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STUDY ON OIL QUALITY SENSOR PERFORMANCE

TUTKIMUS ÖLJYN KUNNONVALVONTASENSORIN SUORITUSKYVYSTÄ

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Tutkimus öljyn kunnonvalvontasensorin suorituskyvystä.

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Hakusanat:

Työn tavoitteena on asettaa ohjeet ja tutkia epäpuhtauksien vaikutusta mittaustuloksiin öljyn kunnonvalvonta-anturille. Kirjallisessa osuudessa tutkitaan anturin teoriaa ja verrataan sen ominaisuuksia muihin tarjolla oleviin öljynkunnonvalvonta-antureihin. Kokeellisessa osuudessa anturin suorituskykyä tutkitaan näytteillä, jotka sisältävät kolmea epäpuhtautta. Jokaista kolmea epäpuhtautta sekoitetaan kuutta määrää puhtaaseen voiteluaineeseen ja mitataan epäpuhtaudesta aiheutuva mitattu voiteluaineen kuluminen. Käytetyt epäpuhtaudet ovat hiekka, vesi ja rautajauhe.

Kirjallisen osion mukaan anturi, joka mittaa kapasitanssia ja konduktanssia on toteuttamiskelpoinen tapa mitata voiteluaineen kuntoa. Kyseisen tavan lisäksi on muita tapoja mitata eri epäpuhtauksien määrää tai öljyn kulumista. Kokeellisen osuuden tuloksissa epäpuhtauden määrä ja mitattu kuluma eivät korreloineet ollenkaan. Tämän lisäksi kokeiden toistotarkkuus oli huono. Odottamattomien tuloksien takia kokeen suorittaminen korkeammassa lämpötilassa olisi ollut turhaa, joten tästä luovuttiin.

ABSTRACT

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Study on oil quality sensor performance

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The scope of the study is to set guidelines and study the effect of impurities on the measured wear and impurities for oil condition sensor. In the literature part theory of the sensor is studied and compared to other available oil condition monitoring technologies. In the experimental part the sensor is experimented with six samples of each three impurities. Six different amounts of each impurity are mixed with pure gearbox lubricant to study the effect on the amount of impurity to the measured condition of the lubricant. Three impurities used are sand, water and iron powder.

According to the literature part oil condition sensor based on measuring conductivity and capacitance is a viable way to measure its condition. In addition to such technology, there are many more ways to measure different types of impurities and wear components. In the results of experimental part the amount of impurity did not correlate with measured lubricant condition. In addition repeatability of the measurements was low. Due to the unexpected results in the first experiment it was not repeated in higher temperature.

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SYMBOLS LIST

C	Capacitance [$A^2 s^4 kg^{-1} m^{-2}$]
f	Frequency used by the sensor [Hz]
I	Current measured by the sensor [mA]
I_C	Capacitor leakage current [mA]
I_R	Conductive component [mA]
R	Resistance [Ω]
$\tan\delta$	Dissipation factor
TDN	Tan Delta number

1 INTRODUCTION

1.1 Scope of the study

The scope of the thesis is to study usability of oil quality measuring sensors, and study practical usage of the sensor. The goal is to compare the limits given by the sensor to the limits set by the target company and to set guidelines for limits of different impurities based on the experiment. In the experiment sensor is studied by measuring impurities in lubricant samples. Lubricant samples are mixed with three types of impurities: water, sand and metal powder. Concentrations are compared to limits used by the target company. Theoretical performance of the system is compared to other technologies on the market.

