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Oil System Health Management for Aerospace Gas Turbine Engines

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Abstract— **The oil system of a gas turbine performs essential lubrication and thermal management functions, providing that the fluidic and tribological properties of the oil can meet functional requirements. New engine designs place increasing thermal and mechanical loads on the oil, and thus increase the risks of accelerated degradation potentially causing the oil properties to deviate from requirements. Presented with these risks, there is a potential business benefit for in-situ oil condition knowledge to support oil system health management.**

Starting with the business needs elicited from stakeholders, a Quality Functional Deployment process is performed to derive sensing system requirements. Sensing principles are reviewed for their capability to assess tribological failure mechanisms, and this is related back to stakeholder requirements. A set of sensors were procured and a testing programme performed that exercises the sensors against different degradations of oil and the noise factors representative of service. These sensors are evaluated for their ability to provide oil condition information. The framework presented in this paper uses system engineering principles to derive a health system design and verification process. The results from verification are reported to aid in providing overarching system availability management.

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1. INTRODUCTION

Lubrication systems are a critical aspect of the overall efficiency and reliability of many types of equipment. New engine designs, such as large geared turbofans, place increasing thermal and mechanical loads on the oil, increasing the risk of accelerated degradation and thus oil lubrication properties deviating from system requirements. Presented with these risks, there is an essential need to avoid unexpected failures, and minimise oil consumption, maintenance activities, and frictional losses. Condition monitoring of lubrication systems may prove to be a significant tool in meeting efficiency demands and increasing system availability, while reducing the need for oil replacement. The technologies discussed in this paper are therefore an important contributor to equipment health management (EHM) for a variety of mechanical systems.

Oil condition monitoring in gas turbine engines is largely carried out today through offline measurements, such as titrimetric analysis of total acid number (TAN), spectroscopic analysis and analytical ferrography. These oil quality measurements require manual sampling and long analysis times. On-board system are typically limited to debris characterization, with an aim to detect lubricated component damage, as opposed to measuring the quality of the oil. Development of online analysis techniques to monitor lubricant condition has advantages for early diagnosis and prognosis to prevent faults, though few deployed solutions exist today in any industry [1][2]. A gas turbine environment introduces particular challenges in application of existing sensors to aerospace applications. Particularly pertinent challenges in aerospace include – high and transient temperatures, high mass flow rates, and significantly different oil chemistries to other markets.

The quality of oil is ultimately defined by its properties, for example: physical (viscosity, density), chemical (stability, volatility), and thermal (heat capacity, conductivity). Contaminant concentrations, both internally generated through degradation processes or from external sources, are key contributors to functional system health and can further catalyse degradation reactions. System health state interacts with oil system as both a cause of change and as effect from oil degradation (Figure 1). Existing sensing of system pressures, temperatures and dynamic viscosities can provide some indication of this system health, and this can also be augmented with direct or inferred measures of oil characteristics such as its chemistry. Detection of leakage, bearing wear and other oil system coupled faults throughout the system may potentially be detected with this new capability, adding to the value provided by directly detecting oil quality changes that may be precursors or causal of other failures.

Oil characteristics are defined as symptoms of oil properties, which may themselves be unmeasurable. Characteristics, such as acidity, contaminant concentration, opacity are correlated to measurable phenomena that are used as a basis for a sensing technology. Viscosity, being a measurable physical attribute of an oil, is classified as both an oil property and characteristic, quantifiable through a variety of sensing technology exploiting some phenomena as a basis of measurement (see Section 2).

In a condition monitoring system, such those widely deployed in aerospace, the sensor output is acquired through on-platform electronics and processed on board or after transfer to centralised asset management function. The analysis undertaken should combine oil condition sensing output with system-level measurements, along with the operational history and context, to produce a decision on asset maintenance.

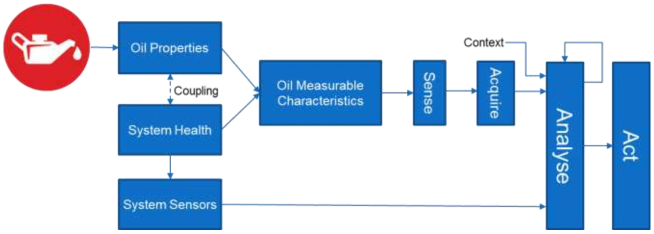

Figure 1: Oil condition health management strategy

Within such a condition monitoring capability, there are a number of stakeholders to consider in order to achieve an effective design. The views of representatives of the through-life operation of the product, including manufacturers, operators and users, are likely to drive different trade-offs that should be considered using best-practice systems engineering (Section 3).

