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Full-Flow Debris Monitoring in Gas Turbine Engines

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For oil wetted components of gas turbine engines, such as bearings, reduction and accessory drive gears, debris monitoring is the most successful and cost effective condition monitoring technique. However, extensive field service experience demonstrates that full-flow debris monitoring is essential. Full-flow debris monitoring devices, as opposed to chip detectors installed in sumps or lines, monitor the entire scavenge flow. The detection efficiency of properly designed systems can reach 100 percent. This paper briefly discusses models for debris generation in bearings and gears and reviews the principles of successful debris separation and incipient failure detection in gas turbine engines. Several devices are discussed which represent the state-of-the-art in this field, including a centrifugal debris separator for aircraft jet engines which has been shown to be highly effective in field service. Of particular interest to the user of stationary gas turbines is a quantitative debris monitoring system which provides a real-time read out of debris production levels and gives reliable advance warning of impending failure; thus reducing down time, secondary damage and overhaul costs.

DEBRIS MONITORING

Although there are some gas turbine engines with a low incidence of bearing and gear failures, they are becoming rarer. Increasing power to weight ratios take their toll in bearing reliability and accessory gear box life. Especially military aircraft engines with their highly loaded thrust bearings are vulnerable in this respect. However, industrial power turbines which have to operate continuously over long operating periods are also affected. The failure of engine shaft bearings tends to be progressive and the repair cost increases with operating time, once the failure has started. An effective diagnostic system for the oil-wetted components is therefore essential. As on-condition operation becomes more prevalent, in aircraft as well as industrial engines, the cost of the diagnostic equipment is easily saved in one failure with scheduled overhaul and little or no secondary damage.

Oil debris monitoring is the most cost effective diagnostic method for bearings and gears. For over twenty-five years, magnetic plugs and electric chip detectors have been used for this purpose. Some gas turbine manufacturers have emphasized this technique and have significantly contributed to its effectiveness by proper placement of these devices within the lube system, accessibility from outside for inspection and training of operators in their use. This is especially true for European manufacturers and users, [1]). For example, the RE-211 engine nacelle on the TriStar aircraft has access doors for the master magnetic plug. This makes visual inspection as easy as a filter bypass check.

Spectrometric Oil Analysis is also a widely used debris monitoring method. Its chief disadvantage is the logistic problem associated with taking, transporting and remotely processing the oil samples. There are also failure modes for which its effectiveness is limited. Surface fatigue spalling, a common failure mode of gas turbine thrust bearings, is one of them.

WEAR DEBRIS PRODUCTION MODELS

The wear history of a set of bearing'or gear surfaces can be categorized into wearing-in, normal operation and abnormal wear or failure. Every component completes this sequence, unless it is replaced by the failure of another one or at time-limited overhaul. The rate of debris production as a result of the sliding and rolling contact of the wear surfaces first declines during the wear-in phase, remains roughly constant during normal operations and increases by several orders of magnitude during failure (see Figure 1). Figure 2 shows the abnormal wear debris production rate measured on a large commercial gas turbine engine during the failure of an intermediate (right angle) gear box bearing. The decline in the debris production rate following gear box replacement reflects the run-in phase of the new component. The normal wear rate lies several orders of magnitude below the abnormal level.

The debris production rate curve contains no information about particle sizes. Whether particles are "large" or "small", depends on the failure mode. A debris particle spectrum applicable to surface fatigue failure or spalling is shown in Figure 3. The normal spectrum is limited to particles below 10 microns. As spalling begins and progresses, more and more particles of larger and larger size are produced until the entire wear surface is affected (Figure 4). The spall flakes are shields lifted out of the wear surface by the "delamination process"(2).