1.2 Introduction

The maintenance of machines can be classified to three categories. The simplest way of maintaining condition of a machine is to repair it after a defect. The second option for maintenance is to maintain it according to predetermined schedule. The most complex way is to maintain the equipment according to the real state of it. Many industries are highly dependent on the machinery they use, thus they prefer to use scheduled maintenance. This leads to high amount of needless maintenance work done. As much as ≥ 50% of maintenance work is unnecessary. Too frequent maintenance might not decrease defects. (Myshkin & Markova 2018, xvii-xviii) To decrease both costs and failure rate equipment can be serviced only when needed. For successful maintenance by state of the machine, the condition of the machine has to be monitored, thus studying the technologies available to monitor the condition of gearboxes is important. For gearboxes monitoring technologies include, temperature, vibration and oil condition monitoring. (Myshkin & Markova 2018, xvii-xix)

The study is conducted to find the limitations of the studied sensor in real life applications. In the target company the sensor would be used to monitor lubricant condition in industrial gearboxes. By monitoring the condition of the lubricant customers can optimize oil changing intervals. In case of potential break down the sensor might give early warning, for example high amount of metallic particles might refer to bearing failure. In case of large amount of metallic particles service can act before total breakup. In that case the user can act before catastrophic failure takes place. Financial gains from monitoring the lubricant condition can be significant.

The oil condition monitoring system uses its own scale which determines the condition of the lubricant. The system uses Tan Delta Number to detect the condition of the lubricant. Tan Delta number is derived from conductivity and capacitance of the lubricant. The measured data is compared to the limits set by the target company, thus users get more information from the sensor and set limits for the Tan Delta number. The sensor used in the experiment is designed by Tan Delta Systems Limited. The sensor and the monitor used in the experiment is showed in the figure 1. In the figure 1 can be seen the sensor itself and the logger used to display data.

Figure 1. The picture shows the Tan Delta oil condition sensor and monitor.

2 METHODS

2.1 Economies of maintenance

The goal of improving maintenance is to improve the machines technical performance, dependability and capacity utilization. Higher performance, dependability and utilization lead to lower production costs, undistracted production and lower maintenance costs. The end result of improving usability and utilization is higher profit. In metal industry cost of maintenance is 2,1%-5,3% of the revenue and 11% of the labor works for maintenance. Maintenance can also have indirect effect on the company's profit from its goodwill value. (Järviö, 2004 p.17-27)

2.2 Lubricant contamination

The biggest impact on the physical properties of lubricant is result from changes in its chemical structure and impurities mixed with lubricant, like water and metal particles. Changes in chemical composition include oxidation and decomposition of additives. (Myshkin & Markova 2018, p.vi)

Impurities of the lubricant can either come from the system itself or come externally. Impurities from the lubricant itself are caused by oxidation or the additives reacting with other impurities. (Antila 2006, p.115-116) Metal debris in the lubricant is caused by wear of the transmission components. Types of damage that occur in gearboxes are wear and Hertzian fatigue. Wear includes adhesion and abrasion. Hertzian fatigue includes macro- and micropitting. Pitting fatigue is fatigue of contact surfaces caused by varying shear stress. Adhesion is wear caused by the contact between gear teeth. Abrasion is caused by contaminants wearing the components. (ANSI/AGMA/AWEA 6006-A03 2003, p.61) Lubricants can also be contaminated by impurities from paint or seals. External impurities can enter the lubricant from air filters, seals or during maintenance. These contaminants include: water, sand, metal debris or process chemicals. (Antila 2006, p.115-116)

Cleanliness of a lubricant is defined in the standard ISO 4406:2017 by the cumulative amount of particles in three grain sizes: ≥ 4µm, ≥ 6µm and ≥ 14µm. The cleanliness of lubricant in the standard is scaled from 0-25. Cleanliness of the lubricant is important to avoid excessive wear and to have sufficient lubricant film. (Antila 2006, p.120-121)

2.3 Lubricant quality monitoring technologies

The condition of a lubricant can be determined by measuring its: "viscosity, dielectric permeability, conductivity, corrosive activity, acid and base numbers, spectral absorption, optical density, oil fluorescence, etc." (Myshkin & Markova 2018, 3) Lubricants can also be analyzed more accurately in laboratories. Many sensors are only able to detect certain type of wear or impurity in the lubricant, for example water content or particle debris. If used these sensors, several sensors for different risks should be used. Using more complex monitoring systems might be unnecessary for some applications.

