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ADVANCES IN OPTICAL OIL DEBRIS MONITORING TECHNOLOGY

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Abstract: The status of two optical debris monitoring programs is described. The optical debris monitors are directed at developing on line technology for identifying type and severity of faults in machinery through measurement of size, shape and morphology of debris particles in real time. Operational characteristics of the monitors in two different size ranges is described.

Key Words: Bearings; early warning; catastrophic failure; gears; hydraulic fluid; real-time; shape classification; wear debris

Introduction: We have previously described real-time, imaging optical debris monitors. [1,2] These allow real time or near real time detection of ferrous, non-ferrous and non metallic debris in lubricating oil or other fluids in the general size range above about 5 micrometers. The optical debris monitor provides the capability for determining both the type of fault and its severity through combined analysis of particle size, rate of production and particle morphology. The general form of the optical debris monitor is illustrated in Fig. 1. It consists of a laser illuminator, an image detector and an image processor. Because of limitations associated with optical resolution and depth of field we have found it convenient to break the size of the detected particles into two ranges - 1) larger than about 50 μm and 2) larger than about 5 μm.

The large particle detector, referred to as LASERNET, is appropriate for detecting failure related debris in machinery lubricating oil in real time. One application of the monitor in this form is in helicopters to provide improved early warning of faults before they advance to catastrophic failures. Because the relatively large particles are trapped in the filter, the LASERNET detector will typically be located in the scavenge oil line ahead of the filter. The particles must then be detected on their only pass through the viewing cell. Typical operating conditions (flow speeds of 10 m/sec, viewing apertures of ~ 1 cm), along with the requirement to illuminate all of the oil column to maximize the detection efficiency, requires that the laser pulse duration be of the order of 1-2 μsec, the repetition rate be of the order of 0.5 - 1 kHz and that the image detector have approximately 1000 x 1000 elements and be capable of framing at 1 kHz. The images must be scanned in real time to determine the presence and characteristics of debris particles. Besides the high data rates the greatest challenge is to distinguish debris particles from air bubbles. In our system air bubbles are identified on the basis of their round shape, while debris particles larger than 50 μm will have irregular shapes.

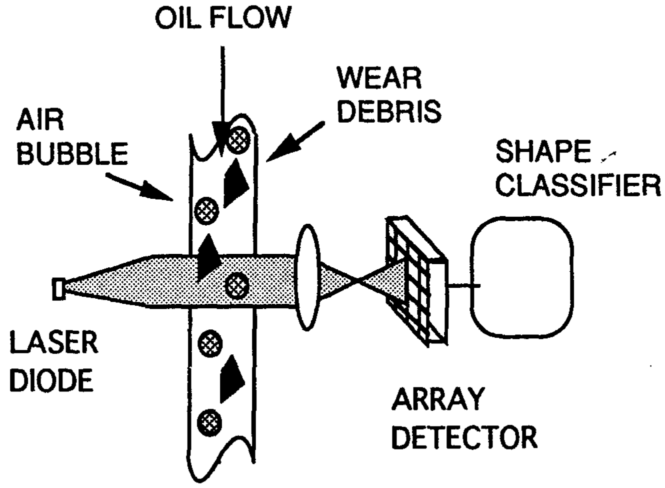

Fig. 1. A schematic diagram of the optical oil debris monitor, showing the illuminating laser diode, the array photodetector and the shape classifier. Objects suspended in the oil flow are imaged in transmission onto the array detector, appearing as dark shadows against a bright background.

LASERNET AVDS SYSTEM: We have implemented the LASERNET detector for test on the T700 engine and the main gearbox of an SH-60 power train in the test cell at the Naval Air Warfare Center Aircraft Division at Trenton, NJ under the US Navy's Air Vehicle Diagnostic System (AVDS) Advanced Technology Demonstration program. The test system is illustrated schematically in Fig. 2. The LASERNET system consists of a laser illuminator, a flow cell adapter, a high speed camera and a high speed image processing system. For the tests at Trenton, additional components for test validation have been included. These consist of a video camera for visualizing the flow conditions, an auxiliary high speed memory and a standard chip detector.