An oil condition diagnostic strategy is outlined in Figure 2. The sensed data from system and oil debris sensing is assumed to be already available (as it is in large civil aerospace engines). This data is fused with oil quality measurements in the following ways. State estimates, such as those made with a system model embedded in an observer [3], can be used to reject the disturbances caused by flow, pressure and temperature of the oil under test and also to understand the exposure of oil to thermal degradation sources. The residence time of oil within the system can be estimated and used to update a model of oil chemical degradation. Through a physical mapping of oil chemistry to oil characteristic, the sensed signal residual to expectation can be used for fault diagnosis and improving the accuracy of the characteristic estimate. The provision of a rich portfolio of sensed values can be used to update the oil chemical estimate. The oil condition estimate is improved by a combination of system, oil chemistry and oil characteristic models and these can then detect incipient departures from normal behaviour. A key requirement is the selection of the correct sensor suite to support this monitoring strategy from the available technologies introduced in the next Section that address the estimation of oil property changes as a result of degradation processes. This paper focuses on this sensor suite, leaving the development of chemical and state estimation to future work.

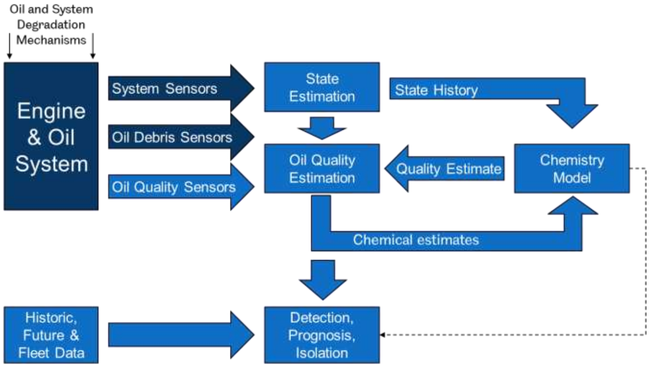

Figure 2: Oil quality diagnostic strategy

2. OIL QUALITY SENSING REVIEW

Oil Degradation Process

Air contact and combustion by-product contamination is an unavoidable aspect of operation for typical lubrication systems, this combined with moderate temperatures can accelerate all degradation modes: oxidation, nitration and sulfation. Oxidation results in the formation of weak acids while combustion by-products react to generate strong acids [4]. Water contamination can occur in infrequently used engines, causing hydrolysis, in which water molecules react with the base lubricant to split them into acids and alcohols. Typically, this results in carboxylic acids which are precursors to polymerisation.

Fault modes, termed as thermal degradation in Figure 3, are typically a result of non-standard operational conditions when local temperatures can greatly exceed the normal operational range or mechanical issues. For example, intermittent lubricant flow can result in components operating starved of lubricant for short periods resulting in high surface temperature which effect the lubricant when flow resumes. Such conditions do not always appear as increases in the bulk system temperature. The process of thermal degradation through thermal cracking, where the breakage of bonds within lubricant molecules produce reactive short chains (which may polymerise other molecules) and/or carbon deposits. This process can also result in free hydrogen ions, although base oil molecules are more likely to break at the weaker carbon – carbon bond.

The polymerisation process is a result of the reaction of carboxylic acids, generated by the above contamination or thermal degradation, with base oil molecules to form larger hydrocarbon chains. The increased complexity of the molecules leads to increased intermolecular interactions during shear and increased lubricant viscosity.

Shear degradation is typically the result of running time and high load conditions. The mechanical forces that act on the base oil molecules during high shear can be sufficiently high to break the covalent bonds within molecular chains. This results in chains of lower molecular weight and a lower viscosity fluid [5], without change in acidity.

It can be seen from Figure 3 that the lubricant additive pack can prevent some of the causes from realising an effect in the lubricant system. This protection comes at the cost of reducing the additive component of the lubricant and the protection cannot be maintained indefinitely. Furthermore, chemical degradation is the result of a significant number of molecular interactions and the additives cannot provide complete protection. Despite the increased reactivity of the antioxidant for example, some oxygen will meet and react with base oil molecules before they can be neutralised by the antioxidant. Antioxidants act sacrificially to prevent chemical reaction with the base oil. Detergents and dispersants seek to keep contaminants contained in suspension by forming micelle layers.

