject to different types of mechanical stresses, such as friction and heat that degrade their properties, which ultimately lead to failure of the mechanical parts [104]. Some of the typical causes of degrading are high temperatures, due to the friction of mechanical parts and the oxidation of the lubricant, when it is exposed to external environment [105]. Changes in lubrication properties are also due to contamination from the surrounding debris and dust particles over a period, which increases the rate of lubricant degradation [106, 107].

Common misconception in many industries is that, this problem can be prevented by lavish application of lubricants, if excessive lubrication will not lead to any danger to machines other than the waste of material [108-112]. However, this give rise to another problem, such as bearing failure, as excessive lubrication may cause excessive loading that would overheat the bearing and leads to degradation of lubrication. Therefore, the goal is to devise a way to measure the quality of the lubricants in the system and monitor the lubricant film thickness, to be able to schedule maintenance service in order to ensure correct amount of lubricant is applied [113-117].

There are various monitoring methods. For instance, ultrasonic condition monitoring was developed to monitor condition of lubricants through the detection of variations in the physical and chemical characteristics of the applied lubricant. Moreover, movement of mechanical parts produces a wide spectrum of sound including low frequencies that can be detected by human ear [118, 119 and 120].

2.1 Lubricants Functions and Degradation

As shown in Figure 2.1, even finely polished metal parts in mechanical systems have microscopically rough surfaces that, when they are in contact, causes wear and heat due to friction. Lubricants have essential tasks of obtaining enough separation
between these rough metal surfaces, and to dissipate resulted heat. They are also providing sealing against entry of contaminants, reducing the running noise, as well as, protecting the parts against corrosion [121]. Thus, maintaining lubricant adequate condition is important for the reliable operation and long operating life of the machine [122, 123].

![Figure 2.1 Microscopic Rough Surfaces.](image)

During service, lubricants are subjected to wide range of environmental and working conditions that could influence, i.e. change their properties and degrade them. The first factor that leads to the degradation of lubricants is excessive heat. When the temperature of lubricant exceeds its recommended stable temperature or dropping point (in the case of grease), it will thermally breakdown, causing increase of viscosity and degradation of the lubrication properties.

The second major reaction, experienced by lubricants in service, is the oxidation process appearing when they are exposed to atmospheric air with high concentrations of oxygen, along with the presence of high temperature. Lubricant is oxidized and sludge is formed [125]. This reaction increases the viscosity to the point of extreme thickening, which leads to loss of the lubrication properties [126]. Contamination of the lubricant with foreign substances, such as dust from surrounding, or copper and iron particles, resulting from the wear mechanical parts, influences greatly the rate of
lubricant degradation [127, 128]. These particles can change the properties of lubricant directly, or become catalysts to the oxidation process [129, 130].

2.2 Grease Properties and Composition

Since the lubricant used in our experimental work was grease, the properties and formulations of grease are discussed in this section.

2.2.1 Grease Properties

Grease is semi solid lubricant. It consists of oil, that does the lubrication, a thickener and some additives [131]. The characteristic which distinguishes it from lubricating oil is high initial viscosity property due to the presence of the thickener. National Lubricating Grease Institute (NLGI) defines grease as:

"A solid to semi-solid product of dispersion of a thickening agent in a liquid lubricant. Additives imparting special properties may be included" [131].

Greases are applied to machineries that need to be lubricated irregularly and where lubricating oil will drip or would not stay in position. Furthermore, grease is easier to contain than lubricating oil, which might require expensive circulation system and complex retention devices [132, 133]. On the other hand, due to grease rigidity, it is easily contained and retained in the mechanisms. Also, grease hold solids in suspension unlike lubricating oil which settles down and is unable to withhold the separation required between parts.

2.2.2 Grease formulations and types

As previously mentioned, grease consists of three components which are base oil, thickener and additives. The proportion of each component, to the other, differs from grease to another, but the base oil always accounts between 80% to 90% while
the thickener is between 2% to 20 % of the mix [134]. Additives are not a major component as some grease are free from additives, but they can constitute up to 15% of the mix as displayed on Figure 2.2.

![Figure 2.2 Proportions of oil ingredients.](image)

The base oil used, and the component of the thickener, dictate the type of the grease. There are mainly three types of base oils used in greases which include mineral, synthetic and natural oils. Mineral oils are mixtures of alkanes and are a product of the petroleum distillation [135]. Synthetic oils are a mixture of chemical compounds. They are artificially made. Natural oils, on the other hand, are either vegetable oils, or animal fats [136].

Grease thickener is the material that in combination with base oil gives the grease its solid to semi-fluid structure [137]. Type of the thickener is the main factor that defines the grease type. As shown in Figure 2.3, thickeners are divided into two major families: soap and non-soap thickeners. Soap thickeners are produced from acid and base reaction that generates soap and water. They constitute over 90% of thickeners used and are subcategorized into straight soaps, mixed soaps and complex soaps. Non-soap thickeners are such as clay and polyuria [138].
Figure 2.3 Types of grease thickeners.

2.3 Current Methods for Testing Condition of Lubrication

Methods used to monitor the condition of lubrication incorporate oil quality sensors that provide indication of the lubricants’ condition by measuring some key physical and chemical properties, including viscosity, density, optical (light scattering) and electrical properties (permittivity and conductance) [139]. In this section of literature review some of these methods are identified and explained briefly.

Traditionally, machine operators relied on time-based lubrication scheduling which is dependent on the operation hours recommended by the suppliers for each machine. It is common, in the time-based lubrication schedule, that the machine operators are instructed to lubricate the machines at short-term intervals, by applying excessive amounts of grease [140]. Lubrication intervals are based on a simple principle of keeping the equipment running optimally by preventing parts in contact from running dry and causing disastrous damage [141]. To achieve this goal there is a balance which must be kept between the prevention of lubricant starvation and gross over lubrication. Lubricant starvation is well known for causing heat that lead to severe failure in machines [142]. Yet most people assume that over-lubrication does
not constitute any danger to machines besides the material waste. However, this is not true as over-lubrication is a one of the main reasons behind bearing failure. It causes excessive loading which overheats the bearing and leads to lack of proper lubrication. To achieve the goal of optimizing the equipment life it is necessary to know when to lubricate and when to stop lubricating. This can be accomplished with a condition-based lubrication strategy which leads us to the techniques that are used to inspect the condition of lubricants.

2.3.1 Grease Analysis

Periodic inspection of the lubricant condition is a necessity to guarantee the machine running optimally. This periodic inspection is done by checking the change of important properties, which is grease consistency, or stiffness. Grease stiffness, or penetration number, is measured in the laboratory using a test such as Active Standard Test Methods for Cone Penetration Lubricating Grease (ASTM D217) [143]. This test requires the use of grease penetrometer, which is not generally at hand in an industrial plant environment. However, Surapol Raadnui overcame this problem through the finding of a simpler inspection method using a simple glass syringe. The test depends on measuring the time it takes for a fixed volume of grease, contained in a glass syringe, to be completely ejected from the syringe’s chamber, at a controlled temperature [144]. A drawback of this test method is the requirement of taking grease sample which, with the repeat of this process, in periodic inspections can lead to grease starvation.

2.3.2 Operation Inspection

Many machine operators resort to operation inspection through conducting a running test. Using the running test and measuring some of the required parameters
of the machine such as rotation smoothness, temperature, running speed and response time, they decide if the lubricant is still intact. However, this method of lubricant inspection might not give a proper indication of the lubricant condition as many factors may affect the parameters tested such as misalignments and corrosion [145-147]. In addition to that, this test can cause severe damage to the machine in the case of lubricant starvation, as the machine might run with insufficient lubrication. Finally, this test method is not suitable for some cases when the machine is linked to a system and the running of the machine affects the whole system. This case happens mostly in the static mechanical systems which are the main scope of this study. In the case of spring-actuated circuit breaker for instance, operational testing will trigger the breaker and affect the power grid.

### 2.3.3 Capacitive Method

This method is one of the electrical techniques used to measure the electrical impedance of asperities, which enables the measurement of the lubricant film thickness [148]. In this method the main objective is to measure the capacitance between two surfaces that are separated by lubricant. Capacitance based inspection is a simple method that involves sensor consisted of a pair of conductive plates with the lubricant enclosed as seen on the Figure 2.4. Equation (2.1) gives the expression for the sensor capacity [148]:

\[ C = \varepsilon \frac{A}{d} = \varepsilon_0 \varepsilon_r \frac{A}{d} \]  

(2.1)

Where

- \( \varepsilon \) is liquid permittivity
- \( \varepsilon_0 \) is electric constant, permittivity of space, equal to \( \sim 8.854 \times 10^{-12} \text{Fm}^{-1} \)
- \( \varepsilon_r \) is relative static permittivity, or dielectric constant, \( \varepsilon_r = 1 \) for space, >1 for all material, \( \sim 1 \) for air,
A \([\text{m}^2]\) is conductive plate overlapping surface area
d \([\text{m}]\) is the distance between the plates, as shown in the Figure 2.4.

![Figure 2.4 Capacitive method](image)

The main drawback of this method is the difficulty in the detection of grease constant \((\varepsilon)\). The constant \((\varepsilon)\) of grease is attributed by the general properties of the lubricants that have relatively much higher viscosity compared to water. Generally, it should be easy to detect it because the dielectric constant \((\varepsilon)\) of lubricant is normally lower than for water. Since hydrocarbons have non-polar nature, it is expected they have value of dielectric constant between 2 to 5, for most grease-based lubricants, while the dielectric constant for water is about 80. Different materials have different inherent dielectric properties which means that different lubricants surely have differing dielectric constants [149].

Hence, it is assumed that the change in the properties of the lubricants, such as degradation, can be detected by observing the change in the dielectric constant. The increase of the dielectric constant of the lubricants is assumed to be due to the increased polarizability caused by the oxidation of the lubricants that are exposed to the external environment, products and contaminants. They are water, soot particles, glycol and ferrous and non-ferrous metallic particles. Most sensors for monitoring the
condition of the oil, detect the change in dielectric constant of the applied lubricants. It is essential to determine the degradation of the applied lubricants [148-151].

