

Latest Developments in Online Oil Condition Monitoring Sensors

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Abstract

Oil condition monitoring is an accepted part of integrated asset health management. With an increasing impetus towards real-time decision making, the inevitable delay incurred in offline laboratory oil analysis is unacceptable. Kittiwake is pursuing an active R&D programme to develop robust, cost effective sensors for continuous online oil health monitoring. This paper presents recent developments in three key areas; Metallic Wear Debris, Total Water Content and Viscosity. Quite different technological solutions have been adopted to monitor these vital oil parameters. The rationale behind each chosen technology is discussed. Results from both in-house and field trials will be presented.

Metallic Wear Debris: significant improvements in the sensitivity of the wear metal particle counter have enabled the detection of individual ferrous debris particles down to 40µm spherical diameter and to 135µm for non-ferrous metals. Independent validation on a test rig employing case hardened straight cut gears loaded to initiate micro-pitting shows very good correlation with the observed progression of damage on the gear flanks.

Total Water Content: a sophisticated sensor utilising Infrared transmission measurements has been developed and successfully trialled on board ship. The sensor has been designed primarily for marine diesel engine applications but is capable of measuring the water content in virtually all oils. The maximum water content measurable is 2%. A correction methodology has been developed to increase the accuracy of the measurements in oils contaminated by soot. The method correlates to an accepted DIN standard, reporting soot content as an additional parameter.

Viscosity: a cost effective device employing a low amplitude vibrating sensor element is the most recent Kittiwake development. Key features of this latest sensor include accurate measurement over a very wide viscosity range (1 cP to in excess of 1300cP) and an operating range which covers combustion engine oil temperatures and pressures.

In addition, work is also in progress to provide a unified network and connectivity scheme employing the CANopen standard for all of Kittiwake's current and future sensors. Straightforward integration of a distributed network of sensors with, for example, a ships management system is the driving force behind this work. Results and lessons learnt from field trials will be presented.

1. Introduction

Oil condition based maintenance (CBM) in which active monitoring of key oil parameters is used to determine machine health and variable service intervals is an emerging maintenance philosophy. CBM provides the potential for reductions in operational costs, increases in operational performance and improvements in machine safety. Offline laboratory oil analysis at regular sampling intervals has traditionally provided the data for CBM programs, however the case for online, real time sensing and monitoring of oil condition is easily made. In-situ sensors address concerns of sampling issues, time lags from sampling to report delivery and analysis errors, particularly in field testing. It is not surprising, therefore, that considerable activity is in progress to develop simple, robust, cost effective sensors and systems for monitoring important oil condition parameters.

Oil analysis laboratories employ a suite of test methods and instruments for lubricant testing. Not all of these methods are directly transferable to online sensing without encompassing significant complexity and therefore expense. In the automotive market, where cost is a significant driver, essentially only two technologies have been adopted thus far; (i) dielectric measurements for trending oil quality and (ii) solid state oscillating crystal devices for viscosity sensing. Capacitance based sensors, e.g. the TEMIC QLT-sensor [1], have been fitted to high end passenger cars by several manufacturers since the mid 1990s. The dielectric properties of lubricating oils are determined by many factors, e.g. oxidation, fuel dilution, soot loading, additive depletion and water/coolant ingress, and it is not possible to readily deconvolute individual influences from the observed changes. Nevertheless, in combination with a few other engine parameters, reliable prediction of the remaining useful life of in-service oils can be made with these sensors, resulting in flexible servicing intervals and optimised operational costs. Viscosity sensors, employing flexural or surface wave oscillators [2], [3] are beginning to make inroads into automotive applications although have yet to be adopted in any significant numbers.

In other markets where capital investment costs are considerable, e.g. the marine and shipping world, and where the need for real time monitoring of critical equipment is even more relevant, the uptake of online oil condition monitoring sensors is still at a somewhat early stage.

Commercially available oil sensors for “high ticket” engines and machinery include capacitance, humidity (dissolved water), wear debris (including ferrous content and particle counting) and viscosity. Of these the so-called “oil quality” capacitance sensors seem to be the most established notwithstanding their inability to diagnose precise oil issues, as noted previously. Humidity sensors, discussed later, also have some limitations to their use and are rarely used in engine applications, where significant water levels are often encountered. However, total ferrous content wear debris sensors are routinely employed with great effect in the optimisation of cylinder oil feed rates in two stroke marine diesel engines [4] but wear debris particle counting finds sparse usage. Viscosity sensors are common in fuel-oil control systems but, as yet, have seen little use in lubricating oil applications.

