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The Application of Inductive Wear Debris Sensors to Diesel Engines

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Abstract

This paper outlines the application of inductive wear debris sensors to large diesel engines during engine run-in following refurbishment. The sensors and their supporting electronics were initially used, as supplied, to observe the run-in process on refurbished engines. They were then modified with programmable LabVIEW hardware to create the DSTG Wear Debris Monitoring System. The features of this system include the recording and real time graphical display of wear debris metrics such as total debris particles counted, total mass recorded, debris generation rates, or mass and count by pre-set size bins. Statistical metrics were then monitored by pre-set alarms. The capacity to monitor the engine state (pre-lube, run, post-lube), oil pressure, oil flow and oil viscosity were added to extend the system flexibility and utility. Trials confirmed the sensor's ability to record and display, in real time, the generation of ferromagnetic wear debris particles down to the specified minimum size of 160 µm when using a 3/4" (19 mm) bore inductive wear debris sensor. The monitoring system also identified a correlation between the cleanliness of the engine build process, the amount of ferrous debris detected, and the run time taken to achieve the reduced debris generation rate associated with a successful engine run-in.

Keywords: wear debris, diesel engines, inductive debris sensor

Introduction

All internal combustion engines generate metallic wear debris during operation. Nearly all wear debris is carried away in either the exhaust gas stream or lubrication oil flow. As the engine progresses through its life, the rate and size of wear debris can indicate excessive mechanical wear and/or incipient failure [1, 2]. The idealized progression to failure due to escalating wear proposed by Tauber [1] is indicated by an increasing wear debris production rate and corresponding increase in the mean particle size. More recent work by Becker et al. [2] showed that progression to failure can be measured solely by monitoring the number of wear particles generated. Monitoring oil-borne wear debris in real time is proposed as an effective method of diesel engine condition monitoring to facilitate the early intervention and prognosis of engine faults.

For most engines, traditional methods of examination rely on the extraction of wear debris from the oil filter, and/or by off-site laboratory analysis of routine oil samples. The test results rely heavily on the sampling technique used, and the analysis type employed. Spectrometric oil analysis (SOA) is the most common analysis technique undertaken in laboratories and is usually only effective for material less than 10µm in size [3], with larger (and likely more critical) material unable to be detected. Interpretation of spectral data also relies on knowledge of the material types present (material mapping) and the components most likely to wear.

Inductive Wear Debris Sensors

Metallic wear debris flowing with lubricating oil can also be detected in real time through the non-intrusive use of a flow-through inductive wear debris sensors (IWDS). The sensing element consists of a nonconductive flow-through tube wound with two outer field coils and a central sensing coil (Fig. 1(a)). The passage of metallic particles through the tube produces a disruption of the balanced magnetic field resulting in a voltage pulse in the sensing coil. The initial rise or fall of the signal pulse signifies if it is of ferromagnetic (Fe) or non-ferromagnetic (NFe) material (Fig. 1(b)). The pulse amplitude and wavelength, indicates the debris size and speed. From this, an equivalent spherical diameter (ESD) and the approximate mass (if ferrous) of the debris is determined. IWDS systems are made by manufacturers such as Gastops, Kittiwake, and Poseidon Systems and they have found application in sectors such as aeronautical propulsion and wind turbines.

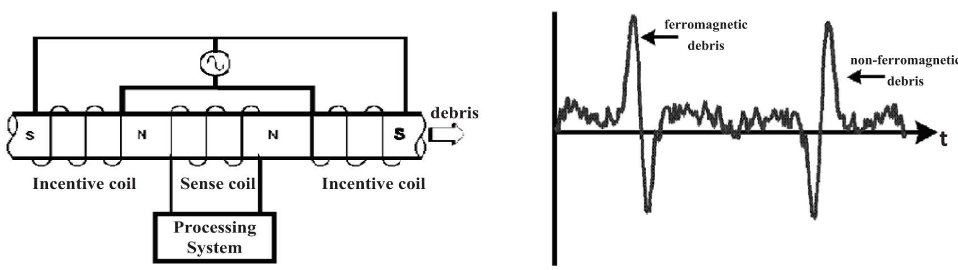

Fig. 1 (a) Schematic of wiring of IWDS and (b) Resultant pulse from passage of metallic debris [4]

Using Inductive Wear Debris Sensors on Diesel Engines

IWDS research was conducted by the Defence Science and Technology Group (DSTG) on large marine diesel engines using both the 3/8” and 3/4” diameter MetalSCAN IWDS systems in series with an Oberg disk filter system, which was used to capture and verify the sensed debris. The performance characteristics for the IWDS sensors are contained in Table 1 [4].

Table 1 Performance Specifications for GasTOPs MetalSCAN IWDS.

