Condition Management of Marine Lube Oil and the Role of Intelligent Sensor Systems in Diagnostics

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Abstract. Failures in marine diesel engines can be costly and can cause extreme inconvenience when they result in ships becoming stranded. Lubricating oil is a crucial component in maintaining engine reliability and so monitoring its condition is essential. Furthermore the lubricating oil offers early indication of various other engine faults. Current approaches to oil-based condition monitoring involve samples being sent for land based testing which involves considerable delay during which the situation could deteriorate further. Furthermore there is a substantial risk of contamination. The POSSEIDON project aimed to address this by developing a system involving real-time condition monitoring sensors observing the properties of the lubricating oil. Novel sensors were developed which address the specific issues associated with the marine environment. Furthermore, to complement the sensor system outputs, specific monitoring and diagnosis software has been developed to support the operation of onboard personnel with specific advice. On-line management of engine and lubricant condition aboard the ship may thus be achieved. In this paper we will describe the progress achieved in this area by the recently completed POSSEIDON project, outline the opportunities for ongoing development in this area and describe the roadmap for future development. The Reliability Centered Maintenance (RCM) paradigm will be applied to identify critical aspects of oil condition and prioritize parameters for measurement. The critical issues for development of the prototype unit into a viable commercial unit will be discussed including hardware design constraints, sensor miniaturization and display optimization. Issues such onboard connectivity, ship to shore communications will also be addressed.

1. Introduction
Successful and effective reliability management and maintenance are critical to successful operations in the marine industry. Failures in marine diesel engines can be costly and can cause extreme inconvenience when they result in ships becoming stranded. Ship owners and operators can experience technical problems with ship machinery at any time and usually while the ship is at sea. Engine failures can prove to be costly due to delays, time to repair and, in certain cases, environmental costs due to ships running aground. Stranded ships are also vulnerable to weather conditions. Furthermore failures can result in the loss of reputation for shipping companies. Failures also have serious implications where perishable goods are being carried. Equipment failures on passenger ships also have serious implications where compensation and refunds may be payable in the event of failure. Furthermore such incidents can lead to extreme passenger dissatisfaction and negative publicity. Detecting failures and taking preventive and, where necessary, corrective measures are therefore of great importance.
In terms of monitoring the overall condition of the engine, lubricating oil is of vital importance. Degradation of the oil’s performance can lead to rapid deterioration in engine lubrication and cause mechanical wear, chemical corrosion and overheating. Furthermore the lubricating oil can act as a condition indicator for other aspects of the engine’s operation. Current approaches to oil-based condition monitoring often involve samples being sent for land based testing which involves considerable delay during which the situation could deteriorate further.

The POSSEIDON project aimed to address this by developing a system involving real-time condition monitoring sensors observing the properties of the lubricating oil. To complement the sensor system outputs, specific monitoring and diagnosis software has been developed in order to achieve fully automated control of the lubrication system. On-line management of engine and lubricant condition aboard the ship may thus be achieved.

This paper provides an overview of the POSSEIDON project covering its motivation, implementation and testing set against the context of the current state of the art which immediately follows this introduction. Prior to conclusions being drawn, a roadmap for the next stages of development of the system is described.

2. Current State of the Art in Marine Lubricating Oil Condition Monitoring

The primary purposes of oil are to reduce friction in moving components and to prevent metal to metal contact. Oil can also be used as a means of transporting and removing wear particles and heat and transmitting power in hydraulic systems. Analysing oil not only allows the condition of the oil to be managed but also allows other faults in mechanical systems to be detected. Oil analysis tools include spectrographic analysis which can be used to determine the chemical composition of the oil to indicate both its ability to perform its function and other engine faults which could cause contamination; particle analysis which can be used to identify mechanical wear by detecting and analysing metal fragments found in oil and determining their likely source by studying their shape and size. Monitoring lube oil condition is currently, in the main, achieved in two ways: Samples are drawn off and checked using portable equipment and test kits or samples are drawn off and dispatched for on-shore laboratory assessment. An area achieving increasing attention is the use of online condition monitoring sensors which automatically collect and interpret condition data. Each of these techniques is described in the subsequent sections.

2.1. Use of onboard test kits

The use of onboard test kits involves drawing off oil samples and checking them using portable equipment and test kits. This allows many parameters to be measured but has the drawback of requiring manual sample taking and checking in the hostile environment of the engine room. Furthermore great care is required to ensure samples are handled correctly and not contaminated between being drawn off and tested. Parameters which can be investigated include but are not limited to:

- Water content
- Alkalinity
- Base Number
- Viscosity

The advantage of the use of onboard testing is the immediacy of the results which can be critical in monitoring suspected faults and avoiding imminent failures.