Ultrasonic lubricant condition monitoring is used to detect debris particles mixed with lubricant. Ultrasonic sensors are based on the particles effect on the sound wave. When a sound wave interferes with a particle the amplitude of the waves is attenuated. The amount of attenuation can be used to detect the size and amount of debris in the lubricant. Ultrasonic sensors could be used to prevent bearing failures in gearboxes. The downside of the ultrasonic sensor is that it can not differentiate between metallic and non-metallic particles. Also most ultrasonic sensors react on air bubbles since they have similar effect on sound waves than solid debris. Other limitation of ultrasonic detection is that they are only able to detect particle debris, not for example water content. (Du & Zhe 2011, p.3-4)

Another type of sensors is optical particle counters. The working principle of optical sensor is based on the solid particles in the lubricant blocking light from entering the detection cell. Particle blocking the light will cause measured voltage drop in detection cell which amplitude is dependent on the size of the particle. Optical sensors give similar false detection for air bubbles than ultrasonic sensors. Optical sensors can detect water droplets unlike ultrasonic sensors. (Rinkinen 2007, p.35)

Oxidation of oil can be measured by studying fluorescence of the lubricant. As the oil oxidizes changes in composition of unsaturated molecules causes increase in polarity of the lubricant. Increasing polarity causes a shift to longer wavelengths in the emission spectrum. By comparing the shifted spectrum to clean oils spectrum degree of oxidation can be determined. The level of oxidation can also be determined from change in intensity and change in lifetime of fluorescence. Benefits of fluorescence sensors are their low cost, simple design and high reliability. (Myshkin & Markova 2018, p.17)

There is earlier research conducted on similar sensor. The research was study about oil condition sensor based on measuring the same parameters. They studied the sensor by measuring the effect of oil oxidation. The research suggests that measuring complex permittivity and conductivity is able to determine the wear. The data also suggests that without temperature compensation, temperature has an effect on the output value of the sensor. (Perez & Hadfield 2011)

The sensor consists of the oil quality sensor, display device and software for the system. Generally permittivity sensors are made of internal and external electrodes that act as a capacitor. Measured lubricant flows between the two electrodes. Sensor also has temperature meter. Two capacitors and the temperature meter are in a single casing. (Myshkin & Markova 2018, p.4-6)

Tan Delta oil condition sensor is based on the measured fluids capacitance and conductivity. The sensor also measures the temperature of the fluid. As the oil degrades capacitance decreases and conductance increases. The measured permittivity is compared to the clean lubricants permittivity to analyze the condition. Aging of the oil increases conductivity and permittivity of the lubricant. (Risos 2018, p.1) The amount of wear is calculated from the tan value of phase angle between conductivity and capacitance. Tan Delta Number is derived from the percentage of wear. Equation 1 is used to calculate the phase angle $\tan\delta$. Equation 2 is used to calculate the loss factor δ. In equation 1 variable I_R is the conductive component and I_C is capacitive component. Both are measured in mA. In equation 2 f is the oscillation frequency of the sensor which is measured in Hz. C is capacitance and R is resistance.

$$\tan\delta = \frac{I_R}{I_c} \tag{1}$$

$$\delta = \frac{1}{2\pi fCR} \tag{2}$$

The frequencies used by complex permittivity sensors are generally in the range of $1\text{MHz} - 100\text{MHz}$. The oscillation frequency used by the sensor should be as low as possible to increase sensitivity of the sensor.(Perez & Hadfield 2011 p.8) Lower frequencies should be used to increase sensitivity of the sensor. With Tan Delta oil condition sensor the frequency can not be manually changed, thus the configuration profile should be chosen correctly. (Perez & Hadfield 2011)

The sensor should be configured for each lubricant type and manufacturer for reliable results. Viscosity and additives will affect permittivity of clean lubricant. The sensor also accounts the effect of temperature to the measurement. Measured wear is used to derive Tan Delta Number for the oil. Tan Delta number is a scale ranging from 1200 to 0. For gearboxes the caution limit given by Tan Delta is 580 TDN and critical limit is 500 TDN. As the number decreases the quality of the lubricant is lower. The real measured data can be calculated using the equation 3. In the equation 3, I is the measured current converted from Tan Delta Number.

