

Survey of Lubrication Oil Condition Monitoring, Diagnostics, and Prognostics Techniques and Systems

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Abstract- Recently, an increasing demand for performance assessment of lubrication oil has been noticed. Considerable techniques and systems in lubrication oil condition monitoring have been developed and successfully utilized in many applications such as gasoline/diesel engines, gearboxes, etc. This paper provides a comprehensive review of the existing lubrication oil condition monitoring solutions and their characteristics along with the classification and evaluation of each technique. The reviewed techniques are analyzed and classified into four categories: electrical (magnetic), physical, chemical, and optical techniques. The characteristic of each solution and its sensing technique is evaluated with a set of properties which are crucial for oil health monitoring, diagnostics and prognostics. A comprehensive comparison among a wide range of different lubrication oil condition monitoring solutions is conducted.

Keywords- Lubrication Oil; Performance Assessment; Condition Monitoring; Diagnostics; Prognostics

I. INTRODUCTION

In modern industries, lubrication oil plays a critical part in condition maintenance of complicated machineries. In recent years, health condition monitoring and prognostics of lubrication oil have become a significant topic for people and groups from academia and industry. More and more efforts have been put into oil diagnostic and prognostic system development and research. The purpose of most research is, by means of monitoring the oil degradation process, to provide early warning of machine failure and also extend the operating duration of lubrication oil in order to increase machine availability, prevent unnecessary cost of oil change, waste or environmental pollution.

Lubrication oil is an important information source for early machine failure detection just like the role of the human blood sample testing in order to perform disease detection. The condition of lubrication oil and its circulation system reflect the health status of the machinery and its components. Excessive metallic particle contamination in the lubrication oil circulation system often indicates unusual machine wear and may result in overheating and component failure. Nonmetallic particle in the oil often indicate the circulation is not well sealed against dust and debris from outside environment. Therefore, the lubrication oil health has a great impact on the mechanical system health condition. As stated by Sharman and Gandhi and many other researchers, the primary function of lubrication oil is to provide a continuous film layer between surfaces in relative motion to reduce friction and prevent wear and thereby prevent seizure of the mating parts. The secondary function is to cool the working parts, protect metal surfaces against corrosion, flush away or prevent ingress of contaminants and keep the mating component reasonably free from deposits (Sharma and Gandhi, 2008). In a lubricated system, variation in physical, chemical, electrical (magnetic) and optical properties changes the characteristics of the lubrication oil which lead to its degradation in protective properties. In general, the reasons of lubricant deterioration are oxidation, wear particle contamination and water contamination. The parameters that describe the lubrication oil performance or level of degradation are called performance parameters. These parameters include viscosity, water content, total acid number (TAN), total base number (TBN), particle counting, flash point, Spectrometric oil analysis program (SOAP) and so forth. Each performance parameter can be measured by certain sensing techniques. The relationship among the basic degradation features, performance parameters, and available oil condition sensors is shown in Fig. 1.

In most industrial applications, one needs advance notice or early warning of oil replacement. Otherwise, even with sufficient diagnostic information, sudden diagnose of failure which needs immediate action will have influence on the production rate because the equipment needs to be shut down in order to prevent unnecessary wear or damage. With less functioning producing units, the production rate will certainly be affected which will result in the reduction of profit margin and difficulty of maintenance scheduling. In large applications like wind turbines, by precisely predicting the remaining useful life of lubrication oil, one can optimize the general maintenance schedule of the entire wind farm, therefore reduce the maintenance cost. Moreover, if the diagnostic and prognostic can be conducted online, companies do not have to send workers to climb up the towers on regular basis to collect oil samples one by one which will cut the labor expenses.