2.2. On-shore laboratory testing

The use of laboratories on-shore allows a much more extensive analysis to be made using high precision instruments. However, in addition to the need to take samples and correctly handle and package them, there is a substantial time delay due to the need to dispatch samples to the laboratory in
the parcel post. The results process has been accelerated by new technologies allowing results to be delivered by email, but the delay can still lead to further degradation before the fault is isolated and attended to.

Oil analysis at land based laboratories makes advanced analysis possible. Measurements taken include:

- Measurement of water content using Karl Fisher titration
- Measurement of TBN
- Particle counting using optical techniques to detect wear particles
- Infrared spectroscopy techniques for measuring oil condition and contaminants.
- Magnetic PQ index testing to measure iron particle content
- Density
- Viscosity
- Viscosity Index
- Fuel Content
- Flash Point

In addition to the advantages offered by access to a comprehensive range of tests, laboratory analysis also allows samples to be investigated and assessed by specialist personnel who can draw upon levels of experience which cannot be sustained in on-board engineers.

2.3. **Online condition monitoring**

One of the major developments in maintenance management which has occurred in recent years has been the advent of integrated condition monitoring solutions. Condition monitoring has existed for many years in various forms but now offers increased potential through the ability of systems to take measurements, compare with bespoke thresholds, detect trends, record and analyse data, provide data to shore based personnel and simultaneously make appropriate recommendations to onboard personnel to remedy problems and to extend lifespan until repair is possible. Such techniques have already been applied to diesel engine condition monitoring [1][2][3][4][5] and are beginning to receive attention for application to marine lube oil [6] and the POSSEIDON project represents a successful attempt at demonstrating the concept.

3. **POSSEIDON Project**

The Progressive Oil Sensor System for Extended Identification ON-Line (POSSEIDON) project aims to address the flaws in current practice by developing and online oil condition monitoring system which will allow oil to be analysed while still in service. This has the following advantages:

- The need for operator intervention in the sample preparation process is removed.
- The possibility of sample contamination is reduced.
- There is no delay in obtaining results so further fault development can be limited.

The system consists of two components. Firstly a set of condition monitoring sensors developed by the partners of the consortium which monitor appropriate parameters. This data is then processed, interpreted and displayed by an intelligent software tool. These two aspects of the system are described in the subsequent subsections.
3.1. Sensor System

Analysis of the fault modes of diesel engines and the applicability of current and robust sensor technology led to the selection of the parameters to be measured online. The parameters chosen and the sensors which will be used are shown in table 2 [7].

| Sensor                     | Output                  |
|----------------------------|-------------------------|
| IR sensor [8]              | • Water concentration  |
|                            | • Soot concentration   |
|                            | • TBN                  |
| Viscosity sensor           | • Viscosity            |
|                            | • TBN                  |
| FTIR sensor                | • Water content        |
|                            | • Insoluble content.   |
| Optical Particle detector [9]| • Particles           |

The selected measurements offer a comprehensive overview not only of the condition of the oil but also of the condition of the engine measurable via the oil. The viscosity of the oil influences its ability to form a lubricating film. The TBN is a measure of the oil’s ability to neutralise acid contamination due to high sulphur fuel. Water causes oxidation of lubricating oil and can affect the behaviour of the oil’s various additives [10]. Particle content can indicate the types of wear that are occurring in the engine.

One of the advantages of the chosen selection of sensors is that some fault conditions will be detected across several sensors. This will allow such faults to be detected more robustly. Soot contamination and water contamination are examples of this phenomenon, where an increased level will not only be detected by the IR sensors but will also cause an alteration in the viscosity of the oil.

The developed sensors were tested and calibrated in a controlled environment. Their performance was validated using laboratory tested oil samples and accuracy and repeatability of measurements were found to be within design parameters. The sensors were then integrated into a prototype test system and ship based trials were carried out. The sensors system was found to perform well when validated against samples drawn and tested in a laboratory. The prototype sensor system can be seen in figure 1.
3.2. Software

In order to maximise the benefits of the sensors described above, software for fusing the data from the various sensors and extracting information for both maintenance and fault detection/early warning purposes is required. There are two levels of functionality for the system, at the most basic level the software must log and display the data, provide simple assessments of oil condition and potential faults and offer simple guidance messages to the operator. More advanced requirements include the ability to exploit the multivariate nature of symptoms to support diagnosis and the ability to detect both immediate, fast developing faults and longer-term, incipient faults.

