YRKESHÖGSKOLAN NOVIA

Evaluation of Oil Condition Monitoring sensors

Wärtsilä Finland

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Bachelor's thesis

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EXAMENSARBETE

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Titel: Utvärdering av givare som övervakar smörjoljans kvalitet

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Abstrakt

Detta examensarbete har utförts på uppdrag av forskning-, och utvecklingsavdelningen vid Wärtsilä Finland. Syftet med detta examensarbete var att utvärdera givare som övervakar smörjoljans kvalitet. I den teoretiska delen av arbetet redogörs för smörjoljors egenskaper, och de olika metoderna för konditionsövervakning av smörjoljor presenteras. De utvalda givarna presenteras och deras underliggande teknologi förklaras. Teoridelen utgör en botten för formuleringen av en hypotes och används som referens vid tolkning av resultaten. Utvärderingen görs genom att efterbilda två typiska fall av smörjoljekontaminering och studera givarnas respons. Smörjoljan kontamineras med vatten och diesel i respektive test. Testplaner för båda fallen gjordes upp och testades i en testrigg för att verifiera hypotesen och för att se i vilket skede givarna känner av kontaminering.

Resultaten visar att givare som mäter förändringar i smörjoljans elektriska egenskaper, kan detektera vatten-oljeemulsioner i låga koncentrationer. Detekteringsförmågan för diesel-oljeemulsioner är svag. Resultaten visar att givare som mäter viskositet är kapabla att detektera diesel-oljeemulsioner i låga koncentrationer.

Språk: engelska
Nyckelord: smörjolja, givare, tillståndsbevakning av smörjolja

BACHELOR'S THESIS

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Abstract

This thesis was done on the behalf of the research and development department of Wärtsilä Finland. The purpose of this thesis is to evaluate different oil condition monitoring sensors. In the literature part of the thesis, the properties of lubricants were studied, and different methods for oil condition monitoring are presented. The selected sensors are presented, and their respective technologies are studied. The literature part serves as a base for formulating the hypothesis and as reference for interpreting the results. The evaluation was done by replicating two typical lubrication oil contamination cases and studying the response of the sensors. The lubrication oil is contaminated with water and diesel in respective tests. A test plan for each case was set up and tested in a test rig to verify the hypothesis and to see at what stage the sensors detect the contaminant.

The results imply that sensors based on measuring electric property changes are capable of detecting water-oil emulsions in low concentrations. Their ability to detect diesel-oil emulsions is weak. The results show that sensors measuring viscosity are capable of detecting diesel-oil emulsion in low concentrations.

Language: English

Key words: oil condition monitoring, on-line, lubrication oil

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PREFACE AND ACKNOWLEDGEMENTS

While studying my third year of my bachelor's degree in mechanical engineering I applied for a summer internship at Wärtsilä. I was contacted by Mr. Mathias Björklund, manager for a component expertise team called Ancillary Systems. He was looking to hire a summer trainee to join their component expertise team for the summer. After a series of interviews, I was hired to the team as a summer trainee. I was introduced to this topic early in the summer and began by commissioning a test station that would later be used in this work. During the end on my internship, we began discussing the possibility to write a B.Sc. thesis about oil condition monitoring sensors. We agreed that this would be a suitable topic, as I had gained knowledge and contacts during the summer.

I would like to thank everybody at Wärtsilä for the support I received during the process and for giving me the opportunity to conduct this thesis work. I would especially like to thank Oscar Sunngren for his support throughout the whole process. I would also like to thank my supervisor from Novia University of Applied Sciences, Kenneth Ehrström, for reviewing and assessing the thesis.

ABBREVIATIONS

AC =Alternating current

cSt = Centistoke

cP = Centipoise

LF = Loss factor

TBN = Total Base Number

PPM =Parts Per Million

VI = Viscosity Index

1 Introduction

Lubrication oil is the blood of the engine. It is one of the most important components in an engine since it directly influences the engine's operation. Lubrication oil serves many important roles within the engine, it circulates thru the engine, lubricating surfaces and cooling the components. The stress that is subjected to the lubricant, causes its properties to degrade over time. As lubrication is such an important part of any engine, it is routinely analysed or changed, to ensure that the quality of it is within certain predetermined limits. By analysing the lubricant oil of an engine much more than the lubricants condition can be found. It provides in-depth information of the engine's health during the time of the analysis. By doing this, early signs of wear can be detected, and counter-active measures can be taken. The two most common contaminants found in lubrication oils are fuel residuals and water, both of which are harmful for the lubricant oil and the engine internals. It is therefore in the operator's best interest to monitor the condition of the lubrication oil, in order to save both time and money.

Increasing machine costs and strict user requirements regarding its availability has forced manufacturers to develop and incorporate different condition monitoring system into their products. Many engine manufacturers are today offering so called on-line oil condition monitoring. The on-line method allows the lubrication oil to be continuously monitored, providing the earliest possible warning to the operator of the engine. This method is becoming increasingly more popular thanks to the developments in sensor technology and as a clear benefit of using the method is seen. However, it should be noted that lubrication oils are complex and are affected by the ever-changing conditions of the engine. Therefore, the quality of the lubrication oil cannot easily be determined by measuring one single property. Typically, several different parameters, and therefore sensors, are used to monitor the lubricant oil. By combining the two methods (off-line and in-line) the highest possible reliability and efficiency of the engine can be reached.

"You can't manage what you don't measure."

- Peter Drucker -

1.1 Wärtsilä in brief

Wärtsilä is a world leader in advanced technology and complete lifecycle solutions that is shaping the marine and energy market. The company employs over 17000 professionals worldwide, operating in 68 countries. Wärtsilä's vision is to enable sustainable societies through innovation in technology and services. (Wärtsilä, 2022). Wärtsilä is a committed partner that supports its customers on their decarbonization journey. Wärtsilä's aim is to be carbon neutral in its operations by 2030 and having a product portfolio ready for zero carbon fuels by 2030 (Wärtsilä, 2022).

1.2 Background

Wärtsilä has been approached by its customers, requesting help with lubrication related issues. The issues are related to both water and fuel diluting the lubrication oil which is leading to breakdowns. In severe cases complete engine overhauls have been done, causing customers to spend excessive amount of time and money. Other customers want to monitor their lubricant to ensure that no unexpected changes go unnoticed.