The illuminator is a commercial laser diode operating at 830 nm. The laser is coupled to a single mode fiber and the output beam expands to the desired final diameter and is collimated with an output lens. The final diameter is chosen to be larger than the illuminated area of the LASERNET viewing cell to ensure uniformity of illumination for the image detector. Typical center to edge variation in intensity is 0.8. The center of the viewing cell is imaged onto a high-speed camera from Silicon Mountain Design. This camera is capable of framing at speeds up to 1 kHz with up to 8 bits per pixel. In order to accommodate the speed requirements of the image analysis in the LASERNET system we have implemented the camera with 1 bit for the current set of tests. The high speed camera thus provides black and white images for analysis. Some control over the details of the image can be obtained by adjusting the bright-dark threshold of the camera and the peak laser intensity.

Each existing engine or gearbox requires its own adapter and fittings for retrofit. For the engine tests at the Trenton test cell we have chosen to attach the LASERNET system to the engine auxiliary gearbox manifold at the chip detector port as shown in Fig. 3. Since the T700 engine has cast internal oil channels the engine adapter has a re-entrant design. The oil flows out of the engine through a center column, into the LASERNET chamber and then returns to the engine through an outer annulus. The flow pattern at the engine is similar to that provided by the existing chip detector.

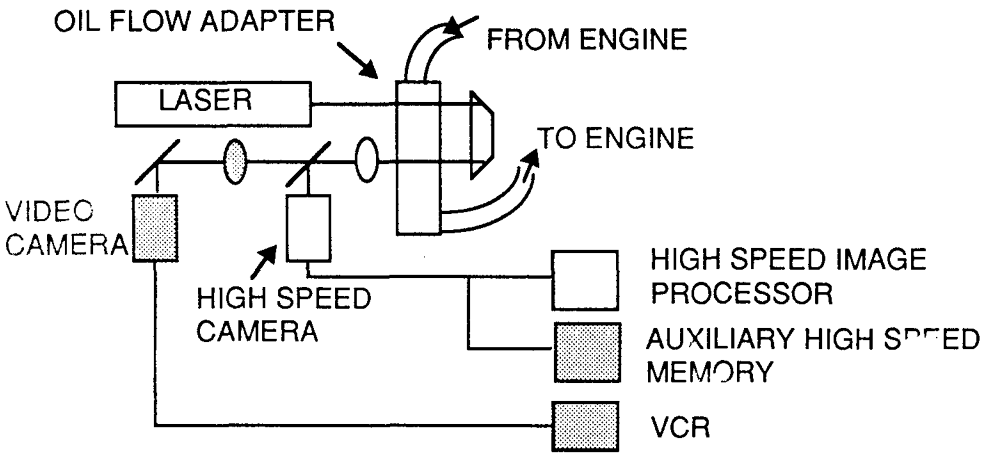

Figure 2. Schematic Diagram of LASERNET test system for T700 engine at the Trenton test cell. Items shown shaded are for test validation and not part of basic debris monitor.

