

Lubricants Health Monitoring

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ABSTRACT

Fault inception and growth in the components of a mechanical power drive are often heavily affected by the lubricant health. As a consequence, monitoring the lubricant health status and signaling a degradation of the lubricant properties could improve the reliability of the mechanical drive. A further merit of implementing a lubricant health monitoring system is the possibility to move from a time-based maintenance to a condition-based maintenance with the ensuing decrease of operating costs and reduction of the environmental impact. This would be of a particular advantage for those applications in which loss of operation generated by poor lubrication could cause a service disruption or lead to a safety critical condition. The proposed paper presents the initial part of an ongoing research activity on lubricants health monitoring. The work so far performed consisted of the following activities: perform a critical review of the studies addressing the lubricants condition; determine which are the significant features of the lubricants used in the majority of mechanical systems, that need to be extracted to assess the lubricant health; which occurrences affect the lubricant health and how the oil health status can be assessed by different techniques, whose relative merits will be discussed; define the progression of the degradation of the lubricant health status; present the initial study of how different lubricant health monitoring techniques can be fused together to develop an efficient on-line lubricant health monitoring system. The paper thus presents the summary of the work performed to establish the fundamentals onto which a reliable PHM system for the lubricants of mechanical drives can be developed, that will be the final objective of the on-going research activity.

1. PROBLEM STATEMENT

Several research activities in prognostics and health management have been performed to evaluate the health status of mechanical components by analyzing the condition of the lubricant used in their operation. Optical and magnetic particle detectors have been proposed as sensors capable of providing useful information on the characteristics of the contamination particles entrained by the lubricant (Sjödin & Westin, 2013). Oil debris monitoring seems in fact to be one of the most effective approaches for PHM of the components of a mechanical drive. In fact, it seems logical that the gradual degradation of a component can lead to the accumulation of various types of particles in the lubricant. Therefore, monitoring such accumulation can provide an indication of the progression of the wear of the mechanical component and hence allow an estimate of its remaining useful life. An example of this technique is the oil debris monitoring sensor developed for the Pratt & Whitney F119, that relies upon sensing the disturbances to an electromagnetic field created by the passage of metallic particles. The sensor is based on an inductive measurement technique which enables detection, count and classification of wear metal particles by size and type.

In all these applications the lubricant is actually used as a diagnostic tool able to provide useful information on the health status of the mechanical drive, while no specific attention is paid on the health of the lubricant itself.

However, an ongoing research on the failure mechanisms for the mechanical components of the electromechanical actuators for aerospace applications showed that fault inception and growth are often heavily affected by the lubricant health. Most of the faults of the components of mechanical drives, such as gears and bearings are in fact caused by insufficient lubrication (Stachowiak & Batchelor, 2005). Poor lubrication leads to a direct contact between the surfaces of the mating components in relative motion with an ensuing progressing wear. The type and rate of the wear depends on several factors, such as component type, rubbing

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speed and contact pressure, but the root cause is normally poor lubrication. Therefore, monitoring the lubricant health status, in particular the oil oxidation stability and not only the quantity of oil debris, and signaling a degradation of the lubricant properties could provide significant benefits and improve the overall reliability and availability of the actuator.

Of course, a simple way of preventing poor lubrication due to a decay of the lubricant properties is to replace the lubricant at small time intervals. Though this ensures good lubrication of the components throughout their life, it entails high operating costs. The costs are not only determined by those of the lubricant, but also by those associated to the maintenance time and to the lubricant disposal. It must be further emphasized that scheduled maintenance most of the time leads to the replacement of a lubricant that is still in good conditions and could effectively perform its function for a much longer time (Bowman & Stachowiak, *New criteria to assess the remaining useful life of industrial turbine oils. Lubrication Engineering*, 1996). Extending the time interval between two replacements of the lubricant is however a risky business unless a reliable information on the lubricant condition is available, since the operation of the mechanical components without proper lubrication leads to their premature failure.

A possibility for optimizing the combination of the two issues: reducing the frequency of lubricant replacement and ensuring a good lubrication of the mechanical components, is to carry out periodical laboratory tests of the lubricant during an initial operational phase of the actuator. By observing the evolution of the properties of the lubricant during the actuator operation an optimal time interval can be established between two consecutive replacements of the lubricant. Although this procedure is logical, it falls short of providing meaningful results if the actuator can operate in highly variable conditions, as it is the case of the actuators used in the aerospace or mobile machinery applications. In these cases the lubricant characteristics can evolve in a rapid and unpredicted way with the ensuing risk that the established replacement interval, that seemed to be acceptable during an initial test campaign, turns out to be inadequate. This risk is further enhanced if no other monitoring is performed of the operational characteristics of the actuator, such as the alert of possible hot spots that could cause a breakdown of the lubricant properties.

The development of a continuous and reliable method to evaluate the lubricant health status and its associated remaining useful life can thus provide a valuable contribution to the improvement of the availability of a mechanical actuator and to the reduction of its life cycle cost. From a PHM perspective this leads to a paradigm shift: the lubricant is not any longer simply a tool for assessing the health status and the remaining useful life (RUL) of the mechanical components, but it becomes itself

an element subjected to continuous health monitoring and whose remaining useful life is determined by appropriate algorithms based on processing the collected data.