As of today, Wärtsilä offers water-in-oil sensors for their customers, this is however not useful to all. Therefore, Wärtsilä decided to investigate if a solution with additional capabilities could be offered. This solution could then be offered to customers for retrofits and new builds. A potential solution was discussed in the company some years ago, when a solution was offered by a third-party service provider. The offered concept was tested and had a positive reception from customer side, but the offered business model was unacceptable, and co-operation did not proceed.

Currently the aim is to develop and offer a standard solution that consists of one or more sensors which allow the oil to be monitored in a satisfactory way. The solution should be simple at first but the ability to develop the system further is of course beneficial. One proposed solution would be to have a user interface where the condition of the lubrication oil is given in a simple way, for example with a "traffic light".

Today, there are many companies that have specialized in oil condition monitoring and are actively offering their solutions to Wärtsilä. Some companies offer hardware, some partnership. In order to support this project a testing rig for sensors was setup in the summer of 2022, with the purpose to test acquired sensors in order to verify their capabilities.

1.3 Purpose

The purpose of this thesis is to understand how the selected sensors work and then assess them based on their performance in the test rig. The purpose of the test is to see if the acquired sensors can detect typical dilution cases. Wärtsilä has its own standards relating to lubrication oil quality which will be used as reference in testing. The ulterior purpose will be to compare the cost of the acquired sensors, in order to get a fair comparison.

1.4 Goal

The goal of this thesis is to find a sensor or sensors that are able to detect diesel and water dilution in lubrication oil as early as possible. The result of this thesis will serve as a support for further testing in field and in-house. This thesis will also develop know-how within the company.

1.5 Delimitation

On-line oil condition monitoring is actively discussed within the company, new problems and opportunities are discovered on a regular basis. As there is limited time and not to go off topic delimitation must be considered. As earlier mentioned, water and diesel fuel are the two most common contaminants affecting the condition of the lubricant oil today. Therefore, this thesis will be delimited to these two dilution cases.

1.6 Disposition

- Introduction: Serves as an introduction to give the reader and overview of the current situation in the company and to give a brief introduction to the subject.

- Lubrication oil: The properties of lubrication oil are studied from a theoretical standpoint.

- Oil condition monitoring: Different principles of oil condition monitoring are presented, and pros and cons are listed. This chapter also serves as support from a theoretical standpoint for understanding how the sensor work.

- Sensors: In this chapter the sensors included in testing are presented.

- Method: This chapter describes what equipment was used to test the sensors and how the testing was done.
- Hypothesis: A hypothesis is presented based on the literature review.
- Results: The result from testing is presented. Individual sensors are assessed based on their performance in the test.
- Discussion: Discusses the work in its whole and conclusions are presented. Recommendations for further work is presented.

2 Lubrication oil

Lubrication oil has many purposes within an engine, such as reducing friction between moving parts, heat-, and power transfer, transporting wear particles, protecting against corrosion etc. This causes stress on the lubricant which eventually starts to degrade the additives. Contamination is another factor that affects the lifetime of the lubricant. These contaminants originate within the engine as combustion products or from external sources. In order to prevent excessive wear of the engine components the lubrication oil must be changed, or its properties must be enhanced. (Barwell, 1984).

Lubrication oil is seldom changed in medium speed diesel engines, instead the properties of the lubricant are enhanced by a process called sweetening. Sweetening is done by adding fresh lubrication oil to the engine in order to compensate for the depleted additives. Artificial sweetening must be done in severe cases, where the oil has been contaminated or depleted to such an extent that simply sweetening of the oil cannot be done, to not overfill the engine. Artificial sweetening is done by draining some of the used oil and then replacing it with fresh oil. The best-case scenario is when the oil is depleted at a phase that matches the lubrication oil consumption of the engine. In this case, only regular topping-up is required. (Granlund, 2023).

2.1 Additives

Additives are chemical compounds that are added to the base oil in order to prevent the lubricant breaking down prematurely. Additives enhance some of the existing properties of the base oil, others are used to combat the formation of undesirable compounds. The type and number of additives used vary between lubrication oils, in some cases a lubricant can consist of up to 30 % of different additives. On the other hand, additives also have side effects. They may affect other additive compounds in a harmful way, hence, and an optimum balance must be found. (Willis, Additives, 1980).

Additives can be sorted into groups according to their function. The performance properties of the oil will remain relatively unchanged until the additives are consumed. (Barwell, 1984)

- Corrosion inhibitors react with a metal surface forming a protective coating to prevent corrosion of the engine internals. Corrosion inhibitors are used to neutralize strong acids that form in the combustion process, these strong acids cause corrosive wear on engine components.
- Oxidation inhibitors are used to counter the chemical breakdown caused by heat.
- Detergents and dispersants provide a cleaning function by removing deposits from metal surfaces and bulk deposits.
- Viscosity Index improvers improve the viscosity of the oil at certain temperatures.
- Emulsion modifiers are added to achieve a stable emulsion of water-in-oil. Demulsifies also exist which in turn makes the emulsion of water-in-oil unstable allowing the separation of water.
- Foam decomposers providing a low surface tension allowing gas bubbles to escape.

Figure 1 illustrates where the additives serve their function within an engine

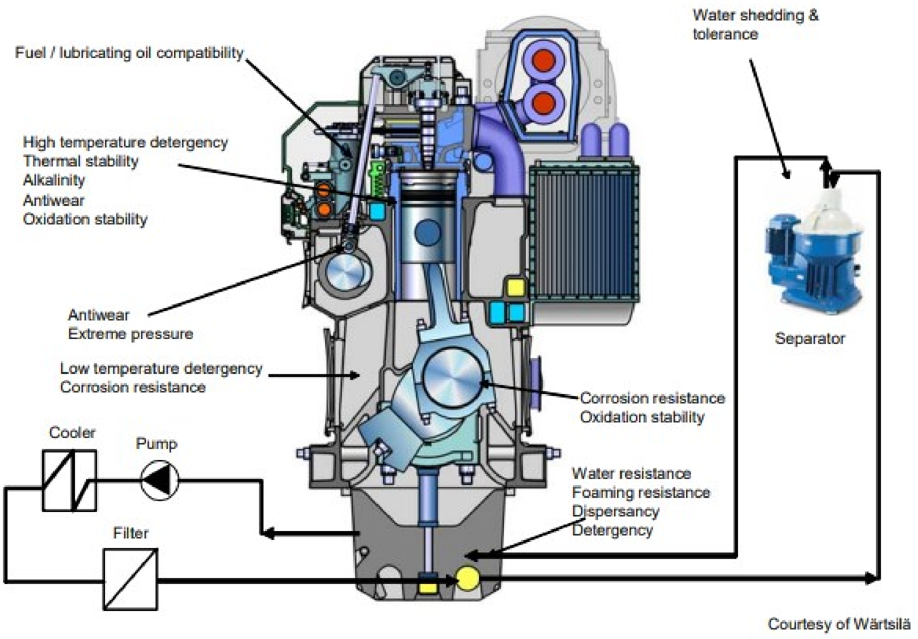

Figure 1 Additives within an engine. (CIMAC, 2008).