2. Main part

2.1 Wear Debris

Metallic wear debris particle counters employing inductive technology [5] have been commercially available for some time. Using a combination of balanced field coils and a sensing coil, these devices are able to determine particle sizes and differentiate between ferrous and non-ferrous metals. Classification into the two material channels is straightforward due to the reversal in signal phase. The sensitivity to ferrous particles is greater than non-ferrous due to the difference in the mechanism by which these two materials interact with the magnetic field. In addition, sensitivity to both materials increases with reducing bore size. For practical oil line diameters around the 10mm mark, the smallest particle sizes have previously been limited to 120 μ m equivalent spherical diameter (ESD) for ferrous materials and around 300 μ m ESD for non-ferrous materials. Kittiwake Developments has made significant improvements in signal conditioning circuitry to improve these figures to 40 μ m and 135 μ m ESD respectively. These improvements dramatically increase the chances of catching early onset wear before significant damage can occur. Wear modes in machinery take many forms, e.g. abrasion, spalling, pitting and scuffing, and give rise to a large variety of shapes and sizes of debris. Nevertheless, the more sensitive the detector, the better able it is to distinguish between normal and abnormal wear patterns.

Typical applications of wear debris sensors are in turbine, gear box or drive train installations, with an increasing interest in wind energy gear boxes which exhibit variable loading, due, in part to the somewhat erratic nature of the primary power source. We present some recent results from a controlled gear test rig and a field trial below.



Figure 1 - Kittiwake Particle Sensor

2.2 Gear test rig investigation

In to Figure 5, we show the setup and results from an 18 day (75 million cycle) test, in which a wheel/pinion pair were progressively loaded up to 370 Nm. At this point scuffing occurred, the particle counts in all size bins increased dramatically and the test was stopped.

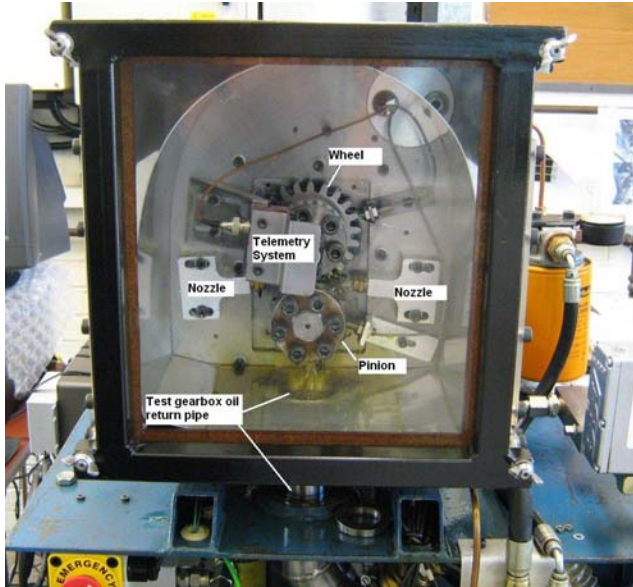


Figure 2 - gear test rig

Observation of the gear flanks during the test (Figure 6) showed increasing levels of micro-pitting followed by small scale macro-pitting before the final scuffing event. The cumulative ferrous particle counts in 5 bin sizes follow this pattern with distinct steps at each loading stage (Figure 7).

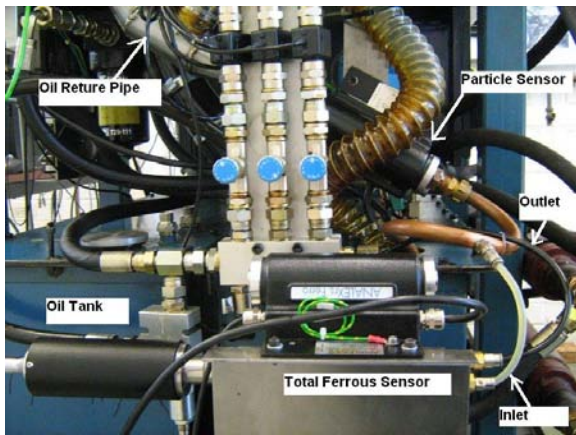


Figure 3 - sensor location

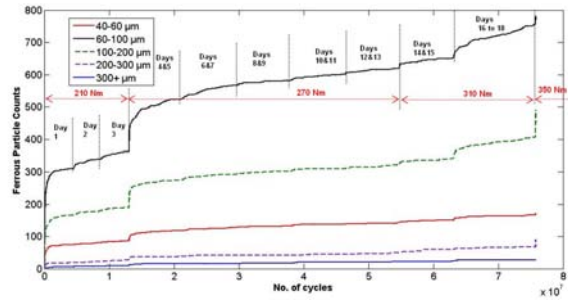


Figure 4 - cumulative ferrous particle counts

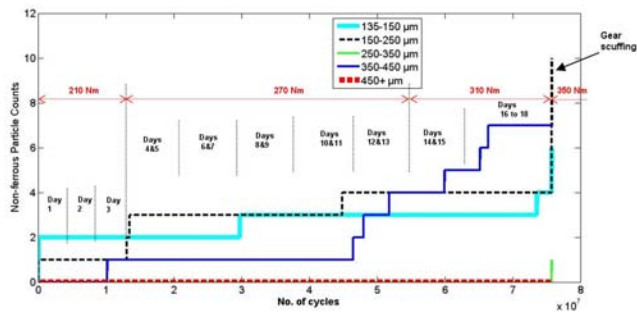
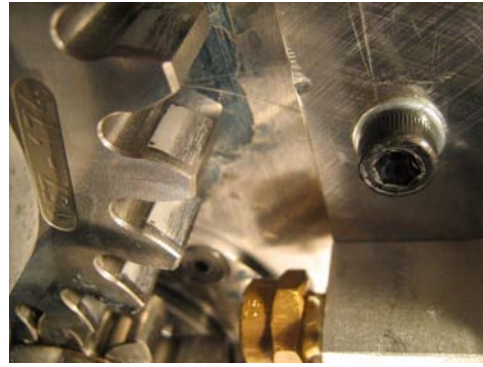