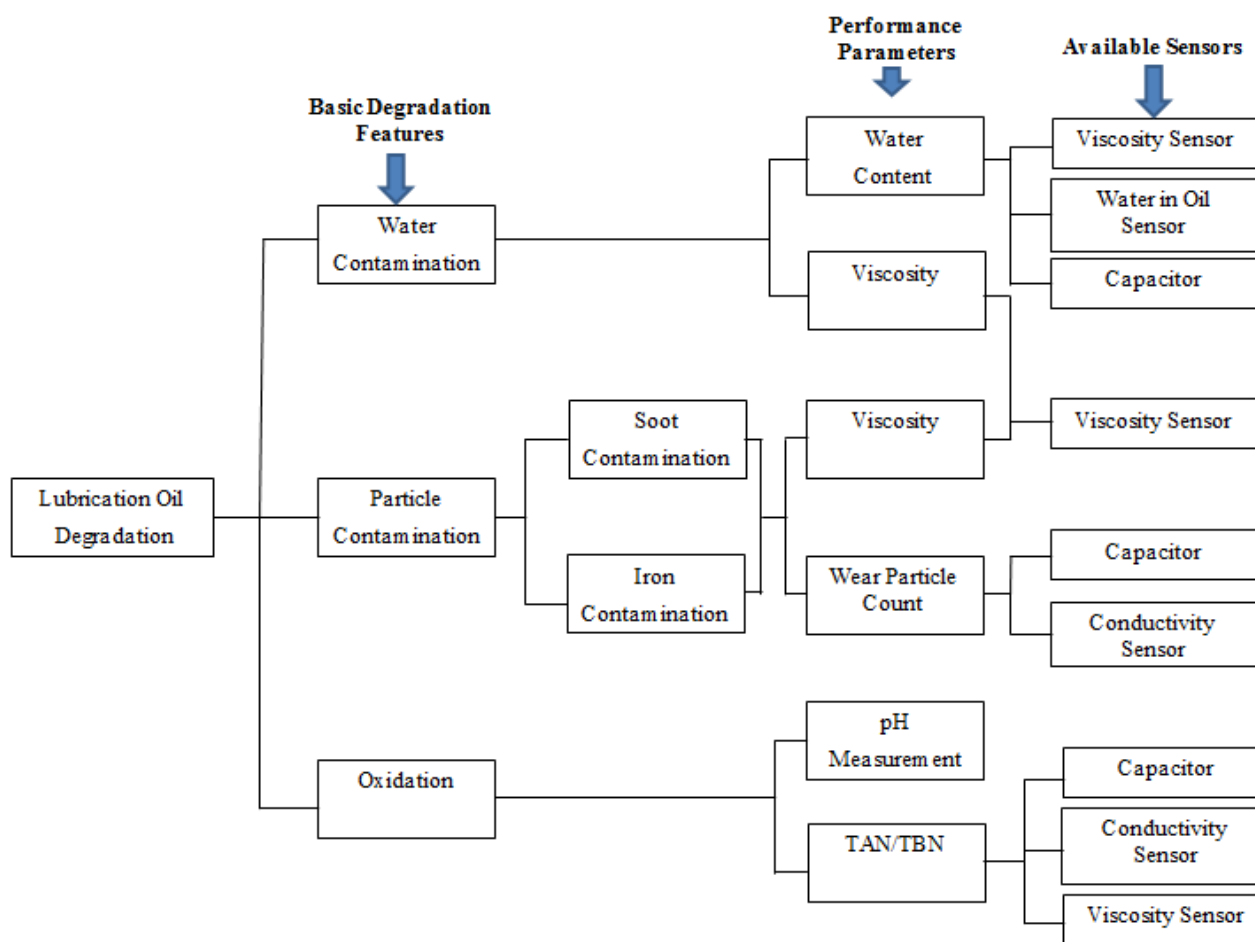


Fig.1 The relationship among the basic degradation features, performance parameters, and available oil condition sensors

For passenger vehicles and many other applications, the oil change timetable provided by the manufacture is relatively conservative considering different operating condition, individual driving habits, ambient condition and fuel quality. As a result, in most cases, lubrication oil was discarded well before it reaches its maximum usable life. Lubricating oils are refined from finite natural fossil resources, and the cost of producing synthetic oils is relatively expensive. By the year 2010, the lubrication oil consumption of the world is 36.3 million tones. Among them, 21.9 %, approximately 8 million tones, was consumed by United States. If this lubrication oil consumption is reduced by even 1%, it will greatly benefit the environment. Also, lubrication oil replacement process requires time for the oil to completely soak the filters and diffuse into the entire lubricant circulation systems. Frequent lubrication oil change without the proper transition time, which is sometimes ignored, will cause unnecessary engine or machinery damage.

Over the years, scientists and experts developed considerable sensors and systems to monitor one or some of the performance parameters in order to monitor the oil condition effectively. These sensors and systems can be summarized into four categories including electrical (magnetic), physical, chemical and optical techniques. For example, the proved most effective electrical technique for oil health monitoring is detecting the dielectric constant change of the lubrication oil. According to recent research, the capacitance or permittivity change can be used to monitor the oxidation, water contamination and wear particle concentration. On the other hand, for physical techniques, viscosity is commonly discussed. The lubrication oil oxidation, water contamination, particle concentration, and some other property changes all have influence on the oil viscosity. So, viscosity is considered an objective mean of oil degradation detection. However, there are two types of viscometer, one of them is kinematic viscometer and the other is micro acoustic viscometer. The former is classified in the physical technique category and the latter is an electrical technique.

The final goal of all above mentioned systems is to achieve lubrication oil online health monitoring and remaining useful life prediction in industrial machineries. Most sensing systems are only capable of off-line monitoring, in which oil samples are collected by specialists from the machinery and sent to laboratories for oil condition analysis. In this way, the actual condition of the lubrication oil cannot be determined because there is always a sampling and analysis delay. Moreover, in order to deploy the sensors in the industrial environment, they have to present a long life span and aggressive ambient condition tolerance.

The purpose of this paper is to conduct a survey of current lubrication oil condition monitoring, diagnosis and prognostics

techniques and systems. And by presenting an overview and detailed comparison between the latest developed sensors or systems, one can obtain an insight of the current status of oil health monitoring in order to understand the existing challenge and the future direction of lubrication oil diagnostics and prognostics development.

The remainder of the paper is organized as follows. Section 2 covers the principles of lubrication oil condition monitoring and four categories of techniques along with the sensors and systems in these categories. Section 3 summarizes and evaluates all the sensing techniques with a set of properties which are crucial for oil health monitoring, diagnostics and prognostics. Based on the set of the defined properties, a comprehensive comparison of different lubrication oil condition monitoring solutions is conducted in this section. Finally, Section 4 concludes the paper.

II. PRINCIPLES OF LUBRICATION OIL CONDITION MONITORING METHODS

The Principles of lubrication oil condition monitoring are by means of various sensing techniques to directly or indirectly monitor the basic lubricant degradation features. The basic degradation feature includes oil oxidation, water contamination, particle contamination, oil dilution and so forth. These features' variation can be detected by a set of oil performance parameters. The following table (Table I) presents the performance parameters and its benchmark for lubrication oil degradation indication. The benchmark of degradations is chosen upon specific lubrication oil (15W-40) as a case demonstration. These benchmarks are tested for the specific lubrication oil. In Table I, the application section means the performance parameter (in the first column) is feasible to describe oil health condition in certain applications. Data are referenced from published papers (Raadnui and Kleesuwan, 2005; Agoston et al., 2005; Sharma and Gandhi, 2008).

TABLE I PERFORMANCE PARAMETERS AND THEIR BENCHMARK FOR LUBRICATION OIL DEGRADATION

Performance Parameters	Measurement Function	Unite	Benchmark of Degradation	Applications					Available Measurement Approach
				Gear box	Hydraulic system	Engine	Compressor	Turbine	
Viscosity (40 °C)	Contamination of lubricant by some other oil, oxidation	Cst (mm ² /s)	≥ 55	yes	yes	yes	yes	yes	Kinetic Viscometer
Viscosity (100 °C)			≤ 50						Micro-acoustic Viscometer
Water Content	Presence of water	%	≤ 2	yes	yes	yes	yes	yes	Capacitance sensor (Dielectric constant)
									Kinetic Viscometer
									Water in oil sensor
TAN/TBN	Acidity/alkalinity of lubricant (oxidation level)	mgKO H/gm	≥ 0.6 ≤ 0.05	no	yes	yes	yes	yes	Capacitance sensor (Dielectric constant)
									Kinetic Viscometer
									Conductivity Sensor
Flash point	Presence of dissolved solvents or gases in the lubricant	°C	≥ 220 ≤ 140	no	yes	yes	no	no	Thermometer
Wear Particle Count	Wear particles in parts per million	ppm	≤ 40	yes	yes	yes	yes	yes	Capacitance sensor (Dielectric constant), Kinetic Viscometer, Conductivity Sensor
Particle Counting	Detect number of particles for sample size of 100cc	mg/L	≤ 200	no	yes	no	no	yes	

The following subsections illustrate different lubrication oil monitoring techniques in four categories. Most electric (magnetic) and optical approaches are indirect techniques of oil health monitoring. They usually monitor the specific property and correlate the data with that acquired by direct oil degradation feature monitoring approaches while most of the physical and chemical techniques are direct degradation feature monitoring techniques.