2.2 Water dilution

Water can in some cases be introduced to the lubricant oil from internal sources such as leaking components. In small amounts water can be dissolved into the oil, but if a significant amount is introduced it can be harmful for the engine. The presence of free-, or emulsified water in a lubrication system has many negative effects, mainly it decreases the load carrying capacity of the lubricant film leading to excessive wear. Water presence in oil causes other problems also, such as (Promaint ry, 2013):

- Corrosion of the internal components.
- Acid formation, speeding up the ageing process.
- Cavitation damages in bearings and other components
- Foaming of the oil, leading to a reduced heat transfer
- Hydrogen embrittlement, making the steel brittle and prone to cracking.

A water-oil emulsion can cause micro-pitting. The emulsion is exposed to a high pressure, causing the water droplets to implode. Water vapour is created by the high pressure which pushes away the lubricant film resulting in a metal-to-metal contact. (CJC Jensen, 2019).

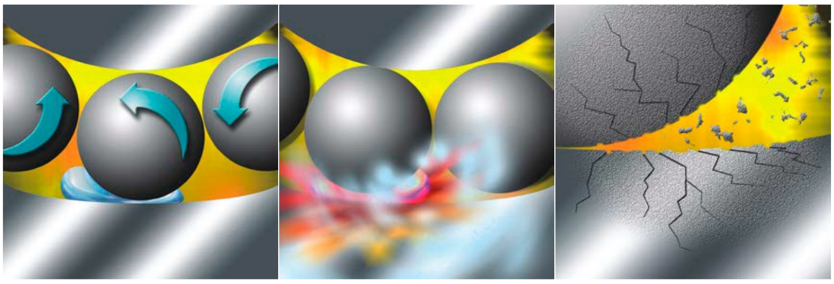

Figure 2 Water droplets are exposed to a high pressure, which results in an implosion, causing the bearing surface to crack and releasing particles. (CJC Jensen, 2019).

As briefly mentioned, water can exist in three different phases in lubrication oil; dissolved-, emulsified- (saturated) or as free water. The most harmful phases are emulsified and free water, since these lead to lowered load carrying capacity, resulting in wear of the engine components. All fluids, including lubrication oil, have an ability to dissolve a certain amount of water. The amount of water that can be dissolved is dependent on the saturation point of the lubricant. When the saturation point is reached, the lubrication oil cannot absorb more water, and a water-oil emulsion is formed. In this phase microscopic droplets can be found mixed within the lubricant oil. The water-oil emulsion appears hazy. If more water is introduced, the two fluids will separate from each other completely, resulting in a layer of free water. (Rudolphi & Kassman, 2014).

The amount of water that a lubricant oil can dissolve depends on many factors, such as, base stock (mineral or synthetic oil), temperature, pressure, additives, and the condition of the oil. Due to the dynamic nature, saturation curves for lubricants do not readily exist, as they have little to no use since the saturation curve will change as the lubricant starts to wear down. Figure 3 illustrates a fictive saturation curve for a lubricant. (Promaint ry, 2013).

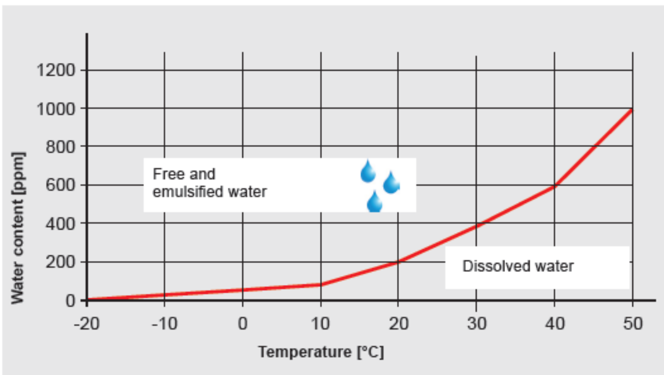

Figure 3 Saturation limit of water in oil. (Hydac filter systems GMBH).

Two main types of solutions have been developed for measuring water in oil. One type of measurement is absolute water content. This measures the absolute water content in the lubrication oil in PPM. This is uncommon practice, since it does not give any indication of how close to the saturation point the lubricant oils is. As earlier mentioned, emulsified and free water are the most harmful phases for a lubricating system. Knowing when the saturation limit has been reached is therefore valuable information. (Vaisala, 2009)

The more commonly used method is to measure relative saturation (%) which gives indication of how close the moisture level is to the lubricant's oil saturation point. An oil that is 0 % saturated it means that it is free of water, and an 100% saturated oil means that the saturation point is reached. (Tic & Lovrec, 2017).

It is important to note that these are two completely different measures, saturation percentage (%) does not correspond to water content (ppm). In other words, one cannot determine the amount of water by knowing the saturation percentage, due to the dynamic nature of the lubricant.

Relative saturation Φ can be calculated with the equation:

$$\Phi = \frac{e_w}{e_{w,max}} \cdot 100\% \qquad (1)$$

Where:

- e_w quantity of water present in the oil
- $e_{w,max}$ is the maximum quantity of that can be present in the oil at a given temperature. (Tic & Lovrec, 2017).

Capacitive sensors are commonly used for measuring relative saturation in lubrication or hydraulic oils. The sensor consists of two electrodes with a polymer in between that allows water molecules to penetrate it, leading to a change in capacitance. (Fontes, 2004).