It was decided to develop the software using the Java programming language to provide platform independence. The modular nature of the initial design was maintained in order to support maintainability and extensibility of the software. In terms of storing the condition monitoring limits, the messages to be passed to the operators and the sensor readings which must be stored and read, Extensible Markup Language (XML) was selected. The advantage of such a scheme is that these files can easily be opened and read by the human eye since a simple XML structure was developed. Furthermore the use of XML means the file format can be extended and altered without rendering the data unreadable to previous versions of the software. Furthermore an XML configuration file is used to provide the location of various other data files and other important parameters.

The software is designed to read data from individual bespoke sensor output files. In addition to displaying and storing the readings the data is also written to an XML output file which allows it to be read into a spreadsheet externally if needed. Furthermore this means the data is backed up to a file regularly giving some protection against crashes. The software is also capable of reading data directly from the XML file.

The software is illustrated in figure 2. It can be seen that the main interface shows the current values of the measured parameters and their recent history to support trending. Furthermore probabilities of specific component failures are estimated using a Bayesian network, greater detail of which is available to the operator using the provided controls. The interface also includes elementary guidance to the operator which is generated by a lookup table using parameter combinations based on those provided by the lube oil supplier.
The software was tested alongside the hardware in the on-board trials discussed above. The software was found to perform correctly and the design of the interface was judged to be appropriate by engineering staff consulted. Based on the results of the on-board trials the prototype hardware and software were considered to have proved the viability of online condition monitoring for marine lubricating oil. Based upon this success it is now necessary to consider the role of such a system in use in order to inform the creation of a roadmap for future development.

4. Application of Reliability Centred Maintenance to Marine Maintenance Management

Reliability Centred Maintenance (RCM) is a method for determining the maintenance needs of a particular asset, component and sub-component. The focus of RCM is on maintaining system function rather than restoring equipment to an ideal condition. RCM allows the maintenance ‘team’ to identify the critical components, their function and failure modes, therefore identify failure patterns and possible maintenance tasks to maintain operation. RCM, according to [11] is characterised by the following features:

- Greater safety and environmental protection, due to improved maintenance
- Improved operating performance, due to more emphasis on the maintenance requirements of critical components
- Greater maintenance cost-effectiveness, due to less unnecessary maintenance
- A comprehensive maintenance database, which reduces the effects of staff turnover with its attendant loss of experience and expertise

Figure 2. Screenshot of POSSEIDON software.
RCM is described by Chan et al [12] as a maintenance methodology that allows a progressive logical approach based upon the collection and analysis of basic equipment data. The primary reason for the development of RCM is to implement a preventive maintenance strategy that could adequately address system availability. Availability is the key criteria for marine engines since failure is costly for the reasons described above. RCM is, however, time consuming and applying a full-blown RCM methodology requires large amounts of data, including historical data which may not be available. The main stages of the RCM methodology involve determining the answers to the following questions:

- What is the function of the equipment?
- What causes each functional failure?
- What causes each failure and identify failure modes?
- What is the failure effect?
- What is the consequence of each failure?
- What proactive task(s) should be done to predict or prevent each failure?
- What default action should be done to if a suitable proactive task cannot be found?

Application of the principles of RCM is believed to be a key component of successful implementation of online lube oil condition monitoring for the following reasons:

- An RCM analysis will enable the correct sensor configuration to be determined for the application. Different combinations of engine and lubricant mean the criticality of the parameters various in each application.
- The application of such technology may be seen as unproven in this context. A detailed RCM analysis will form the basis of a business case since it ties any investment to where it is most needed.

5. Roadmap for Future Development

The POSSEIDON project described above has successfully demonstrated the viability of lube oil condition monitoring. Such a system offers clear benefits over current approaches and offer genuine operational improvements if implemented following the best practices identified using an RCM approach.

In order to advance both the concept of online condition monitoring and the technology of the prototype towards widespread commercial use, five key areas have been identified where further development. These areas are listed below:

- Hardware and Miniaturisation
- Display technologies
- Extensibility and Sensor Selection
- On-board/Off-board connectivity
- Design Issues

Each of these areas will be considered in the following sections.