Figure 5 - cumulative non-ferrous counts



Start of test



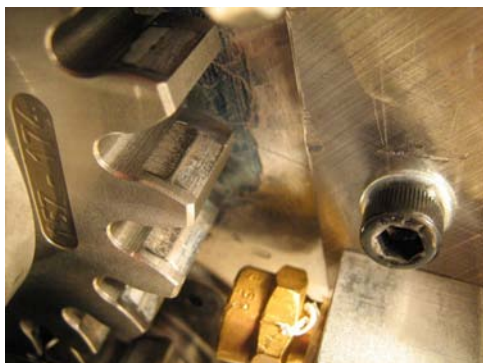
After 210Nm loading



After 270Nm loading



After 310Nm loading



After 370Nm loading

Figure 6 - wear progression photographs

2.3 Wind turbine gearbox trial

Figure 7 and Figure 8 show the cumulative particle counts in the ferrous and non-ferrous channels respectively for a sensor fitted to the oil return line before the main filter in a wind turbine gearbox. This particular wind turbine is exhibiting a classic failure wear pattern but is still in operation at the time of writing (Jan 2010). An imminent boroscope inspection should reveal the extent of the damage. This is thought to be bearing related as both the ferrous (rolling elements) and non-ferrous (cages etc.) channels are showing high particle generation. Some further data in Figure 9 showing total particle counts accumulated during a sudden grid trip illustrates accelerated wear due to (essentially) a crash stop of the gearbox.

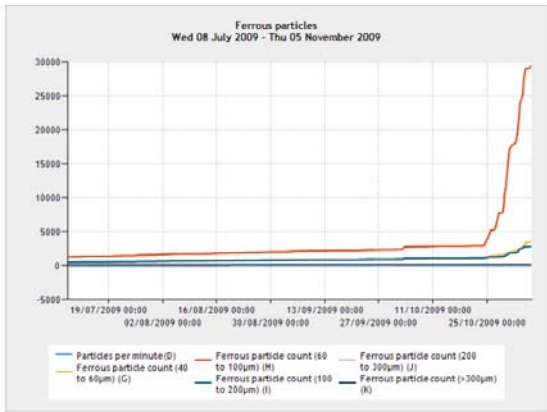


Figure 7 - cumulative ferrous counts

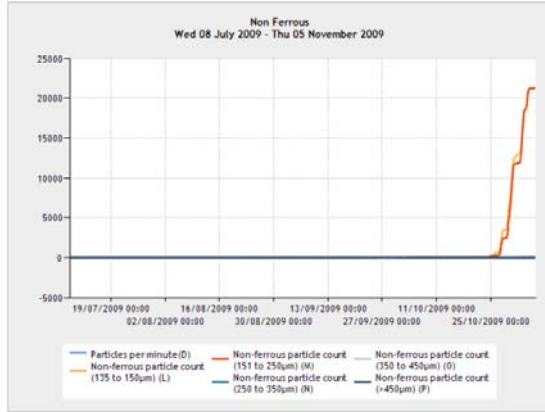


Figure 8 - cumulative non-ferrous counts

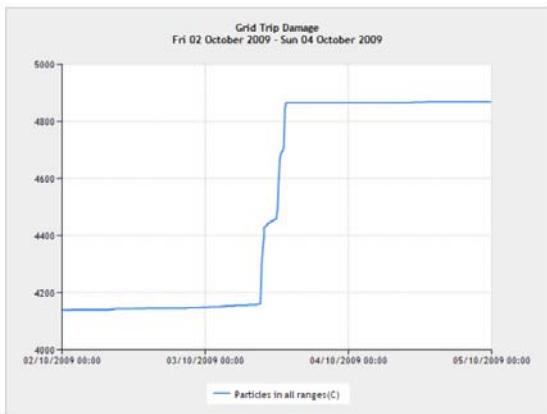


Figure 9 - accelerated wear profile

2.3 Total Water Content

Water contamination of lubricating oil has serious consequences and can lead to catastrophic failures – for example bearing lifetimes can be reduced to 25% of their normal expected level by as little as 0.1% (1000 ppm) of water [6]. It is not surprising, therefore, that water content measurements are often at the top of laboratory oil analysis reports. For online applications, several manufacturers offer relative humidity (RH) sensors adapted for oil use, which make use of capacitance measurements to monitor the amount of dissolved water in the oil. A porous polymeric material in contact with the oil functions as the dielectric between measurement electrodes. Migration of water molecules into this polymer – driven by the chemical energy, or activity, of the oil/water solution – causes a change in the capacitance between the electrodes, which can be measured. Humidity sensors respond to increasing water levels but plateau at the saturation limit - at this point any additional water will exist in the free, undissolved state. The saturation level depends on the oil type and state; in particular, age and temperature. Saturation can occur as low as a few hundred ppm which is easily exceeded in combustion engine operations. Consequently, humidity sensors are more appropriate for monitoring very low water levels, for example in oils used as insulating media in electrical transformers. In addition, correlation between sensor output – usually reported as equivalent relative humidity (ERH) – and water content in ppm, is neither linear nor easily determined. ERH is the RH of a sample of moist air which