2.3 Diesel fuel dilution

Fuel is introduced to the lubricant via the combustion process, but can is some cases originate from other internal sources such as leaking components. Fuels diluting the lubrication oil is a common occurrence and does not cause severe problems if not diluted by several percentages. Dilution is considered excessive when it reaches 2,5 – 5 %. The fuel evaporates from the lubricant but causes harm to the additives. In large amounts, fuel dilution leads to a decrease in viscosity and a reduction in lubrication film strength. Fuel dilution directly or indirectly causes other problems also such as:

- Lowered flashpoint
- Additive depletion
- Accelerated wear
- Formation of soot and acids

Fuel dilution causes the flashpoint of the lubricant oil to be lowered. If the flashpoint is lowered to 150°C a serious risk of crankcase explosion exists. As such, fuel dilution is usually tested by measuring the flashpoint or viscosity of the lubricant. (Willis, Internal combustion engines, 1980).

3 Oil condition monitoring

Condition based maintenance is a maintenance strategy where information about the condition of an asset is collected. Based on this information the need of maintenance actions is assessed. Oil condition monitoring is considered an important part of any condition-based maintenance program, as early signs of breakdown can be seen from the lubrication oil. Studies show that 50 -70% of all equipment failures can be traced to lubrication-related issues (Des-case, 2021). Therefore, it is important to analyse the lubricant oil routinely as it informs about the engine’s current health. The purpose of the analyse is to identify the source of the contaminant and its rate of change. By comparing the sampled lubricant oil to fresh oil, the current condition of it can be assessed. (Promaint ry, 2018).

Oil condition monitoring can be divided into three general groups:

- Off-line monitoring: an oil sample is taken which is analysed outside of the engine.
- In-line monitoring: Oil is analysed directly from the main flow with the help of sensors.
- On-line monitoring: Oil is by-passed from the main oil flow to a sensor and then returned.

Figure 4 illustrates the different methods of monitoring oil condition.

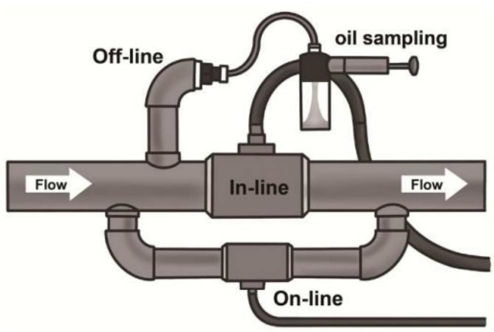

Figure 4 Methods of analyzing lubrication oil. (Promaint, 2018).

Off-line monitoring is done by taking a sample of the lubricant oil and analysing it elsewhere, outside of the engine. The method is commonly used as it provides the operator with a great deal of information and early signs of wear can be detected. These analyses are often done in laboratory conditions, which allow the lubricant to be analysed to a great extent, providing good insight to the current condition of the engine. (Promaint ry, 2018). Wärtsilä recommends an oil sampling interval of 500 running hours during the first year of engine operation. There after the recommended interval is 500 – 1000 running hours. (Wärtsilä Corporation, 2020).

Off-line method is an effective tool for monitoring lubrication oil condition, but it is directly linked to the sampling frequency. Due to the nature of this method, fast-developing faults are hard if not impossible to catch. Information is received with a delay, during which, the conditions of the engine have changed and the result from the analysis is outdated. It can also be hard to relate result from the analyse to the engine's condition of the time of sampling. However, in most cases, changes in lubrication oil condition tend to happen slowly, and the signs of brake down can be seen at an early stage by using the off-line method. (Des-case, 2021).

Development in mechatronics has allowed further use of the on-line / in-line method and is widely used today in many different machines. This type of monitoring is done with sensors that continuously monitor the lubrication oil condition. This method has its advantages, possibly the greatest advantage being that the lubricant oil can be monitored continuously. This allows detection of sudden changes in the oil. In other words, lubricant oil quality can be monitored in real-time. The method has many indirect benefits, such as extending the lifetime of the lubricant as faults are detected early on. Another valuable feature is that data is collected and stored, which allows later analysis. (Tic & Lovrec, 2017). The disadvantage of the on-line method is that it does not give the same depth information as a laboratory analysis would. (Des-case, 2021). The exact source of the problem might be hard to pinpoint.

An important thing to remember when monitoring lubrication oil with any of the stated methods, is that the person understands what is being presented. Since decisions are done based on the gathered data, it is of high importance that the data is interpreted correctly. As lubrication oil degradation is in most cases a long-term process it is easy to overlook the small changes. (Conwan, 2012).

3.1 On-line oil condition monitoring

There are many existing techniques for on-line oil condition monitoring. The most common techniques can be divided into three general categories:

- Electrical, the electric property of the lubricant oil is studied, usual parameters are permittivity, electric conductivity, magnetic susceptibility among others.
- Optical, the oil is analysed by optical sensor, often used for particle detection. This method is well suited for use in hydraulics since the oil is often clear even after a long period of use. As optical sensors require a clear fluid to function, these sensors are not suited for lubrication oils used in internal combustion engines as the oil darkens throughout its life.
- Physical, this method is based on measuring the physical of the lubricant as it correlates with the condition of the lubricant oil. Viscosity and density measurements belong in this category.

All techniques have their own advantages and are best fit for certain applications. (Promaintry, 2013). The flowchart below describes the relationship between causes of oil degradation, the affected performance parameters, and the methods used for detection.