The development of an efficient and reliable PHM system for the lubricant goes through three logical steps:

- Step #1 is to clearly identify the physical quantities that provide the most significant indication of the lubricant health status
- Step #2 is to define the most appropriate sensors and measuring techniques that allow the extraction of the previously identified significant features
- Step #3 is the development of the algorithms capable of performing a reliable assessment of the lubricant health status and its RUL starting from the collected data

2. LUBRICATING ACTIONS IN MECHANICAL COMPONENTS

Relative motion between two solid bodies causes a series of complex interactions between the mating surfaces of the two bodies that are well described in tribology literature (Stachowiak & Batchelor, 2005). These interactions eventually lead to a wear of the surfaces of the two bodies, which depends on a large number of factors. When a lubricant, either liquid, solid, or gaseous is in contact with the surfaces of the two bodies in relative motion, the mutual interaction between the two surfaces is completely changed and can be even nil if a sufficiently deep layer of lubricant is created to physically separate the two surfaces. The end result is a reduced wear of the bodies surfaces with an ensuing increase of their life and a reduction of the energy dissipation.

Although several types of lubricants are used in mechanical components, the most common ones are oils and greases. Unless the system operational environment mandates special requirements, oil and grease are the preferred type of lubricant because they allow the development of a lubricant layer between the two solid surfaces with a relatively large thickness. This entails a decrease of the interactions between the surface irregularities of the two bodies; the greater the thickness of the lubricant layer, the lower the interactions between the two surfaces and the ensuing wear.

The lubricant layer thickness is strictly related to the physical properties of the lubricant. As an approximation, the layer thickness is proportional to the lubricant viscosity; however, increasing the viscosity brings about an increase of the energy dissipation in the lubricant layer with a consequent increase of the local temperature. This leads to potentially negative effects, such as the oxidation of the lubricant which in turn causes an increase of the viscosity. The selection of the optimal lubricant viscosity is thus the result of a careful tradeoff among several different needs.

The explanation of the lubrication mechanisms has been a long standing research subject that started at the end of the

19th century. In particular, most of the research studies addressed the physics of the formation of the lubricant layer as a function of the operating conditions. Except for the case of hydrostatic lubrication that uses an external power source to create the lubricant pressure necessary to create a separation between the two facing bodies, in all other cases the development of the lubricant layer is tied to the lubricant viscosity, to the relative motion between the two bodies and to the loads acting on them. Three main types of lubrication can be identified: hydrodynamic, elastohydrodynamic and boundary lubrication.

Hydrodynamic lubrication occurs in journal bearings in which two conformal bodies are in relative motion and is originated by the relative sliding velocity between the two bodies.

Elastohydrodynamic lubrication takes place in case of non-conformal contacts subjected to large loads, such as the case of gears teeth and rolling bearings. In this case, a very thin film of lubricant is created, that is anyhow sufficient to greatly reduce friction and wear. Three main factors play a role: hydrodynamics, elastic deformation of the solid bodies under load and the characteristic of the viscosity increase with pressure. This entails that only those lubricants showing a large increase of viscosity with pressure are suitable for elastohydrodynamic lubrication.

Boundary and extreme pressure lubrication is the prevailing type of lubrication in numerous mechanical applications, such as the metal cutting tools. This lubrication type is different from the previous two. An extremely thin film of lubricant is created on a very hard material, which leads to a reduction of the shear stresses with consequent low friction forces. The formation of the lubricant film mainly depends on the chemical properties of both the lubricant and the solid material.

The complex interactions among surfaces, lubricant, contaminants and environment conditions sometimes lead to a temporary reduction of the friction forces, even if severe wear occurs. However in the long term, whichever is the lubrication mechanisms, degradation of the lubricant properties generally leads to an increased wear of the solid surfaces and to greater friction forces. These increase the dissipation of mechanical energy and in consequence the lubricant temperature rises. Thereby the degradation of the lubricant properties is accelerated.

The lubricant positive action is not only limited to adhesion wear, consisting of the loss of material due to the mutual contact between the irregularities of the two solid bodies. Good lubrication also reduces abrasive, corrosive and oxidation wear. The physical properties of the lubricant must be such to prevent the development of chemical reactions on the surfaces of the two solid bodies. These chemical reactions can in fact entail a rapid wear of the bodies surfaces, especially when the reaction product

consists of an oxide that can be easily entrained by the relative motion between the two bodies. Chemical reactions can be originated by different chemical agents. Of a particular interest is the case of the corrosive action of the lubricant itself. The proper selection of the lubricant is not only dependent on its viscosity characteristics and on the operating pressure and temperature, but also on the chemical reactivity of the lubricant with the bodies materials. The lubricant must be selected to be non-reactive with the materials of the lubricated surfaces; improper or anomalous operating conditions, or a prolonged use can however bring about chemical modifications of the lubricant which can then become a source of corrosion for the wetted materials.

3. DEFINITION OF THE LUBRICANT HEALTH STATUS

Whichever is the lubricant type, whether its base stock is mineral or synthetic oil, and whether the lubricant is oil or grease, its health status is defined by a few measurable properties. With reference to the fundamentals of lubrication outlined in the previous section, the most significant features describing the lubricant health and its ability of performing its function are:

- Viscosity
- Corrosive behavior
- Contamination level
- Oxidation stability

Other characteristics of the lubricant, such as pour, flash and fire points are important for the initial selection of the most suitable lubricant for a given application, but are less critical for defining the lubricant condition during its life.