would give the same capacitance value as that measured in the oil at the same temperature. There remains, therefore, a clear need for an online water-in-oil sensor which can operate over a wide range, from zero to well beyond the saturation limit, with good accuracy.

Kittiwake has developed such a sensor using infrared (IR) transmission measurements to measure water-in-oil levels up to the 2% (20,000 ppm) mark. A schematic is shown in Figure 10. In this sensor, IR radiation from a broadband source is focussed through an inline flow cell fitted with IR transparent windows. The transmitted IR is recorded by two solid state detectors, each fitted with a narrow bandpass optical filter. The centre wavelengths of one of these filters has been chosen to coincide with the absorption of the IR by water (actually the O-H bond vibration in water) and the other to a wavelength showing no water absorption (reference channel). In clean oils, the difference in the transmission seen by these two channels is related to the absorption of IR by the presence of water – the width of the water filter allows for any slight shift in the peak of absorption due to the different water states within the sample (free, hydrogen bonded etc.). In dirty oils, additional attenuation in both channels is seen due to scatter from particulates, most notably soot in the case of diesel engines. During operation, an estimate of the amount of soot is made by comparing the transmission of the dirty oil to a previously determined clean oil value at the reference channel. A published protocol, DIN 51,452 [7], can then be used to calculate the soot percentage by weight from the observed reduction in transmitted radiation. IR attenuation due to scatter by soot has a wavelength dependence [7] and appropriate correction for the different filter centre wavelength used in the water channel must take this into account.

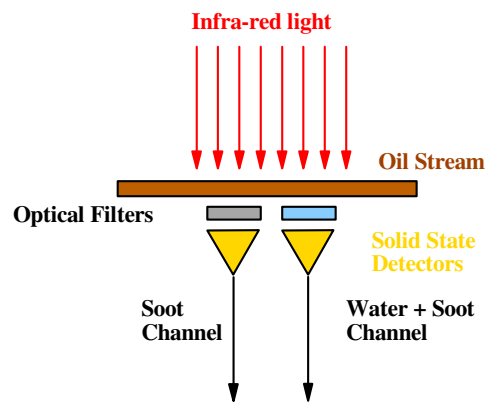


Figure 10 - IR sensor schematic

Calibration of the instrument response has been accomplished by measuring the IR transmission as a function of water spiked oil samples. Figure 11 shows absorbance data for a typical unused mineral diesel lubricating oil accurately dosed with water contents from 0 to around 14,000 ppm. The absorbance is measured as the log (base 10) of the ratio of the IR transmission measured for the empty flow cell, within the bandpass defined by the optical filter, to that of the spiked sample. The slope of the calibration curve thus defines the response of the sensor to changes in water content and the offset is due to any inherent absorbance in the oil or its additives itself (e.g. glycol and carboxylic acids contain O-H bonds) together with that due to any trace water level in the new, as supplied, oil. This latter value can be independently measured by e.g. Karl

Fisher titration, to determine the overall (total) water content and therefore it is possible to completely define the calibration curve for any particular oil type.