2.3.4 **Inductive Methods**

These methods are based on similar principals as the capacitive methods, but here the difference in inductance of the lubricant is measure of its conditions [137]. Inductance, as a physical property of the material, is represented by the magnetic permeability. Inductive method is mainly used to detect metallic particles produced during oxidation of the degrading lubricants, by placing coil of wire in the path of flowing lubricant fluid. A fire fabric transducer is used in detection of small ferrous and non-ferrous debris to measure the level of contamination [137].

Eddy current is produced when a conductor is situated between alternating magnetic field. This important phenomenon relates to the change in the inductance of coil, which can be analysed to acquire the information about lubricant condition and state. Inductive transducer, which incorporates magnetic coil assembly, is used to detect wear metal particles. The particle signal detected by the coils (in the transducer) is transformed into an electric signal by the circuit unit and displayed on the monitor connected [137].

In an attempt to differentiate ferrous and non-ferrous debris, as well as to eliminate the influences caused by air bubbles and water droplets, inductive sensors based on 3-D solenoid coils were developed by Gill Sensors [138]. Its general working principle is illustrated in Figure 2.5. The inductance change of the sensor is determined by two factors, namely magnetic permeability and eddy current. If a non-ferrous conductive metallic debris particle is present in the magnetic field (Figure 2.4 (a)), an eddy current is induced inside the debris to oppose the existing magnetic field; this decreases the
total magnetic flux, leading to a decrease of the coil’s equivalent inductance. On the other hand, if a ferrous conductive metallic debris particle is introduced into the coil (Figure 2.5 (b)), the two aforementioned factors work in a competing way. While the high relative permeability increases the magnetic flux, the eddy current causes a decrease of the magnetic flux. However, at low frequencies, the induced eddy current is small, making the total magnetic flux to be dominated by the debris’ magnetic permeability [139, 140, and 141]. Thus, the coils’ inductance is increased by the passage of a ferrous debris particle. In contrast, the coils’ inductance is decreased by the passage of a non-ferrous debris particle because of the dominance of the eddy current effect at higher frequencies. In this way, the ferrous and non-ferrous debris particles can be differentiated at an appropriate frequency, which is important for condition monitoring of rotating and reciprocating machinery.

Figure 2.5 Illustration of the sensing mechanism for inductive sensors. (a) Magnetic flux (black lines) induced in the solenoid coil is attenuated owing to the eddy current generated magnetic flux (red lines) in the non-ferrous debris. (b) For ferrous debris, magnetic flux is enhanced owing to high relative permeability (blue lines) but also attenuated owing to eddy current.
2.3.5 Conduction/Resistance Methods

Conduction/resistance methods are another set of electrical techniques based on the basic principles of electrical resistance measurement. Resistivity measurements can give average values for the film thickness of the applied lubricant in moving parts of mechanical systems.

Condition of the lubricants can be evaluated based on the set of electrical properties measured. There are different products, with sensors, available, designed based on permittivity and conductivity measurements at a specific frequency [155, 156]. Another principal used requires applications of electrodes made of different kinds of metals. Potential differences are measured between the reference electrodes and the sensitive electrodes. This method is used to monitor the degradation of the lubricants in automobile engines [149].

2.3.6 Spectroscopy

Spectroscopy is vastly used as measurement method in many applications including inspection of lubricant condition within several industries. The principal that constitute the method can be classified as absorption, diffraction, emission, resonance, impedance and inelastic scattering. Relative oxidation, depletion of additives and change in acidity are the typical phenomena involved in the change (degradation) of the quality of the applied lubricant [150]. Two of the most reviewed spectroscopy methods are the absorption and reflection methods which were developed using smaller sensors and can be scaled down to feasible size. The spectroscopic method typically involves emission, either by burning or fluorescence in infrared, fluorescence and Raman spectrometry. The infrared spectrum in Fourier Transform Infrared Spectroscopy (FTIR) can provide substantial information about
the condition of the lubricant under investigation through the detection of water and other impurities [161]. The amount of infrared absorbed could differ depending on the condition of the lubricant that can change due to oxidation and contamination of soot. There are studies that were undertaken to identify infrared oxidation bands in engine oil. Based on these studies, the limitation of these methods is identified mainly because the degradation products of lubricants are not well defined in IR spectrum, as the petroleum hydrocarbons that constitute the lubricant [151, 154].

The other spectroscopy method is the Electrochemical Impedance Spectroscopy (EIS) that can provide time dependant quantitative information about the condition of the lubricant under investigation. Completely formulated lubricant that is typically composed of combination of synthetic base oils with dipolar nature. The dipole nature of this oils enables the investigation of their properties and conditions with electrochemical impedance spectroscopy where small potential (5–10 mV) is used for excitation and to initiate electrochemical activity of the system (oil film coated metal). The objective of EIS characterisation of the organic film is to investigate the degradation and reactivity of the oil film.

2.3.7 Ultrasonic Method

Other researchers utilized ultrasonic method to determine some properties of a thin oil film as done by Dwyer-Joyce et al. Pulse echo technique is commonly used in inspecting thickness of metal parts and welds [151-156]. In Dwyer-Joyce et al research, the thickness and the viscosity of an oil sample were realized from the proportion of incident signals reflected [166].

There are several names for this method listed by various sources. These measurement names include but are not limited to sonic impedance, sonic velocity
and sonic scattering. Changes in viscosity will change the received signal. In addition, if more sophisticated monitoring techniques are used. Some wear debris can also be detected as particles attenuate the signal when it passes between. Some level of distinction can be made as to the size of the particles (claims are made all the way down to 3μm) [166] but they have problems distinguishing the difference between air bubbles (small or big) and debris as bubbles cause scattering of the ultrasonic signal as well.

A very similar method to the approach sought have been utilized in research carried out by Kouki Nagamune et al [165] to evaluate the degradation of insulating oil in transformers using two transducers (pulsar and receiver). Ultrasonic through transmission method was utilized where a pulse has been transmitted from the pulsar while the receiver captures the passing wave and echoes. It was found empirically that the echoes amplitudes will be reduced due to the attenuation property of sound in the propagation path. The scale of attenuation was found to be relative to the newness of the oil.

Nowadays, ultrasound technology became handy for maintenance technicians in their preventive maintenance duties. It assisted in maintaining equipment in satisfactory operating conditions by its emergence in most inspection procedures [167, 168]. Ultrasound has been used for years in corrosion, cracks and welds inspection but only recently emerged as a solution for condition-based lubrication. Ultrasonic inspection utilizes the properties of generated high frequency sound waves in materials which include speed, attenuation and reflection to evaluate the condition of the material. The technology of ultrasound condition-based lubrication relies on the sensing and analyzing of high-frequency sounds.

For example, a properly fixed bearing, with the proper condition and amount of lubricant, will roll around the raceway without any stress causing minimal noise. As
the lubricant quality falls to a certain limit, the metal in the raceway, roller or ball bearing begins to fatigue. This situation will produce uneven surfaces, which will cause an increase in the emission of ultrasonic sound waves. This discovery was made by NASA while they are experimenting on ball bearings [169-173]. Researchers found that the amplitude of frequencies between 24 and 50 kHz indicates the failure before any other indicators including heat and vibration. Ultrasound frequency starts at 20 kHz, which is the frequency threshold where the human hearing stops [174]. Inspection equipment manufacturers utilized this finding by designing devices that receive inaudible high-frequency noises and electronically translate them into the audible range so inspection technician can hear them. The final product, which is called Grease Caddy is used nowadays in inspection and re-greasing of rotating machines in major industries as shown in Figure 2.6 below.

Figure 2.6 Using grease caddy in regressing.
2.3.8 Pulse-Echo Inspection Technique

Since passive ultrasonic inspection is not applicable to static mechanisms, as there are no acoustic emissions to be captured, the proposed Pulse-Echo method will be discussed in this section. The understanding of Pulse-Echo technique is based on the understanding of the basics of ultrasound which will be explained in brief. Main advantages of ultrasound or Pulse-Echo method in comparison to other methods [176-180], are:

1. It is sensitive to both surface and subsurface gaps.
2. The distance of penetration for detection or measurement is superior to other Non-Destructive Testing (NDT) methods.
3. Only single-sided access is required when the pulse-echo technique is used.
4. It is highly precise in determining reflector position and estimating size and shape.
5. Minimal part preparation is required.
6. It delivers instant results.
7. Detailed images can be created with automated systems.
8. Safer to operators or nearby personnel and does not disturb the material being tested.
9. It has multiple uses, such as thickness measurement, in addition to flaw detection.
10. Its gear can be highly portable or highly automated.

2.4 Basic Ultrasound Principals

Ultrasound is a sound pressure wave with frequency, which is higher than the limit human ear can hear [181]. Ultrasound frequencies are used by devices that are in ranges from 20 kHz to several GHz. Ultrasound has same properties of speed and reflection as audible sound. Thus, ultrasonic applications are used in many different
fields. Ultrasonic is used in measuring distance, imaging, detection and cleaning [182, 183]. Due to the high frequency of ultrasound, it cannot be detected by human ear. Following that, special instruments are used to translate ultrasound to electrical signals which are then altered to visual signals, or audible sound. The device used to convert ultrasound to electrical signals or vice versa is called ultrasonic transducer.

2.4.1 Ultrasonic Transducer

Ultrasonic transducer is the device which is used to convert electrical energy to ultrasound or vice versa. Ultrasonic transducers are made of piezoelectric crystals which oscillate at very high frequencies, producing ultrasound when alternating current is applied through them thus, they are used in ultrasonic transmitters [184]. Piezoelectric crystals also produce electric currents when they are exposed to ultrasound thus, they are used in ultrasonic detectors. Some transducers use single piezoelectric crystal for transmitting and receiving electrical currents. They are called single element transducers, while other use two separate crystals and they are known as dual element transducers as showing in Figure 2.7 [185].
Ultrasonic waves are based on the vibration of atoms in materials which have different motion patterns. Depending on the transducer type, the sound can either propagate as longitudinal or shear wave. In longitudinal waves, the oscillations occur in the same direction as the propagation. In the transverse or shear waves, particles oscillate at a right angle to the direction of propagation. Shear can propagate solids effectively but are unable to propagate liquids and gases.