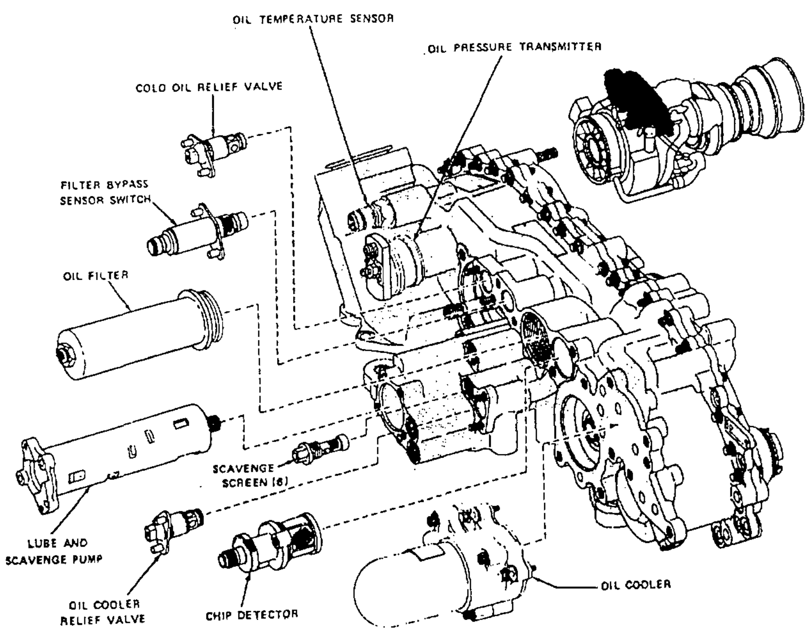

Figure 3. Illustration of the T700 auxiliary gearbox manifold showing location of chip detector port where LASERNET is connected.

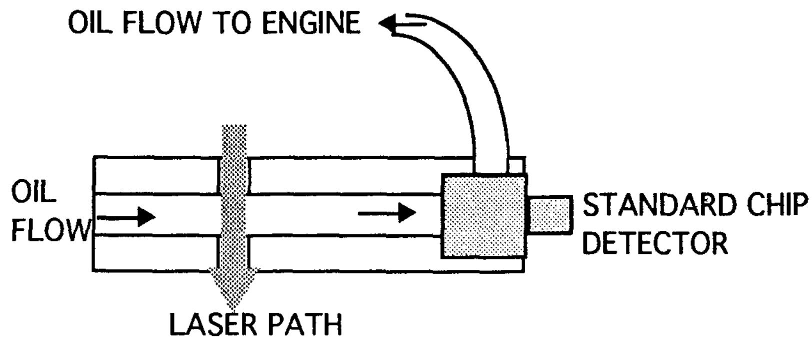

Figure 4. Schematic diagram of a portion of the LASERNET oil flow adapter showing the location of the standard chip detector after the laser viewing port for performance evaluation.

A portion of the LASERNET flow system is shown in Fig. 4. The viewing port is a rectangular section with flat windows for illumination and imaging. Typical dimensions of the viewing chamber are 0.5 - 1 cm in all three dimensions with specific values chosen to optimize debris detection and analysis performance levels, while minimizing illumination depth and required optical beam area. The standard T700 chip detector is located just after the viewing area for verification of LASERNET performance.

The image processing is broken into four stages shown schematically in Fig. 5. The raw image data is stored in a frame buffer and processed in a field programmable gate array to identify addresses of bright-dark transitions. These pixel addresses are transferred to a dec α digital processor for identification of individual objects. The objects are then subjected to a series of tests to determine shape. Roundness is first tested on the basis of variation of the length of normalized radial spokes. Objects that are determined to be round are identified as bubbles and discarded. Overlapping objects and objects at the edge are handled separately. Objects at the edge are tested for roundness of the partial circle contained in the image. Overlapping bubbles are identified by testing for the roundness of the partial circles of two potential objects lying on a line joining the centers. If the two objects are identified as partial circles, the entire objects is identified as overlapping bubbles and discarded. Any remaining particles are identified as debris particles and are analyzed for shape. The shape analyzer extracts a feature vector as described later and the particles are then classified according to wear source.

The auxiliary high speed memory is operated as a continuously streaming FIFO which can be interrupted by a response at the chip detector. In this way, image frames associated with debris detected by the chip detector can be retained for visual inspection and for evaluation of the real time processor performance. This comparison will establish the relative performance of the LASERNET system and the chip detector, allowing comparison not only of debris detection but also of false alarms by both systems. A second high speed memory system is contained within the real time image processor and retains images of frames in which debris particles are detected for visual inspection. Long term behavior can be compared to debris collected in the engine filter.

