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Fluorescence Spectroscopy for inline oil contamination and condition monitoring to improve HUMS

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Abstract

Lubricant failure, whether through contamination or degradation, is among the dominant causes of oil-wetted component failure within various forms of engines and gearboxes across marine, industrial applications and aviation. Furthermore, with the marine and aviation industry driving for reduced oil consumption and longer intervals between changes, there is an increased potential to have extended periods of use with heavily contaminated or degraded oil. Monitoring and detecting lubricant contamination and degradation are key to pro-actively address lubricant shortcomings before it can cause damage to the critical components. This type of predictive maintenance practice is key to modern Health and Usage Monitoring Systems (HUMS) to reduce operational costs and protect these high value gearboxes and engines. Unfortunately, current measurement of lubricating oil health using online sensors does not provide sufficiently accurate data to drive maintenance decisions. This is largely due to the requirement of HUMS systems to provide actionable and reliable output. However, a novel oil contamination and condition sensor has been presented that can not only monitor oil degradation, but also contamination of fuel in the oil using Fluorescence Spectroscopy. Previously, this sensor prototype was shown to provide a direct and reliable measurement of oil condition through the presence of antioxidants and oxidation by-products. In this paper, experimental data will be presented proving the capability of the sensor to accurately and reliably quantify measures of fuel leakage in the oil. This measurement can even detect fuel contamination below 1.0 wt.% by measuring a specific subset of compounds present only in the fuel that would not be detected in uncontaminated oil. Furthermore, the leakage detection has resolution, for the purpose of establishing multi-stage condition indicators such as warnings and alarms, to ease the decision-making burden on the operators of critical machinery.

Keywords: Oil Condition Monitoring, Fluorescence Spectroscopy, Antioxidants Depletion, Fuel Contamination, Online Sensor, Condition-Based Maintenance

Introduction

Many failures of high value machinery can be attributed to the failure of the lubricating oil. The failure of the oil can be owing to various causes, but common failures are contamination and/or the breakdown of the oil. Common contaminants include water, coolant, fuel, combustion soot, incorrect oil top offs and metallic wear particles released from the rotating machinery itself. Contaminants in the oil can cause damage to the surfaces of the rotating or mating parts, such as gears and bearings. When the oil itself breaks down, such as through thermal oxidation, there is a reduction in the lubricity, and the oil no longer performs its role in protecting the rotating equipment. This is why these high value machines need to have Health and Usage Monitoring Systems (HUMS) which have reliable real time accurate outputs to be able to manage the maintenance decisions accurately. There are currently no products that are sufficiently accurate at providing advanced notice for oil condition monitoring in an unambiguous way [1]. HUMS technologies for oil monitoring can use several parameters to determine the appropriate time for maintenance, including directly or indirectly measuring breakdown of the base oil and contamination. One method that will be introduced in this paper will be directly measuring the breakdown and contamination of the oil through Fluorescence Spectroscopy.

Oil species emit fluorescent light by first adsorbing energy that will excite the molecule. The adsorbed energy will elevate an electron in the molecule from a ground or base state to an elevated or excited state. One way to excite these electrons is through UV light. When this electron drops back to the ground state, energy is released, this energy is in the form of light as shown in Figure 1.

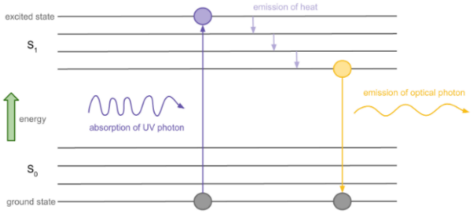

Figure 1 How species fluoresce though absorption and emission [2]

Lubricating oil is a mixture of species, and some of these are fluorescent under ultraviolet light. Each of these species has its own unique emission spectrum. The emission spectrum for the oil is therefore a mix of these individual spectrums. If the intensity and wavelength of the emission is measured, then a spectrum can be made for that oil as shown in Figure 2. If the ultraviolet excitation wavelength is plotted vs the intensity of the emission spectrum, then an Excitation Emission Matrix Spectrum (EEMS) can be made. A typical EEMS is shown in Figure 2 for a sample of Shell diesel oil.