Specification	3/8 inch	3/4 inch
Minimum ferromagnetic particle size (µm)	70	160
Minimum non-ferromagnetic particle size (µm)	280	380
Maximum pressure (kPa)	3500	3500
Minimum flow rate (L/min)	0.21	1.9
Maximum flow rate (L/min)	42.8	380
Maximum temperature (°C)	190	190

The IWDS sensor systems were installed on large marine diesel engines following refurbishment at the end of their service life. The purpose was to witness the characteristics and rates of debris generation during engine run-in prior to release back into service. The sensors where plumbed either in series with a centrifugal oil filter kidney loop or by pumping and returning directly to the sump.

The following metrics were recorded using the IWDS system:

- Cumulative Fe mass versus instrument run time,
- Current (weighted) average Fe mass rate,
- Cumulative Fe count by size (ESD) bin,
- Fe particle mass distribution by size (ESD) bin,
- NFe count versus time, and,
- NFe count by size (ESD) bin.

IWDS measurements of debris on engines during run-in showed that oil-borne Fe and NFe debris could be detected. Results of accumulating Fe mass can be seen in Figure 2.

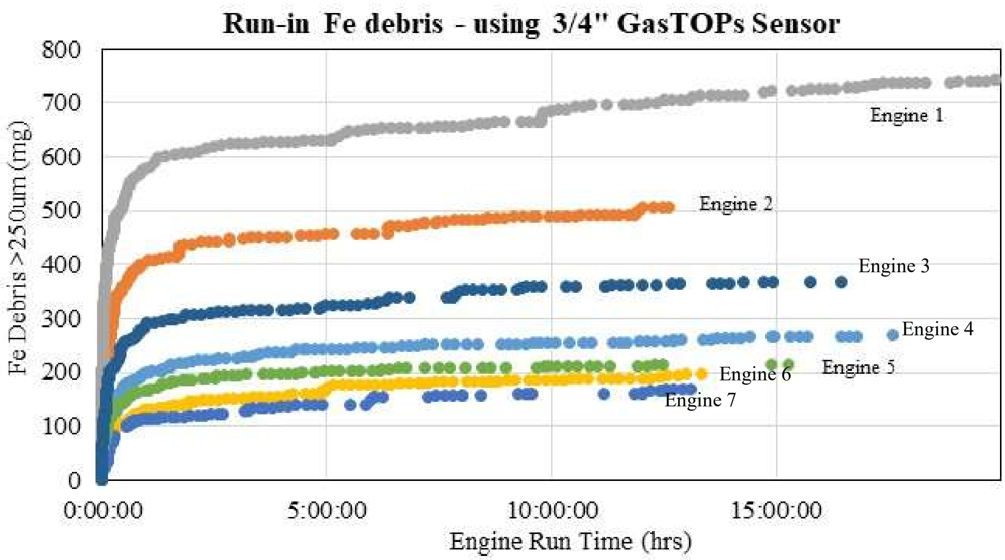

Fig. 2 Accumulating Fe debris mass versus engine run time for seven similar marine diesel engine run-ins

For this type of engine, an initial high mass rate of debris generation with a distinct transition to a lower rate at between 40 and 120 minutes of engine run time was observed. This was indicative of transition from the early danger period of run-in to a more normal running condition. Later measurement and microscope examination of the debris captured by the downstream disk filters during this period showed it to comprise of some engine generated wear debris, but a high proportion of the contaminants consisted mainly of abrasive media, grinding and environmental debris and legacy engine residue not removed during the initial engine cleaning.

The total Fe mass recorded and the time taken to transition from the initial high to later low Fe debris production rates appeared directly related to the total mass of material captured at the disk filters. It was found that the extent of contamination within the engine at the end of its re-assembly had influenced the amount of wear debris generated, and the time taken to transition through the initial run-in period to a safer "normal" running condition. This was a novel and important finding for the builders of this engine. It resulted in improved engine build hygiene, and provided a method of visualising wear-in in real time during recommissioning.

In using the as-supplied IWDS system, there was no facility to synchronize the timing of the sensor recording with the engine operation. Periods when the engines were not running had to be manually subtracted from the total data record. The as-supplied instrumentation was also not able to determine the number of engine starts, or the duration of pre- and post-lubrication. It was also found that the sensors were less sensitive at detecting NFe debris than specified and, for later versions of the software supplied, that some data available on earlier versions was no longer available for download.