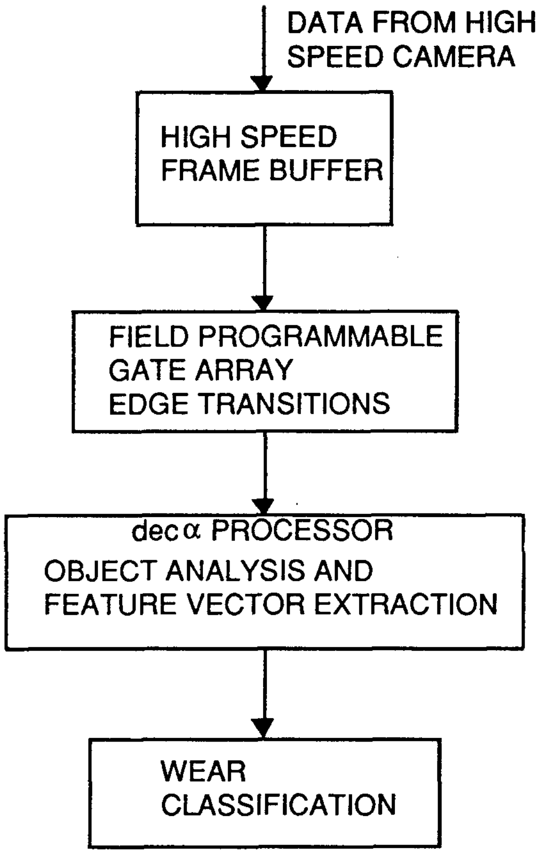

Figure 5. Block diagram of image processor for LASERNET

Long term tests on the T700, which is expected to be a relatively clean system, are planned to test the false alarm performance of the LASERNET system. Provisions are also being made to attach the LASERNET system to the SH-60 main gearbox, into which seeded faults will be introduced. This system will verify the ability of LASERNET to detect and classify debris particles.

LASERNET FINES: The fine particle detector, LASERNET FINES, is designed to detect and classify particles in the size range above 5 μm. It is appropriate for detection of debris particles associated with normal and early wear in lubricating systems. It is also capable of detecting particulate contamination in hydraulic and fuel systems, and in other fluids. Again the goal is to identify type and severity of fault through determination of particle size distribution and morphology. However, since it is sufficient to determine the representative concentration of particles in the size range of LASERNET FINES, rather than counting each and every particle, sampling in time and space is acceptable. This allows a reduction in the amount of fluid sampled and slower data detection and processing rates that are compatible with standard tv formats, reducing the special demands on the imaging system. The depth-of-field requirements for detection of the smaller particles requires use of cells that are of the order of 100-200 μm thick. The increased spatial resolution required for detection of the smaller particles is obtained with magnification of the image of the order of 10x. With the particle concentrations that are typically encountered, particle distributions from different frames must be combined to obtain statistically significant results. Total detection time and image processing rates can be traded within an overall system. The LASERNET fines system can be configured as a batch processor, a full autonomous in line processor or a hybrid in which the sampler is located in line, but the fluid sample is ported to the unit.

We have currently configured the LASERNET Fines unit as a benchtop batch processor. In the present unit the illuminator is a commercial laser diode operating at 830 nm with 100 mW peak power. The fluid is gravity fed through a cell approximately 200 μm thick. In our current configuration the image is obtained with a Cohu full field tv camera using 4x magnification. The images are captured and processed on a Power Macintosh 8100 computer.

The image processing code scans the frame for objects. It determines the largest dimension of each object and then develops a record of particle number for various size ranges. Once finished with a frame, the program acquires another frame and repeats the analysis routine, after which it combines the results with the results of the previous frame. The process continues, providing a cumulative record of particle numbers in various size ranges, which can be chosen to coincide with the current ISO size ranges. The program can be set to accumulate data for a set number of frames, a maximum number of particles in a given size range or a set counting time.