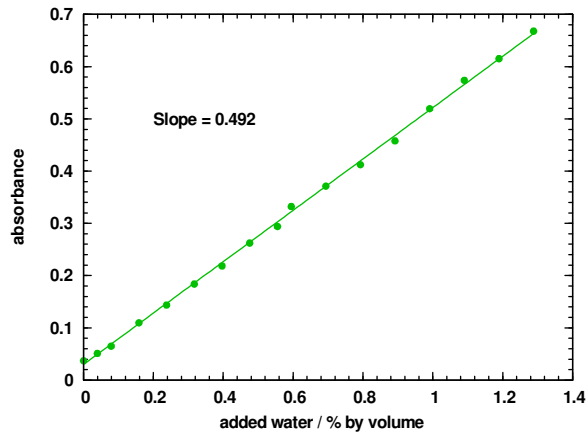


Figure 11 - calibration for clean diesel lubricating oil

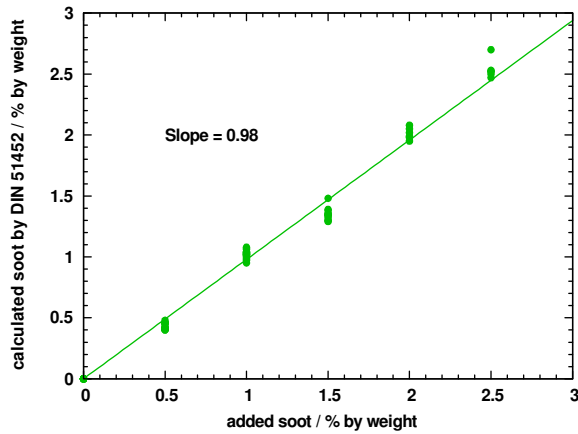


Figure 12 - soot correlation

Figure 12 shows the correlation of soot measurements using DIN 51452 at the reference channel for oil samples prepared with varying soot and water contents (1000 to 10,000 ppm). For each prepared soot content set there is some slight scatter within the group of spiked water contents but nevertheless the correlation shown is still very good. A further set of data, Figure 13, shows the water absorbance for samples of the same type of oil as that in Figure 11, which contain a similar amount of soot (0.5%) after correcting the response for the attenuation due to the soot. The important point to notice is that the slope of this calibration line (0.487) is in excellent agreement with that of the clean oil in Figure 11 (0.492)

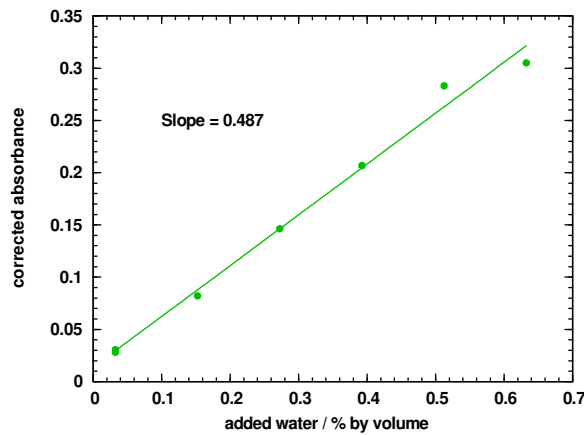


Figure 13 - water content calibration for dirty oil

In developing this sensor, many different types of oils have been tested and virtually all of them show calibration curves which fall into one of three “families” within reasonable accuracy. The family types are; mineral, synthetic hydraulic and synthetic gear oils. To a first approximation it is only necessary to choose between these three for accuracies of about $\pm 5\%$ but higher accuracies of $\pm 2\%$ can easily be achieved by calibration of the sensor with oil of the particular type to be placed in service. The lower limit of detection (LOD) depends, in part, on the pathlength of the IR radiation through the oil with a longer pathlength leading to increased sensitivity. However, a trade-off exists between this sensitivity and the maximum water and/or soot contents that can be measured since complete attenuation will be reached earlier as the pathlength increases. A compromise pathlength has been adopted resulting in an LOD of 100 ppm for water. Increasing soot levels lead to a reduction in the maximum water content measurable, since the two are additive in their attenuation power – for a 0.5% soot level, the maximum measurable water level is reduced to around 10,000 ppm (1%).

2.4 IR Sensor Prototype trials

Two prototypes of the water sensor are currently undergoing sea trials in independent marine main engine installations. Figure 14 shows a picture of one of the installations which is monitoring the system oil of a 9 cylinder Sulzer RTA-96C slow speed crosshead diesel. Figure 15 shows some typical trend data from this sensor. Very little soot content is recorded due to the clean nature of this engine design, with the system oil well separated from the combustion chamber. Figure 16, however, shows data from an 8 cylinder Sulzer ZA40S medium speed diesel installation where the soot content is noticeably higher. The data from these two installations has been verified by offline periodic sampling and testing in an independent analytical laboratory.



