Direct Image Analysis for Detecting Abnormal Wear and Contamination in Used Oil Samples

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LASERNET FINES (LNF), developed by Lockheed Martin and the Naval Research Laboratory with support from the Office of Naval Research, is a particle shape classifier that also provides a highly accurate particle count for particles greater than 4 µm. Using laser imaging techniques and advanced image processing software, silhouette images of all particles larger than 20 µm in major dimension are automatically classified into six categories: cutting, severe sliding, fatigue, oxides, fibers, and water droplets. Percent free water is reported based on the calculated volume of the detected water droplets. Air bubbles are recognized and eliminated from the count. The design of the LNF will be reviewed with emphasis on recent improvements in hardware and software. Correlation of LNF analysis with conventional oil analysis techniques, such as spectrometric analysis, particle counting and ferrography will be presented and discussed with a view toward assessing the capabilities of the LNF as a routine screening tool for detecting abnormal wear and contamination in used lubricant and hydraulic oil samples.

Introduction

Optical emission spectroscopy instruments, both rotating disc electrode (RDE) and inductively coupled plasma (ICP) have been the mainstay of used oil analysis laboratories. They provide rapid elemental analysis of wear metals, contaminants and additives in used lubricating oils. Results are usually reported to the nearest part per million (ppm). Spectrometers determine the concentration of dissolved material from atomic and molecular size up to a maximum particle of size of just a few micrometers. (ICP) spectrometers suffer the most from particle detection inadequacies. Rotating disc electrode (RDE) spectrometers are responsive to somewhat larger particles, but the detection capability decreases rapidly as particles become larger than a few micrometers. There is practically no response for particles larger than 10 µm.[1, 2]

It was known as long ago as the early 1970's that certain types of failure modes were not easily detected by spectrometric oil analysis. Severe wear modes such as spalling, severe sliding wear and cutting wear generate large particles which may go undetected by standard spectroscopy. In fact, ferrography was developed at that time with financial support from the Office of Naval Research to overcome the detection inadequacies of spectrometric oil analysis in regard to rolling element bearing failures in aircraft gas turbine engines.[3] Ferrography provides information on size and particle morphology, but investigation requires a skilled technician and interpretation is subjective.

Work had been done about 20 years ago to develop a particle size independent method in which the oil sample was treated with strong acids to digest the large particles. The resulting solution was then run on an ICP spectrometer with an acid resistant sample introduction system.[4] However, it was subsequently determined that a particle size independent method was, in many cases, not sufficient to detect abnormal wear conditions because the contribution of large particles to the total wear metals concentration was often a much smaller fraction then the contribution from fine particles and dissolved material.[5] From this experience, the rotrode filter spectroscopy (RFS) method was developed which physically separates the large particles from the rest of the used oil sample.[6] RFS provides elemental analysis of large particles, but provides no information on size or morphology. Making RFS data quantitative is also a challenge because the sample is filtered through a RDE spectrometer disc electrode, the porosity of which, and hence the filtration efficiency of which, is hard to control.

Modern oil analysis laboratories check for large particles by a number of different means, none of which are ideal. Magnetic screening techniques can be quite sensitive, but are specific for ferrous particles. Analytical ferrography, while very powerful, is time consuming and requires skilled technicians. Conventional particle counters have proven useful for “clean” samples such as hydraulic oils, but they give no shape information and cannot be used for dark oils, oils with free water droplets, or oils with high particle concentration typical of machine and engine lubricating oils. Pore blockage particle counters overcome some of these difficulties, but particle shape is still unknown.

The LaserNet Fines was developed to identify the type, rate of production, and severity of mechanical faults by measuring the size distribution, rate of progression, and shape features of wear debris in lubricating oil.[7]

LaserNet Fines Technology

The basic operating principle of LNF is illustrated in Figure 1. A representative oil sample is drawn from the lubricating system and brought to the unit. The oil is drawn through a patented viewing cell that is back-illuminated with a pulsed laser diode to freeze the particle motion. The coherent light is transmitted through the fluid and imaged onto an electronic camera. Each resulting image is analyzed for particles, with several thousand images ultimately used to determine the characteristics of the suspended particles and to obtain good counting statistics. Concentrations are measured for particle sizes between 5 µm to over 100 µm.

Figure 1, Basic Operation of LNF.

LNF reports particle size in terms of maximum chord and also calculates equivalent circular diameter for compatibility with ISO cleanliness codes. Shape characteristics are calculated for particles greater than 20 µm, and the particle is classified into either a wear category or contaminant category. Classification is done with an artificial neural network that was developed specifically for the LNF system. Shape features were chosen to give optimal distinction between the assigned classes of fatigue, cutting, severe sliding, nonmetallic, fibers, water bubbles, and air bubbles, Figure 2. An extensive library of particles, which were identified by human experts, was used to train the artificial neural network.

