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Development of a Modular In-Situ Oil Analysis Prognostic System

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Abstract—An in-situ system for analysis of lubricants and hydraulic oils is discussed. The system comprises specially designed X-ray fluorescence, non-dispersive infrared, and visco-metric modules, as well ferromagnetic and non-ferromagnetic particle detection. It is controlled by one or more microprocessors and can be incorporated directly into the lubrication systems of larger engines to provide near-real time information on oil chemistry, contamination, and wear materials. Oil analysis results can be automatically uploaded to remote locations by means of cell phone or other wireless technology.

Introduction

Ensuring proper function of lubricants is critical to the successful operation and maintenance of mechanical systems. Lubricated machinery wear and breakdown result primarily from particulate contamination or molecular breakdown of the oil. Laboratory analysis of lubricating oils has been an indispensable prognostic tool in assessing the condition of lubrication fluids and identifying developing faults in machinery. However, these analyses are expensive and time consuming and result in oil waste streams and products.

Development of small, ruggedized analytical instruments and sensors for on-board lube and hydraulic oil monitoring and prognostics is now underway. Use of these sensors with suitable microprocessors and software results in a powerful new tool for on-board diagnostics and prognostics of wear status and condition of lubricated equipment. This paper describes the development of an onboard oil analysis system with component sensors and analytical modules for determination of most common lube oil parameters. The instruments and sensors have been designed to be modular and sets of these modules have been optimized for oil analysis in various applications.

Background

Oil analysis is a major requirement for commercial and government vehicles in a variety of business, manufacturing, military and transportation applications. Oil analysis is time consuming and costly since it requires that technicians collect the oil samples, send them to laboratories for analysis, and wait days or months for results to be returned from the laboratory. Even so, a high percentage of such tests turn out to be normal: Typically 50% of the analysis find no problems and only 5% detect serious problems; the remaining 45% of cases indicate imminent problems or increased trends, which might require further testing. In some military applications, it is estimated that more than 90% of the samples taken do not result in actionable findings. Such methods also create waste streams with environmental impact. The technology is now available to conduct the analysis on site, and when appropriate on-board the vehicles or equipment. Deployment of such technology will save time and money, and will provide timely information needed to enable condition-based maintenance.

Research and development projects underway at Battelle's Pacific Northwest National Laboratory that focus on prognostics technology have motivated a recent effort to develop in-situ oil analysis capabilities. The general approach for application of prognostics technologies that is embodied in these programs (Greitzer et al. 1999a, Greitzer et al. 1999b) involves the following:

- consider needs from platform/system viewpoint
- take prognostics approach to whole systems/platforms
- make existing sensors smarter, cheaper, more robust
- add enhanced, smart sensors where appropriate and feasible
- combine data from multiple sensors using sensor fusion techniques.

Analysis software incorporates rules, artificial neural networks, and statistical analysis techniques to diagnose or predict problems, develop trends, display results, and interpret outcomes with warnings, advisories, and the like. Development of the in-situ oil analysis system stemmed from lessons learned in these earlier studies as well as a recognition that oil analysis capability would provide an important complement to the other technologies and approaches currently being pursued.

Approach

Laboratory-based oil analysis determines lube oil condition (e.g., viscosity, oxidation, total acid, total base, and additives), lube oil contamination (e.g., water, coolant, dirt, fuel), and lube oil wear debris (ferrous and non-ferrous metals, elemental analysis, and other particle characteristics). In the railroad industry as well as in DOD applications, for example, well defined alarm and flag limits have been established based on data available from laboratory tests. Where limits criteria are established based on a variety of analytical parameters, simple "go/no-go" lube oil test systems do not provide the data required to support prognostics. Sufficient data to make decisions as to the condition of the lubricant based on all flag and limit parameters are required for successful condition-based maintenance programs in the just-in-time logistics environment.

In designing the in-situ system, it was recognized that a central objective should be to provide maintenance technicians with the same information that has been traditionally used in laboratory-based oil analysis: oil condition, contamination and wear materials. These requirements, and the additional need to minimize size, weight, complexity, and cost, led to the selection of the analytical techniques employed (elemental analysis, dynamic viscosity, infrared absorption, and ferromagnetic and non-ferromagnetic particulate).

The system has been developed both as a stand-alone on-board system and as a component of more extensive health monitoring systems such as the TEDANN system currently under development on the M1 Abrams tank (Greitzer et al., 1999). The prognostic and diagnostic results available from oil analysis will be most valuable when used in conjunction with prognostic and diagnostic analyses based on other sensor data, such as those incorporated into TEDANN.

Materials and Methods

Hardware*:* Determination of wear and contaminant elements in the oil (by elemental analysis) is accomplished using a specially designed X-ray fluorescence spectrometer. The XRF system uses a small amount of suitable radionuclide in a well- sealed fail proof container as a source of X-rays. The system is designed to operate using very little power. XRF analysis can detect and quantitate wear metals such as iron, copper, chromium, aluminum, silver and lead as well as elements commonly used in lubricant additive packages such as zinc and molybdenum.

Lubricant viscosity can be measured directly using specially designed capillary viscometers. These are optimized for the range of viscosities associated with lubricants found in individual applications. Determination of viscosity can help determine heat and shear stress induced oil degradation and be used by the intelligent agent software identify possible oil dilution by fuel or water or unintended addition of improper lubricants.

