Please select category below:
Normal Paper ☒
Student Paper ☐
Young Engineer Paper ☐

Using accurate online oil condition monitoring sensor data to improve HUMS

Greg Horwich [1], Dr. Timothy Mack [1]

[1] *Gastops Ltd, 1011 Polytek Street, Gloucester, ON, K1J 9J3, Canada*

Abstract

High value equipment including aviation turbine engines and medium and large diesel engines require Health and Usage Monitoring Systems (HUMS) which provide actionable and reliable output. Many component failures in oil lubricated systems can be attributed directly to oil condition and contamination, yet the measurement of lubricating oil health using online sensors does not currently provide sufficiently accurate data to facilitate maintenance decisions. In this paper, the direct measurement of oil condition and contamination is discussed through the use of new sensing technologies which give a direct measurement of oil antioxidants and oxidation by-products, as well as quantified measures of water, fuel, coolant, and soot and carbon contamination. By generating unambiguous data and directly measuring individual parameters of the lubricating oil, advanced data processing including physics-based digital twin modelling and machine learning techniques can be applied to the generated data to accurately diagnose lubricant health and identify issues that may affect equipment health. The enhanced model can be used to accurately diagnose lubricant health in near-real-time. This paper presents a novel sensing technology for measuring oil condition accurately in an online, real-time environment, facilitating future work in the development of improved HUMS to facilitate a shift of the most common predictive maintenance tasks to condition-based maintenance tasks, and ultimately to true predictive maintenance.

Keywords: Oil condition monitoring, online sensor, aviation, diesel engine, condition-based maintenance

Introduction

High value equipment including aviation turbine engines and medium and large diesel engines require Health and Usage Monitoring Systems (HUMS) which provide actionable and reliable output. Many component failures in oil lubricated systems can be attributed directly to oil condition and contamination, yet the measurement of lubricating oil health using online sensors does not currently provide sufficiently accurate data to facilitate maintenance decisions. Currently available technologies may provide ambiguous condition indicators (CI) and unreliable data with respect to equipment health status. CIs are the parameters used in condition-based maintenance activity to measure the “health” of machinery and to establish the point at which maintenance must be triggered. The CI must identify the impending failure in an unambiguous, statistically reliable, and accurate fashion, while providing sufficient advanced notice to permit maintenance to be scheduled. A condition indicator can be derived from one or several parameters which can be measured during operation. Common measurement techniques include, but are not limited to, performance analysis, oil analysis, and vibration analysis. Here we show an example of a sensing technology whose CIs are sensitive, unambiguous, statistically reliable, and can be applied online, in real-time to operational equipment.

Theory

Fluorescence spectroscopy

Lubricant oil formulations are mixtures of various molecular species, some of which are fluorescent. Fluorescent molecules typically emit light of longer wavelengths when illuminated by Ultra-Violet (UV) light. More generally, fluorescence is a phenomenon that occurs when a photon with sufficient energy is absorbed by a molecule. This energy of the absorbed photon is said to promote the molecule from an initial ground state to a temporary excited state. Over time, the excited molecule can relax back to the ground state through the emission of light (fluorescence) or through other non-fluorescent pathways. The measurement of the intensity of fluorescent light resolved by wavelength is a fluorescence emission spectrum.

Excitation Emission Matrix (EEM) Spectroscopy is a variant of fluorescence spectroscopy and refers to the way the spectroscopic data is collected: a fluorescence emission spectrum is measured for several fluorescence excitation wavelengths, and the various plots are stacked together to create a 3-dimensional plot. Figure 1 shows an example an EEM spectrum of a typical diesel lubricant oil.

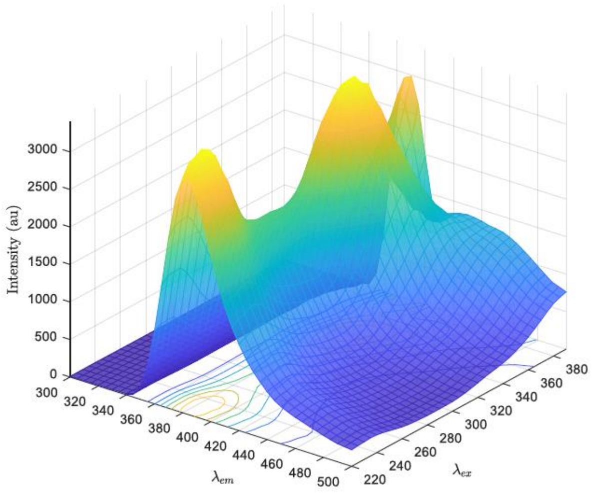

Figure 1: EEM Spectrum 3D Diagram of Shell Rotella T6 5W-40 Diesel Oil

There are two common approaches to generate excitation light used for fluorescence and/or EEM Spectra. In one approach, a broad-spectrum UV- source is used with a scanning monochromator to select a single narrow band of the lamp's spectrum as excitation light. Another approach is to use a narrow wavelength excitation source such as an LED or a Laser. The former approach is more versatile since is not limited to any pre-selected excitation wavelengths; however, the latter is more robust (no moving parts), fast (the entire emission spectrum is collected in one shot) and in-expensive.