Small changes in operating conditions can cause large changes in the prevalence of the individual failure modes, resulting in different concentrations of acids, polymer chain length distributions and additive pack depletions. Monitoring symptoms is thus key to oil quality estimation.

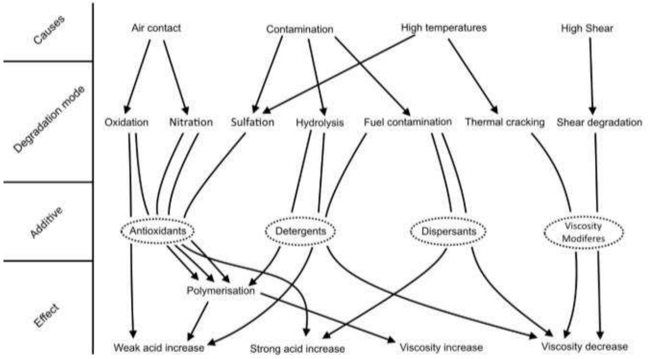

Figure 3: Summary of the causes, modes of lubricant degradation, additives effected and the effect on the lubricant.

Sensing Technologies - Viscosity

As viscosity is a measure of a fluid's reaction to a force, measurement techniques require a force to act upon the fluid. We highlight four main technologies available for the measurement of viscosity and suitable for in-line condition monitoring systems; micro-acoustic, electro-mechanical, vibrational and system inferred (Figure 4).

In-line acoustic sensors may apply shear-polarised waves to the fluid, these thickness shear mode sensors avoid compressional wave losses so that the dissipated energy is mainly viscosity and density dependent. Due to the high frequency of operation (around 1-100Mhz) and the thin film thicknesses accessed the non-Newtonian behaviour of the fluid can be measured and results can have low repeatability [6]. Thickness shear mode acoustic sensors offer measurement of a wide range of viscosity, 0 to 200 cP have been reported [7] and good repeatability [8]. Tuning fork viscosity sensors operate by oscillating two tines. These are excited by AC voltage at a resonance frequency while the measured electric current corresponds to the velocity of its oscillations and from this viscosity can be determined, with a repeatability of better than 1% [9]. The tuning forks are typically made of quartz, however, quartz tuning forks are very delicate and thus might be easily damaged during cleaning or the regular measurement process. As a result alternative materials have been used and found to be more appropriate for engineering applications although less sensitive than the quartz designs [10].

Electromechanical sensors mechanically shear a lubricant with measured or inferred forces. Micro-pistons viscometers employ an oscillating piston in an electromagnetic field, shearing lubricant and monitoring the piston velocity. Rotational viscometers apply a similar principle but use a rotating disc, spinning at a constant rotational velocity, and a stator disc with a torque sensor mechanism. Viscometers of these types have been shown to be in good agreement with other viscosity measurements in the range of 0.2 mPa.s to 160 mPa.s [11], while complying with relevant standards [12]. Devices of this nature are stable thermally but also larger than many alternative sensors, contain moving components and may be effected by the motion of the sensor.

Vibrational viscosity sensors actuate a paddle on a cantilever arrangement or torsional oscillations. Vibrational viscometers offer high sensitivity, a simplicity of design that ensures robust performance and can assess the bulk viscosity with less impact from non-Newtonian dynamics. Both the micro-paddle design and torsional vibrational viscosity sensors monitor the resonance in oscillations to determine the fluid viscosity. Vibration tuning fork sensors consist of two cantilevers submersed in the fluid medium. As with other vibrational sensors, there is an excitation and the response is recorded in order to ascertain the fluid damping and relate it to viscosity. Tuning fork technology has been shown to be effected by fluid permittivity, and, reportedly, magnetically actuated sensors have developed issues in operational conditions as ferromagnetic wear material can disturb the electromagnetic machine flux [13].

System inferred viscosity sensing, uses the relationship of flow to pressure drop over the components, but must consider the considerable uncertainties of temperature variation over the system. This can be used with more conventional sensing but at the cost of poor accuracy and repeatability.