2.4.2 Pulser Receiver

In order for ultrasonic transducers to generate ultrasound waves large amplitude electric pulses are required. After ultrasound wave go through the test piece, only minimal amount of the returned sound is received as electrical voltage pulses. Thus, Pulser-Receiver are needed to induce the transducers and amplifying the received signals to be detectable. Within the pulser control panel, the amount of time and the energy of the pulse applied to the transducer can be controlled [186, 187]. In the receiver section, the gain or signal amplification can be controlled as well as the filters to be applied.
2.4.3 Acoustic Impedance and Couplant

Acoustic resistance represents the energy transfer of an acoustic wave. The pressure and motion are in phase, so work is done on the medium ahead of the wave; as well, it represents the pressure that is out of phase with the motion and causes no average energy transfer. Every material has a property which is called acoustic impedance. When there is difference in the impedance of the materials, ultrasonic waves will reflect at the interface or boundary between one medium and another. The portion of the incident wave power reflected can be derived based on the fact that particle velocity and local particle pressures must be continuous across the boundary. The reflection coefficient is the portion of the incident wave power that is reflected when the acoustic impedances of the materials on both sides of the boundary are known [166]. Transmission coefficient is the amount of reflected energy plus the transmitted energy, which passed through the interface.

There is always a thin layer of air present in between the transducer and the metal piece. The acoustic impedance mismatch between air and metals is large due to air (At 20° C) having low acoustic impedance of 413kg/m²s while steel for example having acoustic impedance of 46.1x10⁶ kg/m²s. This causes most of the acoustic signal to reflect back without passing through the metal piece. For example, when inspecting a steel piece using immersion inspection through water only 1.3% of the transmitted ultrasound signal penetrates the test piece and reflects back as shown in Figure 2.8.
To overcome the impedance mismatch problem, a couplant, which is a liquid material that facilitates the transmission of ultrasonic energy from the transducer into the test specimen, is used. The couplant displaces the air, making it possible to deliver more sound energy into the test piece. A thin film of oil, glycerin or water is normally applied between the transducer and the test piece as a couplant. On the other hand, if shear wave transducers are used, the couplant is generally selected to have a significant higher viscosity such as honey.

### 2.4.4 Attenuation of Sound Waves

When sound travels through materials, its power weakens with the distance. In materials the amplitude weakens due to the wave spreading, but in natural materials it is more weakened due to the scattering and absorption. The scattering of sound in different directions, its absorption by the material and conversion to other energy forms, is called attenuation [167].
The attenuation in solid materials is low compared to the liquids and gases. This is due to the fact that solids have very high viscosity compared to liquids and gases. Attenuation coefficient is proportional to the dynamic viscosity $\eta$ according to the Stock’s law of attenuation [168].

In general, there are two ultrasonic evaluation methods used to inspect lubricants’ condition. They are passive and active testing approaches. Passive testing depends on listening to the acoustic emission from the moving parts of the mechanical mechanisms, while active testing depends on sending an ultrasound pulse and listening to the echoes reflecting from the surface of the lubricant or through the lubricant.

2.4.5 Research work carried out by Miettinen

Most research work done on lubricant condition monitoring with ultrasound have used the passive acoustic emission measurement method such as the research done by Miettinen [166]. In his study, the condition of grease lubricated rolling bearings was monitored using acoustic emission measurements. In an attempt to develop a tool that predicts the condition of grease lubricated roller bearings, acoustic emission measurement equipment’s were used. Acoustic emissions and temperature of real rolling bearing were measured. Signatures of each condition of grease were analyzed. The results have established that lubricant-film monitoring through ultrasonic acoustic emission measurement technique provides early warning of bearing failure. Although this method is very effective for dynamic systems such as rotating bearings, it is not suitable for static systems since they do not emit any acoustic noise signals.
2.4.6 Research work carried out by Dwyer-Joyce et al

Some other researchers utilized the pulse echo method to determine properties of a thin oil film as done by Dwyer-Joyce et al. [151] and Kasolang & Dwyer-Joyce [157]. Pulse echo technique is commonly used in inspecting thickness of metal parts and welds. In the Dwyer-Joyce et al research, the thickness and the viscosity of an oil sample were realized from the proportion of incident signals reflected. Shear wave ultrasonic pulses were produced to penetrate the lubricated piece, portion of the pulse reflects from the surface of the oil and other portion penetrates depending on the impedance mismatch between the piece and the oil. Then, the impedance of the oil can be used to define its physical properties.

This technique is not suitable for testing lubricants in service where both lubricant thickness and viscosity are variables in such conditions.

2.4.7 Research work carried out by Kouki Nagamune et al

A very similar method to the approach sought have been utilized in research carried out by Kouki Nagamune et al [165] to evaluate the degradation of insulating oil in transformers using two transducers (pulser and receiver). Ultrasonic through transmission method was utilized where a pulse has been transmitted from the pulser while the receiver captures the passing wave and its echoes. It was found empirically that the echoes’ amplitudes will be reduced due to the attenuation property of sound in the propagation path. The scale of attenuation was found to be relative to the newness of the oil. This is due to the increase of the oil viscosity, because it thickens as it gets older, therefore reducing the attenuation.
Using the attenuation and newness, which is directly proportional, fuzzy inference system was designed to estimate the kinetic viscosity of the oil. This method has proven a correlation coefficient of over 0.92 with the viscometer readings [189].

However, due to oil container having fixed and large dimensions, [190] this typical method is not valid for applications where lubricant film thickness is variable and tiny such as the case that we studied. Although transmission method requires two transducers, it can be reduced to single transducer for transmitting and receiving operations when pulse echo technique is used.

### 2.5 Chapter Summary

The chapter initially provides basic background about the grease and its properties. Then, the popular methods used in the inspection of grease condition were explored, including ultrasonic inspection technique which is the most viable for our approach. Finally, previous research works utilizing ultrasonic technique in grease condition inspection were discussed. This chapter lays the basic knowledge that is necessary to understand the methodology, which is presented in the next chapter.
CHAPTER III

METHODOLOGY

This chapter explains the carried procedures used to implement the proposed method of ultrasonic inspection, tools and apparatus used and their setup. The first section illuminates the experimental setup and equipment’s used. The following sections discuss in detail the procedures carried out in the various phases of empirical work. Then general methods used to extract the results are summarized at last.

3.1 Novel Ultrasonic Testing Procedure

This section reviews proposed pulse echo inspection technique with wavelet feature extraction and fuzzy classification.

Ultrasonic pulse-echo technique is used in weld defect inspections where the thickness of solid piece of metal is gauged. However, same principle can be applied in the inspection of lubricant where the ultrasound waves are propagated through a specimen which is consisted of solids metal pieces and greases with high viscosity that are expected to show different acoustic impedances, as presented in Equation (3.1) [168, 191].

\[ R = \left( \frac{Z_2 - Z_1}{Z_2 + Z_1} \right)^2 \]  
(3.1)
Where; the proportion is known as the reflection coefficient, $R$ and can be related to the impedances of the two materials $Z_1$ and $Z_2$ according to the acoustic impedances of the plate’s material and lubricant.

Since the amount of reflected energy plus the transmitted energy, which passed through the interface, must be equal to the total amount of incident energy, the “transmission coefficient”, $T$, is calculated by simply subtracting the reflection coefficient from one to get [168]:

$$T = 1 - R$$ (3.2)

When testing a metal piece, the transducer is placed on the top of the piece and ultrasonic pulses are transmitted. Some portion of the transmitted pulse will be reflected by the surface of the oil and the other portion will pass through according to the known difference of the impedance of the grease and the metal piece to which it is applied to. The receiver is used to capture reflected wave pulse echoes.

Studies show that the amplitudes of the reflected wave pulse echoes are reduced due to the attenuation property of sound in the path of propagation. The attenuation scale was found to be relative to the “newness” of the grease [169].

As shown in Figure 3.1 and 3.2, the proposed inspection technique involves two key steps.

a) Wavelet feature extraction
b) Fuzzy classification.

Ultrasonic measurements are performed either by using pulsed, or continuous ultrasound waves. Instruments can operate optimally and automatically, and the measurements can be interpreted quickly and easily. In pulse echo technique, the desired
ultrasound waves are produced by the ultrasonic transducer which is converting current into acoustic emissions and vice versa.

Figure 3.1 Ultrasonic Inspection of Lubricant Condition Diagram.
Figure 3.2 Ultrasonic Inspection of Lubricant Condition Process
In pulse-echo technique a signal pulse is generated to propagate through the test sample to be reflected at the opposite wall of the test piece producing an echo. Each echo travels a distance equal to twice the thickness of the test piece before it reaches again the transducer as shown in diagram. Pulsar-Receiver is used to amplify returned low-level signal. The amount of time and the energy of the pulse applied to the transducer can be controlled by pulsar control panel. Oscilloscope is used to capture and digitalize the waveform, so that it can be viewed on its monitor and loaded into the computer. Shear wave ultrasonic pulses were produced to penetrate the lubricated piece; portion of the pulse reflects from the surface of the oil and other portion penetrates depending on the impedance mismatch between the piece and the oil.

When sound travels through materials, its power is weakened due to the scattering and absorption motion/process. The scattering of sound in different directions and absorption by the material, to other energy forms, is called the attenuation. The relation, which governs this phenomenon and explains the wave amplitude, $A$, change, is [191]:

$$A = A_0 e^{-\alpha z} \quad (3.3)$$

Where symbols refer to:

$A_0$: initial amplitude

$\alpha$: attenuation coefficient

$z$: travelled distance

The attenuation coefficient $\alpha$ depends on the transmitted medium. Attenuation in solid materials is low compared to liquids and gases. This is due to the fact that solids have very high viscosity, compared to liquids and gases, and the
attenuation coefficient, $\alpha$ is proportional to the dynamic viscosity $\eta$ according to the Stocks law of attenuation which is [192]:

$$\alpha = \frac{2\eta \omega^2}{3\rho c^3}$$  \hspace{1cm} (3.4)

Where:

$\eta$: dynamic viscosity

$\omega$: sound frequency

$\rho$: density

$c$: sound speed

The time between reflected signals is related to the thickness of the test sample inspected. As already mentioned, each echo travels a distance equal to twice the thickness of the test piece before it reaches again the transducer as viewed Figure 3.3.