An advantage of molecular fluorescence spectroscopy in general is its ability to be conducted through a fiber probe. A fiber probe is a bundle of optical fibers used to deliver the excitation radiation to the sample and to collect the emission radiation and route it back into the detector. Such a probe allows separation of the sensitive spectroscopic equipment from the potentially hazardous environment in which the analysed sample might reside. Examples demonstrating the combined use of molecular fluorescence with fiber optic probes are described in previously published work. Use-cases include the detection of antioxidant additive depletion in aviation turbine oils [1], heavy-duty gas turbine oils [2], and diesel engines as well as the ability to detect aviation oil ingestion into aviation fuel, and diesel fuel and coolant contamination in diesel lubricating oils.

Methodology

Experimental detection of additive depletion and fuel contamination in lubricating oils

The real-world applicability of molecular fluorescence to oil condition and contamination assessment including antioxidant detection was first determined in a laboratory setting. A summary of the methodology used, and the experimental setup employed is provided below.
Fresh oil samples were thermally oxidized in the lab for approximately 1200 minutes at 210ºC using a hotplate. Samples were collected at specific interval times and, after reaching room temperature, analysed through fluorescence spectroscopy.
Throughout the test, the consumption of the additives and the condition of the oil under test was monitored using in vitro measurements conducted with the molecular fluorescence apparatus and its fiber probe. The oil under test was stirred throughout the thermal degradation process to avoid constant exposure of the same volume of lubricant to the UV light and associated potential of photodegradation.
Fluorescence measurements that were used in this study and analysis were taken using the hardware prototype (herein referred to as “the system”) while the samples were confined in a box during the measurement to block ambient light from contaminating the fluorescence signal at lower temperature to minimize the thermal interference with the signal. This was deemed to be representative of the practical conditions since stray light is not expected to be an issue in a machine engine and oil in the sump is typically at much lower than the temperatures that were selected for this experiment to accelerate the degradation process. Figure 2 illustrates the experimental setup used during the accelerated oil thermal degradation process.

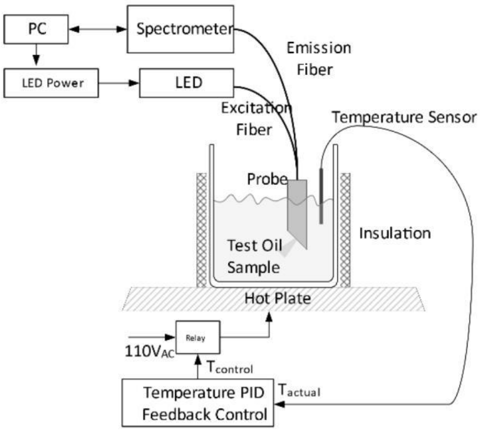

Figure 2: Oil Degradation Experimental Apparatus

Results and Discussion

Molecular Fluorescence spectra were analysed for features that correlated with a change in additive depletion. For example, typical fluorescence spectra of a lubricant oil at various thermal degradation times are shown in Figure 3.

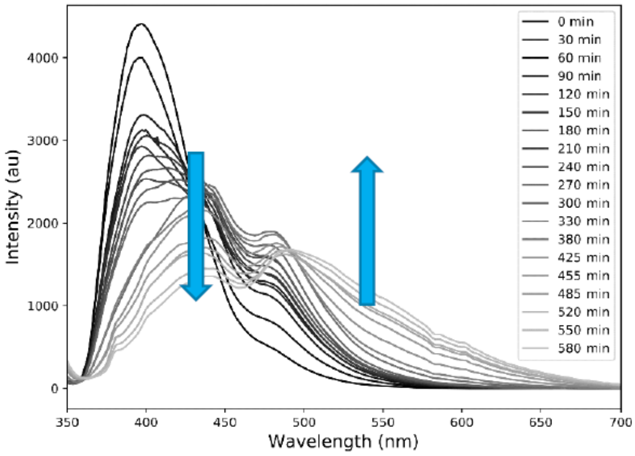

Figure 3: Example of a Typical Lubricant Fluorescence Spectrum and Changes Associated with Thermal Degradation and Additive Depletion