Figure 2, Shape Classification of LNF.

Particle Counting Capability of the LaserNet Fines

The LaserNet Fines was designed primarily as an automatic wear particle shape classifier and trending tool to assist in condition monitoring programs. However, because of its direct imaging capability it is also an extremely accurate and reliable particle counter (ISO 4406:1999 compliant) without the need for any calibration. Once the magnification of the optics is set during manufacturing, using objects of know size, it is unnecessary to recalibrate periodically. A suspension of test dust in oil such as NIST Standard Reference Material SRM 2806 may be measured by the LNF periodically to insure proper operation of the instrument, but the Standard Reference Material is never used to calibrate the LNF. To fully understand why the LaserNet Fines can be used as an accurate particle counter, it is useful to review the calibration methodology for automatic particle counters which has been used and modified over the last thirty years.

Automatic particle counters have generally replaced optical microscopy as the primary method for quantifying particulate contamination in fluid wetted systems. In the late 1960's a calibration procedure was developed to ensure that particle counts obtained with optical particle counters agreed as closely as possible with counts obtained by optical microscopy. AC Fine Test Dust (ACFTD) supplied by AC Rochester had been used since the late 1960's to calibrate optical particle counters and ultimately became International Standard ISO 4402. The ACFTD test dust size distribution was measured using a sieve and an optical microscope resulting in a size distribution based on maximum diameter. During the early 1990's, with the use of more sophisticated scanning electron microscopes (SEM's), it was noticed that there was a substantial increase in the number of particles in the ACFTD (especially particles below 10 µm) than was previously reported by the optical microscopes given in ISO 4402. Also in 1992 AC Rochester stopped the manufacture of ACFTD so the ISO standards committee together with the National Fluid Power Association (NFPA) decided to develop a revised particle counter calibration method based on a new contaminant whose distribution was traceable to NIST (National Institute of Standards). ISO Medium Test Dust (MTD) was selected and was suspended in MIL-H-5606 hydraulic fluid, resulting in NIST Standard Reference Material SRM 2806.

There is a significant difference between the two distributions and this can be shown when an automatic particle counter calibrated with ACFTD measures an ISO MTD as measured with a scanning electron microscope, Figure 3. The results showed that below about 10 µm, NIST showed significantly more particles than with the ACFTD calibration. This can be explained because of the increased sensitivity of scanning electron microscopy compared to optical microscopy carried out in the 1960's. The opposite occurs above 10 µm, fewer particles were observed by NIST compared to the ACFTD calibration. This is because the equivalent circular diameter used by NIST for it's particle distribution is smaller than the maximum diameter used in the ACFTD, Figure 4.

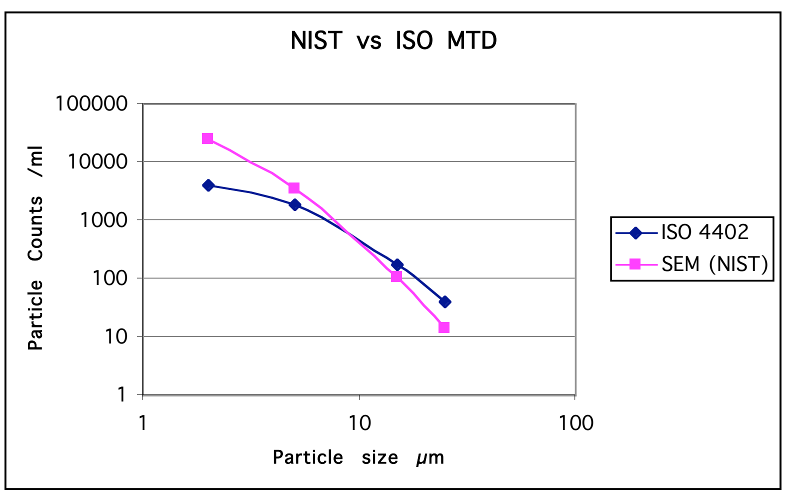

Figure 3, NIST Size Distribution vs. ISO 4402 Size Distribution.

Figure 4, Maximum Diameter versus Equivalent Circular Diameter.