Figure 14 - prototype installation

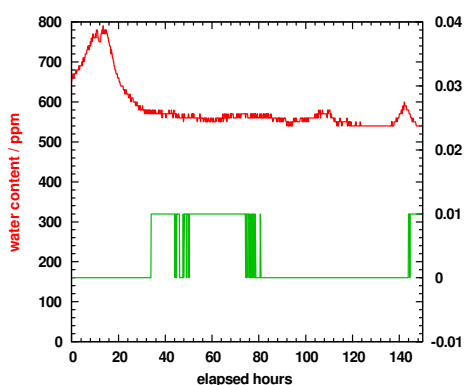


Figure 15 - slow speed diesel engine data

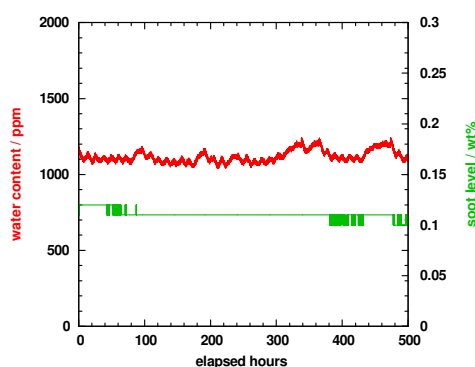


Figure 16 - medium speed diesel engine data

2.4 Viscosity

Viscosity is a key physical property of a lubricating oil – engine and machine builders specify viscosity grades after rigorous tests in order to minimise wear and optimise equipment lifetimes. Significant changes in in-service oil viscosity can indicate potential issues and should be investigated. Despite this very few online viscosity sensors are currently available although there is considerable academic interest [8], particularly in miniaturised devices. The majority of research has focussed on the use of microacoustic resonators operating at ultrasonic frequencies. In a typical device, a crystal oscillating in thickness shear mode (TSM) is in contact with the oil and either the change in resonant frequency or the increase in driving power required to maintain the oscillating amplitude are monitored as both are a function of the viscous loading of the crystal. However the penetration or sensing depth of such a device is inversely proportional to the square root of the oscillation frequency and deviation from expected behaviour can be seen in the case of oils containing long-chain viscosity modifiers [9]. Here, the “macroscopic” character of the oil clearly exceeds the “microscopic” sensing scale of the crystal.

Kittiwake has developed a vibrating element viscosity sensor based on an earlier device which is no longer available [10]. In this sensor, a thin metal strip is excited into a resonant longitudinal vibrational mode in a pulsed fashion. The fundamental longitudinal vibrational mode of a strip has a node at the mid point along the length of

the strip which can be used as a position for a suitable “bulkhead” to separate the oil from air. A concept sketch of the sensor is shown in Figure 17 where the excitation and sensing make use of the magnetostrictive properties of a ferromagnetic strip. Small dimensional changes, of the order of a few parts per million, occur in ferromagnetic materials when they are subjected to varying magnetic fields (Joule effect). By applying a short magnetic pulse, for example via a current pulse through an electrical coil, a magnetostrictive strip can be given a mechanical impulse which will induce vibration. The converse effect – known as the Villari effect – in which a change in the mechanical stress of a magnetostrictive material gives rise to a change in the magnetic susceptibility of the material can be used to follow the resulting decay pattern.

Vibrating viscosity sensors, of both the tuning fork and torsional design, are prevalent in the process industry with the vast majority employing piezoelectric excitation and sensing. Careful design in these viscometers is required to ensure that the input mechanical energy is not dissipated into additional unwanted vibrational modes or heavily attenuated in the support structure, and, also that the mode damped by the process fluid can likewise be detected with sufficient sensitivity. In the sensor presented here, contact-free axial magnetic pulsing leads to efficient excitation of the fundamental longitudinal mode causing shear motion of the wide transverse strip surfaces with respect to the oil.

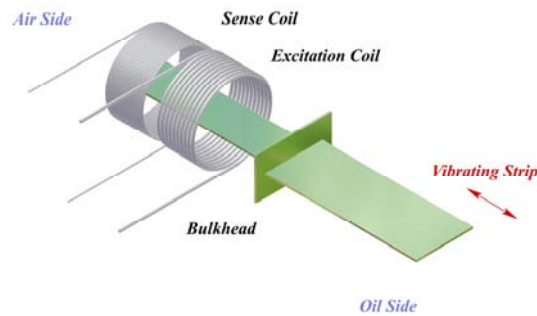


Figure 17 - viscosity sensor concept

Figure 18 shows a block diagram of the sensor electronics. A capacitor bank, of moderate value, is charged and triggered periodically to produce a current pulse through the excitation coil which provides the mechanical impulse as described previously. Following this impulse, the decay of the longitudinal vibration can be followed by a pickup coil and the resulting waveform captured by a fast analog to digital converter (ADC) for subsequent processing, using a digital signal processor (DSP). This latter device also controls the periodic pulsing. Active filtering of the signal, centred around the fundamental vibrational frequency, allows the signal to be cleaned and any noise rejected with high efficiency (Figure 19).

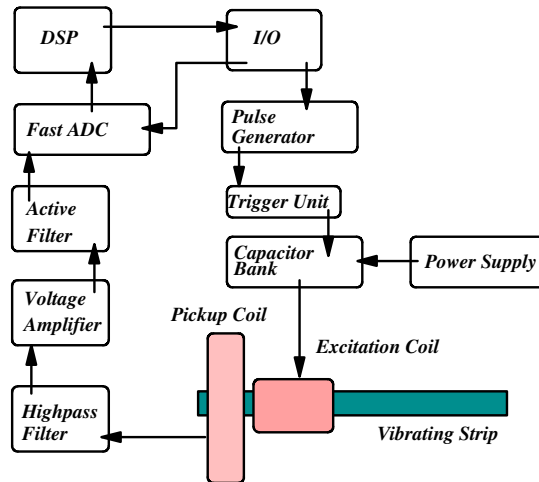


Figure 18 - electronics block diagram

Figure 20 shows typical decay profiles for a strip vibrating in air (red) and in an oil of moderate viscosity (green). The increase in the rate of decay of the individual oscillations, shown expanded in the insert, is quite marked between air and the oil. This additional decay is due to the damping effect of the oil on the strip and follows a simple exponential form characterised by a single decay constant;

$$S(t) = a.e^{-b.t}$$

where, $S(t)$ is the observed signal after time t , a is the initial amplitude at $t=0$ and b is the decay constant.