![Figure 3.3 Pulse-Echo inspection of a metal piece.](image)

Since the sound signal travels through the test piece back and forth sweeping the piece twice thus the thickness can be deduced from the travel time according to the relation [168]:

43
\[ \chi = \frac{ct}{2} \]  

(3.5)

Where we have:

\( \chi \): thickness of the test piece

\( c \): sound speed

\( t \): travel time

Multiple reflections will occur after the ultrasonic pulse is transmitted into an oil film if the pulse wavelength is greater that the thickness of the film. Referring to the Figure 3.4, the height of echo (\( h \)), of the first reflected waves from the boundary, depends on the thickness of the oil film. Hence, the mean film thickness \( h_m \) can be estimated as given by Equation 3.6 [159].

\[ h_m = h_0 + h = \frac{(R_{y1} + R_{y3})}{2} + h \]  

(3.6)

Where, \( h_0 \) is the mean distance between rough surfaces at the onset of solid contact, while \( R_{y1} \) and \( R_{y3} \) are the roughness maximum height of the first and third boundary material respectively [168].

**Figure 3.4.** Analysis of the concept of ultrasonic pulse-echo measurement method.
3.1.2 Pulse-Echo in Inspecting Lubricant Condition

As discussed in literature review chapter, ultrasonic inspection is the most suitable method for checking lubricant condition in static mechanisms whereas pulse-echo technique is the most common technique used in ultrasonic inspection. However, pulse-echo technique is usually used in thickness gauges to measure thickness of solid pieces of metal or used in weld and defect inspection. In lubricant inspection, the ultrasound waves are required to propagate through a specimen which incorporate solids metal pieces and high viscosity liquid greases, as shown in Figure 3.5, which have different impedances.

![Figure 3.5 Proposed inspection setup.](image)

Therefore, the reflection and penetration behavior of the ultrasound waves and signals cannot be anticipated theoretically and can only be obtained empirically. From the signals detected, the data which describe the degradation of the grease is extracted after the digital processing. Then, this data is used as features which are translated by a fuzzy classification system into the condition of the inspected grease.

A program routine, which does the processing, feature extraction and fuzzy classification is developed. Finally, the new software module is then tested and validated with other samples.
3.2 Proposed Framework

To develop the grease inspection procedure the work was divided into two categories, project methodology and research methodology. Both project tasks and review of necessary related information will go side by side to achieve the project objectives.

3.2.1 Project Methodology

Project methodology includes all general tasks completed throughout the project period.

![Flowchart of project procedures.](image-url)
3.2.1 Research Methodology

Research methodology includes all the literature reviewed. Many aspects of the project can be viewed in Figure 3.7.

![Figure 3.7 Areas of literature review.](image)

3.3 Experimental Setup

3.3.1 Selecting Equipment

There are three main components that are necessary for every ultrasonic inspection job; the ultrasonic transducer, pulser/ receiver module and the oscilloscope.

Additionally, a computer was required for signal processing and classification. Equipment’s specifications should match the application they are employed in, like frequency bandwidth of the oscilloscope, or transducer characteristics.
3.3.1.1 Ultrasonic Transducer

Ultrasonic transducer generates the desired ultrasound waves by converting the current into acoustic emissions. Selection of the right transducer depends on the application. In general, there are two important parameters which should be in consideration when selecting ultrasonic transducers:

1. the mode of sound wave propagation and
2. the frequency of the sound generated.

When considering mode of sound propagation, there are two commonly used modes which are; shear propagation and longitudinal propagation. Since the specimen to be inspected is grease (which is a viscous liquid), shear propagation is not suitable for the task because shear waves are not effective in propagating liquid materials due to the high attenuation rate in liquids. Regarding the second factor, which is the frequency of the transducer, high frequency transducers are considered the best for such application because sensitivity and resolution of the system generally increases with the frequency. The higher the frequency, the smaller the wavelength and this relationship is shown by the following equation [159, 191]:

\[ \lambda = \frac{c}{f} \]  

(3.7)

Where:
\( \lambda \): Wavelength,
\( c \): Speed of sound,
\( f \): Frequency of the sound wave

Selecting a high frequency transducer requires the other parts of the system to have a high sampling rate as well. For optimum sensitivity, the test piece should be
much thicker than the wavelength in the direction of the propagation. Hence, when choosing a high frequency transducer, other parts of the system that does the sampling should have proper high sampling rate. The higher the sampling rate, the higher the cost, thus some sensitivity can be sacrificed for the cost. Considering all the factors, two different longitudinal wave transducers have been selected. Selection of appropriate ultrasonic transducers – shear wave:

- 10MHz Shear low frequency wave contact transducer
- 20MHz High frequency wave contact transducer

- Pulser and receiver system selection:
  - ultrasonic frequencies limitation 400-volt square-wave
  - 35MHz Bandwidth Pulser/ Receiver
  - work with both Low and high Frequency Transducers
  - Interfacing the transducers to PC with DAQ

3.3.1.2 Pulser /Receiver Module

Ultrasonic pulser/receiver generates high frequency high voltage pulses to drive the transducers, and also receives and amplifies the reflected pulses. When selecting the pulser/receiver unit, the voltage, frequency and amplification factors should be considered. The voltage should be high enough to induce the transducer, the frequency of pulses generated should match the frequency of the transducer and the amplification should be sufficient to get observable signals. Panametrics 5072 pulser/receiver was found to be fit for the inspection job.
3.3.2.3 Oscilloscope

Oscilloscope is used to capture and digitalize the waveform so it can be viewed on its monitor or loaded into the computer. Initially a DAQ (Data Acquisition Card) was to be used in digitalizing the signal to be viewed on the computer but it did not have a sufficient sampling rate. To be able to retrieve vibrant signals the sampling rate of the device should be at least twice the frequency of the transducer. Since the signals received will be processed in a computer, the oscilloscope must have communication port such as USB or Serial Port. Having a high sampling rate is not important if the communication bus cannot transfer the samples to the PC at higher rates. If the interface bus cannot sustain continuous data transfer at the sampling rate of the oscilloscope on board, memory space on the oscilloscope should be large enough to cater for the samples until they are transferred to the PC with all the specifications required in mind. Agilent 54621a oscilloscope was selected for the task. Although it uses low data transfer rate, RS232 bus has 2000 sample on board memory, and it has a high sampling rate of 200 MSa/s.

3.3.1.4 Computer and Software

The computer used for processing of the signals and classification was the Dell Dimension E510 with Windows XP and 3 GHz Intel Pentium EM64T Processor, with Matlab R2017b installed and used in the processing and classification.

3.3.2 Interfacing Equipment

Our research test system was set up as shown in Figure 3.8. “TX/RX” terminal of the Ultrasonic pulser/receiver was connected to the transducer using BNC to BNC cable and the appropriate frequency of 10 and 20 Mhz has been set on the pulser/receiver
control panel. “RF OUT” port was connected to Channel 1 of the oscilloscope to monitor the signal. In order to keep the signal synchronized “SYNC OUT”, which sends the synchronization pulses, was connected to the “External Trigger” of the oscilloscope. Finally, the “SERIAL PORT” of the oscilloscope was connected to the computer’s “SERIAL PORT” using RS232 null cable to load the graph data into the PC as shown in Figure 3.8.

![Figure 3.8 Research workstation with equipment interfacing shown.](image)

### 3.3.3 Communication with the Oscilloscope

Standard Commands for Programmable Instruments (SCPI) which is the instrument command language has been used in controlling the oscilloscope. It is used to control a wide variety of instrument functions in a standard manner. For some measurement functions, such as frequency or voltage, SCPI defines the dedicated commands that are available for those functions. Therefore, two oscilloscopes from different manufacturers can be used to make frequency measurements in the same way. As the oscilloscope used has a serial port, these commands can be sent to the oscilloscope through serial port using HyperTerminal but since Matlab is used for the
data processing, it is better to use Matlab to send the command lines through the serial port. Using Matlab in acquiring data, as well as, processing helps in automating the whole process by writing one script which does the entire process and displays only the result of the inspection.

3.4 Data Collection

3.4.1 Samples Preparation

Several samples of lithium soap greases and complex lithium soap grease, with properties shown in Table 3.1 were used for preparing the specimens. The top part is different geometric than the bottom part. The test sample was prepared by placing same amount of grease between two different metal parts as shown in Figure 3.9 and 3.10. In Figure 3.10, the top plate is thicker than the bottom plate to allow the wave reflected from the interface of bottom plate and air to pass without overlapping with the wave reflected from the interface of top plate and grease. To simulate the aging process of static grease, each type of grease sample was aged by the mean of heating into three stages using a furnace oven at temperatures 100, 200 and 300°C for 5 hours each. Grease tends to cake and dry out due to the natural tendency of oil to drain out of the grease thickener over time.

Table 3.1 Properties of different greases

<table>
<thead>
<tr>
<th>Property</th>
<th>Pennzoil Grease</th>
<th>Lubrimatic Grease</th>
<th>Abro Grease</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soap type</td>
<td>Lithium complex</td>
<td>Lithium</td>
<td>Lithium</td>
</tr>
<tr>
<td>Dropping point</td>
<td>272°C</td>
<td>177°C</td>
<td>183°C</td>
</tr>
<tr>
<td>Base oil</td>
<td>Mineral</td>
<td>Mineral</td>
<td>Mineral</td>
</tr>
<tr>
<td>Color</td>
<td>Yellow</td>
<td>Carbon Black</td>
<td>Blue</td>
</tr>
</tbody>
</table>
3.4.2 Samples Inspection

After samples were removed from the furnace, they were left to cool so that, the thinker that liquefied after the heating process, can solidify again. Afterwards, a small quantity of water-based glycerin ultrasonic couplant was smeared on the top plate of the test piece. Following that, the transducer was placed on the top plate over the couplant drop while applying constant force using a 150g mass. Then, the pulser/receiver is switched on to generate pulses. Oscilloscope view was adjusted by turning the knobs to change the divisions so that only the part of interest from the signal is observed. Next, the program routine, which communicates to oscilloscope, was run on the Matlab to capture the signals data. Finally, the data of each sample was named and saved into Matlab workspace to be processed subsequently. Figure 3.9 and 3.10 below, show how the transducer is attached to the top metal part 1, which generates a positive pulse, that trigger a signal generator through the crease film, and the bottom metal part 2.