The two distributions intersect around the 10 µm region. The revised method was approved on December 9, 1999, as ISO/FDIS 11171 for automatic particle counters The procedure includes many other enhancements to enable optical particle counters to be traceable to NIST. On December 2, 1999 ISO modified the ISO 4406 code numbers from >5 µm/>15 µm to a 3-digit code, >4 µm/>6 µm/>14 µm to reflect the new calibration procedure using the NIST standard. The sizes 6 µm and 14 µm were chosen so that no significant shift in code numbers occurs due to changes in the particle counter calibration method. Some organizations had previously introduced their own 3-digit form of the ISO 4406 coding method with the third digit representing 2 µm (equivalent to 4.6 µm NIST).

The NIST SRM 2806 used to calibrate optical particle counters is a dust which consists of particles which are partially transparent. The certified distribution is measured using a scanning electron microscope and the equivalent circular diameter is calculated from the total area of the particle. Optical particle counters which use a light blocking technique cannot perform a calibration which will be traceable to NIST with SRM 2806 MTD without following the enhancements which are documented in procedure ISO/FDIS11171. This is because the particles in the distribution have varying degrees of transparency and the sensing method used by these counters is light blockage. Once a particle counter is calibrated using the new ISO MTD the size of any solid particulate sensed will be over estimated because it will be blocking more light than a particle of the same diameter with transparent areas with which it was calibrated with, Figure 5.

Figure 5, Over-estimation of Size by Optical Particle Counters.

The LaserNet Fines does not require calibration using NIST SRM 2806 because it directly images the particles. It fills in any translucent areas of fibres or oxides which it may encounter in a sample, and calculates both the equivalent circular diameter and maximum diameter values for the hydraulic cleanliness (ISO CODES) and wear particle trending, respectively. Because the LNF instrument records the total size resolution of all the particles which it records, it is able to report NAS and NAVAIR cleanliness codes. NAS 1638 was developed by the Aerospace Industries Association of America, and is similar to ISO 4406 in that it classifies cleanliness according to pre-defined particle counts of certain particle sizes. NAVAIR 01-1A-17 is the Navy standard for particulate cleanliness.

The LaserNet Fines has been shown to be traceable to NIST SRM 2806 and is hence an ISO compliant instrument.

Case Histories

The LNF is a new and innovative analytical instrument that provides the oil analysis laboratory with invaluable information in a relatively short period of time. Although it is new to the market, in a very short period of time it has already demonstrated the additional analytical power it brings to the market of machine condition monitoring through oil analysis. The LNF can be used as complimentary technique to other oil analysis instruments, or by itself as a particle shape classifier and particle counter.

Several case histories are cited below to demonstrate the capabilities of the LNF.

A. Case History - Caterpillar 755 Transmission

Particle count shows high ISO code and high counts in all severe categories.

Figure 6, Hydraulic screen showing particle count.

The quantity and severity of the wear particles would indicate that the equipment was undergoing a severe wear mode. This was confirmed as the transmission failed soon thereafter.

Figure 7, Composite image map.

B. Case History - Engine of Caterpillar 988F

ISO particle counts appear normal, however, the number of fatigue particles may indicate possible severe wear.

Figure 8, Wear summary.

The abnormal wear in the form of fatigue particles warrants some concern and possibly a further ferrographic analysis.

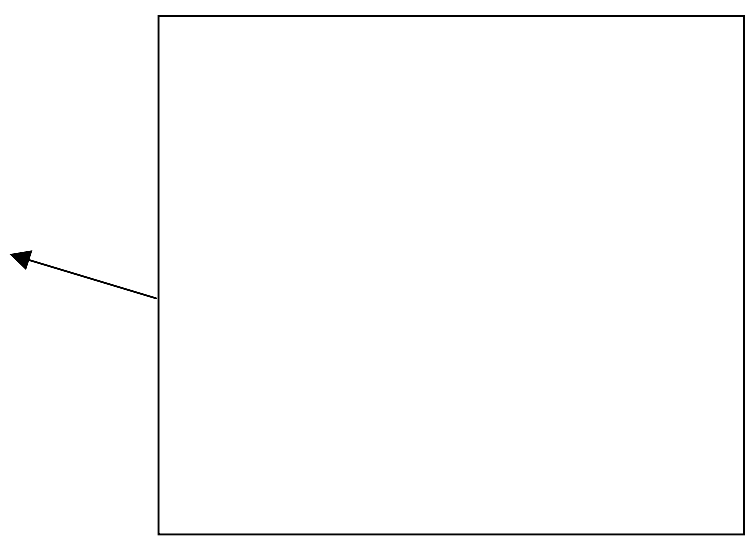

Figure 9, Composite image map.

C. Case History - Cummins Marine Diesel

Analysis shows an increase in all severe wear categories for particles >20 µm. Majority of particles were so large that spectrometric results did not show a trend.

Figure 10, Wear summary.

Figure 11, Composite image map.

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