Detection of Precursor Wear Debris in Lubrication Systems[1]

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Abstract—On-line health monitoring of aircraft propulsion systems may realize substantial cost savings through implementation of condition-based maintenance programs. Currently, aircraft engine and gearbox oils are monitored using chip detectors that warn the pilot of excessive wear conditions. However, they can only detect large (> 200 µm) ferrous metal particles. Oil samples are also taken for laboratory spectrographic analysis, however, this procedure is time-consuming and manpower intensive. Several new technologies have emerged. Inductive sensors can now detect both ferrous and non-ferrous metallic particles in the oil, down to about 100 µm in size. Vibration monitors have also been developed to detect damage conditions. We report on an alternative method using acoustics for detecting precursor wear debris particles as small as 3 µm. By monitoring the size and generation rate of these very small particles, wear trend analysis can predict accelerated wear conditions before significant or catastrophic damage occurs.

The acoustic method works by insonifying the oil with a high-frequency acoustic impulse and analyzing the reflected signals. The detection algorithm discriminates between particles and entrained air bubbles on the basis of differences in acoustic signature. Next, the algorithm estimates particle size and computes a statistical history of the particle size distribution and generation rate which is used to determine the wear status of the engine or gearbox. This paper describes the operation of an acoustic sensor and presents test data acquired in a lubrication system simulator.

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1. INTRODUCTION

The military and other aircraft fleet operators are seeking ways to reduce the total cost of ownership. To this end, Health and Usage Monitoring Systems (HUMS) are now an essential component of new aircraft designs to reduce inspection time and cost, as well as enabling time-scheduled maintenance to be replaced by condition-based maintenance actions.

Engine and gearbox wear is commonly monitored using magnetic chip detectors that can detect ferrous particles larger than 200 µm in size. These large particles are indicative of a serious wear condition. Some HUMS systems now use vibration monitors that listen for mechanical noises created by worn bearings or chipped gear teeth. Inductive sensors are also available for detection of both ferrous and non-ferrous metals larger than about 100 µm.

To fully take advantage of condition-based maintenance practices, a means of detecting and tracking the production of precursor wear debris <100 µm is needed. Particles in this size range occur during normal wear, increasing in size and quantity with the onset of accelerated wear. A typical wear debris process is illustrated in Figure 1.

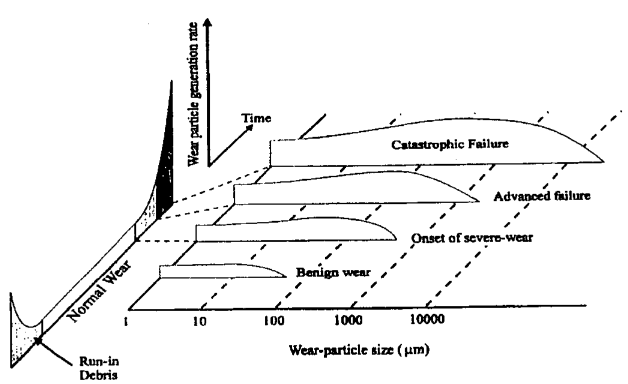

Figure 1 Wear Debris Production History

[1] 0-7803-5846-5/00/$10.00 © 2000 IEEE

Run-in debris occurs during initial operation of a new or freshly serviced/rebuilt engine or gearbox. Run-in debris includes particles remaining from machining operations and gasket material as well as sacrificial metals that aid break-in. Particle statistics remain consistent during normal wear, but increase exponentially in advanced wear stages. By monitoring the production trend of precursor wear debris, one can predict the advent of advanced wear so that timely maintenance efforts can be planned and implemented.

In this paper, we describe an acoustic sensing method that fulfills the requirements for precursor wear debris trend monitoring and wear indication. The acoustic sensor may be used alone or in conjunction with another sensor such as the chip detector or an inductive sensor to provide full-spectrum debris particle detection capability.

2. SYSTEM CONCEPT

The acoustic wear debris sensor is composed of (1) a piezoelectric transducer, (2) an impulse generator, (3) a wide dynamic range amplifier/digitizer, and (4) a microcomputer. The transducer is installed in an oil line with its beam direction perpendicular to the oil flow. A system block diagram is shown in Figure 2.