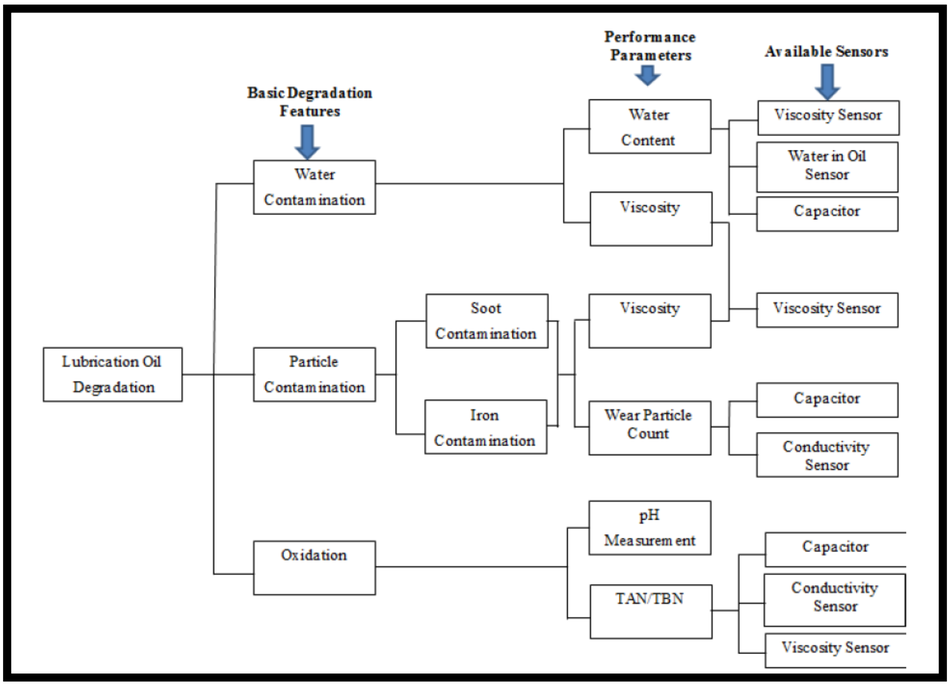

Figure 5 Summary of the basic causes for lubrication oil degradation and their effect on performance parameters. (Zhu, He, & Bechhoefer, 2013).

Figure 5 suggests that most degradation cases can be detected with the use of either a capacitance measuring or viscosity measuring sensor.

3.2 The physical properties of oil

As earlier stated, the physical properties of lubricants are well suited to assess its condition. Viscosity is often measured with on-line solutions since changes in viscosity can be linked to lubricant breakdown and dilution among other things. (Conwan, 2012).

3.2.1 Viscosity

Viscosity is an important property of any lubricant since it dictates a lubricants capability to provide a sufficient oil film thickness between two surfaces. Simply put, viscosity is the measure of a fluid's resistance to flow and can be thought of as a measure of fluid friction.

Viscosity is usually given as dynamic-, or kinematic viscosity. (Torbacke, Rudolphi, & Kassfeldt, 2014).

Viscosity is dependent on temperature, pressure, and shear rate. A high viscosity lubricant will result in a thicker lubricant film but requires more energy to move the surfaces. A high viscosity lubricant will affect the pumpability of the fluid, requiring more energy. A low viscosity lubricant results in a thinner lubrication film, but the drawback is a higher friction. Generally, the lubricant that has the lowest possible viscosity to keep the surfaces apart is desired. (Torbacke, Rudolphi, & Kassfeldt, 2014).

Dynamic viscosity η is a measure of a fluids resistance to deformation at a given rate.

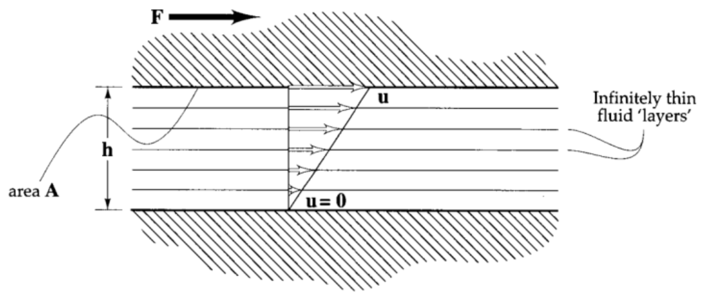

Figure 6 Lubricant separating two surfaces. (Stachowiak & Batchelor, 2005).

As previously mentioned, viscosity governs the lubrication oil film thickness. In Figure 6 the variables that affect dynamic viscosity are presented. The film thickness is given as "**h**", and the force required to move the upper surface is gives as "**F**". This force is proportional to the wetted area "**A**" and the share rate "**u/h**". The force required to shear the surface can be derived by using a rheometer. (Stachowiak & Batchelor, 2005).

The dynamic viscosity η can be calculated:

$$\eta = \frac{\left(\frac{F}{A}\right)}{\left(\frac{u}{h}\right)} \quad (2)$$

Dynamic viscosity is commonly also expressed in Pascal seconds or in centipoise (cP).

Another measure of viscosity commonly used is kinematic viscosity. Kinematic viscosity describes the ratio between dynamic viscosity and the density of the fluid.

Kinematic viscosity can be calculated:

$$u = \frac{\eta}{\rho} \tag{3}$$

Where:

u = Kinematic viscosity [m^2/s]

η = Dynamic viscosity [Pa s]

ρ = The fluid density [kg/m^3]

Viscosity for lubrication oils is commonly given as kinematic viscosity at 40°C and 100°C. The main reason for this is that kinematic viscosity is easier to measure. Kinematic viscosity is measured by letting the fluid flow through a capillary at a given temperature. Kinematic viscosity is then calculated based on the flow time. Kinematic viscosity is often given in centistokes (cSt). (Stachowiak & Batchelor, 2005).

When calculating the kinematic viscosity or dynamic viscosity, it is important to consider the density of the lubricant oil. Density is temperature dependent; it will decrease as the temperature increases. Lubrication oils typically have a density between 800 – 900 kg/m^3. (Stachowiak & Batchelor, 2005).

As earlier mentioned, viscosity is dependent on temperature. When temperature decreases viscosity of the oil will increase (becomes thicker) and vice versa. This temperature dependency is described by the **viscosity index**. The viscosity index (VI) is a property that is often mentioned when oil properties is discussed. An oil with a low VI will experience big changes in viscosity when the temperature changes. Oil with a high VI will have similar flow properties at a wider temperature span. VI is a unitless number that ranges from -60 to 400. (Anton Paar, 2018). The viscosity-pressure dependency can be neglected pressures below 400 bar (OelCheck, 2012).

3.3 The chemical properties of oil

Chemical properties are usually studied in a laboratory and cannot directly be monitored by on-line method. However, an indirect indication of the degradation of chemical properties can be detected.