A. Electrical (Magnetic) Techniques

1) Dielectric Constant:

Several researches have been reported using special designed capacitors to measure the dielectric constant variation of the target lubrication oil in order to monitoring the oil degradation. It has been proved by Schmitgal and Moyer (2005) that capacitance sensor is capable of lubrication oil oxidation, water contamination and wears particle contamination detection. Raadnui and Kleesuwan (2005) used a grid capacitance sensor (Fig. 2) to measure the dielectric constant with artificial oil contamination then use statistical method to evaluate the performance parameter importance and interaction. The capacitance of the sensor can be expressed as follows: $C = (\epsilon_0 \epsilon_y A) / \sigma$, where ϵ_0 is the dielectric constant in the vacuum; ϵ_y is the dielectric constant of the oil between two poles; A is the available area of poles; σ is the distance between two poles; for a fixed sensor, ϵ_0 , A and σ are constant, the capacitance of the sensors is determined by ϵ_y while the voltage is loaded between the emission pole and the detecting circuit is proportional to the capacitance of the sensor.

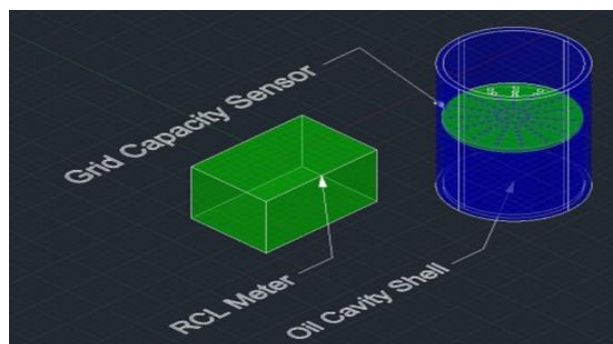


Fig. 2 Grid capacitance sensor

In this paper, the programmable automatic RCL meter is used and the capacitance readout from the measuring apparatus is directly related to the input frequency which is explained in the following Eq. (1).

$$C = 0.5\pi f X_c \quad (1)$$

In Eq. (1), C is the overall capacitance; f is the input frequency; X_c is an inductive of components; Based on the preliminary measurements of dielectric constant of engine oils, the authors find the value of dielectric constant varied from 6.5 to 10 pF in relation to the input frequency (electric current change rate between the poles). Turner and Austin (2003) measured the dielectric constant and magnetic susceptibility then correlated it with viscosity of the lubricant with anointer leaved-disc capacitor. The sensor structure is shown in Fig. 3.

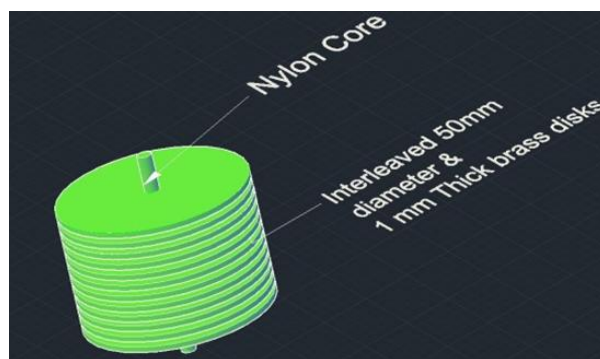


Fig. 3 Interleaved-disc capacitor for measurement of dielectric constant

The authors first measured the capacitance of the air which was around 170 pF. Then, at room temperature of 19°C, the sensor was dipped into the test oil to measure the capacitance of the oil. The dielectric constant was then calculated as:

$$D = C_{oil} / C_{air} \quad (2)$$

Moreover, Cho and Park (2010) designed a wireless sending system which transmits lubrication oil capacitance information and energy between sensor and reader for automobiles with a capacitive IDT sensor. The sensor is shown in Fig. 4.

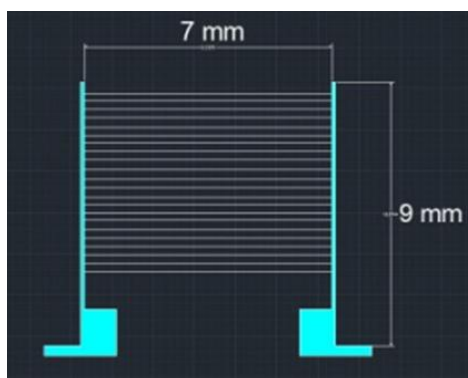


Fig. 4 Capacitive IDT sensor

For the relationship between the field strength E applied to the dielectric substance and the polarization P , the polarization is getting bigger when the field strength increases as shown in Eq. (3).

$$P = \epsilon_0 X_e E \quad (3)$$

$$\varepsilon_r = 1 + X_e \quad (4)$$

And the relationship, which is indicated in Eq. (4), is established between the relative permittivity ε_r , and the electric susceptibility X_e , which presents the degree of polarization caused by the electric field that is applied to a certain substance. The deteriorated oil with polar molecules appear to have a bigger electric susceptibility than the non-deteriorated engine oil with non-polarization, and it is greatly affected by the metallic particles and metallic ions that increased due to corrosion and abrasion. Accordingly, it can be identified that the more the engine oil is deteriorated, the more the permittivity of the engine oil is increased. Jakoby and Vellekoop (2004) combined permittivity (capacitance) sensor with micro acoustic viscometers in order to detect water-in-oil emulsions. MG (Maxwell-Garnett) rule has been identified as a proper tool to predict the size of the effect. Because the relative permittivity of oil ($\varepsilon_{r,o} = 2 - 3$) is quite different from water ($\varepsilon_{r,w} = 80$). The effect of water contamination on the permittivity of the mixture can be expressed as:

$$\varepsilon_{r,m} = (1 - f)\varepsilon_{r,o} + f\varepsilon_{r,w} \quad (5)$$

Where $\varepsilon_{r,m}$ stands for the relative permittivity of the mixture. They proved that permittivity sensors yield a clear indication of the water content in the oil being moreover to first order independent of the exact permittivity of the contaminating water. Also, the output signal of micro acoustic viscometer is hardly influenced by the water content compared to traditional rotational viscometer. Another paper by Guan *et al.* (2011) combined dielectric constant with an analytical method called dielectric spectroscopy to measure the oxidation rate of the lubrication oil. Dielectric spectroscopy (DS) is an analytical technique on the interaction between dielectric material and electromagnetic energy in the radio frequency and microwave range, which is a powerful structural detection technique for dielectric material. This technique is capable of detecting oxidation duration (OD), total acid number (TAN) and insoluble content (IC). The paper proved that DS was the most effective method to extract the dielectric characteristic from dielectric material and could be developed into an efficient oil degradation monitoring technique. The authors believed that the remaining useful life of engine lubricating oil could be predicted based on online or in situ DS data.