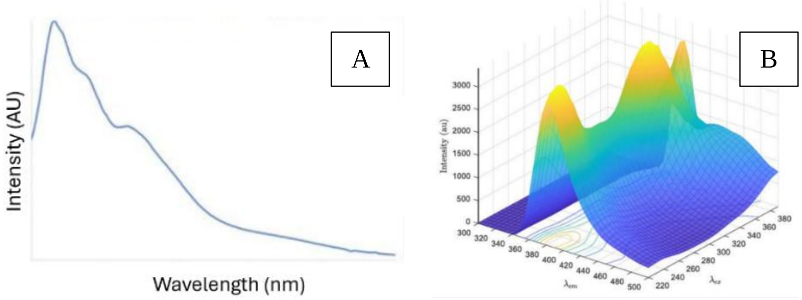

Figure 2 Intensity vs wavelength for diesel oil (A). EEMS for Shell Rotella T6 5W-40 (B) [3]

When there is an addition of another fluorescent species through contamination, or there is a change to the existing florescent species in the oil through oxidation etc, then there is a change in the overall emission spectrum for the oil, and this signifies a problem. The severity of the change in the spectrum will determine if maintenance is needed.

The compounds in the oil that are of interest for developing condition indicators are the antioxidant concentrations and the antioxidant byproduct concentrations. The spectra of Aeroshell 500 that has the antioxidants depleted in an accelerated degradation test is shown in Figure 3.

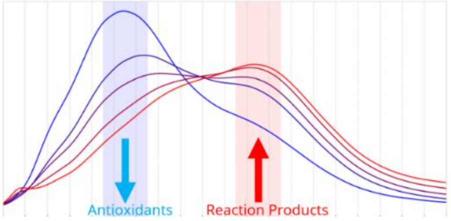

Figure 3 Aeroshell 500 spectrum changes from thermal degradation identifying the trends in the antioxidants and by products [4]

There are two distinct peaks in the spectrum, one is decreasing over time and the other is increasing over time. It has been shown that the decreasing peak corresponds to the antioxidant depletion, and the increasing peak is from the stable byproducts [5]. It is the ratio of these two peaks that can be used as a condition indicator in determining the remaining useful life (RUL) for the oil.

Oil chemistry analysis and other tests are usually performed in a specialized offsite oil analysis laboratory which involves taking oil samples from the piece of equipment and shipping them to the laboratory for analysis. This often induces delays related to analysis turnaround time, and there is potential for errors related to sampling. Additionally, faster progressing failures or contamination events may be missed by infrequent oil analysis programs.

In this paper, a novel online device for measuring the lubricating oils fluorescence spectrum will be discussed. This device uses a compact, optical probe inserted into the oil that can take a spectrum and measure electrical properties of the oil. The device has two key parts, the oil condition probe, and the control unit shown in Figure 4.

Figure 4 Gastops oil condition and contamination sensor

The key advantage of the device is that it uses a fibre probe. A fibre probe is a fibre optic cable that can transmit light very efficiently over long distances. By using a fibre probe it allows the sensitive spectrometer and excitation LEDs to be away from the oil line with just a small glass window in contact with the oil. The fibre probe includes the excitation fibre and the emission fibre shown in Figure 5. These fibres transmit the light into the oil sample and then transport the fluorescence back to the detector. There is also an electrical sensor in the probe (or as a separate probe) to measure the change in dielectric constant of the oil. As water is non-fluorescent but strongly polar, it can be detected by a dielectric sensor.

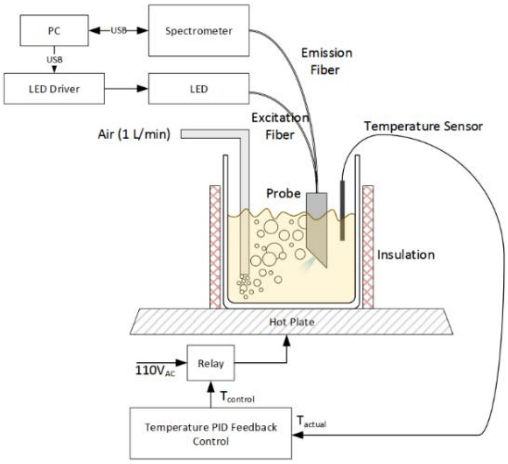

Figure 5 Experimental set up for the thermal degradation experiments

Methodology

A laboratory experiment was set up to measure the change in the EEMS for oils commonly used in high value equipment that was degraded on an accelerated timeline as shown in Figure 5. The oil samples were heated to 210 °C using a PID controlled hot plate with the temperature control probe in the oil. Air was pumped into the oil at a rate of 1 L/min through a sparger to speed up the depletion of the antioxidants. The oil was also agitated with a magnetic stirrer to prevent any localized changes in the samples. The fiber probe was suspended into the oil and EEMS were taken at specified time intervals. These experiments were then compared to real data from a stationary marine diesel engine, and from a field trial with a larger marine diesel engine on a vessel.