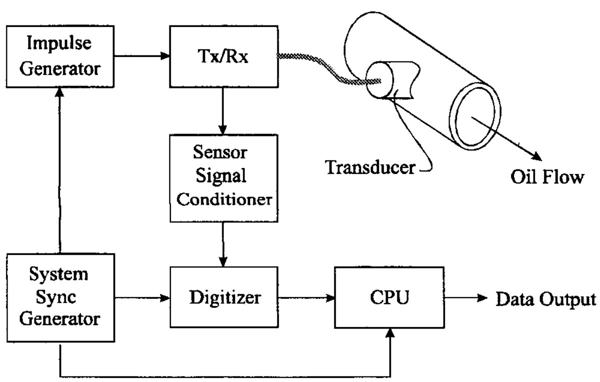

Figure 2 Acoustic Sensor System Block Diagram

The transducer insonifies the oil with a short duration pulse. A particle in the acoustic beam reflects the pulse which is sensed by the transducer. The short duration pulse is created by the impulse generator that electrically excites the transducer at its resonant frequency (5 MHz). Both electrical and mechanical damping are used to shape the pulse into a narrow pulse and control ring-down. A short time duration pulse (which is an ultra-wideband pulse) is needed to provide good spatial resolution.

Figure 3 shows the transmit pulse followed by a ring-down period, then a target reflection, and finally, the reflection from the back wall of the oil line. The transmit pulse is approximately 20 ns in duration. It travels through the oil at an acoustic velocity $c \approx 1.47$ mm per microsecond. Since a reflected pulse must travel to and from the transducer, the time-of-arrival (TOA) for the pulse is $t = c\tau / 2$. The back wall reflection appears at 31.2 μs which corresponds to a distance of 22.9 mm (0.9 in). Because of the transducer focal characteristic, the optimum surveillance region is between 20 and 30 μs which equates to 7.35 mm (0.29 in).

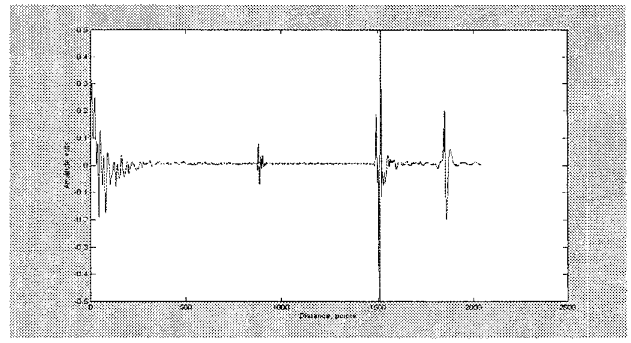

Figure 3 Typical sensor waveform showing the transmit pulse at the far left, ring-down period, particle reflection, and the back wall reflections.

For a 5-MHz impulsive transducer, the nominal wavelength is $\lambda = 300$ μm. The particle size range of interest is $a = 3$ to 100 μm (major dimension). Therefore, the reflections are in the Rayleigh scattering regime [1, 2] which produces a transducer output voltage roughly proportional to a^3. Particle shape and orientation also influence the magnitude of the reflection. Particle size distribution can be determined from a statistical analysis of the reflection pulse amplitudes.

The passing oil volume is sampled by the pulsed and focussed acoustic signal. The number of particles detected is a measurable and statistically reliable count that is proportional to the total particle count. Wear condition is determined using particle size and rate data. The output of the wear status algorithm is a simple indication of wear status - - run-in, normal, or accelerated wear. Accelerated wear indications are cues for on-condition maintenance action. Plans are under way to test the wear status algorithm on an actual gearbox in a test stand. Particle detection and sizing mechanisms have been tested and are discussed in the next section.

Bubble Discrimination

Since bubbles as well as particles are legitimate acoustic targets, a means of distinguishing one from the other is needed. Bubbles and particles differ in their acoustic impedance in relationship to the acoustic impedance of the oil. The acoustic impedance z of a medium is

$$z = \rho c \tag{1}$$

where ρ = density of the medium, and c is the acoustic velocity in the medium. The relative impedance r of an object in oil is the ratio of the object's impedance to that of the oil:

$$r_{air} = 2.9\times10^{-4}\,, \tag{2}$$

$$9.4 < r_{metal} < 29\,. \tag{3}$$

The reflection coefficient is given by

$$R = \frac{r-1}{r+1} \tag{4}$$

and so for air bubbles $R \approx -1$ while for hard particles $0.8 < R < 0.93$. The negative reflection coefficient indicates that bubbles reflect the incident pulse inverted; solid particles are reflected non-inverted. Typical waveforms are shown in Figure 4 for particles and Figure 5 for bubbles. Each target response is correlated with a reference pulse to determine whether the target is a particle or a bubble.