Several commercially available sensors developed by Kittiwake Developments Ltd are also capable of online oil quality detection by way of interpreting lubrication oil dielectric property. For example, the Kittiwake On-Line Oil Condition Sensor (Fig. 5) uses a combination of proven Tan Delta dielectric sensing and smart interpretation algorithms to detect lubrication oil oxidation. As mentioned above, TAN is a commonly used performance parameter to describe lubrication oil oxidation. So, by means of correlating lubrication oil oxidation and the dielectric property variation, online oil oxidation monitoring is achieved. Also, based on similar dielectric property monitoring theoretical base, the Oil Quality Sensor (Fig. 6) developed by Tan Delta Systems Ltd is capable of water contamination and oxidation online detection. Moreover, a specialized Moisture Sensor (Fig. 7) developed by Kittiwake Developments Ltd is also commercially available. This sensor uses a combination of proven thin film capacitance sensor and special developed algorithm to perform relative humidity detection.



Fig. 5 On-Line Oil Condition Sensor
(Kittiwake Developments Ltd)



Fig. 6 Oil Quality Sensor
(Tan Delta Systems Ltd)



Fig. 7 Moisture Sensor
(Kittiwake Developments Ltd)

Since many previous oil conditions diagnostic techniques focus on monitoring the basic degradation features like oxidation and soot concentration. They are not capable of performing online data acquisition. By means of correlating dielectric constant variation data with basic degradation data acquired from traditional lubrication oil condition monitoring sensors, one can achieve online lubrication oil deterioration detection. The advantages of dielectric constant include: all degradation feature coverage, online health monitoring capability, and low data processing complexity and maintenance cost. The disadvantage is that most of them need special design and fabrication.

2) Conductivity:

Like capacitor, special fabricated lubrication oil electrical conductivity sensor is another direction scientists have been working on. Moon, *et al.* (2006) reported that by measuring the oil conductivity with a carbon nano tube (CNT) sensor (Fig. 8), lubrication oil oxidation rate can be monitored. They correlated the CNT conductivity data with TAN of the test oil and the results shows that CNT sensor is effective regarding to the oil oxidation deterioration. Since many sensors with chemical based techniques have relatively short life span problems and not capable on online diagnostics. This CNT sensor reduced the maintenance cost and provided an instant data collection solution. Basu *et al.* (2002) and Lee *et al.* (1994) both found that conductivity changes due to chemical and physical changes in the additives commonly used in commercial lubricant. However, their methods require prior knowledge of the oil formulation and they only tested on gasoline engines, also no thermal effects

were made. While conductivity sensors are capable of online diagnostic and the result is well correlated with oxidation rate of the oil degradation, more experiments are needed to cover other oil basic degradation features.

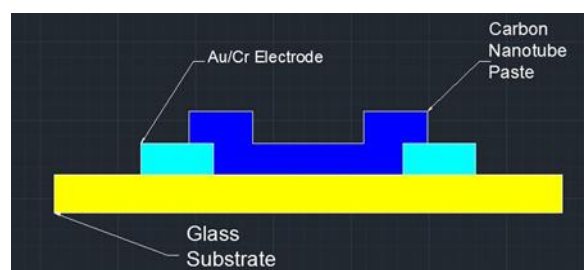


Fig. 8 CNT oil sensor

Hedges *et al.* (2012) developed Polymeric Bead Matrix (PBM) technology for on-board condition based monitoring of fluid-lubricated aircraft components (Fig. 9). This technique utilized the electrical properties of an insoluble polymeric bead matrix to measure oil degradation. Charged ion groups were covalently bound to the matrix. By measuring the impact of solvating effect on the electrical characteristic (conductivity and polarity) of the matrix, lubrication oil deterioration monitoring was achieved. This sensing technique can monitor water and particle contamination along with oxidation. However, the sensor does need to be replaced along with the replacement of the oil.



Fig. 9 CNT oil sensor

3) Magnetic Susceptibility:

Monitoring the magnetic properties changes when oil degrades was the earliest developed system for lubrication oil diagnostic. Halderman (1996) used a magnetic plug placing in the flow of oil. The plug has to be removed and ferromagnetic fragments were collected. The fragments were then inspected for condition analysis. Ferromagnetic fragments analysis usually calls for complicated microscopes and is time consuming. Turner and Austin (2003) used a magnetic susceptibility balance trying to investigate links between magnetic properties of lubrication oil and its usage, measured by viscosity variation. Fig. 10 shows a typical commercial magnetic balance.



Fig.10 Commercial magnetic balance (Sherwood Scientific, Ltd)

The result shows that the magnetic characteristics of lubricating oil do change as the oil degrades, but the measurements were poorly correlated with viscosity and do not seem to offer much promise as the basis of an oil monitoring system. Even though magnetic susceptibility balance and magnetic plug provide the simplest solution for oil deterioration sensors, they have poor correlation with viscosity, not sensitive or calls for complicated further data processing.

Currently, most magnetic based oil condition monitoring techniques are used for oil bourn metallic particle detection like

ferrous particle which is one of the most common results of component wear. Typical systems include Patrol-DM™ Wear Debris Monitor developed by Poseidon Systems, LLC as shown in Fig. 11 and On-Line Metallic Wear Debris Sensor along with On-Line Ferrous Wear Debris Sensor developed by Kittiwake Developments Ltd as shown in Fig. 12 and Fig. 13 respectively. These systems are sensitive with metallic particle contamination. However, particle contamination is only one of the 3 basic degradation features of the lubricant.