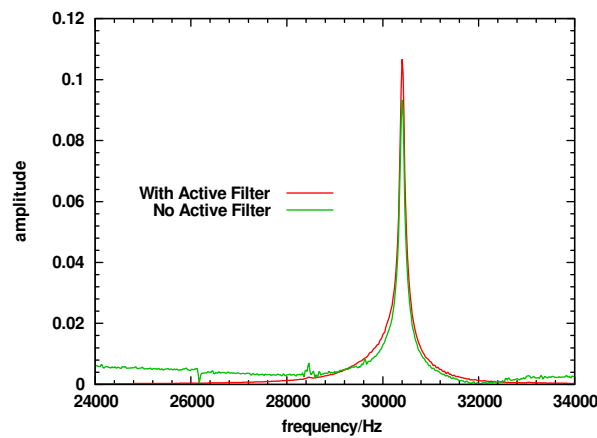


Figure 19 - fourier transforms of recorded waveforms

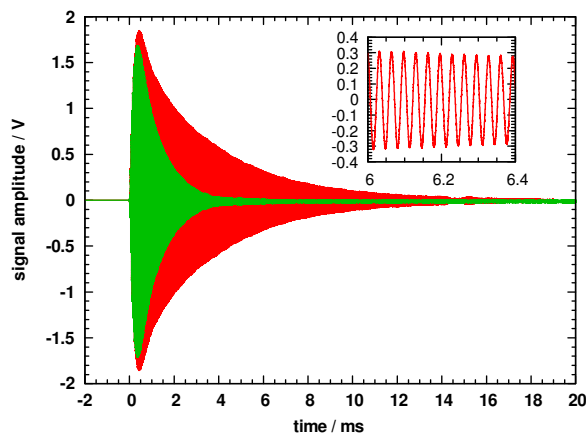


Figure 20 – captured decay profiles

The rate of decay can be shown to be a linear function of the square root of the viscosity-density product [11] of the oil. Figure 21 shows measured decay rates as a function of the square root of the product of certified viscosities and densities, in units of centipoise (cP) and grammes per cubic centimetre (g/cm^3) for various commercially available standards. For each measurement the oil was held at 40°C ($\pm 0.1^\circ\text{C}$) and between 50 to 100 waveforms captured and analysed. The time required to record and process a single waveform is of the order of 20 ms (Figure 20) which allows signal averaging techniques to increase the statistics even over periods as short as 1 second for “live” measurements.

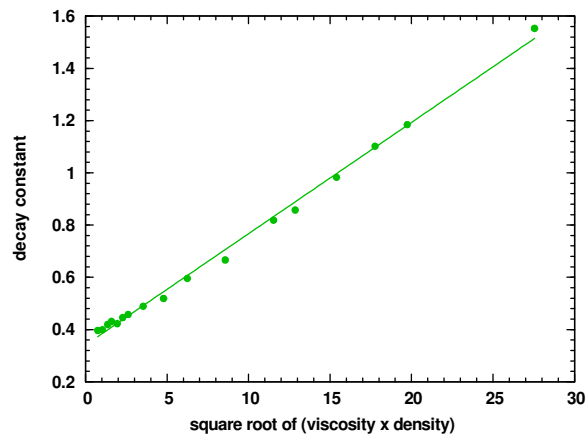


Figure 21 - measured decay rates for various viscosity standards

The range of viscosities used to prepare Figure 21 is from 0.7 cP to 900 cP and a statistical analysis of this calibration data leads to reporting limits of less than 1% for a 99% confidence level.

A sensor based on this concept is currently at the prototyping stage (Figure 22) and will shortly be undergoing field trials.



Figure 22 - viscosity sensor prototype

2.5 Combined Sensor Systems

The CAN protocol, developed by Bosch [12], has become accepted as a versatile, efficient and reliable platform for communication in several markets including automotive, automation and industrial. CANopen is a standardised CAN-based higher level application layer for embedded control systems. The specification is freely available [13] and defines the use of multiple devices and controllers in distributed networks. CANopen has gained a high reputation for being robust and fault tolerant. The ready availability of a wide range of devices, controllers and associated hardware together with established support and authoritative organisations [13] has lead to the adoption of CANopen in a wide variety of applications. Kittiwake has chosen CANopen as its preferred sensor communication protocol allowing for easy configuration of multiple sensors - “sensor suites” – for monitoring and/or control systems.



Figure 23 - thruster Monitoring Unit

An example of such a system is the Kittiwake On-Line Thruster Monitoring System, designed to monitor the condition of both the drive oil and seal oil in azimuthing thrusters. Figure 23 shows an individual unit which samples the main drive oil in the thruster via a pumped loop with the oil flowing through a wear debris particle counter, an oil quality sensor and a moisture sensor. A second oil quality and a second moisture sensor are remotely installed in the recirculating shaft seal oil line. These 5 sensors

communicate over a CANopen network to a local control unit featuring a Human Machine Interface (HMI) screen for control and display.