A second set of experiments was set up to measure the change in the EEMS with increasing concentrations of diesel fuel mixed into the diesel oils. The oil samples were in three different states of degradation (new oil, partially degraded, and fully degraded oil). The oils were degraded using the same thermal degradation as shown in the first experiment. These oil samples were then constantly stirred with a magnetic stirrer while slowly diluted with diesel from 0% up to 10% fuel at room temperature while the EEMS was measured.

A third experiment was conducted to measure the dielectric properties of diesel oil with the addition of an automotive coolant. An oil circulation flow circuit was set up to pump the sample of oil through an electric sensor. The oil was heated up to 70°C with a PID controller and allowed to stabilize before the addition of coolant to increase the concentration in 2000ppm steps. The oil was allowed to mix and stabilize for 10 min before the electrical properties of the oil were measured and averaged for another 10 min before the next addition of coolant.

Results and Discussion

Thermal degradation experiments

The EEMS changes over time from the thermal degradation experiments has identified the two peaks in the oil sample that can be used to determine the RUL of the oil. The ratio of antioxidants left in the oil to the reaction products is plotted over time as shown in Figure 6.

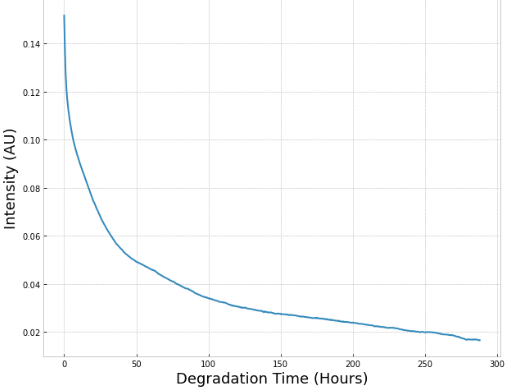

Figure 6 Ratio of antioxidants vs by products left in oil as a function of time [4]

This is now a quantifiable parameter that can be used to determine if maintenance is needed. The user can set limits and thresholds to trigger specific maintenance actions. There could be an early warning limit indicating to the operator that maintenance is needed soon but the oil is still performing its role. This will allow the operator to plan and schedule maintenance for the equipment proactively. Furthermore, the rate of degradation could be analysed to calculate RUL or the time to failure. Then, once the oil is degraded sufficiently, an alarm limit signalling the end of the useful life will be triggered.

Fuel Contamination

The results for the thermal degradation experiment were analysed and it was observed that the fluorescence contribution from the fuel could be isolated from that of the antioxidant response through simple spectral subtraction. This spectral response was then used to plot an integral of the intensity vs the fuel concentration as shown in Figure 7. This again gives a quantifiable parameter that can be used to create warning and alarm limits.

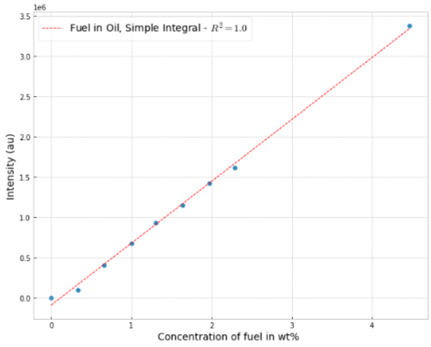

Figure 7 Concentration of fuel in oil as a function of intensity

Coolant contamination

The results from the coolant tests are shown in Figure 8 where the concentration of the coolant was plotted against the dielectric constant of the oil. It shows that there is a good linear fit up to 10000ppm after which there is shown to be a decrease in the dielectric constant. A linear fit was plotted for the range of 0-10000ppm and shows a very good correlation. It was hypothesized that after 10000ppm the sensor was becoming saturated, and the results were inaccurate. This was also not of concern as the extreme limit for most oil is up to 5000ppm.