Viscosity is the most important parameter for determining the lubrication function since it directly affects the thickness of the lubricant layer and the energy dissipation along the sliding surfaces. The viscosity of a given lubricant depends on several factors, among which the amount of lubricant oxidation and the presence of water. Moreover, for a lubricant in optimal conditions, the viscosity decreases rapidly with increasing temperature while it increases with increasing pressure. Appropriate equations can describe the variation of the lubricant viscosity with temperature and pressure (Stachowiak & Batchelor, 2005).

The level of contamination affects both the lubricant behavior and its life. Water is a very common contaminant in the lubricant and reduces its viscosity, while promoting corrosion and oxidation of the bodies surfaces. Other typical contaminants are sulphur and chlorine which are present in different amount in the base stock and must be removed in the refinement process. Sulphur and chlorine make the lubricant highly corrosive, though they might improve its characteristics when they are present in a minimal amount. Debris coming from the wear of the sliding surfaces are a further common contaminant and their

measurement can provide an indication of the condition of the bodies surfaces.

Although all the above mentioned features globally define the lubricant health status, the individual feature that has been recognized as mostly significant for monitoring the lubricant health and defining its remaining useful life is the degree of lubricant oxidation (Bowman & Stachowiak, New criteria to assess the remaining useful life of industrial turbine oils. *Lubrication Engineering*, 1996). The presence of oxygen causes the lubricant molecules to chemically react with oxygen created corrosive compounds which also normally increase the lubricant viscosity. This process takes place at any operating condition, but is enhanced by high temperatures and by the possible presence of catalysts. The compounds produced by the lubricant oxidation are highly corrosive limiting the lubricant life.

Resistance to oxidation can be improved by a prolonged refining process for removing aromatic fractions of the lubricant as well as molecules containing sulphur, oxygen and nitrogen. However, this is an expensive process which also has the drawback of decreasing the performance for the case of boundary lubrication. Therefore, the increase of the lubricant life is normally pursued by introducing special additives into the lubricant that counter the effect of free radicals and peroxides created by the oxidation process.

The conclusion of the analysis performed on the degradation of the characteristics of a lubricant was that though there are different possible degradation patterns, there is a compelling evidence that the most important root cause of lubricant degradation is the oxidation process of its molecules. Therefore, the amount of lubricant oxidation can be taken as the most significant feature for establishing the lubricant health and for determining its remaining useful life. The techniques for measuring the degree of lubricant oxidation, their reliability and their possible applicability to develop a lubricant PHM methodology are outlined in the following sections of this paper.

4. TECHNIQUES FOR MEASURING THE DEGREE OF LUBRICANT OXIDATION

The techniques for measuring the degree of lubricant oxidation can be divided in two groups: conventional and non-conventional techniques, which are briefly described in the following paragraphs.

4.1. Conventional techniques

The best known conventional techniques are those defined by ASTM specifications, namely: RBOT (ASTM D2272), TOST (ASTM D943) and TAN (ASTM D974).

The RBOT (ASTM D2272 - 11, 2009) method consists of putting a given amount of lubricant in a sealed volume containing oxygen and copper, and measuring the time

necessary for the oxidation process to cause a defined decrease of the pressure inside the container.

The TOST method (ASTM D943, 2010) measures the time necessary for 300 ml of lubricant to react with oxygen in presence of a catalyst based on iron and copper. The test is concluded when the lubricant acidity reaches the level of 2 mg of KOH/g.

The TAN (Total Acid Number) (ASTM D974 - 12, 2011) method enables to determine the quantity (mg) of potassium hydroxide (KOH) necessary to neutralize 1 g of lubricant. The measure is performed taking advantage of a pH indicator. The greater the concentration of acid corrosive compounds in the lubricant, the greater the quantity of potassium hydroxide needed for neutralizing the lubricant.

All the above described methods are off-line type methods and are hardly usable for a lubrication PHM system in which the characteristic feature extraction must be performed on a regular basis with an on-line device and without commands issued by an operator. Moreover, the test times of these methods are very long: from 40 hours of the RBOT method to even 1500 hours for the TOST method. Therefore, a lubricant PHM system must rely on innovative non-conventional methods that are presented in the following paragraphs.

4.2. Sealed capsule DSC and Pressurized DSC

Differential scanning calorimetry (DSC) is a new technique for analyzing the thermal properties of a fluid. The DSC enables the determination of the characteristics of a lubricant sample by measuring the differences between the thermal fluxes through the test sample and a reference sample (typically oxygen) when the two samples are heated or cooled according to a specified procedure. The temperatures differences between the test and the reference samples are proportional to the heat fluxes and are originated by endothermic or exothermic reactions occurring in the test sample.

If the fluid under test is a lubricant, it is then possible to estimate its oxidation degree by measuring the induction time, i.e. the time necessary to obtain an impending oxidizing reaction in the lubricant (Sharma & Stipanovic, 2003). If the test sample has a limited oxidation degree, there is a relatively high concentration of antioxidant agents, hence there will be a large induction time before an oxidizing reaction starts. On the contrary, if the oxidation degree of the test sample is high, the induction time will be reduced.

The standard DSC technique is however not suitable for the objective of developing a lubricant PHM system. The high volatility of most lubricants causes an appreciable evaporation during the test leading to a loss of the lubricant mass that greatly disturbs the measuring process (Bowman & Stachowiak, Determining the oxidation stability of

lubricating oils using sealed capsule differential scanning calorimetry (SCDSC), 1996). Modified techniques were thus recently developed starting from the basic DSC with the specific purpose of measuring the oxidation degree of a lubricant. These techniques are known as High Pressure DSC (PDSC) and Sealed Capsule DSC (SCDSC) .