The image processing code for the LASERNET FINES is different from that for LASERNET in several respects. First, round objects cannot be discarded from consideration because there are wear sources that can produce round debris particles in this size range, such as particles from fatigue cracks. Secondly, more than one particle is expected in each frame. As a result, the program does not test objects for roundness and discard round objects, but rather counts and analyzes all objects in the frame. However, because of the sample handling methods, it is anticipated that air bubbles will be much less of a problem. In the event that they remain, side illumination can be used to give the bubbles a characteristic highlight as discussed in previous papers.

TABLE I.

PARTICLE DISTRIBUTIONS FOR CALIBRATION SAMPLE OF MIL-H-5606 HYDRAULIC FLUID

PARTICLE SIZE RANGE (μm)	% PARTICLES Pratt&Whitney	% PARTICLES LASERNET FINES
5-15	87.0	80.2 ± 3
15-25	10.0	15.9 ± 2
25-50	2.7	3.5 ± .95
50-100	.29	.25 ± .27
> 100	.01	.08 ± .14

The LASERNET FINES system has been exercised with samples of MIL-H-5606 hydraulic fluid provided by Pratt&Whitney. The particle distribution in different size ranges for a calibration sample containing A/C Fine Test Dust is shown in Table I, along with the distribution determined by Patt&Whitney with a commercial particle counter. The results for LASERNET

FINES should not be expected to reproduce the results of the commercial counter since the commercial unit determines spherical diameter, while the LASERNET system determines the largest dimension of the particles. Non-spherical particles, which our images indicate are quite prevalent in the calibration sample, will thus be classed differently by the two instruments. Nevertheless, the size distributions can be seen to be quite similar.

PARTICLE FEATURE VECTORS: One of the main goals of this program is to obtain a classification of the particles according to wear source based on an analysis of particle morphology. Several authors have discussed this approach using various characteristics of the particle shape, including aspect ratio, kurtosis of the distribution of angles in the edge contour and variations of curvature in the edge contour.[3-6] We have analyzed images of particles obtained from the Wear Particle Atlas from the University of Swansea, and from bearing test stands. Some of the characteristics that we have investigated are:

aspect ratio, defined as particle area/ $(\text{maximum dimension})^2$
external compactness, defined as average diameter/(diameter of maximum circumscribed circle)
bending energy, defined as the normalized second moment of curvature

An example of the separation of particles into various wear classes using these shape characteristics is shown in Figure 6 for a limited data base. Further investigation of particle classification are underway for a more extensive data base.

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References

1. J. Reintjes, R. Mahon, M. D. Duncan, L. L. Tankersley, A. Schultz, V. C. Chen, D. J. Kover, P. L. Howard, M. Chamberlain, Srini Raghavan, and Naresh Gupta, "Optical Debris Monitoring", JOAP Annual Meeting, Pensacola FLA, November 1994
2. J. Reintjes, R. Mahon, M. D. Duncan, L. L. Tankersley, A. Schultz, V. C. Chen, D. J. Kover, P. L. Howard, M. Chamberlain, Srini Raghavan, and Naresh Gupta "Optical Oil Debris Monitor", in "Life Extension of Aging Machinery and Structures", H. C. Pusey and S. Pusey, eds. pp. 57-66, 1994
3. A. Albidewi., A. R. Luxmore, B. J. Roylance, and G. Wang, "Determination of Particle Shape by Image Analysis-the Basis for Developing an Expert System," in "Condition Monitoring '91," M. H. Jones, J. Guttenberger and H. Brenneke, eds., Pineridge Press, Swansea, UK, 1991, p. 411
4. B. J. Roylance and S. Raadnui, "The morphological attributes of wear particles - their role in identifying wear mechanisms", Wear **175**, 115 (1994).
5. B. J. Roylance, I. A. Albidewi, M. S. Laghari, A. R. Luxmore and F. Deravi, "Computer-Aided Vision Engineering (CAVE) - Quantification of Wear Particle Morphology", Lubr. Eng. **50**, 111 (1993)
6. J. J. Hamalainen and P. Enwald " Inspection of wear particles in oils by using a fuzzy classifier", SPIE vol 2249 "Automated 3D and 2D Vision", 390 (1994).