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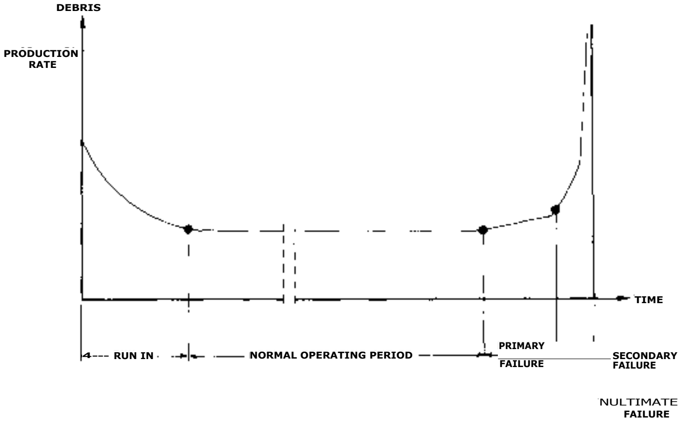


Fig.l Debris Production Rate Over Operational Life

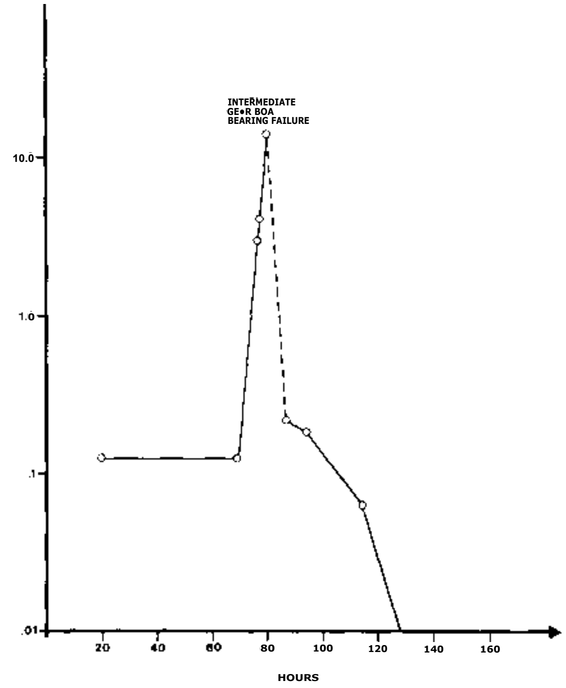
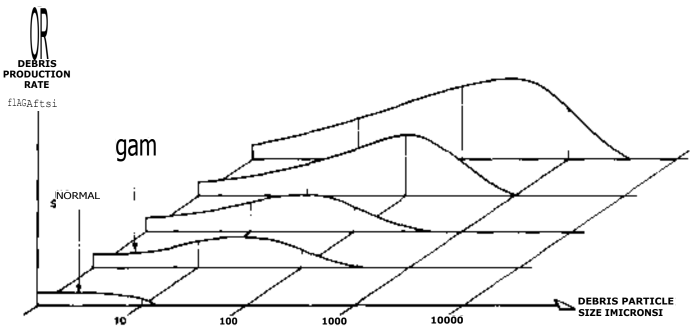


Fig.2 Debris Production Rate During Gear Box Bearing Failure

The increase in wear particle size need not be smooth. Sometimes, only a limited number of large particles are generated (Figure 5). Such failures tend to be detected late or missed entirely by diagnostic techniques involving oil sampling. This is partially due to particle sedimentation processes. An equally important reason is the low probability of obtaining one of these relatively few particles (on the order of 10 to 10^3, depending on failure progression) in a sample representing a fraction of less than 10^{-4} of the lube system content.

The particle spectrum differs from failure mode to failure mode. Abrasive wear, such as bearing