Both PDSC and SCDSC are based on the same operating principle of the standard DSC, albeit with some differences. The PDSC operates in a very high pressure environment in which the lubricant evaporation is extremely low, while in the SCDSC the test and the reference samples are placed in sealed capsule, and no evaporation thus occurs. In both these techniques the greater oxygen concentration also speeds up the lubricant oxidation, thereby reducing the measurement time. The PDSC technique was standardized by the ASTM D6186 specification (ASTM D6186 - 08, 2003), but has so far been used only for research and development since the correlation between the results provided by these tests and the actual behavior of the corresponding lubricant in service has yet to be proven.

4.2.1. SCDSC

Among the different instruments developed to measure the lubricant induction time (OIT), a scansion differential calorimeter with sealed capsules presents several merits, both economically and for the quality of the measure. In these calorimeters, the capsules are hermetically sealed in an environment with purified oxygen. An appropriate selection of the test parameters (Bowman & Stachowiak, Determining the oxidation stability of lubricating oils using sealed capsule differential scanning calorimetry (SCDSC), 1996) enables to perform the test in a maximum time of 35 minutes, which is much lower than required by the conventional techniques.

This technique for measuring the oxidation degree of a lubricant was tested on lubricants with very different composition. In particular, tests were conducted on oil for transformers, for turbines (Bowman & Stachowiak, 1998), for ground vehicles and also for vegetable oils (Fox, Simpson, & Stachowiak, 2001). It is important to point out that not all tests led to clear and satisfactory results. For instance, for the case of lubricants for ground vehicles when the OITs are plotted versus the oxidation times, the corresponding diagram is not monotonous decreasing, therefore the measurement of the OIT alone is not sufficient to define the oxidation degree. On the contrary, tests performed on turbine oils are very accurate and promising (Figure 1).

It is interesting to correlate the results obtained from the SCDSC tests with the kinematic viscosity and composition of the same lubricant (Figure 2).

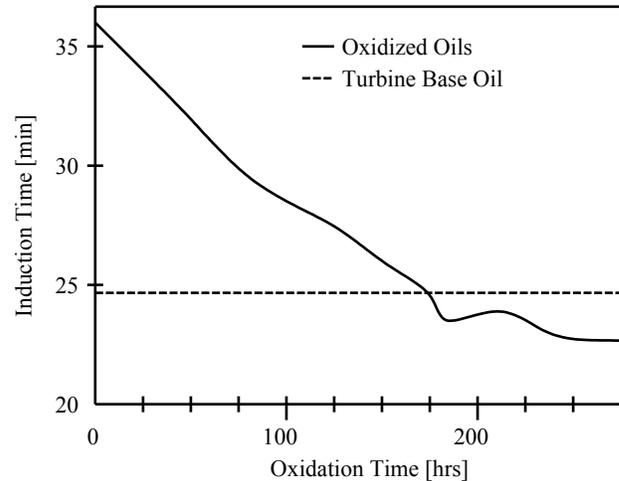


Figure 1. Induction time vs. oxidation time measured for a turbine oil by SCDSC technique (Bowman & Stachowiak, Determining the oxidation stability of lubricating oils using sealed capsule differential scanning calorimetry (SCDSC), 1996)

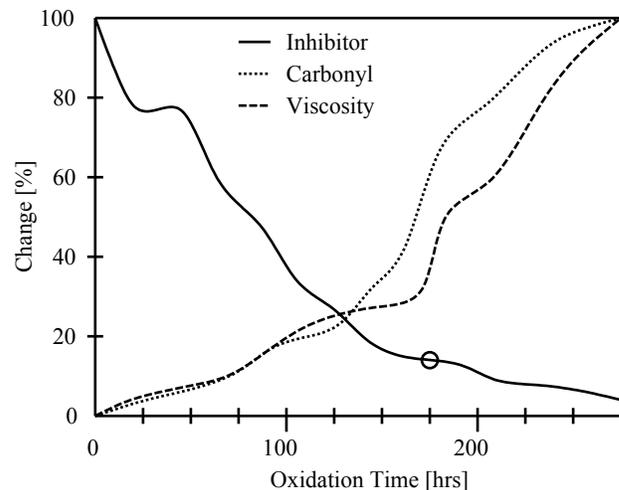


Figure 2. Percentage variations of a turbine oil inhibitor, carbonyl and viscosity vs. oxidation time for a turbine oil (Bowman & Stachowiak, Determining the oxidation stability of lubricating oils using sealed capsule differential scanning calorimetry (SCDSC), 1996)

The percentage change of the quantities shown on the y-axis of Figure 2 refers to the variations with respect to a new oil; as for the viscosity, the initial value of the kinematic viscosity was 68 cS. The chemical composition can be determined with the Fourier transform infrared spectroscopy (FTIR), that enables to monitor the concentration of the antioxidants and of the oxidation products.

As an example, for the case of turbine lubricants a large increase of viscosity is noticed after 175 hours of oxidation induced at 140 °C in a laboratory. The viscosity increase is

due to the polymerization of the lubricant molecules which on its turn is generated by the lubricant oxidation. The sharp viscosity increase occurs when the antioxidant concentration is only 15% of its initial value, and this is the condition for which the lubricant remaining useful life is considered to be zero (Bowman & Stachowiak, New criteria to assess the remaining useful life of industrial turbine oils. *Lubrication Engineering*, 1996).