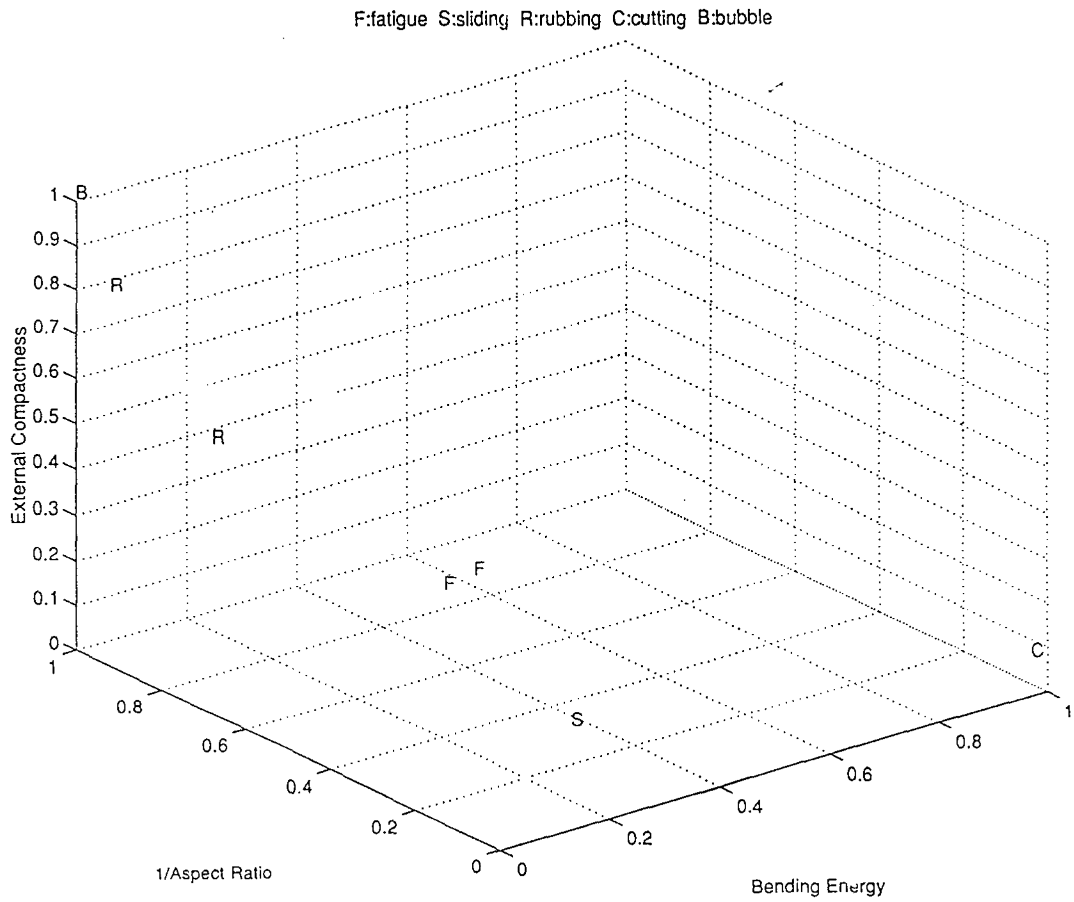

Figure 6. Classification of particles according to wear type using external compactness, aspect ratio and bending energy as shape features.