Pig.3 Debris Particle Spectrum, Surface-Fatigue Failure

Fig.4 Spalled Ball BearinG

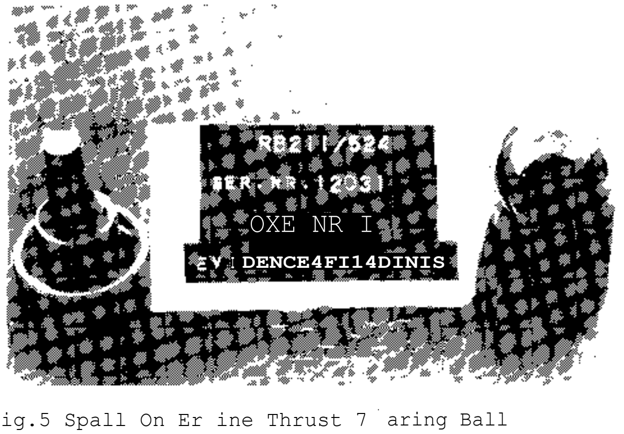


Fig.5 Spall On Er ine Thrust 7 aring Ball

skidding, produces more small particles. Gear tooth fracture, on the other hand, results in only one or at most a few large fragments. Spinning bearing races can produce surprisingly large debris (see Figure 6). In order to obtain the full debris spectrum it is essential to include the sedimented debris and not to limit the analysis to particles obtained by oil sampling.

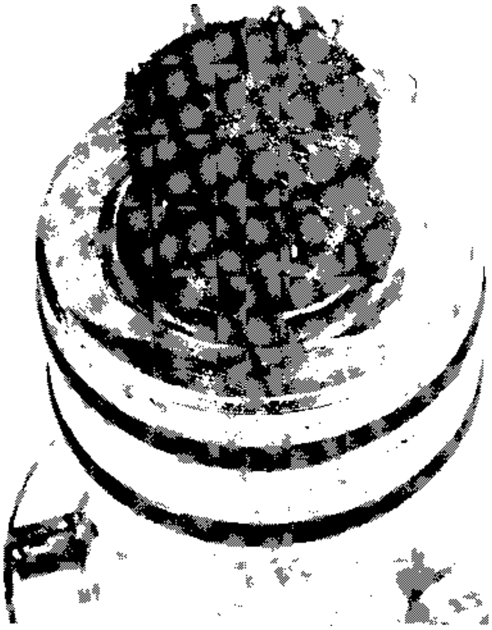


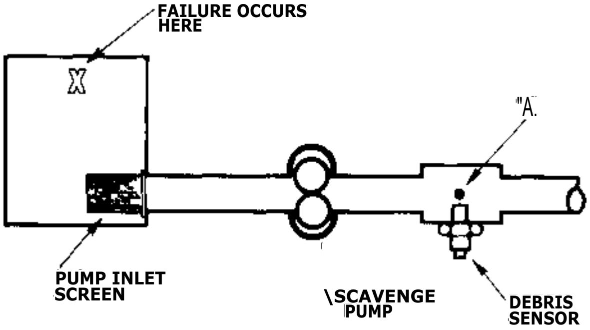
Fig.6 Debris From Spinning Inner Bearing Race

THE IMPORTANCE OF PROPER LURE SYSTEM DESIGN FOR EFFECTIVE DEBRIS MONITORING

The proper functioning of the debris monitoring system is dependent on the transport efficiency of the lube system. This is the quantity el, shown in Figure 7. Debris can be retained by pump inlet screens or in sedimentation traps. Proper shaping of scavenge sumps and lines can improve particle transport substantially. Therefore, the transport efficiency is not only a function of particle size, but also of the lube system design.

The debris sensor may not capture all of the debris entrained in the oil flow. Its capture efficiency e2 is dependent on proper installation of the debris sensor in sump or scavenge line (see Figure 8) and depends on flow velocity and particle size. Finally, not all the debris captured by the debris sensor may lead to indication. Its sensitivity is expressed as an indication efficiency e3. The probability to detect a failure as the result of the release of one particle by the failure source is the product of all three quantities.

FULL-FLOW DEBRIS MONITORING



TRANSPORT EFFICIENCY $e_1 = \frac{\text{PARTICLES TO POINT "A"}}{\text{PARTICLES GENERATED}}$

CAPTURE EFFICIENCY $e_2 = \frac{\text{PARTICLES ON DEBRIS SENSOR}}{\text{PARTICLES TO POINT "A"}}$

INDICATION EFFICIENCY $e_3 = \frac{\text{PARTICLES INDICATED}}{\text{PARTICLES ON DEBRIS SENSOR}}$

FAILURE INDICATION PROBABILITY

$$e_t = e_1 \cdot e_2 \cdot e_3 = \frac{\text{PARTICLES INDICATED}}{\text{PARTICLES GENERATED}}$$