Measuring the antioxidant concentration is by itself not always sufficient to determine the oxidation degree of a lubricant. Cases were observed in which the oxidation products remain small also for small amount of antioxidants, and cases were also observed with presence of high amount of oxides and antioxidants at the same time.

The oxidation induced in a laboratory keeping the lubricant at a constant high temperature allows for measuring the time necessary to bring the lubricant life to the end. This time is a function of the oil temperature and of its contamination level. It allows for identifying on the diagram induction time vs. oxidation time the induction time t_i for which the lubricant remaining useful life is reduced to zero. This time is a characteristics of the lubricant and a map of t_i versus RUL can be created (Figure 3).

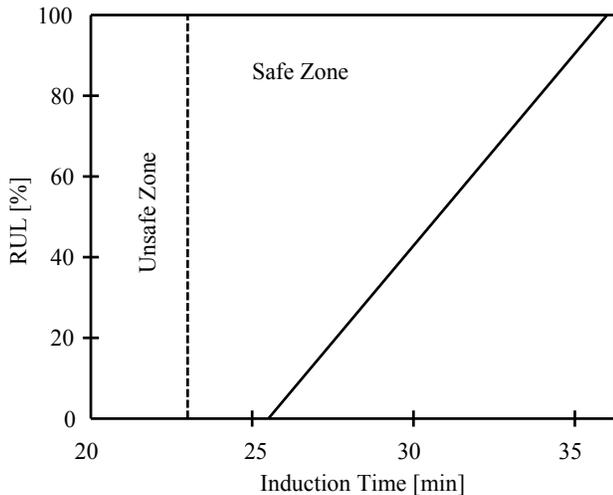


Figure 3. RUL vs. induction time map for a turbine oil analyzed by the SCDSC technique (Bowman & Stachowiak, 1998)

For the case of a specific turbine oil the map obtained from a linear approximation has a correlation coefficient of 99% with experimental data from lubricant oxidized in a laboratory and from lubricants spilled from industrial plants. Of course, such very high correlation coefficient is not obtained for all lubricants that have been tested.

It is interesting to notice that for some types of lubricants there is a fairly good correlation for the evaluation of the oxidation degree obtained from the SCDSC technique and from standard techniques (RBOT, TAN); a correlation

coefficient up to 0.94 is obtained between SCDSC and RBOT techniques. It is thus apparent that SCDSC is a technique to be positively considered in the implementation of a lubricant PHM system since it greatly reduces the measurement time with respect to the conventional techniques.

A research was performed to assess the reliability of SCDSC in case water and metal particles are present in the lubricant. There could be a risk of wrong estimate of the oxidation degree of a lubricant taken from industrial applications for which the contamination degree is not known. Measurements of the induction time for lubricants contaminated with water, solid copper, solid iron and soluble iron ions (Bowman & Stachowiak, Application of sealed capsule differential scanning calorimetry part I: Predicting the remaining useful life of industry-used turbine oils, 1998) showed that only iron ions appreciably affect the induction time, but they are released only in case of very high corrosion and if sludges are present in the lubricant.

4.2.2. PDSC

In Pressure Differential Scanning Calorimetry (PDSC) the oil volatility is decreased by the high pressure making sealed capsules unnecessary. The reference and the sample are in the same environment and oxidation is promoted by oxygen flow rate.

The OIT can be measured in two different conditions: isothermal method and temperature ramp method. For some specific combinations of oil additives the temperature ramp method results fit very well oxidation measures obtained by D 943 method, while for other combinations the results may present some differences (Sharma & Stipanovic, 2003). The ASTM D6186 method is an isothermal method, but the results do not correlate well with those obtained by D943 method. This is the reason why the ASTM D6186 method is not used to evaluate the oxidation stability of used industrial oils. Extensive studies were made in order to improve the repeatability and accuracy of the results of isothermal method. For this purpose, multiple tests were performed by varying one parameter at a time (Sharma & Stipanovic, 2003). In addition, researches proved that soluble metal catalysts improve the results and shorten the OIT measuring time. In conclusion, the optimized PDSC isothermal method showed some improvements against the ASTM D6186: shorter OIT, better results than ASTM method and good correlation with D943 for a set of oil with the same additive package.

In general, thermal methods based on the DSC show a fairly good correlation between the thermal properties of the lubricants and their oxidation stability, so in the future these methods could be used in order to evaluate the oxidation of used industrial oils. Moreover, the time required to measure the oxidation stability (10 – 40 min) is significantly shorter than the standard methods. Nevertheless, it is hard to

believe that they could be integrated in online prognostics and health management systems. They could, however, be worthy instruments for offline health monitoring programs.

4.3. Electrochemical impedance spectroscopy

The Electrochemical Impedance Spectroscopy (EIS) is widely applied to determine some properties of materials. It allows for measuring the impedance of a fluid sample by applying a sinusoidal voltage signal $V(t)$ with small amplitude V_0 and with a frequency f while measuring the current response $I(t)$. The impedance Z is the ratio of $V(t)$ and $I(t)$, hence it depends on the frequency f which usually varies in a wide range during a test (from μHz to GHz) (Lvovich, 2012).

For an ideal impedance consisting of a parallel combination of an ideal resistor and an ideal capacitor the Nyquist plot of the impedance is a semicircle. But for real lubricants the results are different and they depend on the test conditions and the properties of the lubricant. The analysis of the experimental results leads to the development of an equivalent circuit model of the oil which is characterized by a similar Nyquist plot. In this way any variation of the experimental data caused by the oxidation process may be related to one or more variations of the equivalent model parameters (resistances and capacitors).