Fig. 11 Patrol-DM™ Wear Debris Monitor (Poseidon Systems, LLC)



Fig. 12 On-Line Metallic Wear Debris Sensor (Kittiwake Developments Ltd)



Fig. 13 On-Line Ferrous Wear Debris Sensor (Kittiwake Developments Ltd)

Electrochemical impedance spectroscopy (EIS) is another electrical technique that can provide valuable insights into the condition of lubricating oils and their additive packages (Byington *et al* 2010, 2012; Moffatt *et al* 2012). This sensor has been proved to detect chemical and mechanical property variation of lubrication oil including TAN/TBN, soot content, viscosity and degree of nitration. Byington *et al* (2012) correlated EIS sensor output with different performance parameters, then by means of symbolic regression, several data driven models were developed to describe the lubricant deterioration behavior. At last, Sequential Mont Carlo (SMC) technique was used as a remaining useful life prediction tool for oil prognostics.

Typical commercially available EIS sensor is SmartMon-Oil™ developed by Poseidon Systems, LLC as shown in Fig. 14. They developed a technique called “Broadband AC Electrochemical Impedance Spectroscopy”. By means of injecting complex voltage signal into the fluid at one electrode, and received by another electrode, the impedances are measured at different frequencies. The measured impedances are then correlated to the chemical and physical properties of the oils. This EIS sensor is capable of measuring water and soot contamination level as well as general oil quality.



Fig. 14 SmartMon-Oil™ (Poseidon Systems, LLC)

4) Micro Acoustic Viscosity:

Viscosity variation beyond or below operating limits is commonly considered that lubrication oil is degrading. Because all the basic oil degradation features can be detected by a viscometer including oxidation, water/particle contamination and fuel dilution. Also, the mileage of an engine or operating duration of a gearbox cannot be considered equal to lubricant deterioration reference (operating conditions, individual operating habits, ambient condition and fuel quality). Viscosity is usually considered lubricant degradation comparison standard for its independence on various operating conditions. Agoston *et al.* (2005) used a micro acoustic sensor to measure the viscosity electrically for automotive applications. This sensor, whose structure is shown in Fig. 15, is small and has a long life span and can be deployed in aggressive industrial environments. The indirect data provided by the engine management and its relation to the oil wear will depend on the actual engine platform used whereas the data provided by the sensors are directly linked to the oil condition and are thus platform-independent. The micro acoustic viscometer can measure all the basic oil degradation features online with space efficient design. However, the lack of practical tests from industry and problems with oil contained viscosity modifiers may limit its application in the industry.

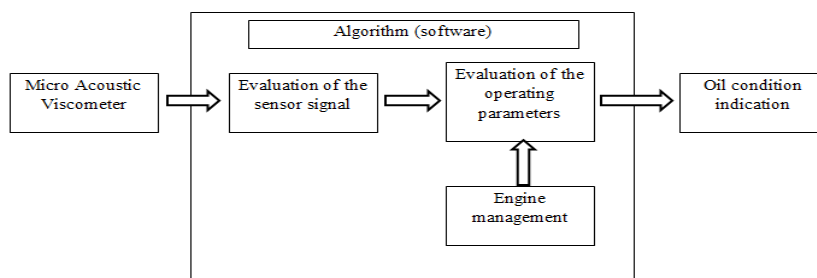


Fig. 15 Structure of a sensor assisted algorithm for a lubrication monitoring system

B. Physical Techniques

1) Kinematic (Electromagnetic) Viscosity:

As it is mentioned in the micro acoustic viscosity sub section, all the basic oil degradation features have influence on the viscosity. Kinematic viscosity can be acquired by a traditional kinematic viscometer which is also called electromagnetic viscometer as shown in Fig. 16.

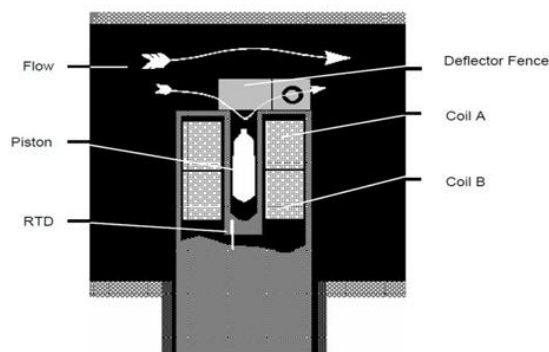


Fig. 16 Typical kinematic viscometer structure (Cambridge Viscosity. Ltd)

This kind of viscometer usually involves a piston that dipped into the test lubricant and the coils inside the sensor body magnetically force the piston back and forth a predetermined distance. By alternatively powering the coils with a constant force, the piston's round trip travel time is measured. An increase in viscosity is sensed as a slowed piston travel time. The time required for the piston to complete a two way cycle is an accurate measure of viscosity. The deflecting fence acts to continuously deflect fresh sample into the measurement chamber. Since measurement of the piston motion is in two directions, variations due to gravity or flow forces are annulled. Also, because the piston has very little mass, magnetic forces greatly exceed any disturbances due to vibration. The investigation of Schmitgal and Moyer (2005) on diesel engines proved that the kinematic viscometer is capable of lubricant soot particle, water contamination and oxidation deterioration detection. The kinematic viscometers are capable of monitoring all the oil basic degradation features online with low data processing complexity and maintenance cost. However, the commercially available kinematic viscometers have a relatively high manufacture cost.

2) Ultra Sound:

Sound and vibration are used for many health monitoring applications. In the case of oil condition monitoring, early research using ultrasound was published in 1980s (BHRA, 1988; Turner and Austin, 2003). BHRA developed a system with a sensor and receiver. They are placed on opposite sides of an oil flow. The receiver is oriented so that it will only detect ultrasound scattered by oil-borne solid particles in clean hydraulic fluid. This technique is capable of online health monitoring. However, no record using this technique to monitor heavy lubrication oil like engine or transmission oil has been reported.

3) Thermal Conductivity:

Another physical approach of lubricant deterioration detection is thermal conductivity. Kuntneret *al.* (2005) reported that water contamination and degradation processes in mineral oil lead to an increased thermal conductivity. This report shows the potential of the thermal conductivity sensors in the field of oil condition monitoring. A special designed hot film micro sensor, as shown in Fig. 17, using a resistive thin-film molybdenum structure on a glass substrate was fabricated with the technique of transient hot-wire method.