3.3.1 Total Acid Number

Total Acid Number (TAN) is a measure of acidic concentration present in a lubricant. TAN can be used to evaluate the condition of the lubricating oil since acids form when the lubricant ages. However, it is good to note that even new, unused, lubricants contain between 0,5 – 2,5 mg KOH/g acidic compounds. TAN is determined by titration and is given as mg KOH/g, a higher value indicates that the oil contains a greater number of acidic components and is aged. A high acidic content will lead to corrosion in the system. (Rudolphi, Kassfeldt, & Torbacke, 2014)

3.3.2 Total Base Number

Total Base Number or TBN indicates the number of alkaline additives present in the lubricant, expressed in mg KOH/g. A new unused lubricant will have a high TBN since the high concentration of alkaline additives. These are used for neutralizing acidic components that form in the lubricant as it ages. TBN will decrease as the additives are consumed leading to oxidation and increased viscosity. Like TAN, TBN is also a good indicator of the reminder of the lubricants remaining life. A too low base number will increase the risks of acidic corrosion, engine wear, and reduced component lifetime, and will be reflected in the maintenance cost. (Rudolphi, Kassfeldt, & Torbacke, 2014).

Some engines operate on fuels with high sulfur content, which will form more acids in the lubrication oil compared to low sulfur fuels. The acids formed causes corrosion; therefore, it is important that they are neutralized by the dispersants. Engines burning high sulfur fuels typically have a high concentration of TBN, which may reach 40 – 50. A fuel with lower sulfur content such as natural gas which is a very clean fuel can use an oil with a lower TBN. A high TBN oil is not recommended to be used when not needed, as there are side effects, such as ash formation. (Wärtsilä Corporation, 2020) (Rudolphi, Kassfeldt, & Torbacke, 2014).

3.4 The electrical properties of oil

The condition of a lubrication oil can be evaluated by measuring its electric properties. Lubrication oils are fluids with low dielectric losses, meaning that they are good electric insulators with low electric conductivity. When the lubrication oil degrades it is reflected in said properties. Most of the sensors on the market are based on measuring this change by measuring permittivity and conductivity at a certain frequency. (Tic & Lovrec, 2017).

3.4.1 Capacitance

Capacitance, C, is a measure of materials ability to store an electric charge. It is an electrical property that exists between two conductor plates that are separated by a non-conductor. When a voltage is applied to one of the two conductor plates an electric field is formed, due to the difference between electric charge between the two plates. Capacitance is affected by three things, the size of the plates, the distance between them, and the material which is in the gap between the plates. (Morris, 2001).

Capacitance is given in Farads and calculated by the formula:

$$C = \frac{\varepsilon \cdot A}{d} \tag{4}$$

Where:

ε = Absolute permittivity [Farads / meter]

A = Area of the plates [m^2]

d = the distance between the plates [m]

If the area and the distance between the plates remains the same, such as in sensors, capacitance will only be dependent on the measured material's absolute permittivity. A material with a high absolute permittivity hence will increase the capacitance.

The absolute permittivity can be calculated by the formula (Morris, 2001).:

$$\varepsilon = \varepsilon_0 \cdot \varepsilon_r \quad (5)$$

Where:

ε_0 = Permittivity of free space (8.8562 x 10^{-12} F/m)

ε_r = Dielectric constant of the measured material

3.4.2 Permittivity and Relative permittivity

Permittivity, ε, is a physical property of a material that describes how well the material can store electrical energy (become polarized) when an external electric field is applied. Permittivity is given as Farads per meter.

Relative permittivity, ε_r, even called dielectric constant, is the ratio between permittivity of the measured material and the permittivity of a vacuum. Relative permittivity is a scalar. It describes how well a material can store electric energy compared to a vacuum. Vacuum is used as the reference as it has the lowest possible ability to polarize in a response to an electric field. Thus, the relative permittivity of vacuum is 1.0. (Lvovich, 2012).

Relative permittivity can be calculated by the formula:

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0} \quad (6)$$

Where:

ε = Measured materials permittivity (F/m)

ε_0 = Permittivity of free space (8.8562 x 10^{-12} F/m)

In Table 1 dielectric constants are listed for lubrication oils and other common materials. As seen, the dielectric constant is low for most lubrication oils, while for example, water has a high dielectric constant.

Table 1 Dielectric constants of common materials. (Emerson Process Management, 2001).

Vacuum	1.0 (by definition)
Metals	Infinite
Gases	1.00xx (at one atmosphere)
Water	87.9 (0°C) to 55.5 (100°C)
Hexane	1.8865 (20°C)
Cyclohexane	2.0243 (20°C)
Benzene	2.285 (20°C)
Hydrocarbon lubrication oils	2.1 to 2.4 (room temperature)

Table 1. Dielectric Constant of Common Materials

Oil Class	Dielectric Constant
Hydrocarbon	2.1-2.4
PAO	2.1-2.4
PAG	6.6-7.3
Polyol Ester PAG	4.6-4.8
Diester	3.4-4.3
Phosphate Ester	6.0-7.1

Table 2. Dielectric Constant of Lubrication Oils

Dielectric constant is temperature (density) dependant but has small effects on hydrocarbon oils (0.001 / °C). Other factors that affect the dielectric constant aside from density, is moisture levels, measurement frequency, and part thickness. An elevated dielectric constant can indicate many things, such as contamination of water, presence of wear particles, or oxidation. A rule of thumb is that if lubricants change in the dielectric constant is greater 0.01, it should be analysed by conventional methods. (Emerson Process Management, 2001) (Carey, 1998) It has been proven that by measuring the dielectric constant of a lubricant oil, water contamination, oxidation, and wear particles can be detected (Schmitigal & Moyer, 2005).

3.4.3 Complex permittivity

In an alternating electric field permittivity is given as a complex value. Complex permittivity, ε^*, has both a real part (ε') and an imaginary part (ε''). The real part describes how well a material can store an electric charge when an external electric field is applied, as earlier mentioned. The real part is measured in Farads per meter. The imaginary part ε'' is a measure of the dielectric losses. Nothing is perfect, all materials dissipate energy if form of heat and other energy forms, these losses can be determined in many ways, for example, by measuring conductance. (Oliver, 2013).

The ratio between these two quantities is often referred to as dissipation factor. (Agilient Technologies, 2009).

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} \tag{7}$$

The dissipation factor describes how much lossy a material is. The increase is influenced by polar components and impurities that are found in the oil (OelCheck, 2011). The degradation of lubrication oil should be seen as an increase of the imaginary part complex permittivity since lubrication oils typically have low dielectric losses.