Assuming that the test conditions are constant, the Nyquist plots of a not oxidized oil and of an oxidized one show some differences (Figure 4) because of their different chemical composition. By analyzing them it is possible to estimate the oxidation stability of the oxidized oil (Lvovich & Smiechowski, 2006).

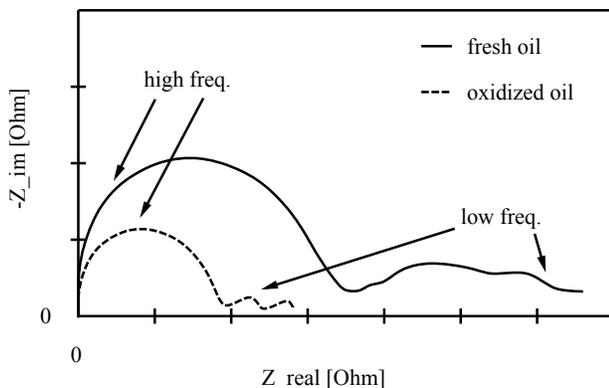


Figure 4. EIS measures concerning a fresh and an oxidized oil in Nyquist plot form (Lvovich & Smiechowski, 2008)

Recent researches coped with lots of lubricants conditions, focusing on the contamination and oxidation influences on EIS spectrum. In the low-frequencies range, where some ambiguous results were collected in the past, improvements were gained by the application of the Non-linear Electrochemical Impedance Spectroscopy NLEIS (Lvovich

& Smiechowski, 2008). However, the development of equivalent circuit models able to describe physical and chemical processes concerning the interaction among electrodes, lubricant and other agents is very complex and requires extensive validation. To overcome this issue, some researchers tried to correlate EIS experimental data with laboratory tribology results (viscosity, TAN, soot measurement, etc) by applying Symbolic Regression and taking notice of the chemical interactions (Byington, Mackos, Argenna, Palladino, Reimann, & Schmitgal, 2012). They implemented an online EIS equipment on several trucks in order to collect lubricant data continuously and in the meanwhile laboratory tests were conducted on oil samples taken from the trucks. The researchers were able to find out numerical models providing good correlation between the features generated by the oil condition monitor and the laboratory tests results by applying symbolic regression. Furthermore, since the models predicted well the laboratory tests results, they argued that the EIS oil condition monitor could be useful for assessing the health and estimating the RUL of the oils in mechanical equipments.

The EIS has surely a great potential in lubricants analysis, prognostics and health management, but there are some critical issues affecting this method: long measurement sessions to gather the complete impedance spectra and high instrumentation cost because of the requirement of high quality electronic equipment, even if cheaper EIS instrumentation was developed (Carullo, Ferraris, Parvis, Vallan, Angelini, & Spinelli, 2000). As a consequence, its implementation cannot be satisfactory for several mechanical applications.

4.4. Viscosity and Dielectric constant

The researchers in the field of lubricant prognostics and health management tried to correlate measures of some physical properties of oils with their contamination (water, metallic particles and soot) and oxidation status. Most of all, oil viscosity and dielectric constant were investigated because of their sensitivity to both the contamination and the oxidation (Zhu, Yoon, He, Qu, & Bechhoefer, 2013). In particular, the dielectric constant measurement of a lubricant was performed by comparing the capacitance of a thin lubricant layer with the capacitance of an air layer of the same dimensions (Raadnui & Kleesuwan, 2005).

Online oil monitoring systems using both a kinematic viscometer and a dielectric constant sensor for prognostics and health management purposes were hence developed. Some interesting results were gained addressing the water-contaminated lubricants. Indeed, the technical literature offers several numerical models able to correlate well viscosity and dielectric constant variations to water contamination level. It is therefore possible to define the contamination level by measuring these oil properties. Some

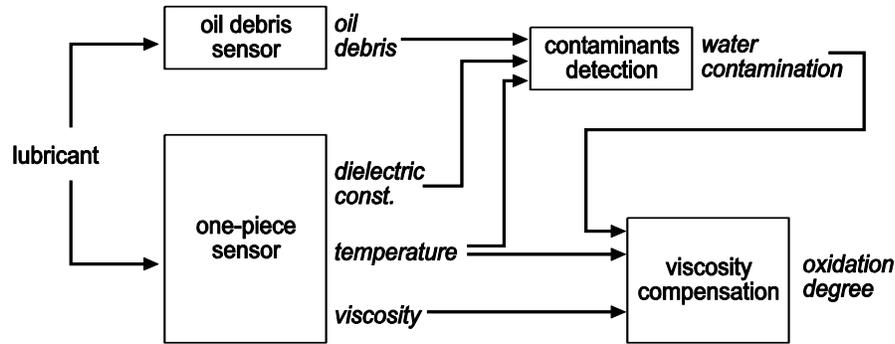


Figure 5. Structure of the proposed lubricant PHM system

tests were carried out for increasing water contamination from 0% to 5% while the measurements of viscosity and dielectric constant were performed. The particle filter technique eventually showed a good correlation between the oil RUL and its viscosity and dielectric constant measures. However, the effectiveness of the method was not proven for different kinds of contamination or in case of oxidation.

Kinematic viscometers and dielectric constant sensors are affordable and commercially available sensors and comparing with other instruments they could be fairly easily integrated in online oil monitoring systems. In addition, integrated sensors were recently developed for vehicle and aerospace applications measuring density, viscosity, dielectric constant and temperature of the oil at the same.