5.1. Hardware and Miniaturisation

The sensor system shown in figure 1 was developed using bespoke, experimental sensors. As such these sensors were time consuming to produce and more expensive than would be viable for a full commercial system. For commercialisation purposes it will be necessary to refine the manufacturing process to ensure that the sensors are both cost effective, easy to manufacture and reliable. It can also be seen in figure 1 that the sensors system occupies a large case. While space is generally readily
available in a ship engine room, further miniaturisation is seen as a priority to simplify installation and
to open opportunities for applying the technology in other applications.

5.2. Display technologies
The initial prototype system utilises a laptop computer for running both the software which handles
the low level control of the sensors and that described in section 3.2 which displays and interprets the
data. A laptop computer is unlikely to provide the long term reliability required and as such other
options need to be evaluated.

Two main options have been identified for replacing the laptop computer. The first is to use an
industrial grade computer with appropriate heavy duty display. The advantage of such an approach
would be the ability to use the current software with little or no modification. The second option
would be to use an integrated display unit such as that pictured in figure 3. Such devices have support
for marine data communications standards such as NMEA2000 and would allow custom user
interfaces to be developed to satisfy the requirements of different users.

![Figure 3. Display unit proposed for potential sensor system.](image_url)

5.3. Extensibility
If an online condition monitoring system for lubricating oil is to be commercially attractive it is
necessary for it to be either extended or integrated with other condition monitoring systems and
sensors. Other sensor techniques which have applications in marine diesel engines include:

- Vibration
- Acoustic Emissions
- Temperature
- Exhaust emissions

Furthermore onboard systems are increasingly becoming subject to greater integration. AS such
online condition monitoring systems should offer the capability of interconnection with systems such
as engine management units and other diagnostic systems. Such integration offers the possibility of
reading data such as engine speeds and fuel consumption to aid diagnosis of faults through the
 provision of a richer data set. Further investigation into the technical barriers and benefits needs to be
undertaken if a comprehensive business case for online condition monitoring is to be established.
5.4. Onboard/ship to shore connectivity
As mentioned above integration with other onboard systems offers additional benefit for online condition monitoring systems. In order to support this it will be necessary to ensure that the equipment is compatible with current onboard network standards. One such example is NMEA 2000 which provides onboard communications based on CAN technology developed within the automotive sector. Wireless Sensor Networks (WSNs) are also receiving attention in many applications [13] and offer potential for easy and low cost system extension, with various examples being developed for operation in unfavourable environments such as marine engine rooms.

Online condition monitoring also offers considerable benefits if the data can be returned to the shore for analysis by oil providers and engine manufacturers, as well as by the operators. Ship to shore communication is, however, more problematic. Satellite communication systems are currently available whose capabilities range from simple low bandwidth systems capable of carrying voice traffic only to full broadband data systems. Despite there being many applications where such systems are desirable (e.g. Navigation, Engine room information, Documents, AV transmission) cost is still seen as a major barrier with full broadband connectivity costing in excess of 10k USD per month. Crew demands for better telecommunication is driving improvement in this area but the costs mean progress is slow [14]. A key question in determining the viability of live data communications will be the cost to benefit ratio of transmission at various data rates. This will be partly informed by the likely rate at which failures develop, which should be determined as part of the RCM analysis stage.

5.5. Design issues
The final area for consideration is the design of the unit in terms of both usability and overall system reliability. In terms of usability, the views of marine engineers were taken into account during prototype development through a process of using web based simulations of the software to allow rapid development and modification of a semi-functional model of the software. It is proposed that an enhanced version of this process is adopted for commercialisation to ensure the system supports the adoption of best practice.

In addition to ensuring the sensors are reliable it will be necessary to consider reliability during the assembly of the sensor unit. Engine rooms are subject to inhospitable levels of heat and vibration so this must considered during design and development. Use of test facilities capable of replicating these conditions and the adoption of accelerated life testing techniques is considered essential alongside comprehensive sea trials.

6. Conclusions
Effective maintenance is essential for efficient operation of commercial shipping. The application of modern maintenance practices such as condition based maintenance has the potential to bring about substantial improvements in terms of both cost and reliability. If these benefits are to be achieved it is essential that the ongoing development of such a system is guided by a detailed analysis of the functional requirements of the system based on the RCM methodology. In this paper we have presented the current state of development in online lube oil analysis. We have also described the roadmap which should be followed to ensure that any developed system meets the functional requirements which will be placed upon it.

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