Fig.7 Factors Influencing Failure Indication Probability

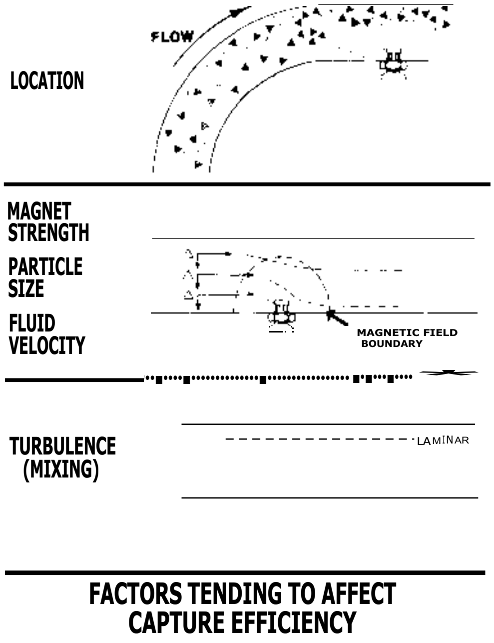


Fig.8 Factors Influencing Capture Efficiency

In the past, the magnetic plugs or chip detectors in most engines were either installed in the accessory gear box sump, in the main scavenge line on the pressure side of the pump or in the bearing scavenge return lines. Unless special provisions are made to enhance debris capture, such installations can be very ineffective. Capture efficiences of less than

2% have been measured in some widely used engines. In such a case, the magnetic plug or chip detector must be considered to be an inconsistent or unreliable failure detection device, since the failure indication probability is low. When a failure occurs, most debris bypasses the chip detector and finds its way into the oil tank, heat exchanger or scavenge filter.

A full-flow debris monitor is characterized by 100% capture efficiency above a certain particle size. As its name implies, the entire oil flow passes through it and is stripped of entrained debris. There are two types of devices of this kind, a filter screen-type and a cyclonic type.

A typical filter screen debris monitor for a turboshaft engine is shown in Figure 9. This unit is designed for installation in the scavenge pump in lieu of a pump inlet screen. It contains an electric chip detector for remote indication.

Fig.9 Screen-Type Full-Flow Debris Monitor

An optimum and very cost-effective layout for a full-flow debris monitoring system is shown in Figure 10. This is the lube system schematic of a large gas turbine engine. The full-flow debris monitor is located in the main scavenge return line upstream of the heat exchanger and of the scavenge filter, if the engine is equipped with such a filter. In order to isolate the failure, which is of great importance to the maintenance personnel, magnetic plugs are installed in the bearing scavenge lines and in the accessory gear box sump. These magnetic plugs capture a few percent of the debris which is sufficient for failure isolation but does not impede the operation of the full-flow debris monitor downstream. This layout is known as a "master/slave" debris monitoring system. Due to the fact that only one debris monitor is used, its unit cost is less critical than if one would be installed in each bearing scavenge line.

A particularly effective full-flow debris monitor suitable for such a system is illustrated in Figure 11. This is actually a cyclonic particle separator. The oil enters tangentially into a cylindrical chamber and creates a vortex with radial accelerations up to 100g. This vortex field separates the denser debris from the oil and deposits the debris on the particle sensor at the bottom of the chamber. The high radial acceleration assures that the device can operate in any attitude. Since the vortex also efficiently separates entrained air, units can and have been designed which not only remove wear debris from the oil but also de-aerate it at the same time. Since the debris monitor is located upstream of the heat exchanger, this reduces its size and weight and increases its efficiency.