![Ultrasonic inspection of a grease sample](image)

**Figure 3.9** Ultrasonic inspection of a grease sample.
3.5 Data Processing

The raw signals received from ultrasonic inspection system are shown in the Figure 3.11 below. The signal waveform has peaks, which represent the reflections within the sample after the initial pulse. Some of the peaks are generated by noise. Following that, further processing is required before the convenient data can be extracted from the signal.
Figure 3.11 Raw ultrasonic signal.

Figure 3.12 Experimental setup in Mechatronics research lab
Figure 3.13 Peaks signal in the sensor Circuit (Peak 1 reflected from top plate and grease interface; Peak 2 is one of the multiple reflections of signal as some portion passes through lubricants), Peak 3 reflected from bottom plate and air interface, surface D.

### 3.5.1 Signal Trimming

The initial pulse transmits from the transducer through the couplant and surface A. The peak labeled as Peak 1 in the Figure 3.13 comes from the ultrasound wave reflected from the interface between the top plate and the grease film, surface B. Peak 2 is from the ultrasound wave reflected from the interface between the top of the bottom plate and the bottom of the grease film, surface C. Peak 3 is one of the multiple original signal reflections, from surface D now, verified using the following relation [168]:

$$t = \frac{2x}{c}$$  \hspace{1cm} (3.8)

Where

- $t$ is time of flight,
- $x$ is the thickness of the plate
- $c = \text{is the sound velocity.}$
There are other small peaks between Peak 2 and Peak 3 which are the multiple reflections of peaks 1 and 2. As Peak 1 is echo of reflected ultrasound wave that did not carry the features of the grease thus can be neglected.

### 3.5.2 Wavelet Signal Processing

The ultrasonic signal of interest is between the Peak 1 and 3 as it carries the grease dryness features. Continuous wavelet transform analysis was applied to the signal using a proper mother wavelet. Daubechies 4 mother wavelet was chosen because it mostly matches the ultrasonic reflected pulse. The raw signal had high frequency noise spikes while the wavelet has the signal decomposed to several frequencies with the noise situated at high frequencies (small scales) and the information signal at lower frequencies (small scales) as shown in Figure 3.14. The wavelet function is written as [195, 196].

\[
x_w(a, b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t) \varphi \left( \frac{t-b}{a} \right) dt
\]

\[a, b \in R, a > 0\]

Where \(a\) is a scale parameter, \(b\) is a translation parameter, and \(\varphi\) represents the conjugate of, the mother wavelet. The raw signal was transformed using Daubechies 4 mother wavelet. This was done to remove the high frequency noise and extract the features.

![3D Wavelet function analysis](image)

**Figure 3.14** 3D Wavelet function analysis.
This research aimed at using Continuous Wavelet Transform (CWT) analysis of waveform signals to develop and adopt a methodology for classification of the signals at different levels. Traditional analysis methods such as Fast Fourier Transform (FFT) could not be used alone because pulse-echo diagnosis requires time-based information [163]. Therefore, CWT was selected for this research as it includes time-based information, as well as, scales that can be converted into frequencies, making the diagnosis easier.

3.6 Features Extraction and Analysis

The wavelet transformed signal contains a lot of data but only a small portion of the data detects the condition of the grease. Thus, further steps were required to extract the data which is associated with changes in characteristics of grease.
3.6.1 Features Extraction

In the wavelet signal a noticeable pattern between the amplitudes, times and scales of the highest coefficient and the aging temperature of the sample was viewed. The scale is the inverse of the frequency so the drier the grease sample the higher the ultrasonic frequency that passes through. Amplitudes and scales of the highest coefficient of each sample were recorded as features. The scales were converted to the corresponding pseudo frequency by computing the center frequency, $F_c$, of the wavelet and by using the following relationship [165].

$$F_a = \frac{F_c}{a\Delta} \quad (3.10)$$

Where:

$a$ : The Scale.

$\Delta$ : The sampling periods

$F_c$ : The centre frequency of wavelet in Hz.

$F_a$ : The pseudo-frequency corresponding to the scale in Hz.

3.6.2 Features Analysis

As all greases showed similar aging pattern, only Penzoil grease was further analyzed. The feature space showing the coefficients and scales of grease with different aging temperatures were plotted as in Figure 3.16. It was noticed that, every feature samples of grease having similar age, are gathered in specific areas of the feature space. Data from the graphs were used to develop a fuzzy classification system with two inputs (coefficient and scale) deciding the temperature/aging.
3.6.2 Development of Classification System

3.6.3 Fuzzy Logic Overview

Multi-level Logic Zadeh (1965) introduced “fuzzy sets”. They are foundation of any logic regardless of truth levels assumed. Continuum of logic levels is between

- 0 for false
- 1 for true

Set of variable values are represented by mathematical formulation, known as membership function, which gives the degree of membership within the set. Membership function, of a fuzzy set A, maps the elements of the universe X into a numeric value in the range [0,1].

\[ \mu_A(X): X \rightarrow [0,1] \]
Fuzzy classification was selected for several reasons [197, 198]. It is inexpensive to develop, covers a wider range of operating conditions and is readily customizable in natural language terms. A self-organizing fuzzy classification can automatically refine an initial approximate set of fuzzy rules. Neural network classification could have been used as another alternative if enough samples were available for the training process [199, 200]. The features space plot data was used in developing the inference system.

In order to design fuzzy membership functions, to determine input ranges scale and coefficient, features were partitioned into ranges of small, medium and large. From borders between these ranges, lines were drawn to split the features space into many partitions. If the different feature classes are situated in separate partitions this will allow high interpretability and easy definition of fuzzy rules. The fuzzy membership functions have been designed based on the borders between classes. The intercept points of membership functions were defined by the class borderlines.

MATLAB programming environment is used to write a program that defines dedicated commands for a specific function. That function was sent through serial ports of the oscilloscope via hyper terminal. MATLAB can enable automation of the transmission, reception and analytic process of data and display final results for the inspection.

3.6.4 Partition of a Feature Space into Fuzzy Subspaces

In order to define fuzzy membership functions, and to determine input ranges scale, coefficient features were partitioned into ranges of small, medium and large. From borders between these ranges, lines were drawn to split the features’ space into partitions as shown in Figure 3.17. If the different feature classes are situated in
separate partitions this will allow high interpretability and easy definition of fuzzy rules. Fuzzy membership functions were designed based on the borders between classes. The intercept points of membership functions were defined by the class borderlines. Lubrication conditions (new, moderate, old) are to be inferred from inputs; attenuation and aging lubrication for the fuzzy system. Data inference fuzzy system, showing the scale membership and coefficient functions, was designed based on the borders between classes as shown in Figure 3.18.

Figure 3.17 Partition of features space.
Table 3.2 Mathematical Characterization of Triangular Membership Functions

<table>
<thead>
<tr>
<th>Linguistic Value</th>
<th>Triangular Membership functions</th>
</tr>
</thead>
</table>
| $A_i^1 = 1$      | $\mu_i A_i^1(x_i) = \begin{cases} 
1 & \quad x = -b_i \\
1 + \frac{2|x_i - a_i|}{b_i} & \quad -b_i < x_i \leq a_i 
\end{cases}$ |
| $A_i^2 = 2$      | $\mu_i A_i^2(x_i) = \begin{cases} 
1 - \frac{2|x_i - a_i|}{b_i} & \quad -a_i \leq x_i \leq 0 \\
1 + \frac{2|x_i - a_i|}{b_i} & \quad 0 < x_i \leq a_i 
\end{cases}$ |
| $A_i^3 = 3$      | $\mu_i A_i^3(x_i) = \begin{cases} 
1 - \frac{2|x_i - a_i|}{b_i} & \quad a_i \leq x \leq b_i \\
1 & \quad x_i = b_i 
\end{cases}$ |
\(a_i\) is a scale parameter, \(b_i\) is a translation parameter, which both are the parameters for range and central location of membership functions respectively, where \(i=1, 2\) is the number of inputs index.

This research takes advantage of the Takagi-Sugeno’s output discourse and defuzzification technique. Takagi-Sugeno’s discourse uses the union of the fuzzy sets and takes the high value of the domain with fast, digital output universe and maximal membership degree. The linguistic variable is the membership function of the antecedent part defined as

\[
\tilde{A}_i^k = [\tilde{A}_i^1 = LN, \tilde{A}_i^2 = Z, \tilde{A}_i^3 = LP] \quad (3.11)
\]

Where \(A_i\) refers to the membership value, index \(k=1,2,3\) is assigned to tally the linguistic input membership functions and index \(i=1\) is assigned to numbers of outputs.

### 3.7.3 Determination of Fuzzy Rules

There are nine rules as the features space is divided into nine areas. Rules were recorded on a rule table and then entered in Matlab fuzzy editor to finalize the design of the classification system. Final step of development was the testing through the fuzzy editor, by giving some input values and verifying the operation of the classification process. These rules are based on two inputs variables, each with three linguistic values defined as: small, medium, large. Small = Large negative, Large = Large positive, and there are at most \(N = 9\) possible rules for the fuzzy systems calculated in Equation (11) [194, 200].

\[
N = (Input\ mf)^{Ni} \quad (3.12)
\]

\[
N = (3)^2 = 9
\]
Where, $m_f$ is the membership function, $N_i$ is the number of inputs. The partition of the feature space rules was determined as given in Table 3.3 via relating membership functions of the input to the output variable is the age of the grease sample.