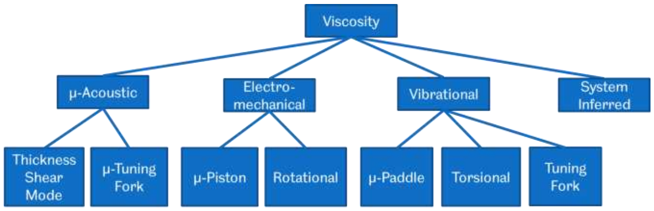

Figure 4: Viscosity sensing means and their classification based on the measurement principle

Sensing Technologies - Acidity

Conventional acidity measurement methods, such as titration methods used in standard offline methods, may not be deployed on-line due to their consumption of titrate chemical and lack of robustness. This fragility also prevents use of other laboratory standard chemical analysis methods. The review thus focusses on optical and electrical methods that are potential on-line methods, as classified in Figure 5.

Optical spectroscopy is the analysis of light interacting with atoms or molecules. Raman spectroscopy uses monochromatic light, typically infra-red (IR) from a laser source. Fourier-transform infra-red (FTIR) spectroscopy measures how much energy is passed through a sample by the IR laser, while Raman spectroscopy measures the energy scattered.

IR spectroscopy can be used to give a complete picture of the chemical system however the acidity/basicity species need to be identified and correlated to total acid number (TAN) or total base number (TBN). This is not a simple task and IR spectroscopy is computationally intensive. Attempts have been made to miniaturise IR spectroscopy although this technology has only recently reached the market [14]. Portable IR spectrometers which are compliant with ASTM D7889 [15] have recently been reported [16].

The polarised molecules within an oil respond to an electric field, and as the length and bonds of these molecules change with degradation, so too do their response to the electrical field. This manifests as a change in the material dielectric permittivity, which can be measured through a change in impedance (real and complex components) [17]. Permittivity has been shown sensitive to various contaminants [18] including water, and soot acid products. The U.S. Patent 6,459,995 [19], suggests a lubricant loss factor (the argument of complex impedance) of a new lubricant sample is expected to be about 0.001 for new oil sample and 0.1 for heavily contaminated one, irrespective of brand. The fluid response can change with frequency of electrical excitation, this leads to Electrochemical Impedance Spectroscopy (EIS). Studies have shown that EIS response to oxidation can be altered through contamination by water, soot or combustion by-products [20][21]. In aviation, the literature evidencing the relationship between permittivity and the specialist oil's degradation are not well established, our work contributes to the quantification of these relations.

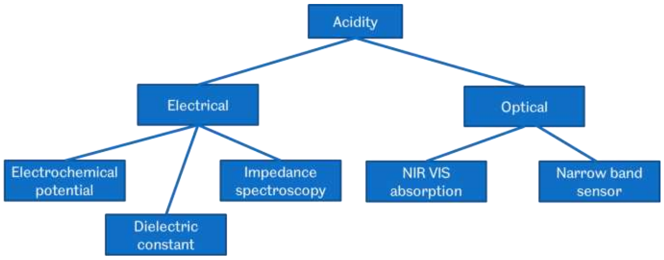

Figure 5: Acidity assesment mmeans using optical and electrical phenomena changes.

3. EHM DEVELOPMENT PROCESS

Overview - Systems Engineering Process

Design, Services, and Manufacturing representatives were amongst attendees to workshops focused on ranking importance of their requirements, the starting point of the process represented top-centre in Figure 6. The top level objectives, were: determine oil properties, understand oil effect on system, diagnose system fault, optimise system, plan maintenance, minimise unit cost, and enabling other new technologies. A customer requirement breakdown of these objectives was fed into a multi-stage quality functional deployment (QFD). The first stage, QFD0, ranked the importance of functional (e.g. determining oil properties) and non-functional (e.g. reliability) against the customer requirements. The resulting system requirements became the input to QFD1, which assessed the functional importance of these requirements. The functions included a characteristic measurement evaluation, i.e. an expert weighted importance to knowing each characteristic. Other functions required to realise an end-to-end equipment health management (EHM) system are not discussed within this paper.

The process acknowledges the difference between test-bed, civil and defence aerospace needs through weightings on requirements, and maps these customer requirements to systems performance metrics allowing system optimisation. For example, in testbed applications, thermally-driven degradation leads to the importance of continuous acidity monitoring becoming paramount, whilst in-service engines may be sufficiently monitored by snapshot viscosity measures taken at steady-state points in the flight envelope.