$$I = \frac{1700 - Tan\ Delta\ Number}{100} \tag{3}$$

Permittivity sensors are able to detect coolant fluid, water, fuel and soot. Lubricants permittivity also increases in thermal oxidation and change of temperature. According to Tan Delta systems the studied sensor should be able to detect all wear and contamination including water, sand and metal particles. Generally oil condition sensors based on the permittivity can not detect the type of impurity. (Myshkin & Markova 2018, 3-6)

Water in lubricant can have three forms: dissolved, emulsified or free water, dissolved water being the least harmful. Water causes corrosion, fatigue, foaming and oxidation. Dissolved water in the lubricant is attracted to the polar additives of the lubricant. (Antila

2006, p.130) Dissolved water can exist only in small quantities below saturation point, which is $200\text{ppm} - 300\text{ppm}$ for mineral oils. Oil aging increases the saturation point of the lubricant. Above the saturation level water can exists as emulsion and free water. Emulsion means the lubricant has small water droplets mixed and free water means that the oil and water are in separate layers. In the experiment smallest amounts of water are likely below the saturation point. The saturation point of Teboil Pressure oil 220 is not given by the producer. (Rinkinen 2007, p.38)

3 RESULTS AND ANALYSIS

3.1 Comparison of the possible monitoring technologies

For gearbox setting the sensor used should be able to detect common type of wear: metal debris, water and oxidation. The sensor should be able to withstand difficult environments, such as heat and moisture. The sensor should be able to function extended periods of time without maintenance.

In addition to sensor based on measuring capacitance and conductivity, optical particle counters can also detect metal debris and water droplets. Optical sensors can only detect more harmful water droplets not dissolved water. It can not detect oxidation either. To be able to detect all of the possible impurities either more than one type of sensor is required, or a sensor measuring capacitance and conductance.

Air bubbles can distort results of ultrasonic, optical and a sensor measuring capacitance and conductivity. Ultrasonic and optical sensors require circulation line. Circulation line would make the system more vulnerable and complex. Price range of the sensors included in the comparison is similar.

3.2 Experiment process

To prepare the samples for the experiment 100ml lubricant sample is mixed with six different amounts of three impurities and one amount of all impurities. Before the measurements Tan Delta Number of pure lubricants is recorded to make sure the sensor is functioning correctly. Pure lubricants Tan Delta Number should be in between 950-850. Measurement is conducted by tipping the sensor in the lubricant. Since sand and metal powder do not dissolve to oil or mix well, it is important to mix the sample strongly. Water will dissolve to the lubricant below the saturation point. Mixture of lubricant and impurity is mixed until the measured value settles. The temperature and Tan Delta number are recorded. Reliability of the measurements is ensured by repeating the measurements as many times as it is seen necessary. The measurement is not stopped until the value settles. Temperature is kept constant during the experiments.

Measurements are taken for two used lubricant samples in addition to the prepared samples. The samples are from oil used in two different gearboxes. The real type of lubricant is not known, thus the data is not reliable. Also the impurity contents of the used lubricants are not known. Visually both samples look dark when compared to pure lubricant.

3.3 Lubricants in the experiment

The lubricant used in the experiment is mineral oil based Teboil Pressure oil. Lubricants viscosity is 220 $\frac{mm^2}{s}$ at 40°C. Sensor does not have profile for the lubricant used. The configuration profile used for the sensor is for the BP Energol GR-XP oil. Same configuration is used for the two used oil samples. Both lubricants are mineral oil based with same viscosity and similar viscosity indices and similar additive composition. Both oils are used in gearboxes. Table 1 includes the technical data of the oil used in the experiment and oil the sensor was configured for.

Table 1. Technical data of the lubricant used in the experiment and configuration lubricant. (Oy Teboil Ab, 2010; BP Marine Limited, 2009)

	BP Energol GR-XP 220	Teboil Pressure oil 220
Viscosity ($\frac{mm^2}{s}$ at 40°C)	220	220
Density ($\frac{g}{ltr}$)	890 at 15°C	891 at 20°C
Pour point (°C)	−18	−18
Flash point (°C)	226	246
Viscosity Index	96	90

3.4 Impurities used in the experiment

In the standard ISO 4406:2017 oil condition is defined as the amount of particles sized of 4µm, 6µm and 14µm, thus particles as small as possible are used in the experiment. Three impurities used in the test are sand, metal powder and water.