Table 3.3 Fuzzy Rules

<table>
<thead>
<tr>
<th>Scale/Coefficient</th>
<th>Small</th>
<th>Medium</th>
<th>Large</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>Old</td>
<td>New</td>
<td>New</td>
</tr>
<tr>
<td>Medium</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Old</td>
</tr>
<tr>
<td>Large</td>
<td>Old</td>
<td>Old</td>
<td>Old</td>
</tr>
</tbody>
</table>

3.8 Testing and Validation

The full inspection procedure of the grease was validated in two ways. Firstly, by newly acquired ultrasonic waveforms from the fresh samples, to test the algorithm and build database with properties of the tested greases, and secondly, by real time inspection of the specimens.

3.8.1 Using Stored Ultrasonic Waveforms

Ultrasonic signals acquired from prepared samples were stored into Matlab workspace. A programming routine process the signal, extract the features then complete the classification. The fuzzy inference system output of the age of the grease was compared to the known condition of the real sample.

3.8.2 Real Time Inspection

A complete integrated program that acquires, process, classifies and gives the grease condition was used for the real time inspection. Finally, the output of the program was compared with the known condition of the sample inspected.
Chapter Summary

The chapter has presented the approach used to develop the system for the inspection of the grease condition, utilizing pulse-echo ultrasonic technique. Initially, the proposed method was explained concisely. Then, in the second section the work plan was explained in brief. Following that, the steps adopted to select and setup the equipment were described. Next, the phases taken in developing the algorithm used in processing and classification of signals were defined. Finally, the procedures followed to verify and test the system were stated.

The next chapter will present the results achieved from the research as whole as well as the result gathered from the different stages of the work.
CHAPTER IV

RESULTS AND ANALYSIS

In this chapter results and data analysis are presented. Results extracted from experimental procedures were presented and discussed in the first sections. The subsequent sections present the comparative analysis between the actual grease condition and the result output by the inspection system to validate its operation.

4.1 Experimental results

4.1.1 Raw ultrasonic signal results

In order to develop new testing procedure and to monitor the grease condition using ultrasonic inspection, fresh and used grease are tested. Both have different ultrasonic traces. Those traces depend on their absorptions and reflection rate of ultrasonic signals. Three grease samples have been aged to three different stages depending on their survivability to high temperatures. The results acquired from different grease samples have proven that difference in the sample condition can be observed from raw ultrasonic signals as shown in Figure 4.1, 4.2 and 4.3 for the three types of greases.
Figure 4.1 Black grease raw signals.
Figure 4.2 Yellow grease raw signals.

Figure 4.3 Blue grease raw signals.
From the previous figures, it can be noticed that the pattern between the two peaks differs according to the age of the grease. Three obvious changes happened during the aging process. The amplitude of the peak and time of the peak changed noticeably, and some frequencies were introduced along with the aging. The increase in amplitude is due to the change in the properties of the grease while the change in time is mostly due to the change in thickness of the grease film as it settled down after heating. This was verified by testing different samples and the time was found to be inconsistent. The new frequencies that appeared were found to be related to the age of the grease. The data from the ultrasonic signals for different grease was summarized in Table 4.1.

**Table 4.1 Raw signals data.**

<table>
<thead>
<tr>
<th>Aging period</th>
<th>Peak Amplitude</th>
<th>Peak Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>New Black</td>
<td>0.125</td>
<td>5.235</td>
</tr>
<tr>
<td>Black 100 °C</td>
<td>0.2188</td>
<td>3.735</td>
</tr>
<tr>
<td>Black 200 °C</td>
<td>0.4063</td>
<td>2.69</td>
</tr>
<tr>
<td>Black 250 °C</td>
<td>0.5</td>
<td>2.63</td>
</tr>
<tr>
<td>New Yellow</td>
<td>0.09375</td>
<td>4.99</td>
</tr>
<tr>
<td>Yellow 100 °C</td>
<td>0.09375</td>
<td>4.51</td>
</tr>
<tr>
<td>Yellow 200 °C</td>
<td>0.1875</td>
<td>3.43</td>
</tr>
<tr>
<td>Yellow 300 °C</td>
<td>0.3438</td>
<td>2.85</td>
</tr>
<tr>
<td>New Blue</td>
<td>0.09375</td>
<td>4.925</td>
</tr>
<tr>
<td>Blue 100 °C</td>
<td>0.09375</td>
<td>4.875</td>
</tr>
<tr>
<td>Blue 200 °C</td>
<td>0.2813</td>
<td>3.29</td>
</tr>
<tr>
<td>Blue 250 °C</td>
<td>0.3125</td>
<td>2.62</td>
</tr>
</tbody>
</table>
4.1.2 Wavelet results

The raw signals were transformed using Daubechies 4 mother wavelet. This was done to remove the high frequency noise and extract the features. Results of the transform can be viewed respectively in Figure 4.4, 4.5 and 4.6.

**Figure 4.4** Yellow grease signals wavelet transform.
Figure 4.5 Black grease signals wavelet transform.
The variation of the wavelet signals for different grease conditions can be observed from the previous figures (4.4, 4.5 and 4.6). The shift of the peak along the time axis is noticeable with the aging of the sample. The change in amplitude of the peak can be viewed on z-axis and interpreted using the color bar. A noticeable increase happens to the amplitude of the peak with the aging process. Further investigation also revealed that the scale (frequency) at which the maximum amplitude locates depends on the age of the samples as appeared on the raw signals with the aging of the samples on Figures 4.1, 4.2 and 4.3. The summary of the amplitudes, scales and their corresponding frequencies gathered from the wavelet signals can be viewed in Table 4.2.
Table 4.2 Features of different grease samples.

<table>
<thead>
<tr>
<th>Aging period</th>
<th>Coefficient</th>
<th>Scale</th>
<th>Frequency (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>New Yellow</td>
<td>0.2934</td>
<td>41</td>
<td>3.48</td>
</tr>
<tr>
<td>Yellow 100 °C</td>
<td>0.2683</td>
<td>41</td>
<td>3.48</td>
</tr>
<tr>
<td>Yellow 200 °C</td>
<td>0.4953</td>
<td>36</td>
<td>3.97</td>
</tr>
<tr>
<td>Yellow 300 °C</td>
<td>0.999</td>
<td>27</td>
<td>5.29</td>
</tr>
<tr>
<td>New Black</td>
<td>0.3766</td>
<td>34</td>
<td>4.2</td>
</tr>
<tr>
<td>Black 100 °C</td>
<td>0.6447</td>
<td>30</td>
<td>4.76</td>
</tr>
<tr>
<td>Black 200 °C</td>
<td>1.1916</td>
<td>27</td>
<td>5.29</td>
</tr>
<tr>
<td>Black 250 °C</td>
<td>1.3176</td>
<td>25</td>
<td>5.71</td>
</tr>
<tr>
<td>New Blue</td>
<td>0.2170</td>
<td>44</td>
<td>3.25</td>
</tr>
<tr>
<td>Blue 100 °C</td>
<td>0.2322</td>
<td>41</td>
<td>3.48</td>
</tr>
<tr>
<td>Blue 200 °C</td>
<td>0.8332</td>
<td>30</td>
<td>4.76</td>
</tr>
<tr>
<td>Blue 250 °C</td>
<td>0.8682</td>
<td>22</td>
<td>6.49</td>
</tr>
</tbody>
</table>

The previous results showed that in yellow and blue greases there is minimal change in features between the new grease and the grease aged at 100°C. This can be attributed to their high dropping point compared to the black grease. Although the black grease has dropping point of 177°C, the pressure of the plates reduces it to lower value.

4.1.3 Fuzzy inference system results

After the fuzzy classification system was designed using the rule viewer, some inputs were fed into the system to test its operation. The inputs are chosen according to the real features extracted earlier. The result of the fuzzy system testing can be seen in the following Figures 4.7, 4.8, 4.9 and 4.10.
Figure 4.7 Classification of new grease.

When entering the values of scale and coefficient extracted from the new grease sample into the fuzzy system it classified the grease to be 72% new.
When the values of scale and coefficient extracted from aged sample at 100°C were entered into the fuzzy system, the grease was classified as 76% new.
Figure 4.9 Classification of 200°C aged grease.

The grease was classified to be 51% new once the values of scale and coefficient extracted from aged sample at 200°C were entered into the fuzzy system.
For the sample aged at 300°C, fuzzy system gave an output of 0% newness after the values of scale and coefficient were fed to it. The previous results prove that the fuzzy classification system operates as expected for all cases, except for the new grease, where the reading is lower than expected. This is because new greases have variation in feature values. The variation was attributed to bleed and separation of oil while being in the storage. Some oil has been detected when we have opened the container. The ranges of inputs were increased to cater for all the variations. Numeric percentage of newness was translated to three ranges, which reflected the actual grease condition according to Table 4.3.
Table 4.3 Ranges of grease condition.

<table>
<thead>
<tr>
<th>Range</th>
<th>Newness percentage</th>
<th>Grease visual characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>New</td>
<td>100-70%</td>
<td>New to minor oil bleed</td>
</tr>
<tr>
<td>Moderate</td>
<td>70-30%</td>
<td>Minor to major oil bleed</td>
</tr>
<tr>
<td>Old</td>
<td>30-0%</td>
<td>Major oil bleed to solidification</td>
</tr>
</tbody>
</table>

4.2 System Testing and Results Evaluation

4.2.1 Testing Using Stored Signals

Processing and classification routine were tested using signals stored in the workspace. Signal coefficients and scale are extracted and fed into the fuzzy classification system to determine the percentage of newness. The newness percentage is then translated into grease condition. Illustrations of the testing process and results can be viewed in Figures 4.11, 4.12, 4.13, 4.13 and 4.14.

Ultrasonic inspection is the most suitable inspection method for checking lubricant condition in static mechanisms whereas pulse-echo technique is the most common technique used in ultrasonic inspection. However, pulse-echo technique is usually used in thickness gauge to measure thickness of solid pieces of metal or used in weld and defect inspection. In lubricant inspection, ultrasound waves propagate through a specimen, which incorporate solids metal pieces and high viscosity liquid greases that have different impedances.

The reflection and penetration behavior of the ultrasound waves ‘signals cannot be anticipated theoretically and can only be obtained empirically. From the signals
obtained, data which describes the degradation of the grease is extracted after the processing. Then, this data is used as features which are translated by a fuzzy classification system into the condition of the inspected grease. Novel program routine for the processing, feature extraction and fuzzy classification is developed. Finally, the new method is then tested and validated with other samples.
Figure 4.11 New grease inspection results.