The most important characteristics identified through this process were viscosity, acidity and chemical species, ranked at various strengths depending on application. To sense these, different means were identified through the literature review (see Section 2) and a request for information from product suppliers. The candidate products were evaluated using the Pugh assessment process reported in simplified form in the next section. The remainder of the paper reports the evaluation of the products which will be taken forward into system solutions and refined through tests on both a testbed application and also a large geared turbofan (UltraFan) – planned for 2020.

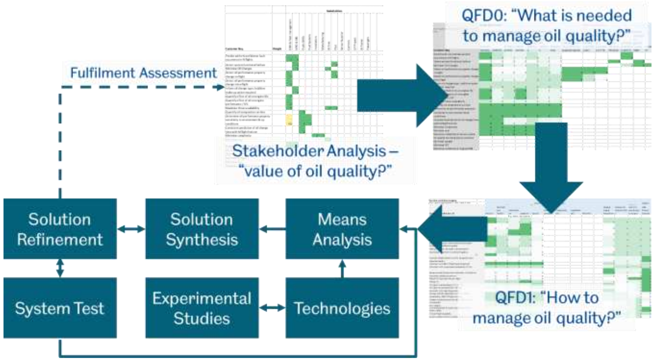

Figure 6: Systems engineering process

Down-selection of sensors through QFD and Pugh matrix

Through a means analysis, the set of sensed phenomena identified in the literature review are qualitatively assessed against their literature reported response to the key oil characteristics of viscosity, acidity and chemistry pack, Table 1.

Table 1: Qualitative assessment of the capability of different phenomena to indicate changes to oil characteristics of viscosity, acidity, and chemical make-up. Low (L) indicates weak capability, in contrast to Medium (M) or High (H).

Phenomena	Oil Characteristic		
	Viscosity	Acidity	Chemistry Pack
Complex permittivity	L	M	L
Conductivity	L	M	L
Impedance spectroscopy	L	M	M
Electro-mechanical vibration	H	L	L
Micro-acoustic vibration	H	L	L
FTIR / near-IR	L	M	M
Optical Transparency	M	L	L

A portfolio of 25 candidate commercial sensors were identified during the work, utilising the phenomena identified in Table 1. The threshold criteria for all the sensors were the ability to survive and operate within the lubrication system environment or the possibility to upgrade the sensor to the environmental requirements – this precluded optical technologies. Another judgment which has been taken into account is the sensor volume and weight which is crucial criteria in the aviation industry.

The functional criteria were only available for viscosity sensing, and as such a ranking on accuracy, repeatability and range were made. Accuracy requirements eliminated large-scale vibrational methods. For electrical sensors the absolute sensing accuracy is less relevant since electrical properties are an abstraction of the oil characteristics.

The full down-selection was captured in three Pugh matrices (not shown) constructed as a relative comparison to an arbitrary baseline sensor choice for each characteristic of interest. The result of the analysis was the identification of four sensors, two viscosity and two electrical, with each exploiting a different phenomena:

- Electrical 1: Multi-frequency impedance
- Electrical 2: Loss factor with proprietor calibration
- Viscosity 1: Micro-piston electro-mechanical
- Viscosity 2: Micro-acoustic tuning fork

These four sensors have been procured and subjected to a test plan as described in the next section.

4. EXPERIMENTAL METHOD

P-Diagram for Oil Condition Sensors

A parameter diagram (P-Diagram) was produced to study the robustness of the condition estimation system. The P-Diagram representation considers the quality of the desired output subject to disturbance noise, and considers the available mitigating control factors. Table 2 reports the summary of the key elements of the analysis, in particular it motivates the need for a test programme that can assess the ability to deliver the ideal outputs in the presence of the listed noise factors. An experimental programme was consequently designed and performed, based on assessing sensitivity to noise factors.

Table 2: Tabular representation of the factors populating a parametric diagram of the oil monitoring system.