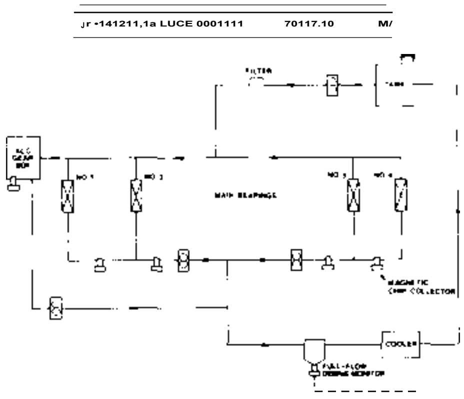


Fig.10 Master/Slave Lube Debris Monitoring System

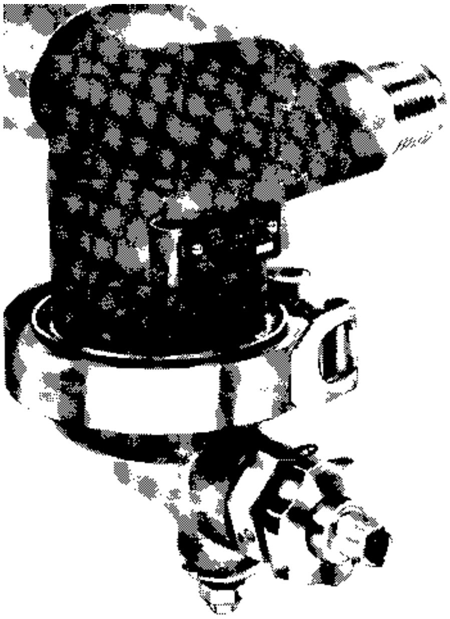


Fig.11 Cyclonic Debris Separator

The debris capture efficiency of a typical cyclonic debris separator is shown in Figure 12. At a particle size of 150 micron it is virtually 100%. The pressure drop of such a device is typically 10 to 20 PSI, depending on flow rate and desired debris separation efficiency.

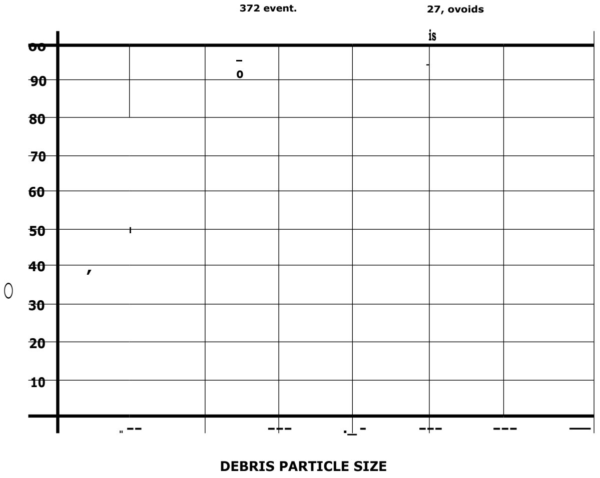


Fig.12 Capture Efficiency Of Typical Cyclonic Debris Separator

Figures 13 and 14 illustrate the effectiveness of a cyclonic full-flow debris monitor in detecting failures at a very early stage. The bearing shown is the No. 2 bearing of a Lycoming T-53 gas turbine engine, a utility helicopter turboshaft engine. The failure mode is the rotation of the outer bearing and is purely of the abrasive type. The debris generated by this failure, collected by the debris monitor and deposited on the chip detector is shown in Figure 14. Contrary to opinions formed from analyzing oil samples, this failure mode clearly generates "large" debris (on the order of 1000 micron) which is easily indicated by an effective debris monitor. At this stage, the wear ridges in the outer race of the bearing were approximately .006 inch (1.5mm or 1500 microns) deep. Tear down inspection showed the bearing to be otherwise in good condition and there was no debris or other secondary damage anywhere else in the engine.