The spectra on Figure 3 features two peaks, one decreasing as the lubricant is subjected to the forced degradation, and the other increases. In [1] the authors were able to show that the left peak that is decreasing can be associated with the antioxidant additive, and the right peak that is increasing can be associated with the stable reaction products that are produced in the process. It was also shown that the ratio of these two features is a robust Condition Indicator (CI) that can be trended to predict the Remaining Useful Life (RUL) of the lubricant.
The time behavior of the peak ratios was shown to correlate with the change in certain regions of the FTIR absorbance spectrum associated with ZDDP, Aminic and Phenolic antioxidant content, as well as a new peak that developed during the degradation process and that could be associated with the accumulation with a degradation by-product.
Fuel contamination in oil was also studied in the laboratory, and experimentation was designed and conducted to measure diesel fuel in diesel engine oil. Previous works also evaluated aviation fuels in turbine oils, with similar results obtained to those presented here. [1] Two diesel oil brands, Mobil Delvac 1300 Super 15W-40, and Irving IDO Premium Plus 15W-40A, were used to produce in lab three set of samples containing different quantities of diesel fuel. For each oil brand, the first set used a fresh oil sample, the second a partially degraded oil sample, and the third a fully degraded oil sample. The oil was degraded in the lab at 210 °C for the time necessary to achieve the above-mentioned degradation level. Each sample was then diluted using commercial Diesel fuel starting from 0% of fuel until 10% of fuel. In all cases, fuel was correctly identified and quantified using fluorescence.

Evaluation of real-world lubricant samples

Following successful evaluation of laboratory-degraded degraded oil samples of both mineral and synthetic base oils from multiple industries, samples of engine oil from operational equipment were collected from industrial partners, including from a major marine operator. For this operator, the engines selected for inclusion in this trial were Caterpillar C32 Marine Diesel engines, which are operated with Mobilgard HSD+ 15W-40 engine oil. Samples were collected during routine operation, with 19 oils samples collected over an approximate two-month period, and a condition indicator was evaluated from each sample using the discussed fluorescence technique.
A consistent pattern of oil degradation was observed in the measurement obtained from these samples, which allowed the experimentation team to hypothesize that the engine oil was being changed during routine stops after the ship had travelled and returned from sea. This hypothesis was subsequently confirmed by the operator. The condition indicator from these

samples is plotted in Figure 4. Individual trends have been separated by colour to clearly show the repeating measurement pattern.

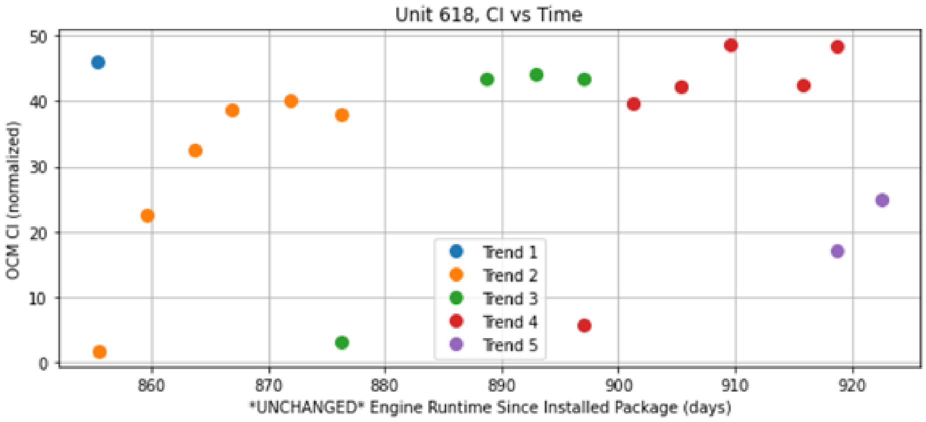

Figure 4: Oil condition indicator values from real world engine oil samples

This data along with additional partner sample data allows for the validation of the technique in relation to real-world data, and subsequent work will focus on collecting continuous data streams from operational equipment.

Fluorescence spectroscopy in online, on-equipment applications

A principal benefit of the discussed technique in condition monitoring is the ability to install the system probe in an oil system in operational equipment and measure several condition indicators related to oil health and contamination in real time. This has been demonstrated to date in a test cell environment by instrumenting a diesel electric generator using the system. Preliminary data collection is underway, and initial results have indicated that the laboratory work previously completed will be successfully validated for live data collection. Photos of the generator (**a**), probe installation in the oil pan (**b**) and preliminary fluorescence measurement data taken while the generator is in operation (**c**) are shown in Figure 5.