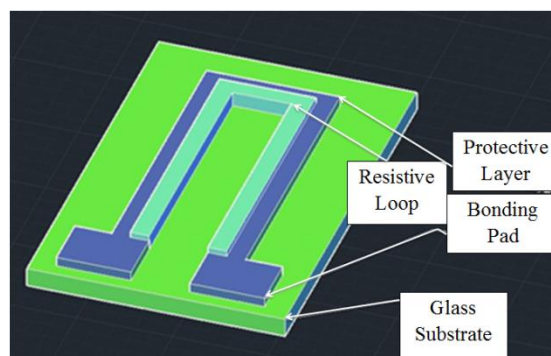


Fig. 17 Miniaturized thermal conductivity sensor

The authors considered a hot film microsensor, which is operated using an adapted transient method. Considering the small dimensions of the sensor compared to the used sample volumes (15ml) of the investigated liquids, the corresponding temperature field at some distance from the sensor can be approximate calculated by solving the heat diffusion equation for a thermal point source switched on at $t = 0$, as:

$$\zeta(r, t) = \frac{\emptyset}{4\pi\lambda r} \operatorname{erfc}\left(\frac{r}{\sqrt{4at}}\right) \quad (6)$$

where $\emptyset$ is the heating power, λ the thermal conductivity, a the thermal diffusivity, and r the radial distance from the point source. Note that for small r , this approximation becomes inaccurate and even yields a non-physical singularity for $r = 0$. The diffusivity is related to the heat capacity C_p and can be computed as:

$$a = \frac{\lambda}{\rho C_p} \quad (7)$$

where ρ is the mass density. For $t \rightarrow \infty$, the complementary error function erfc in Eq. (6) approaches unity such that in the steady state, the temperature distribution depends only on the thermal conductivity and the heating power shown as:

$$\zeta(r) = \frac{\emptyset}{4\pi\lambda r} \text{ when } t \rightarrow \infty \quad (8)$$

It was also proved that this kind of sensor is capable of real time health monitoring and may have potential in oil oxidation degradation monitoring. The robustness and sensitivity balance of the sensor structure may need more tests in order to improve its durability and effectiveness in aggressive industrial environment.

4) Ferrography:

As mentioned in the magnetic susceptibility subsection ferromagnetic fragments are collected and send to a laboratory for further ferrography analysis. Ferrography is a typical traditional oil diagnostic technique for analyzing particles present in lubricants. It uses microscopic examination and was developed in the 1970s for predictive maintenance, initially analyzing ferrous particles in lubricating oils. Levi and Eliaz (2009) conducted ferrography, atomic emission spectroscopy, scanning electron microscopy and quantitative image analysis for the purpose of detecting a variety of wear particles in open-loop oil. The technique is field tested with a Wankel engine. However, this technique is not capable of online health monitoring, requires high level of data processing and costly test equipment.

C. Chemical Techniques

1) pH Measurement:

Lubrication oils contain long-chain oxidizable hydrocarbons. In an operating engine, these hydrocarbons are exposed to high temperatures, which make them more vulnerable to be attacked from free radicals, reported by Turner and Austin (2003). Mann (2003) mentioned that the effects of oxidation due to chemical reaction as well as the by-products of combustion generate relatively high acidic compounds inside an engine. These compounds cause corrosion of internal engine components, deposits, and changes in oil viscosity, varnish, sludge and other insoluble oxidation products that can cause a performance and durability degradation of the engine over a period of time. Wang and Lee (1994) designed a microprocessor-controlled total acid number sensor. Their sensing technique calls for a high degree of signal processing filtering in order to obtain useful data. Others tried pH-based measurement of different lubrication oil condition. However the test result seems unreliable and has repeatability problems questioned by Turner and Austin (2003).

2) Thin-film Contaminant Monitor:

The lubrication oil performance stay stable if the oil temperature is maintained within the manufacture recommended range. In case it is not operating in the required condition, the oil deterioration starts and it reflects the degradation of lubricating oil. As a general thumb rule, a 10°C rise in temperature doubles the oxidation rate and so is formation of oxidation products. Initially these oxidation particles are soft and gummy products. When these particles come in contact with high-temperature zones these lead to formation of hard and abrasive particles. These on contact with the components cause generation of wear particles causing further reduced system performance (Sharma and Gandhi, 2008). The thin-film contaminant monitor approach used a thin metallic film which forms part of an electric circuit to monitor the particle contamination in lubrication oil flow (Halderman, 1996). The film is exposed to the oil flow and continuous eroded by oil-borne solid particles as oil degrades. As a result, the resistance rises. This technique is dependent on the particle size and concentration which needs frequent maintenance. Overall, thin film contaminator is good for online diagnostics but only capable of particle contamination monitoring and the measurement may not be well correlated with viscosity.

D. Optical Techniques

1) Optical Transparency or Reflectometry:

With the goal of achieving online oil deterioration analysis, optical oil condition monitoring techniques was born. This technique usually correlates oil optical transparency or reflection rate with oil general degradation basic features. Tomita (1995)

built a lubrication deterioration sensor based on optical reflectometry in laboratory condition. However, the device is not yet field tested in harsh industrial environments. Zhang (1998) also designed an optical sensor and tested on an internal combustion engine. Kumar and Mukherjee (2005) fabricated an optical sensor with light dependent resistor (LDR) to record the oil transparency and then convert it to resistance. The sensing system is shown in Fig. 18.

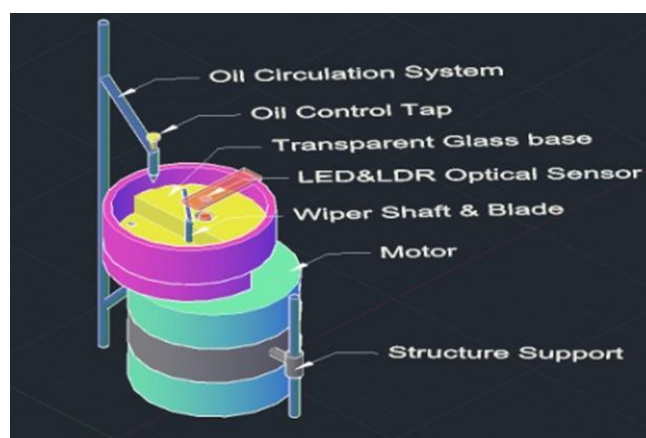


Fig. 18 Optical transparency sensor

The sensor was tested on a six cylinder gasoline engine. The authors correlated the resistance data with working hours, viscosity and oxidation (scaled by pH measurement) and prove the effectiveness of the designed sensor. According to the paper, this optical sensor has full basic degradation feature coverage and online diagnostic and prognostic capability. However, this sensor does have a complicated structure which may cause reliability issues. Also, some paper reported that optical changes do not correlate well with oil degradation process.