Figure 4.11 shows the condition of grease successfully interpreted by the system as 94% new and the condition was classified as ‘New’.
The grease newness percentage was successfully interpreted by the system as 81% new in the previous figure classifying the grease as ‘New’ as shown in Figure 4.12.
Figure 4.13 200°C aged grease inspection results.

The system shown in Figure 4.13, correctly classified the grease sample in the previous figure as ‘Moderate’ with a percentage of newness of 63%.
Figure 4.14 300°C aged grease inspection results.

Figure 4.14 displays how the condition of the degraded grease was classified correctly to be ‘Old’ based on its percentage of newness which was at 19.47%.
In the Figure 4.15, the new grease was misclassified as ‘Old’ because the scale value was out of the range of the fuzzy system. In some tests the new grease was misclassified as ‘Moderate’ because the features barely crossed the line between the two partitions in features space.

Out of 28 samples tested, 24 gave the results that matched the actual condition observed. Two of the samples which were misclassified gave features that were out of the range of the fuzzy classification system, while the other two were misclassified as it crossed the line into the adjacent partition in the feature space. The previous results indicate that the system have achieved inspection accuracy of 81%. By increasing the roles number and feature space of the fuzzy input, the ‘out of range problem’ could be solved.

**4.2.3 Real time inspection**

Real time inspection was done using a programming routine which acquires the signal, then process and classifies it. The real time inspection revealed results similar to
the test using stored signals. System operated within almost the same range of accuracy and in most cases interpreted the actual condition of the grease. Complete integrated program that acquires, process, classifies and gives the grease condition was used in the real time inspection. Finally, the output of the program was compared with the known condition of the sample inspected.

4.1.3 Using stored ultrasonic waveforms

Ultrasonic signals acquired from prepared samples were stored into Matlab workspace. Programing routine that processes the signal, extract the features then classifies them, was developed. The fuzzy inference system output of the age of the grease, was compared to the condition of the real sample.

Chapter Summary

This chapter consolidated the results achieved along the different stages of development. Results were presented according to experimental procedures in the first section. The second section presented the results gathered from the testing of the fuzzy classification system. The last section shows how the routine was developed and the overall system, based on the attained results, were tested and evaluated.
CHAPTER V

CONCLUSIONS & FUTURE WORK

This chapter concludes the thesis and summarizes the research contributions made. The benefits and the key findings of the research study and the achievements with respect to the objectives of the project are highlighted. In addition, this chapter also discusses the suggested future research.

5.1 Key findings of the Research

Results achieved from this research have proven that when the pulse-echo ultrasonic technique is applied, ultrasonic signals will have different traces depending on the grease condition. Changes of these traces appeared in all tested grease samples. This indicates that the pulse-echo technique can be utilized to monitor the condition of various types of grease. Furthermore, it was found that, by using wavelet processing, noise can be eliminated and therefore, features can be extracted successfully.

Different types of grease might have the same patterns to different ranges depending on their physical properties. Finally, it was confirmed that fuzzy classification system can be utilized effectively to indicate the grease conditions based on the features extracted.

5.2 Achievement of research objectives

This investigation has achieved the research objectives outlined in Section 1.3 by the successful development of a procedure to monitor grease condition, using the
pulse-echo ultrasonic techniques, wavelet processing and fuzzy based classification system. This section highlights the research objectives fulfilled with respect to the project. The achievements of the research are highlighted and discussed briefly, as follows:

- Comprehensive literature review was conducted to analyze static and dynamic systems inspection techniques, used in industry and scientific labs.
- Properties of the various greases were extensively studied and analyzed
- Hypothesis was established that ultrasonic techniques could be used for the inspection of static systems
- After hypothesis was defined the first objective of the research was to study whether new grease and old grease have different ultrasonic signal traces. Data collected from experiments have proven that greases of different ages have distinct ultrasonic traces.
- The second objective of this research was to develop a procedure that utilizes the ultrasonic traces to monitor the condition of grease in metal parts. Wavelet transform was implemented to de-noise the ultrasonic signals and find distinct patterns.
- Fuzzy system was developed in order to classify greases into their corresponding ages.
- Finally, the whole procedure was tested and evaluated.
5.3 Research Limitations and Future Work Recommendations

This project is an important step in the development of operational system that detects lubrication condition in static mechanisms. Thus:

1. More advanced phase array transducers might be required to sweep large areas of these different geometrical shaped assemblies without moving the transducer.
2. Investigate more the effect of temperature on the viscosity of the lubricant.
3. The variation due to multiple layers of solids in the detection of peaks.
4. Other improvements will be through improving the accuracy and precision of the inspection system to more grades of conditions. To achieve this, proper equipment to simulate the aging process is required.
5. Additionally, more samples that have variable ranges of condition are necessary because by having more samples the use of the more intelligent neural network classification methods, like deep learning, will be possible.
References


Programming routine

```matlab
obj1 = instrfind('Type', 'serial', 'Port', 'COM1', 'Tag', ''); % Find a serial port object.
if isempty(obj1)
    obj1 = serial('COM1'); % Create the serial port object if it does not exist
else
    fclose(obj1); % otherwise use the object that was found.
    obj1 = obj1(1);
end
set(obj1, 'BaudRate', 19200); % Configure instrument the serial port baud rate
set(obj1, 'FlowControl', 'hardware'); % Configure instrument the serial port baud rate
set(obj1, 'Timeout', 10); % Configure instrument the serial port timeout
set(obj1, 'InputBufferSize', 1000000); % Configure instrument serial port input buffer size
set(obj1, 'OutputBufferSize', 1000000); % Configure instrument serial port output buffer size
fopen(obj1); % Connect to instrument serial port

% Communicating with instrument serial port to set parameters
fprintf(obj1, ':CHANNEL1:RANGE 8;OFFSET 0');
fprintf(obj1, ':TIMEBASE:MODE NORMAL;RANGE 1E-5;DELAY 8E-6');
fprintf(obj1, ':ACQUIRE:TYPE NORMAL');
fprintf(obj1, ':ACQUIRE:COMPLETE 100');
fprintf(obj1, ':WAVEFORM:SOURCE CHANNEL1');
fprintf(obj1, ':WAVEFORM:FORMAT BYTE');
fprintf(obj1, ':WAVEFORM:POINTS 2000');
fprintf(obj1, ':WAVEFORM:DATA?');
% Acquire data from instrument serial port to set parameters
Signal = fread(obj1, 2011, 'uint8');
YINC = str2double(fscanf(obj1));
YREF = str2double(fscanf(obj1));
XINC = str2double(fscanf(obj1));
XREF = str2double(fscanf(obj1));
Signal = Signal-YREF;
Signal = Signal*YINC;
T=0:XINC:(LSignal-1)*XINC;
Tend=T(end);
% Apply wavelet transform to the acquired signal c=cwt(Signal(550:1400),1:48,'db4');
[coef scal]=max(max(c')); % Extract features from the wavelet transform
f = readfis('C:\Users\Fadi\Desktop\fuzzy.fis'); % Read the fuzzy system data
per=evalfis([coef scal], f); % Input features into the fuzzy system
% Evaluate the grease condition based on the fuzzy output
if per >= 70
    cond = 'New';
```

APPENDIX-A
elseif (per > 30 & per < 70)
    cond = 'Moderate';
else
    cond = 'Old';
end

% Clear excess data
clear Signal;

clear T; clear Tend; clear XINC; clear per; clear c; clear f; cla;
YREF; clear XREF; clear YINC; clear LSignal; Disconnect the serial connection
fclose(obj1);

% Clean up all serial configuration
delete(obj1);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%

[System]
Name='classification'
Type='sugeno'
Version=2.0
NumInputs=2
NumOutputs=1
NumRules=9
AndMethod='prod'
OrMethod='probor'
ImpMethod='prod'
AggMethod='sum'
DefuzzMethod='wtaver'

[Input1]
Name='coefficient'
Range=[0.1 1]
NumMFs=3
MF1='small':'trapmf',[0.1 0.1 0.25 0.4]
MF2='medium':'trimf',[0.1 0.4 1]
MF3='large':'trapmf',[0.4 0.9 1 1]

[Input2]
Name='scale'
Range=[26 48]
NumMFs=3
MF1='small':'trapmf',[26 26 28 35]
MF2='medium':'trimf',[26 35 48]
MF3='large':'trapmf',[35 40 48 48]

[Output1]
Name='output1'
Range=[0 1]
NumMFs=3
MF1='New':'constant',[100]
MF2='Old':'constant',[50]
MF3='Degraded':'constant',[0]

[Rules]
%DEVICEOBJECT Code for communicating with an instrument.
% This is the machine generated representation of an instrument control
% session using a device object. The instrument control session comprises
% all the steps you are likely to take when communicating with your
% instrument. These steps are:
% 1. Create a device object
% 2. Connect to the instrument
% 3. Configure properties
% 4. Invoke functions
% 5. Disconnect from the instrument
% To run the instrument control session, type the name of the file,
% deviceobject, at the MATLAB command prompt.
% The file, DEVICEOBJECT.M must be on your MATLAB PATH. For additional
% information on setting your MATLAB PATH, type 'help addpath' at the MATLAB command
% prompt.
% Example:
% deviceobject;
% See also ICDEVICE.
% Creation time: 12-Jan-2018 19:53:42

Create a SERIAL object.
interfaceObj = instrfind('Type', 'serial', 'Port', 'COM3', 'Tag', ');
% Create the SERIAL object if it does not exist
% otherwise use the object that was found.
if isempty(interfaceObj)
    interfaceObj = serial('COM3');
else
    fclose(interfaceObj);
    interfaceObj = interfaceObj(1);
end
% Create a device object.
deviceObj = icdevice('tektronix_tds2012B.mdd', interfaceObj);
% Connect device object to hardware.
connect(deviceObj);
% Execute device object function(s).
groupObj = get(deviceObj, 'Waveform');
groupObj = groupObj(1);
[y,x] = invoke(groupObj, 'readwaveform', 'channel1');
% Connect device object to hardware.
connect(deviceObj);
groupObj = get(deviceObj, 'Waveform');
groupObj = groupObj(1);
[y,x] = invoke(groupObj, 'readwaveform', 'channel1');
% Connect device object to hardware.
connect(deviceObj);
groupObj = get(deviceObj, 'Waveform');
groupObj = groupObj(1);
[y,x] = invoke(groupObj, 'readwaveform', 'channel1');