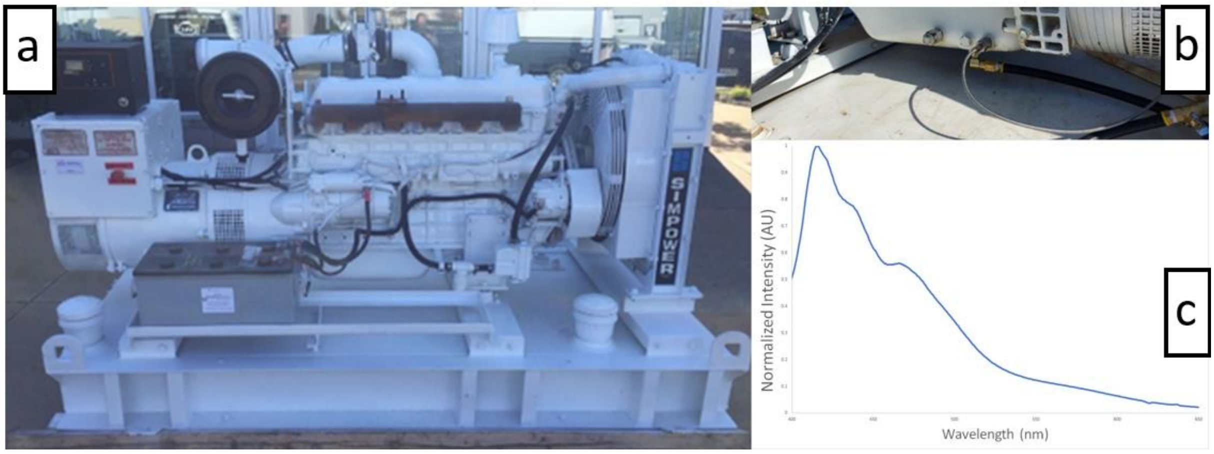

Figure 5: Molecular fluorescence system installed on operational engine

The benefit of molecular fluorescence in oil condition and contamination monitoring practice is that the fluorescence signature of molecules of interest can be directly targeted and measured, giving absolute indication of the concentration of these molecules, thereby eliminating the ambiguity inherent in many oil condition assessment sensing technologies.
The technique is limited to molecules with aromatic structures which produce characteristic contaminant marker bands in the analysis spectrum, including typical lubricating oil antioxidants, oxidation by-products, and some liquid contaminants including fuels and dyes

used in coolant. A contaminant of interest in oil contamination monitoring which does not fluoresce is water, which does make this technology incapable of detecting water in oil contamination. This issue may be mitigated using simple data fusion of this measure with a secondary measure of fluid characteristics such as electrical resistance, which would historically be an ambiguous measure. The combination of techniques will allow electrical characteristic changes to be attributed to water if other possible contaminants are undetected using fluorescence.

Physics-based digital twin modelling of critical equipment has long been utilized in an effort to predict system failures [3] but relies on sensing technologies with sufficient accuracy and validated fault models to predict equipment failures and remaining useful life. The advances in sensing technology and condition indicator effectiveness described in this work will allow for improved performance of existing and future HUMS to shift maintenance practices towards condition-based maintenance by allowing for the oil health information to be used as an input to these models. The combination of feature-rich data generated by EEM spectroscopy and Machine Learning will allow for low limits of detection and quantification of lubricant condition and contamination in lubricating oil in oil wetted systems.

Conclusion

The method proposed by this work including measurement using solid state electronics and fiber optic equipment interfaces lends itself nicely towards a compact hardware platform that can be made lightweight, rugged, and low cost and thus suitable to be installed on the monitored equipment: turbine engines, diesel engines, and gearboxes. By generating sensitive, unambiguous, and statistically reliable data and directly measuring individual parameters of the lubricating oil, advanced data processing including physics-based digital twin modelling and machine learning techniques can be applied to the generated data to accurately diagnose lubricant health and identify issues that may affect equipment remaining useful life. The developed model can be used to accurately diagnose lubricant health in near-real-time. By accurately measuring lubricant health online using this new sensor technology an advanced HUMS can be developed to facilitate a shift of the most common predictive maintenance tasks to condition-based maintenance tasks, and ultimately to true predictive maintenance.

Acknowledgments

This work was funded in part by Canada’s Department of National Defence and the Innovation for Defence Excellence and Security (IDEaS) program.

References

1. H. Omrani, J. A. Barnes, A. E. Dudelzak, H.-P. Loock and H. Waetcher, "Fluorescence excitation–emission matrix (EEM) spectroscopy and cavity ring-down (CRD) absorption spectroscopy of oil-contaminated jet fuel using ring-down (CRD) absorption spectroscopy of oil-contaminated jet fuel using," Analyst, no. 137, p. 2782–2790, 2012.

2. O. Sosnovski, P. Suresh, A. E. Dudelzak and B. Green, "Fluorescence excitation-emission matrix spectroscopy for degradation monitoring of machinery lubricants," in SPI Photonics West, San-Francisco, CA, 2018.

3. “FLTS Cost Benefit Study”, Chief, Research and Development (CRAD) Technical Note DRDA/9401/06, October 1994