The target company has set limits in gearboxes for each impurity. Limits are listed in the Table 2. Values for used in the experiment are chosen from the target company’s set limits for impurities. Lubricants are tested with both caution limit and critical limit, and also with amounts smaller and larger than those. For each impurity six different amounts are used. One value is below the caution limit. The lubricant is also tested with one concentration having all three impurities.

Table 2. List of limits for impurities.

	Iron concentration (ppm)	Silicon concentration (ppm)	Water concentration (%)
Caution limit	100	30	0,05
Critical limit	400	50	0,1

The metal powder used in the experiment is iron powder used in additive manufacturing. Its grain size is approximately 50µm. The grain size is the smallest pure iron powder that was available. The grain size is greater than defined in the standard ISO 4406:2017 which might affect the reliability of the results. The sand used in the experiment is fine grain natural sand. Its grain size is also greater than required. Water used in the experiment is regular tap water. To make sure there is no water mixed with the sand or iron powder, both substances are dried over night in drying cabinet.

3.5 Concentrations used in tests

Table 3 has listed the concentrations of impurities in the test samples. *Table 4* has the concentrations of impurities in the sample with all impurities. The mass of impurities and lubricant was measured with scale. Concentration in tables 3 and 4 means percentage of mass of impurity per mass of lubricant.

Table 3. Concentrations of impurities in test samples.

	Set 1 (Iron powder (%))	Set 2 (Sand (%))	Set 3 (Water (%))
Sample 1	0,005239	0,001829	0,024808
Sample 2	0,010341	0,002859	0,049985
Sample 3	0,020464	0,004088	0,074920
Sample 4	0,039878	0,005271	0,100330
Sample 5	0,061087	0,007401	0,149565
Sample 6	0,080126	0,009925	0,200750

Table 4. Concentration of sample with all impurities.

Iron powder (%)	Sand (%)	Water (%)
0,04062	0,005037	0,100086

3.6 Hypothesis

According to Tan Delta Systems the sensor should be able to detect all three substances used in the experiment. Waters dielectric constant is significantly higher than dielectric constant of mineral oil, thus the measured difference should be great. The difference in dielectric constant between sand and mineral oil is small, thus the measured wear should be smaller than the wear caused by water. Iron powder should cause decrease in Tan Delta Number since iron has high conductivity. If the temperature compensation of the sensor works temperature should not have effect on the Tan Delta Number.

3.7 Measured wear of the lubricant samples

Figures 3, 4 & 8 include the measured averages of the measurements. Table 5 includes the measured averages for two samples of used lubricant.TDN for the sample having all three impurities is 722 TDN. Clean lubricants Tan Delta Number is recorded to be 892 TDN. Appendix I shows example of changing values during the experiment. Recording the data is continued until the TDN value stabilizes. Stabilized TDN value is recorded. If the value does not stabilize, average TDN is calculated from longer set of measuring. If the value did stabilize, average value is calculated from the stabilized set of values. Repeating the experiment in higher temperature was canceled after conducting the experiment in room temperature thus no data of the experiment in higher temperature is included.