As in the laboratory, infrared analysis data are used to determine oil condition. Non-dispersive infra-red and visible band spectrometric instrumentation on-board provides for *in-situ* determination of oil quality indices including oxidation, nitration, turbidity, and (by inference) total acid number (TAN) and additive package condition. The non-dispersive design is rugged and resistant to shock and vibration.

In gas turbine engine applications, ferromagnetic wear particles are collected and quantitatively determined by smart self-clearing magnetic chip detectors. In engines where high oil flow rates are encountered such as large diesels (with rates in excess of 300 gpm) for example, additional methods of detecting and quantitating ferromagnetic and non-ferromagnetic conducting particles are being developed in cooperation with private industry.

Comparison of Laboratory Oil Analysis and In-Situ Oil Analysis Components

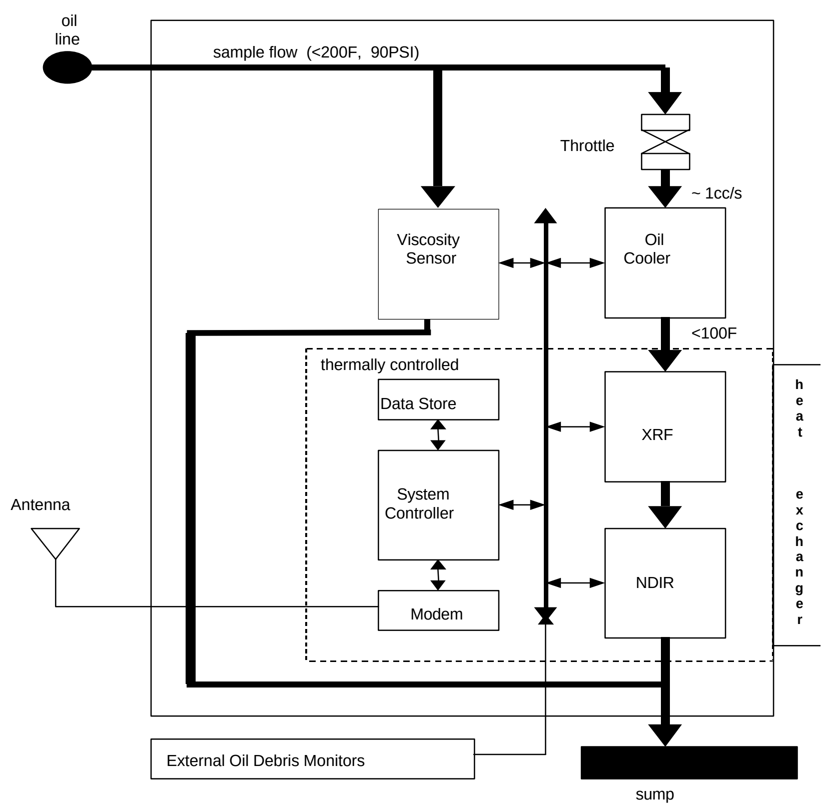
Type of Analysis	Laboratory System	In-Situ System
Wear metals, contaminants, additives	Atomic Emission Spectrometer	XRF Spectrometry
Lubricant physical properties	FT-IR Spectrometer	Proprietary Non-dispersive infra-red analysis
Viscosity	Viscometer	Capillary Viscometer
Wear and contaminant particles	Analytical Ferrograph	Smart debris detectors

Software*:* Microprocessors or gate arrays are used to run software for data acquisition, analysis and interpretation. Model-based techniques and artificial neural networks are used to determine lube oil conditions, identify developing faults and provide statistical estimates of time to failure.

Results

The combination of proprietary on-board instruments and sensors described here, together with the proprietary software described below can provide the data required to determine if oil is within all flag and alarm limits for railroad locomotives. These same instrument and sensor modules can also provide data sufficient for flag and alarm parameters associated with Navy and Army oil analysis programs.

To date, systems have been designed for use with diesel and gas turbine engine lubricants as well as drive train and hydraulic oils. In principle, the sensor suites can be used to determine physical and chemical characteristics of most oils and viscous non-polar fluids. One version of this system has been licensed for use in the railroad industry, and design and development are progressing for operational prototypes in other applications. Variants of the oil analysis system may be deployed directly on host equipment such as gas turbine or diesel engines, drive components or hydraulic systems. Other variants of the modular system are lightweight and easily portable and may therefore be used as portable test devices.



Schematic of the In-Situ Oil Analysis System

Tests to compare XRF results to NIST standards have shown that XRF determinations of 22 elements in five lube oil standard reference material agreed with NIST standards for oil analysis with an error between 0.3% and 1.3% (Sanders et al., 1983). Not all of the individual components of the system are as sensitive as their expensive counterparts in oil analysis laboratories (which require equipment investments in the hundreds of thousands of dollars). However this deficiency is more than compensated for by the fact that the tests may be conducted as frequently as desired. Conventional oil analysis programs conduct tests on a periodic basis, such as quarterly, semi-annually, or yearly. Use of the in-situ system on a weekly or monthly basis would provide more timely data that may be aggregated/averaged to yield comparable results.

Summary and Conclusions

In-situ oil analysis systems will help to reduce costs in oil analysis programs by eliminating the need to collect and send oil samples to a laboratory for analysis and by eliminating the disposal costs for waste products. In addition, they provide timely data on the need for routine service or early warning of pending catastrophic events.

Such systems have significant impact on the conduct of maintenance and the logistics process because they are enablers of predictive maintenance. Logistics and maintenance systems must adapt to these technologies by supporting proactive processes rather than reactive processes that result from more traditional diagnostic methods.

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