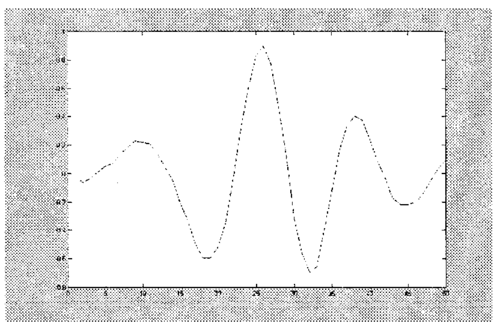

Figure 4 Typical Particle Reflection Pulse

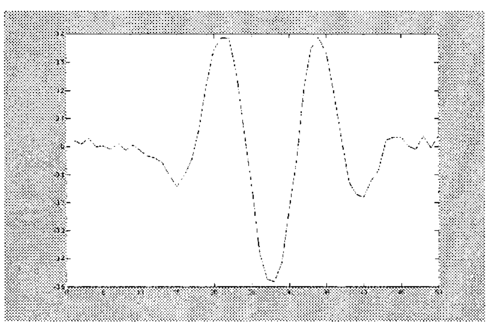

Figure 5 Typical Bubble Reflection Pulse

3. EXPERIMENTAL METHOD

Initial acoustic measurements were made using a static test fixture. These measurements were made to evaluate the performance of various transducer configurations in the detection of particles as small as 3 μm. A key issue is the absorption of acoustic signals in oil. When cold, the high viscosity of the oil highly attenuates acoustic signals. At operating temperature, the viscosity and therefore the attenuation is identical to that of water. The result of these experiments led to the selection of a focussed 5-MHz transducer for the sensor element. Also, it was shown that room-temperature water could be substituted for hot oil during developmental testing. Final testing was performed using a heated oil flow bench at Smiths Industries. Smiths produces an inductive sensor which was tested alongside the acoustic sensor.

Developmental Testing

A prototype acoustic sensor system was developed using a laboratory flow bench at IDI. The flow bench provided control over flow rate as well as a means of injecting particles of known sizes into the flow. A Panametrics 5052PR Pulser/Receiver provided the transducer drive and sensor signal conditioning. A LeCroy 9314AM digital oscilloscope, used for initial measurements was later replaced by a GaGe CS12100 digital scope card installed in a personal computer. Algorithms were developed in Matlab and later compiled into an executable program for on-line operation.

Oil Flow Simulator Test Setup

The acoustic sensor was installed in the Smiths Industries oil flow rig along with SI's inductive sensor and tests were performed to assess the capability of a full-spectrum sensor system. These tests were performed using synthetic turbine lubricating oil at an operating temperature of approximately 240-250°F and flow rate of 15 GPM. Between test runs, the system was flushed by running the system at an elevated pressure and flow rate.

The SI flow rig is designed to simulate a wide range of flow, pressure, and temperature conditions. A series of three 3 micron filters insures the oil is free of contamination both to the unit under test as well as to the 80 gallon reservoir.

Wide-ranging pressure flow characteristics are achieved by a combination of a variable displacement swash plate controlled piston pump and a backpressure control proportional valve at the outlet. The flow can be controlled from the fractions of a GPM to 35 GPM independent of back pressure, while the back pressure can be controlled from 40 PSI to 400 PSI at full flow conditions. At low flow conditions the pressure can be controlled from a few PSI to the full 40 PSI.

Temperature is controlled to within 1 °C using immersed 10 kW heaters, thermocouple temperature measurements, and a dedicated proportional/integral (PI) controller. The flow rig sensor test area is shown in Figure 6.

Because the flow rig has a relatively short loop and includes a set of three filters, there is only one chance, a few seconds long, in which particles injected into the loop pass through the sensors each time particles are injected into the loop. For these tests, we manually coordinated the injection and acquisition processes. Acoustic data were acquired in blocks of 255 waveforms taken continuously at the pulsing rate. Each acquired waveform is windowed to the 512-point region corresponding to the transducer surveillance region.

Particle types used were 5-µm Al_2O_3, 100-µm and 250-µm silica, and 90- to 100-µm carbonyl iron. Iron particles are detectable by both the acoustic and inductive sensors whereas only the acoustic sensor can detect non-metallic particles.

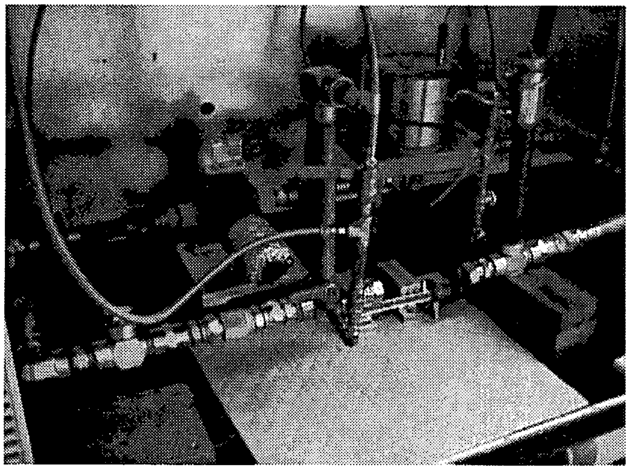

Figure 6 Acoustic Sensor installed in the Oil Flow Bench

4. EXPERIMENTAL RESULTS

Figures 7 and 8 show the windowed acquired waveforms for 5-µm and 100-µm particles respectively. Two sets of waveforms are shown, one for each of the two scope channels. The amplitude difference between the 5-µm case and the 100-µm case is evident. The plots are a concatenation of the 255 waveforms for each test run. One can see the cloud of particles appear and disappear with time as they pass through the surveillance region. The lone high-amplitude reflection seen in the 5-µm case (Figure 8) is most likely due to a larger particle from a previous test run, trapped in the circuit and released during this test run.