In the authors opinion, the estimation of the lubricant health taking advantage of cheap sensors could give a valuable contribution for the development of an effective and reliable lubricant prognostics and health management system. However, more studies need to be conducted in order to identify the actual causes of lubricant degradation.

5. DEVELOPMENT OF AN EFFICIENT LUBRICANT HEALTH MONITORING SYSTEM BASED ON DATA FUSION

It was outlined at the beginning of this paper that the main objectives of the initial phase of the research were to identify the characteristic feature for lubricant deterioration, to perform a critical review of all existing techniques used to measure different properties of a lubricant and to eventually define the structure of an effective and reliable lubricant PHM system. In particular, a comprehensive review of the existing techniques that can contribute to estimate the health status of a lubricant was summarized in section 4. It was shown that all the techniques providing a direct measurement of the lubricant oxidation degree do not suit well for a PHM system since they require long measurement times and cannot be used as on-line measuring devices. The technique based on viscometer and dielectric constant sensor has the advantage of being implementable in an on-line device, but it does not provide a direct measurement of the lubricant oxidation degree, which was

recognized as the characteristic feature defining the lubricant health status. Actually, the lubricant viscosity is affected by its degree of oxidation, but it can also be affected by other factors, such the amount of contaminants. It was shown that viscosity is heavily affected by the oil oxidation and its value can rise up to 140% of the initial value for significantly oxidized oils, but viscosity variations can also be generated by other factors, such as the presence of water and metal particles.

The basic idea for the development of an efficient lubricant PHM system is then to combine the information provided by the measurements of viscosity and dielectric strength with that obtained from a particle detection sensor. Data fusion and processing by means of suitable algorithms will thus allow the necessary feature extraction and the assessment of the lubricant health status.

A further advantage of data fusion from multiple sensors is the possibility to compare data provided by different sensors to detect the cause of the lubricant degradation. This is of a great merit for an oil monitoring system oriented to real industrial applications. In fact, engineers usually are aware of the main issues concerning the degradation of a specific mechanical equipment working in a well-known environment, hence they choose additive packages to make the lubricant life longer. However, an issue is to actually understand which is the deteriorating agent being responsible for the lubricant replacement. Furthermore, detecting the origin of deterioration allows for evaluating correctly the available data. As an example, the dielectric constant of a lubricant grows for different types of contamination: water, metal particles and dust (Raadnui & Kleesuwan, 2005). Obviously it does not represent an issue for laboratory-contaminated samples, while it is an important issue if the sample has just been spilled from a mechanical drive. In fact, some contamination agents affect lubricant deterioration and some mechanical equipments wear more than others.

The authors thus positively came to the conclusion that a reliable lubricant PHM system can be developed by fusing the information obtainable from two sensors:

- One-piece sensor able to measure viscosity, dielectric constant and temperature of the lubricant at the same time
- Magnetic and/or optical particle detection sensor

These sensors provide necessary and sufficient data for calculating the lubricant oxidation level, hence its health condition. In fact, as it was previously described, the variation of the lubricant viscosity is strictly related to its oxidation level, but the viscosity measure requires compensation for oil temperature variation and water contamination. However, temperature is also measured by the one-piece sensor and the water amount can be determined by fusing the information on the value of the dielectric constant measured by the one-piece sensor and the data obtained from the particle detection sensor which allows the PHM system for determining if the dielectric constant variation is a consequence of only water contamination, only particle contamination or both. At the same time his sensor provides information about the health of the mechanical components.

The described oil health monitoring system has then the following main features:

- It is an on-line system, hence suitable for being used in an operating equipment such as an actuator, or a mechanical drive
- Sensors are cheap and commercially available. In addition they could be easily integrated in an online monitoring system
- Data fusion can lead not only to the evaluation of the oxidation degree, but also to the identification of the amount of water and particles contamination, thereby allowing to better define the lubricant degrading agent

It is important to emphasize that the proposed PHM system is not intended as a possible replacement to standard measurement techniques, but as a system to be applied in operating mechanical equipment for a continuous assessment of the lubricant health status. Its purpose is to perform a robust numerical correlation between multiple lubricant physical properties that are easily measurable, and its oxidation degree, thereby allowing the implementation of a lubricant PHM system suitable for industrial applications. Having defined the lubricant PHM philosophy and the associated sensors suite, the next step of the research will be focused on the development of the algorithms needed to perform data fusion and RUL estimate, as well as run simulations to assess the PHM system robustness. Following that, the final step will be the PHM system validation.

Validation can be performed by testing laboratory-prepared samples characterized by different contaminating agents amount and different oxidation levels. The first step will concern the PHM system ability to detect and measure the contaminants and whether it is able to correctly estimate the

water contamination level by simultaneously measuring the oil debris and the oil dielectric constant.

Furthermore, numerical models performing the viscosity and the dielectric constant compensation that were already successfully validated for non-oxidized oils, need to be validated also for oxidized and contaminated oils.

Last, after the PHM system proves its capability of calculating correctly the compensated-viscosity, it will be important to find out if the measurement of the dielectric constant could be used to further improve the estimate of the lubricant oxidation degree.

6. CONCLUSIONS AND FURTHER WORK

The initial phase of a research activity being performed by the authors on health management and prognostics of lubricants was described, highlighting the most important causes of lubricant degradation and how it is possible to measure them by conventional and non-conventional techniques.