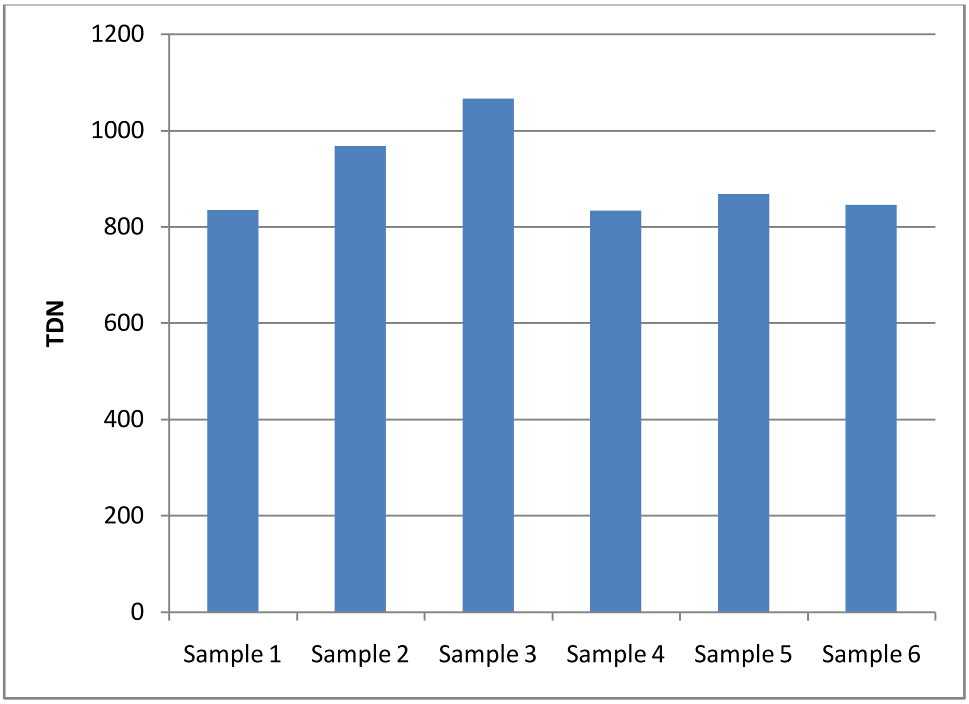

Figure 2. Measured averages for samples containing sand.

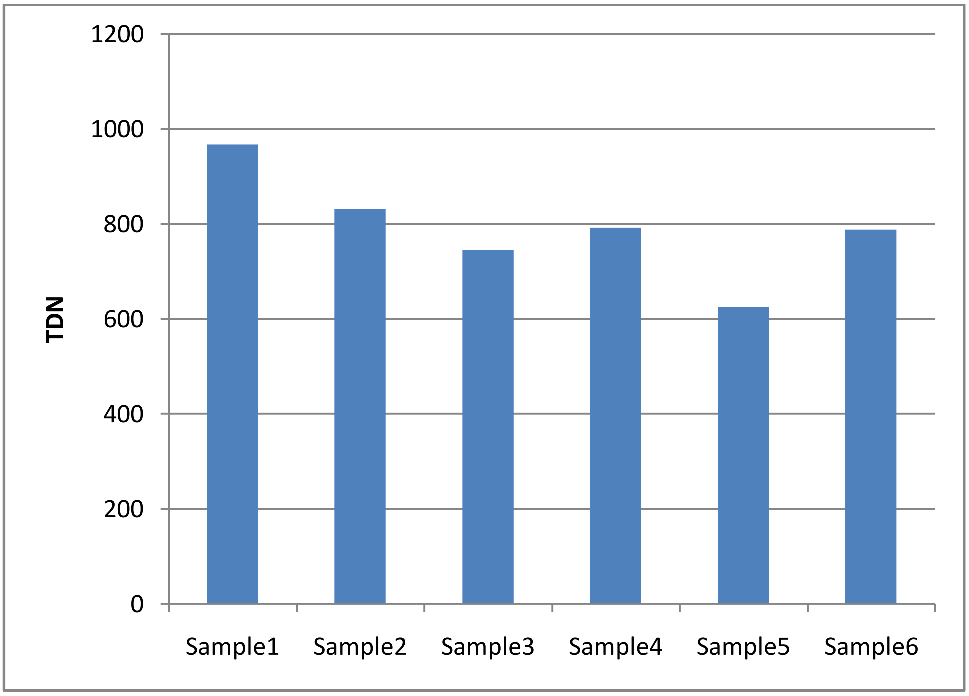

Figure 3. Measured averages for samples containing water.