3.4.4 Electrical conductivity and resistivity

Electrical conductivity, σ, is the measure of a materials ability to conduct electrical current. The standard unit used for measuring electrical conductivity is Siemens per meter. Electric conductivity can be calculated by the formula:

$$\sigma = \frac{L}{R \cdot A} \tag{8}$$

Where:

L = length of the conductor (m)

R = Electrical resistance of conductor (Ohm)

A = Area of the conductor’s cross-section (m^2)

Resistance, ρ, is a reciprocal of conductivity. It is a measure of the opposition of electric current. The resistivity can be expressed by the formula:

$$\rho = \frac{1}{\sigma} \tag{9}$$

Lubrication oils are slightly conductive to prevent electrostatic discharges within the engine. A too low electric conductivity can lead to local electrostatic discharges near the origin of the source, often near O-rings, gaskets, filter elements. (Promaint ry, 2018). If lubricants electric conductivity is below 400 pS/m there is a risk of electrostatic discharges, these discharges or sparks can be between 10.000 - 20.000°C (Lindner, 2013). Factors that affect the change in electric conductivity are broken oil molecules, metallic wear particles, ions, oil soaps etc. The impurities usually have a much higher electric conductivity compared to the base oil. (Mauntz, Gegner, Kuipers, & Stefan Klingau, 2013).

3.5 Additives effect on electric properties

Additives influence the electric properties of the lubricant. The consumption of additives is reflected in the decrease of electrical conductivity and relative permittivity. This is due to the additives in the lubricant combining with acids, impurities, and particles, which results in a decrease of the relative permittivity. This occurs in the beginning of the lifespan of the oil, where additives help to reduce the effects of wear and contamination. Once the additives are fully consumed electrical conductivity and relative permittivity will start to increase. (Mauntz, Gegner, Kuipers, & Stefan Klingau, 2013). This phenomenon can be described by Figure 7

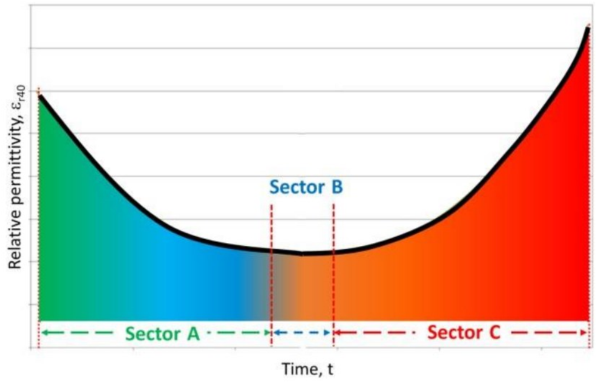

Figure 7 Relative permittivity as a function of time. (Mauntz, Kuipers, & Peuser, 2015).

A new lubrication oil starts at sector A, the lubricant is slowly degrading thru out its life and the additives combine with the impurities. This results in a decrease of both electric conductivity and relative permittivity. At sector B the additives have been fully consumed, after this point, new contaminants can’t be neutralized, which leads to the rise of relative permittivity and the electric conductivity at sector C. (Mauntz, Kuipers, & Peuser, 2015).

4 Sensors

The sensors included in the evaluation are confidential and will not be published.

5 Method

In this chapter the methodology of the test is described. In the first section the equipment used in the test is presented, and the working principle explained. In the second section the fluids used in the test are presented. The third section presents the methodology of the test itself.

5.1 Test station

As a part of this project a test station was commissioned. The test station presented in Figure 8. The test rig itself consists of a gear pump that circulates the lubricant thru a circuit where the sensors are fitted. Flow-, and directional valves are used to control the flow, parts of the circuit will be closed off as it serves no purpose in this experiment.

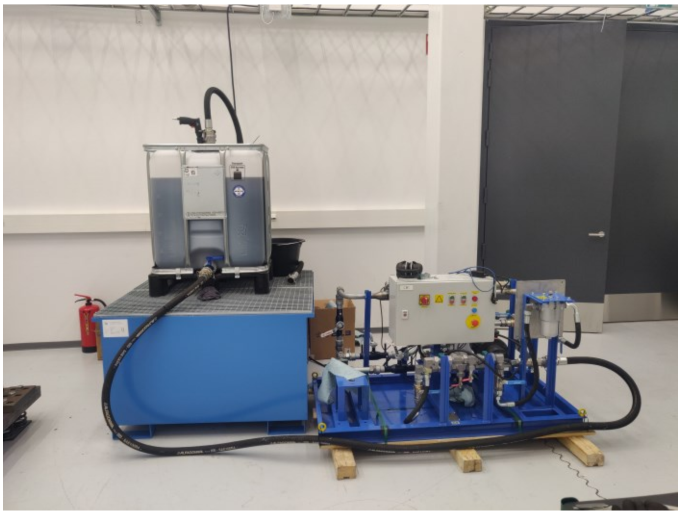

Figure 8 Picture of test station.

General info test station:

— Maximum fluid flow: 14 $\frac{L}{min}$

— Pump speed 1410 rpm

— Maximum pressure: 10 bar

— Operating pressure: 3,5 bar

— Temperature range: -15 .. +80°C

— Viscosity range: 10 – 420 cSt

— Volume of container: 300 L

A gear pump powered by an electric motor drives the lubricant thru the circuit, producing the necessary oil flow and pressure for the test. The pump unit is controlled from the control panel seen in Figure 8. On top of the container is a hatch from which the lubricant can be diluted. A pneumatic drill with a cement mixer attached to it is used to stir the contents.

5.2 Fluids used in experiment

The dilution experiment will be done using Shell Gadinia 40 mineral oil. This oil was chosen as it is commonly used in medium speed diesel engine. The physical properties of the lubricant are listed in Table 2.

Table 2 Physical properties of Shell Gadinia 40.

Properties			Method	Shell Gadinia S3 40
SAE grade (viscosity class)				40
Kinematic Viscosity	@40°C	mm²/s	ASTM D445	128
Kinematic Viscosity	@100°C	mm²/s	ASTM D445	13.7
Viscosity Index			ASTM D2270	103
Density	@15°C	kg/m³	ASTM D4052	890
Flash Point		°C	ASTM D93	230
Pour Point		°C	ASTM D97	-21
Base Number		mg KOH/g	ASTM D2896	12
Sulphated Ash		% m/m	ASTM D874	1.5
Load Carrying Capacity (FZG Gear Machine)		Failure load stage	ISO 14635-1 A/8.3/90	12

For the test 250 L of the lubricant oil was prepared, and is will be changed between the two experiments. The lubrication oil is stored at room temperature.