Furthermore, an original and innovative PHM system for lubricants is proposed. It employs two commercially available sensors (a magnetic oil debris sensor and a multi-purpose sensor) which can be easily integrated in an online lubricant monitoring system. It is the authors' opinion that this system enables to reliably detect type and amount of contaminating agents and the oxidation degree of the lubricant, thereby providing all necessary information to develop an industrially applicable PHM system for a lubricant.

The next step of the research activity will address the process of data fusion enabling to achieve robust and reliable estimation of the oil contaminants and of the oxidation degree. It will then be possible to move to the final goal of the research: the development and the validation of effective algorithms for lubricants RUL evaluation.

REFERENCES

- Adhvaryu, A., Erhan, S. Z., Liu, Z. S., & Perez, J. M. (2000). Oxidation kinetic studies of oils derived from unmodified and genetically modified vegetables using pressurized differential scanning calorimetry and nuclear magnetic resonance spectroscopy. *Thermochimica Acta*, 364, pp. 87-97.
- ASTM D2272 - 11. (2009). *Standard Test Method for Oxidation Stability of Steam Turbine Oils by Rotating Pressure Vessel*.
- ASTM D6186 - 08. (2003). *Standard Test Method for Oxidation Induction Time of Lubricating Oils by Pressure Differential Scanning Calorimetry (PDSC)*.
- ASTM D943. (2010). *Standard Test Method for Oxidation Characteristics of Inhibited Mineral Oils*.

- ASTM D974 - 12. (2011). *Standard Test Method for Acid and Base Number by Color-Indicator Titration*.
- Bowman, W. F., & Stachowiak, G. W. (1998). Application of sealed capsule differential scanning calorimetry part I: Predicting the remaining useful life of industry-used turbine oils. *Lubrication Engineering* , 54 (1), pp. 19-24.
- Bowman, W. F., & Stachowiak, G. W. (1996). Determining the oxidation stability of lubricating oils using sealed capsule differential scanning calorimetry (SCDSC). *Tribology International* , 29 (1), pp. 27-34.
- Bowman, W. F., & Stachowiak, G. W. (1996). New criteria to assess the remaining useful life of industrial turbine oils. *Lubrication Engineering*. *Lubrication Engineering* , 52 (10), pp. 745-750.
- Byington, C., Mackos, N., Argenna, G., Palladino, A., Reimann, J., & Schmitgal, J. (2012). Application of symbolic regression to electrochemical impedance spectroscopy data for lubricating oil health evaluation. *Annual conference of the prognostics and health management society 2012*. September 23-27, Minneapolis, MN.
- Carullo, A., Ferraris, F., Parvis, M., Vallan, A., Angelini, E., & Spinelli, P. (2000). Low-cost electrochemical impedance spectroscopy system for corrosion monitoring of metallic antiquities and works of art. *IEEE Transactions on Instrumentation and Measurement* , 49 (2), pp. 371-375.
- Dupuis, R. (2010). Application of oil debris monitoring for wind turbine gearbox prognostics and health management. *Annual Conference of the prognostics and health management society, 2010*. October 13-16 , Portland, OR.
- Fox, N. J., Simpson, A. K., & Stachowiak, G. W. (2001). Sealed capsule differential scanning calorimetry: An effective method for screening the oxidation stability of vegetable oil formulations. *Lubrication Engineering* , 57 (10), pp. 14-20.
- Kauffman, R. E., & Rhine, W. E. (1988). Development of a remaining useful life of a lubricant evaluation technique. Part I: differential scanning calorimetric techniques. *Lubrication Engineering* , 44, pp. 154 - 161.
- Koza, J. R. (1992). *Genetic programming: on the programming of computers by means of natural selection*. MIT Press.
- Lvovich, V. F. (2012). *Impedance spectroscopy, Applications to electrochemical and dielectric phenomena*. Wiley.
- Lvovich, V. F., & Smiechowski, M. F. (2008). Non-linear impedance analysis of industrial lubricants. *Electrochimica Acta* , 53, pp. 7375-7385.
- Perez, J. M. (2000). Oxidative properties of lubricants using thermal analysis. *Thermochimica Acta* , 357-358, pp. 47-56.
- Raadnui, S., & Kleesuwan, S. (2005). Low-cost condition monitoring sensor for used oil analysis. *Wear* , 259, pp. 1502-1506.
- Sharma, B. K., & Stipanovic, A. J. (2003). Development of a new oxidation stability test method for lubricating oils using high-pressure differential scanning calorimetry. *Thermochimica Acta* , 402 (1-2), pp. 1-18.
- Sjödin, E., & Westin, P. O. (2013). Comparison of optical and magnetic particle detection systems for detection of pitting damage in low speed hydraulic motors. *The 13th Scandinavian International Conference on Fluid Power, SICFP2013*. June 3-5, Linköping, Sweden.
- Stachowiak, G. W., & Batchelor, A. W. (2005). *Engineering Tribology*. Butterworth Heinemann.
- Zeman, A., Sprengel, A., Niedermeier, D., & Späth, M. (1995). Biodegradable lubricants: studies on thermo-oxidation of metal-working and hydraulic fluids by differential scanning calorimetry (DSC). *Thermochimica Acta* , 268, pp. 9-15.
- Zhu, J., Yoon, J. M., He, D., Qu, Y., & Bechhoefer, E. (2013). Lubrication oil condition monitoring and remaining useful life prediction with particle filtering. *International Journal of Prognostics and Health Management* , 4 (20), p. 27.

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