% Connect device object to hardware.
connect(deviceObj);

% Execute device object function(s).
groupObj = get(deviceObj, 'Waveform');
groupObj = groupObj(1);
[y,x] = invoke(groupObj, 'readwaveform', 'channel1');

% Delete objects.
delete([deviceObj interfaceObj]);
set(obj1, 'BytesAvailableFcnCount', 20);
set(obj1, 'RecordMode', 'index');
set(obj1, 'BytesAvailableFcnMode', 'byte');
set(obj1, 'RecordMode', 'terminator');
set(obj1, 'RecordMode', 'index');
set(obj1, 'FlowControl', 'hardware');
set(obj1, 'Timeout', 10);

% Configure instrument object, obj1
set(obj1, 'InputBufferSize', 1000000);
% Configure instrument object, obj1
set(obj1, 'OutputBufferSize', 1000000);
% Connect to instrument object, obj1.
% Connect to instrument object, obj1.

fclose(obj1);

% Disconnect from instrument object, obj1.
close(obj1);
% Clean up all objects.
delete(obj1);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%
t=0.5:5e-3:5;
subplot(211);
plot(t,YG_200_5(500:1400))
xlabel('Time (us)');
ylabel('Voltage (V)');
subplot(212);
c=cwt(YG_200_5(500:1400),1:48,'db4');
c=(c-min(c(:)) / (max(c(:))-min(c(:)));
imagesc(t,1:48,c); colormap hot;
xlabel('Time (us)');
ylabel('Scale');
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

find a serial port object.

obj1 = instrfind('Type', 'serial', 'Port', 'COM3', 'Tag', ' ');
%fopen(obj1);
% Create the serial port object if it does not exist
% otherwise use the object that was found.
if isempty(obj1)
    obj1 = serial('COM3');
else
    fclose(obj1);
    obj1 = obj1(1);
end
% Disconnect from instrument object, obj1.
close(obj1);
% Create a SERIAL object.
interfaceObj = instrfind('Type', 'serial', 'Port', 'COM3', 'Tag', ' ');
% Create the SERIAL object if it does not exist
% Configure instrument object, obj1.
set(obj1, 'BaudRate', 192000);
set(obj1, 'BytesAvailableFcnMode', 'byte');
set(obj1, 'BytesAvailableFcnMode', 'terminator');
set(obj1, 'BytesAvailableFcnCount', 20);
set(obj1, 'RecordMode', 'index');
set(obj1, 'FlowControl', 'hardware');
set(obj1, 'Timeout', 10);
% Configure instrument object, obj1
set(obj1, 'InputBufferSize', 1000000);
% Configure instrument object, obj1
set(obj1, 'OutputBufferSize', 1000000);
% otherwise use the object that was found.
if isempty(interfaceObj)
    interfaceObj = serial('COM3');
else
    fclose(interfaceObj);
    interfaceObj = interfaceObj(1);
end
% Create a device object.
deviceObj = icdevice('tektronix_tds2012B.mdd', interfaceObj);
% Execute device object function(s).
groupObj = get(deviceObj, 'Waveform');
groupObj = groupObj(1);
% Query property value(s).
%get1 = get(deviceObj, 'InstrumentModel');
%get2 = get(deviceObj, 'VerboseEnabled');
%get3 = get(deviceObj.Acquisition(1), 'AcquisitionCount');
%get4 = get(deviceObj.Acquisition(1), 'Delay');
%get5 = get(deviceObj.Acquisition(1), 'Timebase');
%get6 = get(deviceObj.Acquisition(1), 'WindowTimebase');
%get7 = get(deviceObj.Acquisition(1), 'WindowTimebase');
% Configure property value(s).
set(deviceObj.Acquisition(1), 'WindowTimebase', 1.0E-5);
set(deviceObj.Acquisition(1), 'WindowTimebase', 1.0E-4);
set(deviceObj.Acquisition(1), 'Delay', 8E-6);
set(deviceObj.Waveform(1), 'ByteOrder', 'littleEndian');
set(deviceObj.Waveform(1), 'Precision', 'uint8');
set(deviceObj.Acquisition(1), 'Control', 'single');
set(deviceObj.Acquisition(1), 'Mode', 'peakDetect');
set(deviceObj.Acquisition(1), 'State', 'run');
connect(deviceObj);
groupObj = get(deviceObj, 'Waveform');
groupObj = groupObj(1);
[y,x] = invoke(groupObj, 'readwaveform', 'channel1');

[System]
Name='load'
Type='mamdani'
Version=2.0
NumInputs=2
NumOutputs=1
NumRules=25
AndMethod='min'
OrMethod='max'
ImpMethod='min'
AggMethod='max'
DefuzzMethod='centroid'

[Input1]
Name='PV'
Range=[0 8000]
NumMFs=5
MF1='VS':trimf,[-2000 -2.842e-014 2000]
MF2='S':trimf,[0 2000 4000]
MF3='M':trimf,[2000 4000 6000]
MF4='L':trimf,[4000 6000 8000]
MF5='VL':trimf,[6000 8000 10000]

[Input2]
Name='Load'
Range=[0 8000]
NumMFs=5
MF1='VS':trimf,[-2000 -2.842e-014 2000]
MF2='S':trimf,[0 2000 4000]
MF3='M':trimf,[2000 4000 6000]
MF4='L':trimf,[4000 6000 8000]
MF5='VL':trimf,[6000 8000 10000]

[Output1]
Name='Grid'
Range=[-8 8]
NumMFs=9
MF1='VN':trimf,[-10 -8 -6]
MF2='BN':trimf,[-8 -6 -4]
MF3='N':trimf,[-6 -4 -2]
MF4='SN':trimf,[-4 -2 0]
MF5='Z':trimf,[-2 0 2]
MF6='SP':trimf,[0 2 4]
MF7='P':trimf,[2 4 6]
MF8='BP':trimf,[4 6 8]
MF9='VP':trimf,[6 8 10]

[Rules]
1 1, 5 (1) : 1
1 2, 4 (1) : 1
1 3, 3 (1) : 1
1 4, 2 (1) : 1
1 5, 1 (1) : 1
2 1, 6 (1) : 1
2 2, 5 (1) : 1
2 3, 4 (1) : 1
2 4, 3 (1) : 1
2 5, 2 (1) : 1
3 1, 7 (1) : 1
3 2, 6 (1) : 1
3 3, 5 (1) : 1
3 4, 4 (1) : 1
3 5, 3 (1) : 1
4 1, 8 (1) : 1
4 2, 7 (1) : 1
4 3, 6 (1) : 1
```matlab
% obj1=(':RANGE 8;OFFSET 0');
% obj1=(':TIMEBASE:MODE NORMAL;RANGE 1E-5;DELAY 8E-6');
% obj1=(':ACQUIRE:TYPE NORMAL');
% obj1=(':ACQUIRE:COMPLETE:100');
% fprintf(obj1, ':WAVEFORM:SOURCE CHANNEL1');
% obj1=(':ACQUIRE:COUNT 20');
% obj1=(':WAVEFORM:FORMAT BYTE');
% obj1=(':WAVEFORM:POINTS 2000');
% obj1=(':WAVEFORM:DATA?');
Signal = uint8(obj1);
obj2=(':WAVEFORM:YINCREMENT');
%obj2=(obj1);
YINC = str2double(obj2);
obj3=(':WAVEFORM:YREFERENCE');
%obj3=(obj1);
YREF = str2double(obj3);
obj4=(':WAVEFORM:XINCREMENT');
%obj4=(obj1);
XINC = str2double(obj4);
obj5=(':WAVEFORM:XREFERENCE?');
%obj5=(obj1);
XREF = str2double(obj5);
Signal = Signal-YREF;
Signal = Signal*YINC;
LSignal=length(Signal);
T=0:XINC:(LSignal-1)*XINC;
Tend=T(end);
c=cwt(Signal(550:1400),1:48,'db4');
[a b]=max(max(c'));
f = readfis('C:\Users\user\Desktop\classification(y).fis');
per=evalfis([a b], f);
if per > 75
    s = 'New';
elseif 75 > per > 50
    s = 'Moderate';
else
    s = 'Old';
end
clear Signal;
clear T;
clear Tend;
clear XINC;
clear per;
clear c;
clear f;
```
clear YREF;
clear XREF;
clear YINC;
clear LSignal;
clear obj2;
clear obj3;
clear obj4;
clear obj5;
Disconnected all objects.
fclose(obj1);
Clean up all objects.
delete(obj1);
clear ;
## APPENDIX-B

### List of Equipment’s

<table>
<thead>
<tr>
<th>Part Model &amp; Number</th>
<th>Qty.</th>
<th>Description</th>
<th>Purchasing source Link</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>5077PR will work with both lower (i.e. 10MHz) and higher up to 75MHz probes, however when testing through 20mm Aluminium plate 20MHz will likely be the limit of the resolvable returned signal</td>
<td></td>
</tr>
<tr>
<td>Item</td>
<td>Quantity</td>
<td>Description</td>
<td>URL</td>
</tr>
<tr>
<td>----------</td>
<td>----------</td>
<td>-----------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------</td>
</tr>
<tr>
<td>Lubrimatic Grease</td>
<td>1</td>
<td>Lubrimatic marine Grease454g Can</td>
<td></td>
</tr>
<tr>
<td>Abro Grease</td>
<td>1</td>
<td>ABRO SYNTHETIC #3 BLUE LITHIUM GREASE TUB 454g</td>
<td><a href="http://varietypaints.com.au/products/abro-synthetic-3-blue-lithium-grease-tub">http://varietypaints.com.au/products/abro-synthetic-3-blue-lithium-grease-tub</a></td>
</tr>
</tbody>
</table>