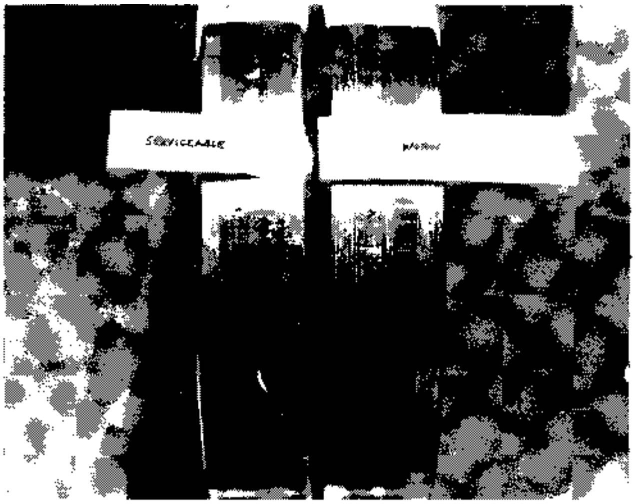


Fig.13 Rotating Outer Bearing Race

Fig.14 Debris From Failure Shown In Figure 13

In a program conducted at the U.S. Army Flight Training School at Ft. Rucker, the engines of 36 UH-1 helicopters have been equipped with full-flow debris monitors of the cyclonic type. In 25,000 flight hours, all eight engine failures involving oil-wetted components have been detected, including shaft and accessory gear box bearing failures. Another evaluation on a General Electric LM2500 engine installed aboard the GTS Callaghan has demonstrated the effectiveness of this type of device(2).

QUANTITATIVE DEBRIS MONITORING

The devices described previously are effective in separating the debris from the oil. Obviously, the mechanism of indicating the arrival of the debris and transmitting this information to the outside world (pilot, maintenance crew, central control system or condition monitoring system) is of equal importance.

Magnetic plugs as shown in Figures 5 and 6 are in wide use in Europe. Although very effective when properly located within the engine, the requirement of frequent visual inspection practically limits their use to airborne engines with flight-critical status. This approach requires good operator training or laboratory facilities for debris interpretation and has not spread much beyond Europe.

The main limitation of electric chip detectors of the type shown in Figure 14 is that they produce only one bit of information about the status of the gas turbine engine - "bad" (i.e. chip light "on"). It goes without saying that a piece of equipment as complex as a gas turbine engine requires signals with more information content (i.e. "how bad?") for proper maintenance action. The inability of the chip detector to furnish this information has been the main reason why it has not found much application in ground-based engines or even in gas turbine engines for fixed wing aircraft.

A debris sensor with quantitative capability is currently under development and has shown considerable promise in early evaluations. It is illustrated in Figure 15. Like a magnetic plug, it can be equipped with a self-closing valve (shown on the right) which permits removal and inspection without the need to drain the lube system. The sensor itself contains a magnet which attracts ferrous debris to its sensing surface. A debris particle arriving at the sensor generates a pulse whose amplitude is a function of particle mass. The sensor therefore generates both information about the frequency of debris arrival and about the size of individual particles.

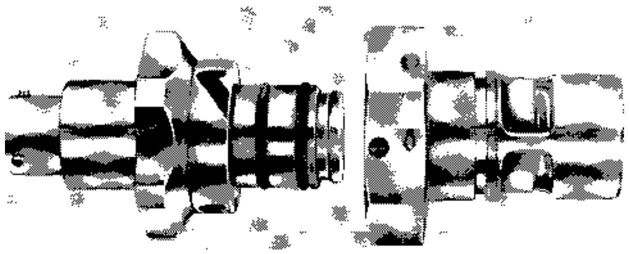


Fig.15 Quantitative Debris Sensor

This information relates directly to failure progression rate and, to a lesser degree, to failure mode. This permits failure trend analysis and provides the basis for anticipated shutdown and scheduled overhaul with minimal secondary damage.

The signal from the sensor can be displayed on a counter with additional output to external monitoring equipment (see Figure 16). There is no doubt, however, that the greatest benefit from this technology can be derived by feeding the signal into a microprocessor or computer-based engine diagnostic system as part of the information provided by other sensors, such as speeds, pressures, temperatures, fuel flow, etc. The increasing use of computers for fuel control and condition monitoring purposes, even in airborne gas turbine engines, makes this technology also applicable to the aircraft environment.

Fig.16 Signal Conditioning Unit

SUMMARY

Oil debris monitoring is the most reliable and cost effective condition monitoring technique for gas turbine bearings. Full-flow oil monitoring ensures early detection of impending failures, when secondary damage is still minimal and scheduled shutdown and replacement is still possible. Cyclonic debris separators are especially promising devices in this respect.

In combination with a quantitative debris sensor, a full-flow monitor becomes a system which provides quantitative information about bearing deterioration. Given sufficient field experience, such a system will permit failure trending and prognosis.

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