In the first experiment the lubricant will be diluted with regular tap water. Properties listed below:

— Viscosity: 1 cSt at 20°C (Anton Paar, n.d.)

— The electric conductivity for drinking water in Vaasa's water network is 280 – 300 µS/cm (Vaasan Vesi, 2021).

— The relative permittivity for water is 80 at 20°C (Serway, 2010).

In the second experiment the lubrication oil will be diluted with Neste Tempera MGO Properties for diesel listed below: (Neste Oyj, 2023). (Engineeringtoolbox, n.d.).

- Kinematic viscosity 2,0 - 4,5 cSt at 40 °C
- Dielectric constant 2,1
- Electric conductivity 150 pS/m
- Density 800 – 850 kg/m^3
- Flash point 55°C

5.3 Test method

Testing begins by first measuring a baseline which the later results can be compared to. After the baseline has been set, testing can proceed with dilution of the lubricant. Diluting of the lubricant will be done in multiple steps, this is done for multiple reasons, but mainly to estimate at what stage dilution will be detected by the sensors. The duration of each step is three hours, the constraining factor being that an operator must be present during testing. During this time the lubricant oil has circulated approximately 10 times thru the circuit. To aid the blending of the two liquids, a mixer will be used to stir the contents of the container.

After the baseline has been set the dilution test can begin. At the beginning of each step the testing rig is first run for one hour before the dilutant is added. This is done in order to reach as close to stationary conditions as possible. The dilutant is then added via the hatch on top of the container and the solution is mixed for fifteen minutes. After this the solution will be mixed once per hour for fifteen minutes. During testing a logbook will be held, were observations, times of mixing etc. will be written down. Pictures of each step will be taken so that they later can be compared.

A test plan for both dilution cases was made by considering the condemning limits set by Wärtsilä.

6 Hypothesis

Based on the theory a hypothesis is formulated which is tested in the method phase. In Table 3 the physical properties of the three liquids that are included in the test have been summarised.

Table 3 Physical properties of liquids included in testing.

Fluid	e_r	σ [pS/m]	Viscosity [cSt] @25°C
Mineral Oil	2,1 -2,4	> 400	310
Water	80,2	280.000.000	1
Diesel	2,1	150	2 - 5

When comparing the properties of water to the lubrication oil used in experiment, water dilution should lead to an increase in both relative permittivity and electrical conductivity. The theory suggested that the additives in the lubricant will combine with the impurities and effect the electric properties. Both the electric conductivity and relative permittivity should first decrease, and then increase after the additives are consumed. It is not known how or if the relatively low temperature of the test will affect this process.

Viscosity of the solution is expected to decrease since water has a significantly lower viscosity. An increase in water saturation percentage is naturally expected. The visual appearance of the lubricant oil should become "cloudy". Theory also suggested that the lubricant will start foaming as the water content increases.

When reviewing the properties of diesel and comparing them to the lubrication oil it can be said that these two fluids share some similar characteristics. Both fluids have similar values for relative permittivity. Electric conductivity of diesel is slightly lower than that of lubrication oil, hence, dilution should lead to a slight decrease in electric conductivity. Relative permittivity should likewise decrease slightly. The effect of the additives is expected to be similar as for the case with water.

Diesel has a lower viscosity to that of the lubrication oil, therefore a decrease in viscosity is expected. Diesel as such should not contain water and dilution should not affect the relative water saturation percentage. The visual appearance of the lubricant oil is expected to be minimal, possibly slightly clearer since a large amount of diesel is added. The smell of diesel might be felt when the lubricant is diluted in large amounts.

7 Results

The results are confidential and will not be published.

8 Discussion

The purpose of this thesis was to test and evaluate different oil condition monitoring sensors. The subject area was unfamiliar for the author and therefore challenging. Much time was spent on understanding the different measurement techniques and the use of them in the tested sensors. Still, the project in its whole has been as fun and interesting.

The goal of this thesis was to find a sensor or sensors that were able to detect diesel and water dilution of lubrication oil.

Generally, it can be said that by applying the on-line method changes in the lubrication oil quality can be detected. As earlier stated in the thesis, it is important the end user understands the results. Relying on only one property makes the interpretation harder, as most sensors will experience “cross sensitivity”. Changes in the measured parameter can be linked to many causes. This gives some uncertainty to what the cause of the oil deterioration is. On the other hand, one should consider what is the purpose and the philosophy behind the measurement. Generally, it is sufficient to know that the oil condition has changed, which gives the operator a cause to take an oil sample. In other words, is important to detect the contaminant as early as possible to prevent further damages. As seen form the results, sensors measuring electric properties could not detect fuel dilution as such. The effect of fuel dilution will affect other parameters in the lubricant which eventually will be detected by the sensors. However important to keep in mind the purpose of the method. As lubrication oil is sampled and analysed on regular basis, the real value is in detecting changes that happen over a short time span.

During the analyse of the results it became clear that systematic errors affected the results. This made the interpretation of the results harder or even impossible, as the full extent of their effects is not known. The method was chosen as it is a simple way of testing the sensors. Installing several different sensors on an engine would be costly, time consuming and such test would be harder to control.

The test should be repeated when the systematic errors should be eliminated or the effects of them can be accounted for.

- Pressure and temperature stability.
- Avoiding contamination from residuals.

- Extended test time in order to reach stationary conditions as close as possible.

The testing should also be done at a higher temperature to see if similar results are achieved. The low temperature possibly gave the viscometer an advantage. As the viscosity difference between the two fluids are greater than one could expect to see in field. On the other hand, the measurable range of the piston decreases considerably at lower viscosities. Finally, the result should be compared to lab analysis results in order to confirm the accuracy of the sensors.

This thesis only included sensors that are based on measuring electrical and physical properties of the lubricant oil. Further research with other measuring techniques should be done. Also, this thesis was delimited to very specific cases, which represent only a fraction of the mechanism that led to lubrication oil degradation. As such, further research is recommended to be done with other pollutants.

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