Inputs	Noise Factors	Ideal Response -Oil Characteristic
Sensor Output	Pressure	Viscosity
Physics Knowledge	Flow	Acidity
Control Factors	Temperature	Contaminants
Sensor suite	Aeration	Chemical signature
Sensor location & packaging	Vibration	**Undesired Response**
Signal Processing	Deposits & Particulates	System failure
Data fusion	Age & Drift	Oil system disturbance
State Estimators		

Test Programme Overview

A number of test objectives have been elicited to characterise the sensors as follows:

O1. Assess the accuracy of sensor against available laboratory test of same measurand
O2. Assess the repeatability of each sensor across the required temperature range
O3. Assess sensitivity of sensor output against the disturbance factors
O4. Compare sensors ability to differentiate between given samples (i.e. degraded oil from new oil)

Figure 7 shows the structure of the verification plan. Since the absolute accuracy of the electrical properties is not directly relevant for meeting the test objectives, only a comparison of sensor differentiability between different degradations of samples is needed, along with the repeatability of these measures. For both electrical and viscosity types disturbance tests are important, within this paper neither metal debris, vibration nor aeration tests are reported.

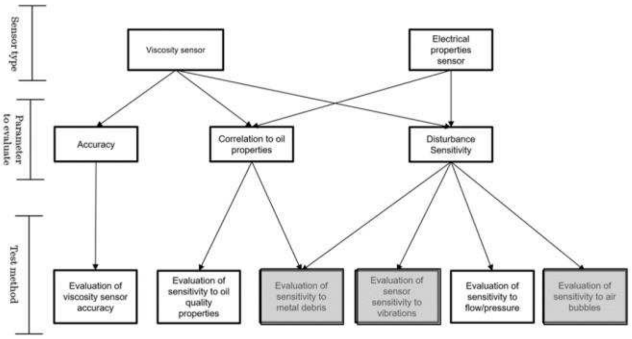

Figure 7: Structure of test plan for two sensor classes

The accuracy with respect to varying temperature was evaluated using a simple temperature controlled container filled with the various oils under test – these experiments are referred to as static tests. To generate the disturbance test results, a hydraulic test rig (Figure 8) capable of up to 60 litres per minute flow and 10 bar of pressure was constructed. The pressure and flow variables were controlled with a pressure feedback to a variable frequency gear pump under different manual restrictor settings. A fully open restrictor allows maximum flow rate variation, whereas a closed restrictor resulted in large pressure fluctuations – these two experimental conditions are shown in Figure 9.

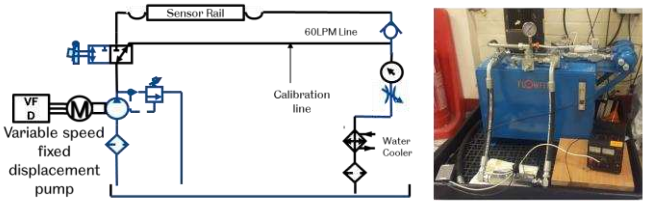

Figure 8: Disturbance rig schematic and constructed equipment

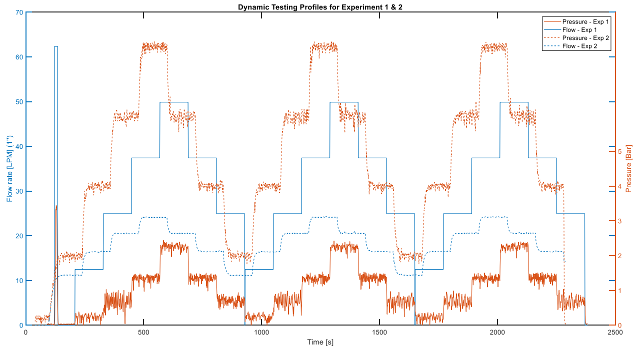

Figure 9: Test profiles for two experiments each used to explore sensitivity to flow and pressure respectively.

5. SENSOR CHARACTERISATION

Viscosity Sensor Results

The static test has been performed using new oil for both the viscosity sensors, resulting in the data shown in Figure 10, along with a reference result from a laboratory test. This 'ground truth' result is obtained using ASTM D341, with the interpolation of capillary viscometer measurements at 40°C and 100°C (reported in Table 3) using the standard specified model. Two experimental runs from each sensor are shown. Over the evaluated temperature range, the micro-acoustic sensor is the closer sensor result to the laboratory prediction model, but displays a slightly lower repeatability (see also Table 4).