This made the IWDS system in its as-delivered form unsuitable for direct application to diesel engine condition monitoring. To address these issues, a modified oil debris sensor system was developed by adding programmable LabVIEW hardware to the existing control module. The combined equipment formed the DSTG Wear Debris Monitor (DWDM). The DWDM provides debris logging coincident with engine run, pre-lube and post-lube states. Debris counts and mass rates were also able to be averaged across a definable (here, one hour) moving engine run time window. This allowed for a higher level of statistical analysis of the recorded data for the purposes of setting alarm limits. More extensive downloadable sensor records and event files were also available, all in CSV format. The addition of the programmable hardware also created potential for other types of condition monitoring sensors to be added.

The DWDM used an interactive touch screen divided into the running and settings pages. Fig. 3 shows a running page (here showing accumulated Fe mass over a run time of fourteen hours).

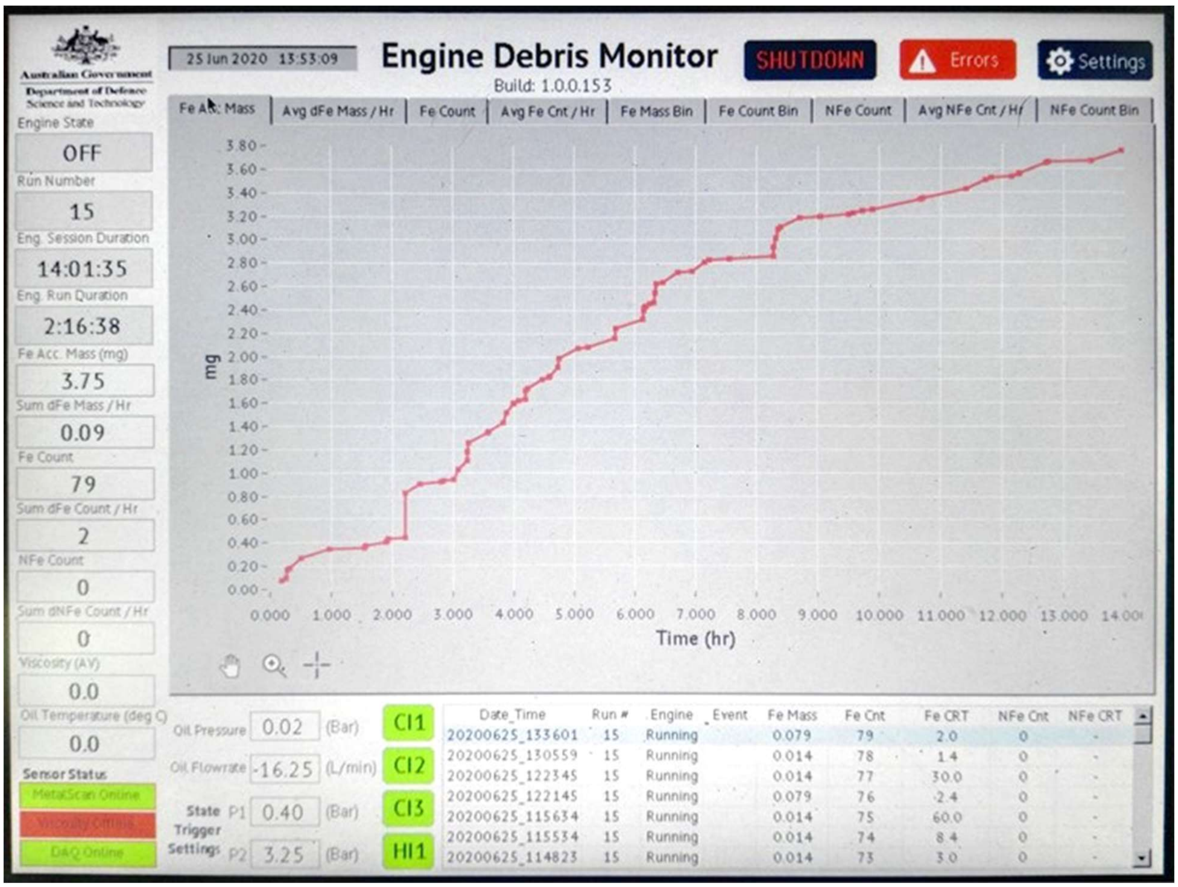

Fig. 3 DWDM Fe mass window after 14 engine hours with functional areas identified.

The screen is divided into areas showing the principle data both numerically and graphically. Different graphs are selectable by tabs on the touch screen. The principle condition monitoring data available are:

- Accumulating ferromagnetic mass with respect to time,

- Average (per hour) accumulating ferromagnetic mass,
- Ferromagnetic material debris particle count with respect to time,
- Average (per hour) ferromagnetic particle count rate,
- Ferromagnetic mass by pre-set size bins (both table and chart),
- Ferromagnetic particle count by pre-set size bins (both table and chart),
- Accumulating non-ferromagnetic debris particle count with respect to time,
- Average (per hour) non-ferromagnetic particle count rate, and
- Non-ferromagnetic count by pre-set size bins (both table and chart).