2) IR Absorption:

When oil deteriorates, nitrate compound is generated. This compound absorbs infrared (IR) radiation with a wave length of $6.13\text{ }\mu\text{m}$. This effect was used in a sensor that measured the IR absorption along a fix path length and attempted to correlate the measurement with oil condition reported by Agoston et al. (2004) and Turner and Austin (2003). Even though it is capable of online oil degradation monitoring, this sensing system may need some future improvement to overcome repeatability problems and reduce the manufacturing cost.

III. PERFORMANCE EVALUATION OF OIL MONITORING SYSTEMS

In this section, the characteristic of each lubrication oil health monitoring solution or sensing technique is evaluated with a set of properties which are crucial for oil health monitoring, diagnostics and prognostics.

A. Defined Evaluation Properties

1) Data Acquisition Instantaneity:

Lubrication oil condition monitoring techniques are evolving from off-line sampling to online instant diagnostic data acquisition. In the past, off-line monitoring is the only solution available. Lubricant samples were collected from machineries and sent to laboratories or companies specialize in oil condition monitoring. A report with raw data was then prepared. The data were then analyzed and several necessary action options were provided thereafter. This process normally takes more than 24 hours and is time and cost consuming (Kumar and Mukherjee, 2005). When lubrication oil analysis is done somewhere else and results turn up sometime later, it is hard to relate the data with the machine's health status at the time of sampling. The burden of collecting representative samples virtually relegates oil analysis to a secondary status in a condition monitoring program. Also, actual condition of the oil cannot be determined as the samples are collected when the machine is not in the running condition. With more and more attention drew into oil condition monitoring field, on-line, onboard diagnostic techniques started to merge which significantly reduced the oil deterioration data acquisition delay. Therefore, whether the oil condition monitoring technique is capable of, instant data acquisition is considered a key evaluation property.

2) Prognostic Capability:

Among all the lubrication oil health monitoring techniques and solutions, many of them were developed with the purpose of extend the life of lubricant. This purpose cannot be achieved without both real time condition monitoring and remaining useful life prediction. In industrial applications, one needs advance notice or early warning of oil replacement. Otherwise sudden diagnose of failure which needs immediate action will have influence on the production rate because the equipment

needs to be shut down in order to prevent unnecessary wear or damage. Also, in large applications like wind turbines, knowing the exact time of lubricant change can optimize the maintenance schedule therefore reduce the cost. Hence, the capability of lubrication oil prognostics is another crucial evaluation property that needs to be taken into account.

3) *Basic Degradation Feature Coverage:*

As mentioned above, the basic lubrication degradation features are oxidation degradation, particle (soot) contamination and water contamination. Some oil health monitoring techniques cover one or more of these features. In practical applications, for the diagnostic system robustness and effectiveness concern, all the basic deterioration features have to be considered. Focusing on one specific feature will not provide a sufficient or objective result regarding to the status of oil degradation or health condition. The more features a technique covers, the more objective the results will be. Basic degradation feature coverage is an important property that has to be evaluated during different approach comparison.

4) *Data Processing Complexity:*

Some of the diagnostic approaches require certain level of data processing. The complexity of the data analyzing has direct impact on processing time and data acquisition delay. Moreover, for on-board instant oil condition monitoring complicated data analyzing algorithm may require extra processing device which will add certain manufacturing cost. Also, developing sensing technique with complicated algorithm for mobile engineering systems will continuously occupy CPU resources of onboard computer which may slow the system down and cause data jam. When it comes to practical industrial applications, simpleness and efficiency are always the basic design principles. Therefore, the data processing complexity should always be considered and evaluated.

5) *Sensitivity:*

The sensor's reaction amplitude upon basic degradation features' variation is defined as sensitivity of the technique. In order to achieve real-time lubrication oil health monitoring, the sensing systems have to exhibit a quick reaction time regarding to the degradation and amplitude that can be scaled by a device that come with the system. Low sensitivity will result in either an unnecessary need for demanding measurement equipment or a delay between the output and the real degradation status of the lubrication oil. For every sensing technique, sensitivity is always an evaluation property that cannot be ignored.

6) *Field Tested:*

The ultimate way to evaluate the effectiveness and robustness of a sensing technique's is to perform field tests in actual industry environment. An oil condition monitoring solution that is not capable of industrial deployment is not reliable. Given the aggressive operating condition the lubrication oil condition monitoring sensors will be in, one must present high tolerance of dust, high temperature, sudden temperature change and many other ambient conditions. A solution that only works in the laboratory has no real world contributions and ought to be improved.

7) *Manufacture Cost:*

Manufacture cost is another property that has to be evaluated. The cost of a lubrication oil sensing technique depends on several factors. Sensor fabrication cost takes a large proportion of the total cost. A complicated sensor or sensing technique needs to be well designed and precise manufactured. This issue may affect the deployment in civilian applications like automotives and limit the wide spread of the technology. The development of data processing algorithm will also increase the cost because it takes time and investment. Moreover, certain sensing techniques focus on only one application, if another application comes up, new sensors or algorithms have to be developed. This is also considered not cost efficient.

8) *Maintenance Cost:*

The life time of the designed oil deterioration sensor determines the sensing system maintenance cost. As addressed in the former sections, lubrication oil condition monitoring sensors should exhibit a long life time in aggressive operating conditions. The sensors should be able to perform continuous condition monitoring without frequent maintenance. The pH measurement and chemical corrosion monitoring techniques need frequent replacement of critical components which will increase the maintenance cost. Sensor component change needs to be performed while the machine is not in the running condition which may also reduce the production rate. The evaluation of oil condition monitoring solutions will not do if this unavoidable issue is not considered.

B. *Performance Evaluation and Comparison*

In this sub-section, the characteristic of each lubrication oil health monitoring solution or sensing technique is evaluated and compared in Table II with the seven properties defined in Section 3.1. Three evaluation properties, data processing complexity, manufacture cost and maintenance cost are scaled as low, medium and high. All the techniques are classified and profiled into its evaluation categories.