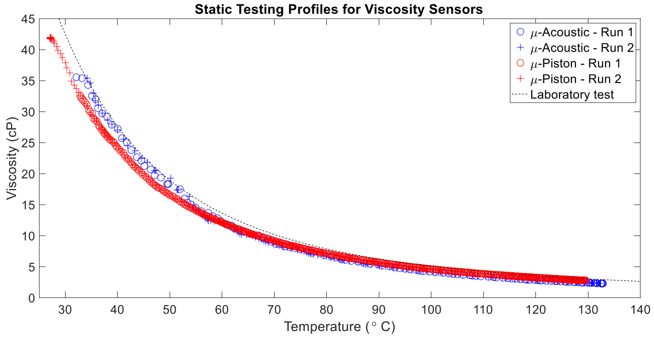

Figure 10: Static test for viscosity sensors, each over two independent test runs

The static tests show the non-linear behaviour of viscosity over the full range, but an approximate linearity over the small (<5°C) temperature range exhibited in the disturbance test, as shown in Figure 11. The mean trend and 99% confidence intervals of the data over this range is for the two sensors is shown as solid and dashed line in red and blue for the micro-piston and micro-acoustic respectively. The data from running the sensor under the two disturbance test conditions are plotted as circle and diamond markers.

An operating problem with the micro-piston result is clear in a large bias compared to the static results. The dynamic test caused a near instant loss of calibration for the device, the cause of which is under investigation. Since it is a constant bias, it is assumed that this may be removed with calibration for the purposes of comparisons made in this paper. The variance to flow and pressure was low after this event occurred. A close examination of Figure 11 shows there is minimal disturbance on the micro-acoustic sensor from pressure, and flow fluctuations; the results are all within the confidence bounds created from the static tests.

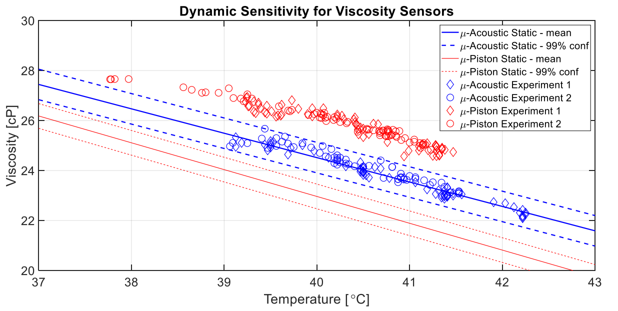

Figure 11: Disturbance tests evaluating sensitivity of viscosity sensors to flow and pressure variation

Electrical Sensor Results

It has been highlighted that the absolute accuracy of electrical measurements is of secondary interest. Thus, whilst the sensitivity to disturbance is important, this should be analysed in the context of the response to different oil chemistries. A set of samples (Table 3) have been acquired from various in-service gas turbines: two new (nominal) but different oil types, two normally aged samples (A&C) and heavily degraded testbed and in-service oil (B&D).

Table 3: Oil samples used for testing and their laboratory derived acidity and viscosity characteristic values

Description	TAN	Viscosity @ 100°	Viscosity @ 40°
Nominal Eastman 2197	0.36	5.28	26.98
Nominal Mobile Jet II	0.03	5.1	27.6
A: Service engine Mobil-Jet II	1.13	5.293	
B: Heavily degraded Mobil-jet II (fault)	16.72	9.288	
C: Service engine Eastman 2197	0.1	5.441	
D: Endurance test engine Eastman 2197	0.18	5.286	

The results from the multi-frequency impedance sensor (Figure 12) showed an ability to discriminate between the different samples, with the higher frequency (10kHz) excitation offering more differentiation at lower temperature in comparison to the 10Hz signal. This is promising, since lower frequency operation required longer acquisition sampling time and is thus more susceptible to temperature variation reducing accuracy of measurement.

These experiments generated data from the four sensors which is synthesised for analysis in the next Section.

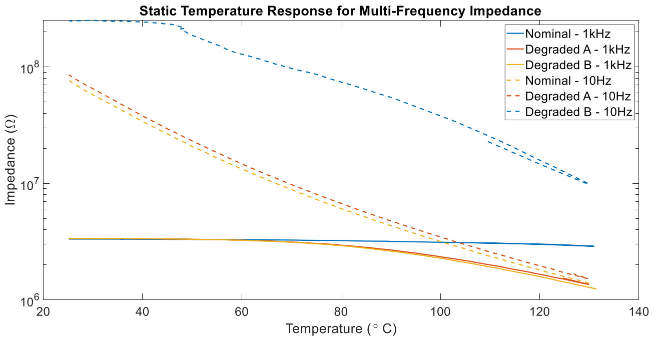

Figure 12: Multi-frequency impedance static tests, showing a high frequency and low frequency response to different degradations of oil over a varying temperature range

Result Summary

Three metrics have been generated to help describe the sensor quality, generated from sensor (y_s) and temperature (T) measurements $z^s(k) = \{y_s(k), T(k)\}$, where s is the label for experiment of K_s data points from a particular sensor under the specific test.