Additionally, three critical statistical condition indicators were installed to give warning of significant change in the ferromagnetic debris counted as specified by Becker in [5]. This consisted of three separate statistical tests (C1, C2 and C3). If all the three tests were satisfied simultaneously, a trigger (H1) was initiated to give a warning message, but this could also be used to initiate either acknowledgement or shutdown procedures. An oil flow measurement was also added to later DWDM systems to facilitate a method of measuring wear debris per unit of oil volume for use with variable speed engines. Additionally, the facility to measure and record oil temperature and viscosity was also installed, but not deployed. These three additional sensors were added to demonstrate the flexibility of this equipment package to measure multiple condition-monitoring metrics on any oil lubricated equipment.

Discussion

The application of IWDS or DWDM systems to monitor engine lubrication (or any critical equipment which has a reticulated oil supply) demonstrates the ability to detect and record, in real time, the production of oil borne metallic wear debris. Systems such as this can provide immediate real time information to maintainers and operators. This can have significant advantages for machinery operating in locations away from immediate access to oil analysis services, as well as providing real time condition monitoring data. Systems such as these would also provide a useful adjunct to current SOA programs, where the maximum detectable particulate size is only 10 µm, compared to the 160 µm to 1000 µm detectable size range available from the 3/4" IWDS, as shown in Fig 4.

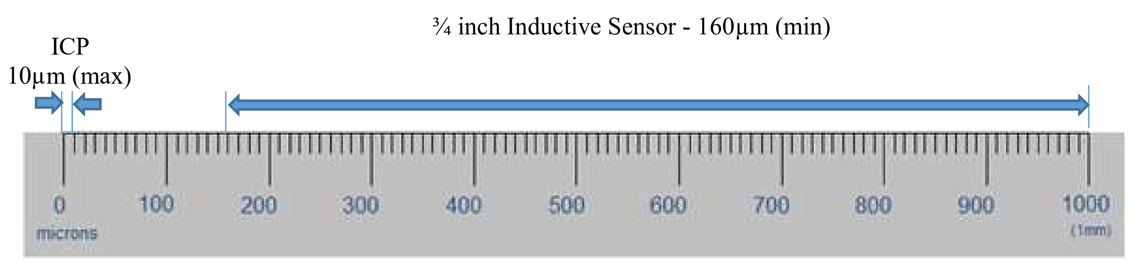

Fig. 4 Ferrous debris size detection comparison for ICP spectra and 3/4-inch inductive debris sensor

It is also anticipated that, along with the current DWDM system, the capacity to integrate other sensors such as oil moisture, turbidity, permittivity, viscosity and oil flow rate would provide a more comprehensive assessment of machine health, and ultimately enable more confident prognostics. This will need to occur alongside exploration of viable installation locations within lubrication systems, and an assessment of any risks associated with installing additional sensors due to their size or failure modes.

To progress this work, the ability of this system to validly detect metallic debris changes during through-life and component failures needs to be fully assessed. This will be most effectively ascertained by both seeding faults on laboratory-based engines, and placing sensor systems on marine or land based engines for the whole of service life to witness the characteristics of long term in-use and engine component failure.

Conclusion

By placing inductive wear-debris sensors on the lubrication systems of marine diesel engines, ferromagnetic wear debris generation can be detected in real time. This wear debris can be detected in a much larger particle size range than that currently provided by spectrographic techniques. To form appropriate metrics for the detection of this debris, a data logging system was constructed to take into account multiple engine starts and pre- and post-lubrication. This in turn allowed higher level statistical condition monitoring indices and real time analysis to be developed. It was also possible to integrate other types of sensors (e.g. oil temperature, viscosity and flow rate) to enhance real time information. During the trial of this system, it was found that the internal cleanliness of the engine after overhaul affected the duration and mass of ferromagnetic wear debris sensed during the initial high risk engine run-in period.

References

1. Tauber, T., “A New Chip detector”, *Aircraft Engineering*, October 1977: pp. 4-6.
2. A. Becker, S. Abanteriba, and D. Forrester, “Determining inductive sensor wear debris limits for rolling contact fatigue of bearings”*, Journal of Engineering Tribology,* 2014. Vol. 229(6): pp. 1-14.
3. Hunt, T.M., Handbook of Wear Debris Analysis and Particle Detection in Liquids, Elsevier, London, 1993.
4. GASTOPs Ltd, MetalSCAN MS4000 User’s Manual, C008036 Revision 6. October 2019.
5. Becker, A., “Health indicator metrics applicable to inductive wear debris sensors”, *Journal of Engineering Tribology*, 2016. Vol. 231(5): pp. 583-593.