TABLE II PERFORMANCE EVALUATION AND COMPARISON OF LUBRICATION OIL HEALTH MONITORING TECHNIQUES AND SOLUTIONS

Oil Monitoring Techniques Classification		Specific Monitoring Technique	Data Acquisition Instantaneity	Prognostic Capability	Basic Degradation Feature Coverage	Sensitivity	Data Processing Complexity	Field Tested	Manufacture Cost	Maintenance Cost
Electrical (Magnetic) Techniques	Dielectric Constant	Grid capacitance sensor	Online	No	Oil oxidation, wear particle concentration, water contamination	High	Low	No	Low	Low
		Inter-leveled disk capacitor	Online				Low	No	Low	Low
		Capacitive IDT (Inter-Digit Type) sensor	Online				Low	Tested	High	Low
		CSI oil view model 5500	Online				Low	Tested	High	Low
		Permittivity sensor	Online	Yes	Water contamination		Low	No	Low	Low
		Dielectric spectroscopy analyzer for Petroleum (DSAP)	Online		Oxidation and particle contamination		Medium	No	Medium	Low
		Tan Delta dielectric sensing	Online		Water Contamination, Oxidation		Low	Yes	Medium	Medium
		thin film capacitance sensors	Online	No	Water Contamination		Low	Yes	Medium	Medium

Oil Monitoring Techniques Classification		Specific Monitoring Technique	Data Acquisition Instantaneity	Prognostic Capability	Basic Degradation Feature Coverage	Sensitivity	Data Processing Complexity	Field Tested	Manufacture Cost	Maintenance Cost
Electrical (Magnetic) Techniques	Conductivity	Multiwall carbon nano tube conductivity sensor	Online	No	Oxidation and wear particle contamination	High	Low	No	High	High
		Conductivity sensor	Online		Particle contamination	Medium	Low	No	Medium	Medium
		Diesel oil condition and level sensor	Online		Particle contamination	High	Low	Tested	Medium	Medium
		Polymeric Bead Matrix (PBM)	Online		Particle and water contamination and Oxidation	High	Medium	Yes	Medium	High
	Magnetic Susceptibility	Magnetic susceptibility balance	Offline		None	Low	Low	No	Low	Low
		Magnetic Plug	Offline		Particle contamination	Low	Low	No	Low	Low
		magnetometry	Online		Particle contamination	High	Medium	Yes	Medium	Medium
	Micro Acoustic Viscosity	Micro acoustic viscometer	Online		Oil oxidation, wear particle concentration, water contamination	High	Low	No	Medium	Low
	Electro-chemical Impedance Spectroscopy (EIS)	Broadband AC Electrochemical Impedance Spectroscopy	Online	Yes	Oil oxidation, wear particle concentration, water contamination	High	Low	Yes	Medium	Low

Oil Monitoring Techniques Classification		Specific Monitoring Technique	Data Acquisition Instantaneity	Prognostic Capability	Basic Degradation Feature Coverage	Sensitivity	Data Processing Complexity	Field Tested	Manufacture Cost	Maintenance Cost
Physical Techniques	Kinematic Viscosity	Kinematic viscometer	Online	No	Oil oxidation, wear particle concentration, water contamination	High	Low	Tested	Medium	Medium
	Ultra sound	Ultra sound sensor and receiver	Online		Particle contamination	Medium	Medium	No	Medium	Medium
	Thermal conductivity	Thermal conductivity sensor	Online		Water contamination and oxidation	High	Medium	No	Medium	Low
	Ferrography	Micro scopes	Offline		Particle contamination and oil oxidation	High	High	Tested	High	High
Chemical Techniques	pH measurement	Micro processor controlled TAN sensor	Offline	No	Oil oxidation	Medium	High	No	High	High
	Thin film contaminant monitor	Thin metallic film connected to a electric circuit	Online		Particle contamination		Low	No	Medium	High
Optical Techniques	Optical transparency or reflectometry	Optical color sensor	Online	Yes	Particle contamination and oil oxidation	High	Low	Tested	High	Medium
		Optical reflectometry sensor	Online	No		High	Low	No	High	Medium
		Optical sensor for internal combustion engines	Online	No		High	Low	Tested	High	Medium
	IR absorption	A sensor measures IR absorption along a fixed path length	Offline	No		Medium	Low	No	High	High

From the summarized information in Table II, we can conclude that viscosity and capacitance sensor have the best lubrication oil basic degradation feature coverage and the lowest maintenance cost. Moreover, kinematic viscosity and dielectric constant are the two performance parameters that are able to perform lubrication oil deterioration online monitoring with the lowest data processing complexity. However, most techniques do not offer integrated lubrication oil remaining useful life prediction solution. Some reported papers used analytical or statistical method to perform lubrication oil prognostic or evaluate basic degradation features' impact on oil protective property degradation. Sharma and Gandhi developed a parameter profile approach with multiple performance parameters data. The data were collected and tested on an internal combustion engine with a promising result. In general, if combined with proper data analysis techniques, online oil degradation monitoring with capacitance and viscosity sensors has great potential and will probably be the future of online onboard lubricant deterioration monitoring, diagnostic and prognostic.

IV. CONCLUSION

In this paper, a comprehensive survey of current lubrication oil condition monitoring, diagnosis and prognostics techniques and systems was presented. Condition monitoring is the process of monitoring a parameter of condition such that a significant change is indicative of a developing failure. An overview with detailed evaluation and comparison among the most recent developed sensors and systems is provided. The survey provided an insight into the current status of oil health monitoring and pointed out the future direction of lubrication oil diagnostics and prognostics development.

The final goal of all the designed sensing systems is to achieve lubrication oil online health monitoring and remaining useful life prediction. According to the detail evaluation of each lubrication oil degradation monitoring techniques, it is clear that viscosity and capacitance sensor have the best lubrication oil basic degradation feature coverage, reasonable manufacture and maintenance cost. Kinematic viscosity is a crucial performance parameter for it can objectively reflect oil degradation process and has been used as a comparison standard to evaluate other sensing techniques. Dielectric constant is another important performance parameter that is capable of performing lubrication oil deterioration online monitoring with the lowest data processing complexity. If combined with proper data analysis techniques, online oil degradation monitoring with capacitance and viscosity sensors will have great potential to overcome all the existing challenges and will probably be the future of online onboard lubricant deterioration monitoring, diagnostics and prognostics.

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