Figure 24 - HMI display

Additional thruster monitoring units – one for each on-board thruster – are networked through a hub to a master control unit sited at a convenient location (Figure 26) to complete the system.

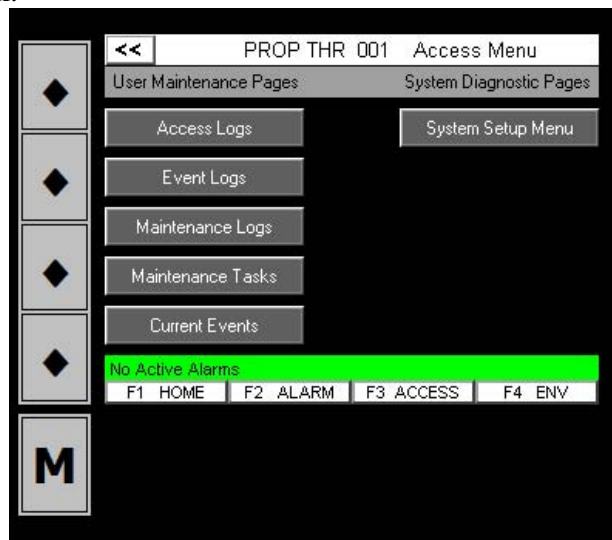


Figure 25 - HMI menu screen

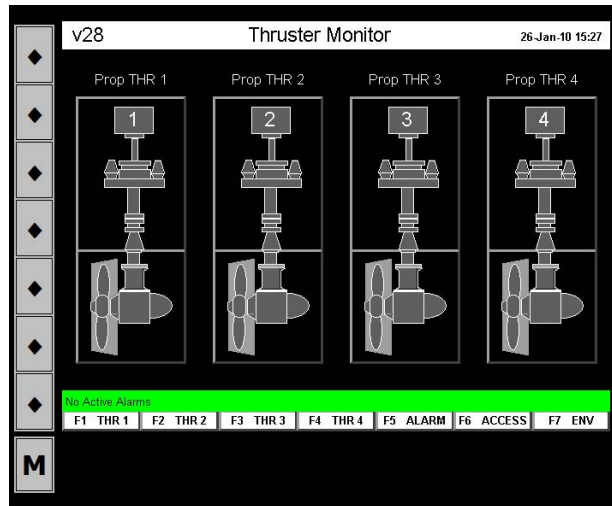


Figure 26 - master control unit HMI

The HMI menu structure allows access to many control and display pages, including logs, alarm limits and maintenance tasks, Figure 25. The master control unit mirrors the HMI displays from all units and allows full access to all control functions thus providing a complete picture of the health of all thrusters. Additional CANopen I/O modules are easily installed in the local control units allowing integration of other important parameters as required. For example, third-party sensors for shaft rpm, temperature and vibrational levels are all straightforward to integrate and control (Figure 27).

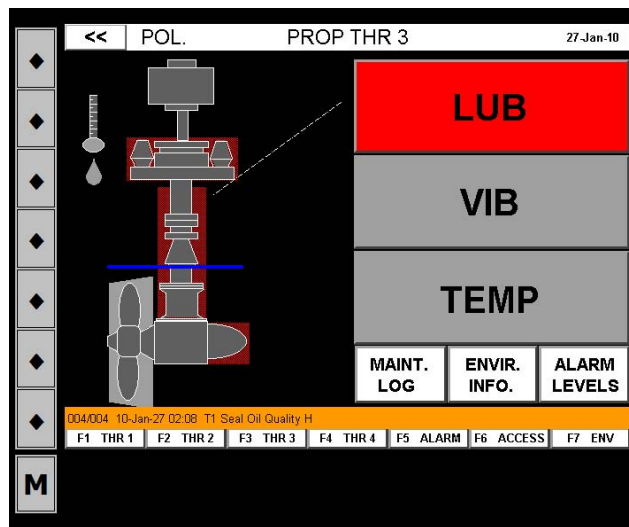


Figure 27 – thruster overall health

3. Conclusions

This paper has illustrated the increasing pace of development of online sensors and provided a view of their future potential in the key role of managing and maintaining operational efficiency of engines and associated machinery.

The uptake in the use of online sensors for oil condition monitoring in engine applications has been relatively slow to date. In part this may have been due to a mismatch between those oil properties currently obtainable and the requirements of CBM programs; in particular the key parameters of viscosity and total water content have been lacking until quite recently. The sensor developments described in this paper address these shortcomings and provide cost effective solutions to monitoring both of these important oil properties.

Further work, in the adoption of industry standard protocols for sensor communications, has enabled the development of “plug and play” like networking between sensors and controllers. This allows the straightforward construction of bespoke sensor packages, which, together with integrated display and control units provide a more complete picture of the health of vital machinery. Extension into the role of operational control based on real-time oil measurements and automated decisions is the obvious next step. Although this is entirely feasible with the systems described here, it will require considerable time spent in purely monitoring functions in the field before sufficient confidence enables such progression.

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