Figure 9 compares the cumulative distributions for 5-µm, 100-µm, and 250-µm particles. The median voltage is seen to increase with increasing particle size. The predicted nominal value for 250 µm particles is actually above the system dynamic range design limit, yet a sufficient number of particles produce reflection in the detection region to yield meaningful data.

Additional tests with a mix of particle sizes were also run. This data shows that changes in the particle size distribution is reflected in the median and 90 percentile values which can be used to track wear particle trends.

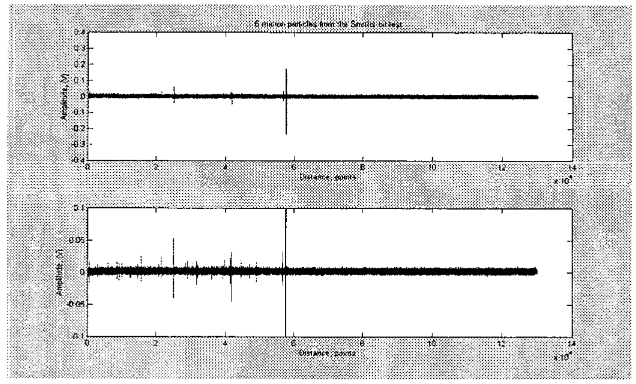

Figure 7 Concatenation of 255 Time Waveforms for 5-µm Particles

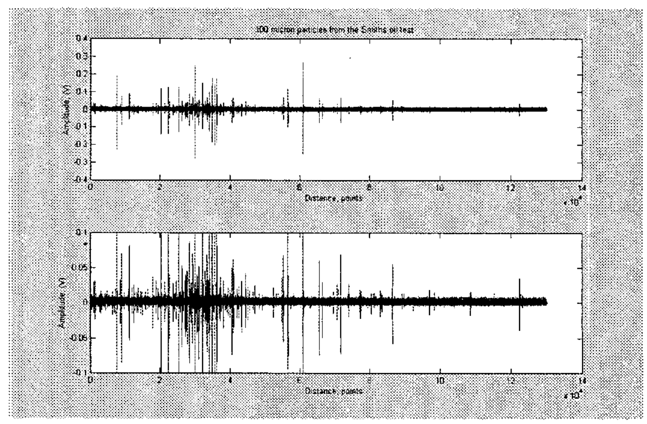

Figure 8 Concatenation of 255 Time Waveforms for 100-µm Particles

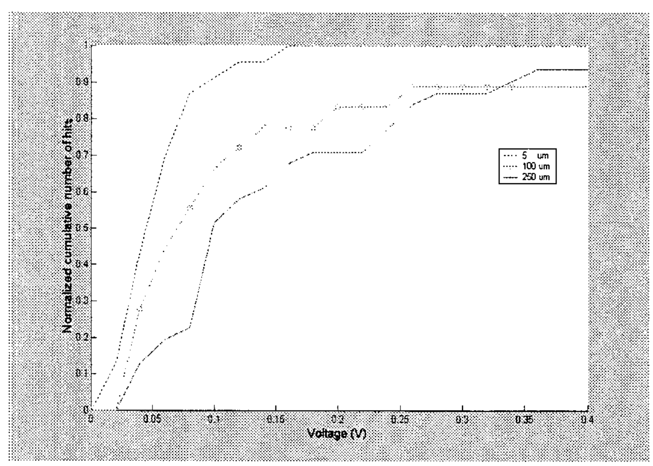

Figure 9 Cummulative Reponse Distribution for 5, 100, and 250-µm Particles

5. CONCLUSIONS

We have shown that an acoustic sensing method is capable of detecting precursor-size debris particles in oil and estimating their size. Tests are under way on an actual gearbox to validate the technique for determining a trend in precursor wear debris production and predicting the advent of significant wear that requires remediation.

6. ACKNOWLEDGEMENTS

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Jack Edmonds is a Senior Scientist at Innovative Dynamics, Inc. where he has developed specialized acoustic and electromagnetic sensor systems for a range of smart structures applications. He has also developed a laser-acoustic system for bathymetry and soil moisture applications and has been a technical contributor on numerous radar, SIGINT, electro-optic/ infrared sensors, and electronic countermeasures projects.