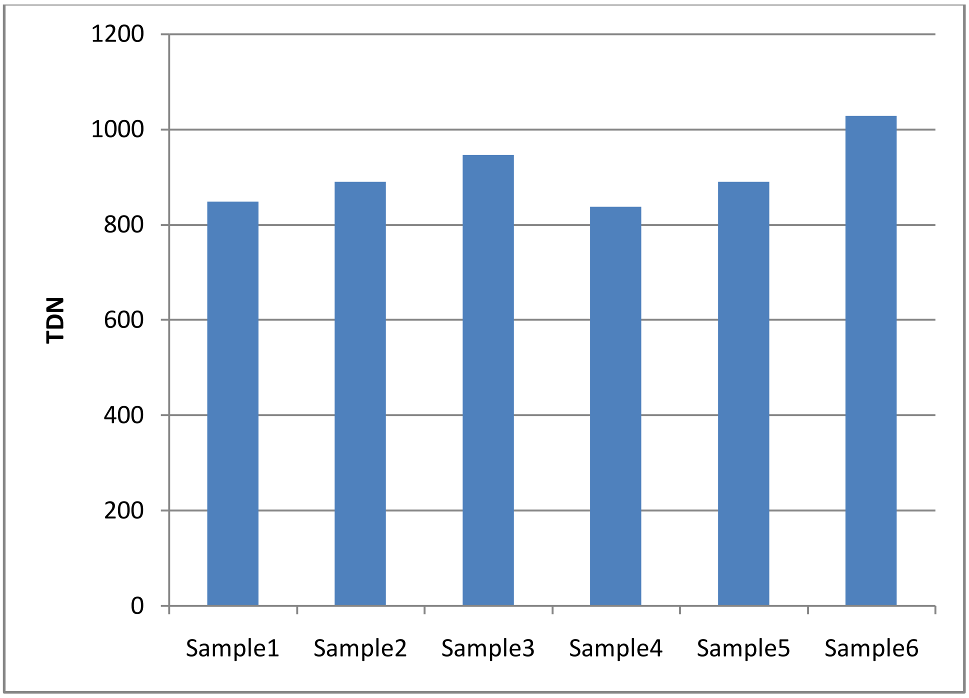

Figure 4. Measured averages for samples containing iron powder.

Table 5. Measured averages for samples from used gears.

	TDN
Sample 1	769
Sample2	481

4 DISCUSSION

4.1 Analysis of the data

The correlation between the amount of impurity and measured change in condition is weak. Between repeated measurements the measurement value changed a lot as can be seen from Appendix I. The measurements did not stabilize well. In repeated measurements the average value of the last measurement was recorded. In all measurements the average value is recorded. As the difference between repeated measurements is great the results are unreliable. The sample with all three impurities also has high TDN value. Temperatures of the samples vary from 18,7℃ up to 24,6℃.

Samples from real used gearboxes have very different results. Sample 1 is not worn much compared to pure lubricant and sample 2 is critically worn. Visually assessed both samples look similar in color. They both look darker when compared to unused lubricant. The contents of the samples are not known thus no conclusions can be made of the results.

Decision was made not to repeat the experiment in higher temperature because of the results achieved in the room temperature. By repeating the experiment in higher temperature no new knowledge could have been achieved thus there was no reason conducting it.

4.2 Evaluation of the results

The goal of the study was to set limits and guidelines for the target company using the studied sensor. Experiment was supposed to include studying the effect of temperature to the measured TDN value. From the results achieved in the experiment no guidelines or limits can be set. In the experiment the sensor could not detect the wear caused by impurities used. According to the experiment Tan Delta oil condition sensor can not reliably detect the condition of lubricant. To verify the claim experiment should be repeated and improved. Since in the data of the experiment conducted in room temperature the amount of impurity did not correlate with measured TDN value, the experiment was not repeated in higher temperature. Not conducting the experiment in higher temperature was justified with the fact that the results of the first experiment were highly unreliable. Set temperature could not be reached accurately with available equipment thus uncertainty would be higher.

Even if the sensor did not reach expected results, oil condition monitoring is useful in some applications. Possible users should compare suitability of the options from wide variety of technologies from different manufacturers depending on the application the sensor would be used in.