Repeatability for each sensor is defined as a sum of squares of each sensor value from experiment runs A compared to an equivalent value from experiment run B. This metric is defined in Equation 1 where $\hat{y}^B(T_k^A)$ is an interpolated value from data set B at the temperature collected in data set A. The data is normalised by the each data point of sensor value from run A, $y^A(k)$ and the sum of difference divided by the number of samples in run A, K_A.

$$r_s = \frac{1}{K_A}\sum_{k=1}^{K_A}\frac{1}{y^A(k)}\sqrt{\left(y^A(k)-\hat{y}^B(T_k^A)\right)}^2 \qquad (1)$$

Disturbance sensitivity (Equation 2) is the sum of squares difference between the data sample, y_k^S, and the expected nominal value at its temperature, T_k, using a regression model built from static test data, $\hat{y}^N(T_k)$. The data, y_k^S, is collected from the sensor subject to the symmetric disturbance profile (Figure 9), which is consistent for each experiment. Due to observed issues that appear to arise from installation location changes, as discussed earlier with reference to Figure 11, a compensating bias term, b_s, is permitted to be trained from the disturbance rig when there is zero flow.

$$d_s = \frac{1}{K_S}\sum_{k=1}^{K}\frac{1}{y^S(k)}\sqrt{\left(y^S(k)-\hat{y}^N(T_k)-b_s\right)}^2 \qquad (2)$$

Degradation distance measures the mean difference between nominal and a tested degraded sample for each sensor, normalised for a number of nominal condition data points (K_N) and the nominal expected value. This this metric indicates the detectability of degradation above the noise factors.

$$DD_S = \frac{1}{K_N}\sum_{k=1}^{K}\frac{1}{\hat{y}^N(T^D(k))}\sqrt{\left(y^D(k)-\hat{y}^N\left(T^D(k)\right)\right)}^2 \quad (3)$$

These metrics are reported in Table 4 and lead to the following comments. An advantage of multi-frequency impedance is apparent by at least one of the outputs always showing maximum differentiability of oil health, but this is at a cost of high repeatability variance. Viscosity is shown to be a useful degradation measure only for oil sample D, with other sample viscosity changes being within the repeatability error of both sensors. Sensitivity to disturbance is low across all sensors relative to the repeatability errors over the wider temperature range, suggesting temperature stability is far more important. From this initial set of results, work to improve the repeatability of the multi-frequency impedance sensor is likely to add most value to producing a good estimate of oil quality.

Table 4: Results summary of sensor testing on test rigs with new and degraded oil. Oil degradation samples are for Turbo Eastman (both

Sensor		Repeatability	Disturbance Sensitivity		Degradation distance for each oil			
			1 – Pressure	2 - Flow	A	B	C	D
Multi-freq impedance	High freq.	0.001	0.0147	0.0136	1.389	0.186	0.060	0.096
	Low freq.	0.104	0.0404	0.0307	1.195	1.212	0.745	0.874
Loss factor		0.004	0.0923	0.0923	0.193	0.963	0.149	0.113
Micro-piston		0.051	0.0231	0.0228	0.031	0.759	0.031	0.001
Micro-acoustic tuning fork		0.076	0.0099	0.0174	0.031	0.759	0.031	0.001

6. CONCLUSION

Maintaining the quality of an oil lubrication system is essential for system efficiency and health, but the precise definition of oil health is dependent on application. As such a structured evaluation of the means to deliver the optimal sensor suite is essential. The oil characteristic measurements should be chosen to reflect the stakeholder needs.

Testing has revealed the relative performance for a set of commercial oil quality sensors in terms of repeatability, disturbance sensitivity and ability to differentiate between new and aged oil samples. The relative strengths of the sensing technology has to be considered in light of the stakeholder derived requirements.

Next steps will involve testing of the sensors on a wider range of degraded oil samples, and developing algorithmic strategies to fuse different sensor technologies together in order to deliver stakeholder requirements.

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