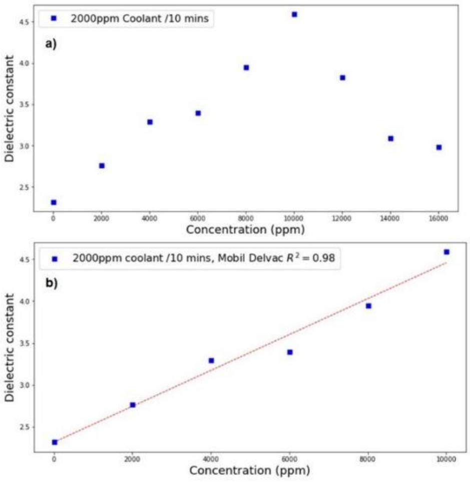

Figure 8 Concentration of water mixed in oil as a function of the dielectric constant

Again, this gives the user a quantifiable parameter to use for monitoring the concentration of coolant contamination.

On-engine results

The results of the condition indicator installed in a stationary diesel engine are shown in Figure 9. The Condition indicator was normalized to be zero at the start of the test.

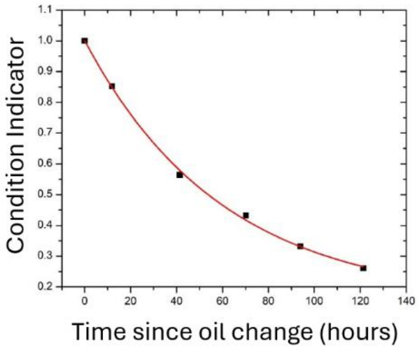

Figure 9 Oil condition indicator vs engine run time

This shows that the depletion of the antioxidant follows an exponential function as shown by the trend line. The antioxidant was depleted by 70% in the first 120 hours of operation confirming that the oil is degrading in a similar decay mechanism to the laboratory thermal degradation experiments.

The condition indicator measured from a 2000 hp marine application is shown in Figure 10 where 19 samples were taken over a period of 2 months.

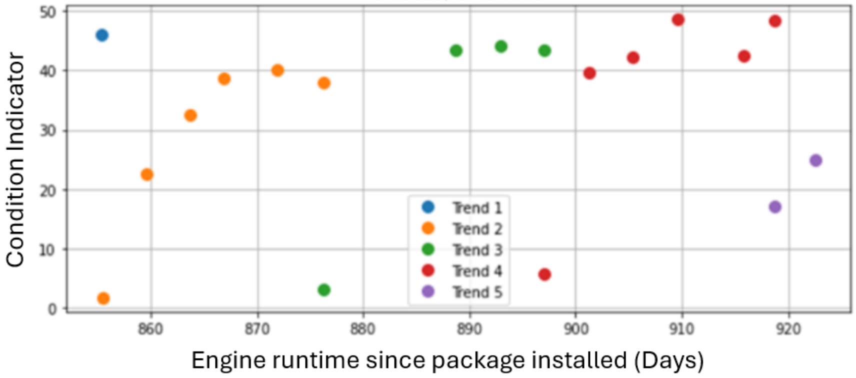

Figure 10 Oil condition indicator vs engine run time [4]

There is a consistent series of trends in the condition indicator, suggesting that the oil was being changed when in port. This was later confirmed by the customer. Detecting these trends in the condition indicator validates the previous work in the laboratory experiments.

Conclusion

The techniques presented in this paper have identified methods of developing unambiguous condition indicators of engine oil RUL in real time. Using a fiber probe inserted in the oil, an online fluorescent spectrum can be captured, which directly analyses the concentration of antioxidants left in the oil. This is done through first identifying the peaks in the spectrum that correlate to the antioxidant and the byproduct concentrations and then using the ratio between the two to develop a condition indicator. The spectrum can also be used to detect the presence of fuel contamination by identifying spatial changes in the spectrum associated with the spectral peaks for fuel. The detection of coolant contamination was done using an electrical sensor and showed that the dielectric properties of the oil can be correlated to the concentration of coolant in the oil. Leveraging both fluorescence and electric sensing technologies allows for better specificity of faults diagnostics, since the most common oil failures can be identified by their own failure signatures. This leads to a clearer and more concise management method of oil condition and contamination and could aid in the change from periodic maintenance to condition base maintenance.

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