4.3 Error analysis

The data achieved from the experiment is far from expected results. The reason for unexpected results are errors made in the experiment or the sensors inability to detect such particles. Possible errors affecting the reliability of the data include: too weak flow, grain size, poor mixing of the impurities or ability to detect by the sensor. Temperatures of the lubricant changed slightly between samples. Different temperatures are caused by the temperature of the sensor. Sensor cools down in the process of cleaning it. Temperature differences are small and sensor has temperature compensation, thus effect of it is small.

In the experiment the sensor was held vertically sensor head downwards. Due to design of the sensor air can not exit above the holes in the outer electrode when held vertically. Some of the air can be removed by turning the sensor as sideways as possible. Air bubbles could be seen when the sensor was tilted. Air trapped inside the sensor will distort the results by increasing the measured TDN value. While cleaning the sensor between samples it was difficult to clean the sensor inside due to design of the sensor. This shows the lubricant flow inside the sensor is insufficient. The user guide of the product recommends the sensor to be held horizontally. When kept horizontally air is freed from inside the sensor and larger holes under the sensor give better flow. During the experiment the sensor could not be held horizontally due to the containers the samples were in. With closed circulation system sensor could be held horizontally and it would improve flow to the sensor.

Grain size and mixing of the impurities also caused error in the experiment. In case of sand, grain size was far greater than the size used in standard ISO 4406:2017. Because grain size was large and amounts small the amount of particles was low as well. Since the particles need to be inside the sensor to be detected, too great grain size diminishes reliability of the results. Iron powders grain size was significantly smaller and the effect of the grain size should not be high. The other factor relating to the impurities is their mixing. Impurities need to be inside the sensor for it to be able to measure change in conductivity or capacitance. If the particles clump or water does not mix the sensor gives unreliable readings. In case of sand and iron powder no clumping could be seen in the samples.

While mixing the sample lot of air bubbles were formed in the sample. Air bubbles mixed with the lubricant have similar effect to the results as air trapped inside the sensor. Air decreases the measured wear of the sample. With current experiment setup air bubbles can not be avoided. They could be avoided with closed circulation setup. In real life use air bubbles could affect the measurement which should be considered. Placement of the sensor will affect the amount of air bubbles entering the sensor.

4.4 Further studies

Functionality of the sensor should be studied more be repeating the experiment with improved sensor placement and oil circulation. Other available technologies should be studied and compared.

5 SUMMARY

The purpose of the study was to study usability of Tan Delta oil condition sensor and set guidelines for users of the sensor. Study included literature study, where theory of the sensor is studied and compared to other existing technologies, in addition to experimental study, where function of the sensor is studied using three impurities water, sand and iron powder.

In the earlier study it was found that measuring complex permittivity and conductivity can be used to determine the level of oxidation of lubricant. By measuring conductivity and capacitance of lubricant and comparing it to the values of pure lubricant can be determined the amount of wear in the lubricant. (Perez & Hadfield 2011) Sensor based on measuring such parameters can not determine the type of wear component in the lubricant. Condition of lubricant can be studied using many other technologies such as visual density and fluorescence. Many types of sensors can only detect certain type of wear component. To reach the best result many types of sensor can be used simultaneously. To detect the most harmful component only one sensor could be used, such as sensor measuring metal debris in a gearbox.

In the experimental study the sensor was tested using six concentrations of three impurities. Impurities were mixed with gearbox lubricant and the amount of wear was recorded. Between repeated recordings measured wear changed a lot. Also the measurement value did not settle well in many recordings. The results did not show any correlation between amount of impurity and measured wear with sand or iron powder. With water weak correlation can be seen in some samples. Differences between repeated experiments were great and the sensor did not stabilize to certain value in many recordings. The experiment could be improved by changing the setup to closed circulation. Closed circulation would allow the sensor to be held horizontally as well as improve the flow for the sensor.

The results of the experiment could not be used to set guidelines for the sensor and it does not support use of the sensor. According to the literature part oil condition monitoring is a great addition that can be used to lower costs in critical equipment. In addition to sensor based on measuring conductivity and capacitance, there are plenty of other technologies available.

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Appendix I

Example of measurement.