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Advanced Oil Debris Monitoring - Now Affordable for Gas Turbines

by

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Abstract

Gas turbines are a critical component of many rotating equipment operations. Gas turbine component failures are very costly both in terms of unit down time as well as repair. These costs are significantly amplified in situations where the outage is unplanned and component failure involves secondary damage. This paper describes the applications and field experience of an advanced technology on-line oil debris monitor that has become the industry standard for aviation and aero-derivative gas turbine applications. Drawing from over 300 installations worldwide, this paper discusses several in-service application case studies highlighting the technical and financial benefits of the technology including the steps for building a solid cost justification argument for fitting such equipment to gas turbines. After all, what good is great technology if it is not affordable!

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Oil Debris Monitoring - Now Affordable for Gas Turbines

The following paper is perhaps a departure from the norm for this forum. This paper goes beyond the classic presentation of technology and why it is a good thing to focusing on the affordability of applying certain technologies to the gas turbine. The analysis presented relates specifically to engine monitoring technologies, particularly those that are recognized as effective condition assessment tools incorporating on-line technologies. For clarity the analysis is presented in this paper in the form of a concrete example - inductive oil debris monitoring (ODM) technology as applied to the aero-derivative gas turbine.

The Technology

Ten years ago the inductive oil debris monitor full-flow technology was introduced into the industrial and marine industries specifically for application to the aero-derivative gas turbine. The aero-derivative was a natural choice since the consequences of undetected bearing or gear failure can be very costly to the operator. This inductive ODM is an on-line, full flow oil debris sensing technology that detects and quantifies virtually 100% of the metallic particles above a minimum size threshold. This is a significant departure from the traditional methods of monitoring for debris in oil, which typically utilize magnetic capture to extract the metallic debris from the flow path and are typically low cost. In conventional usage, these magnetic chip detectors, have poor capture efficiency, and thus, are often not effective at providing early detection of bearing damage. Moreover, they are not capable of capturing non-ferromagnetic

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metal debris and are prone to false alarms due to the build up of fine ferromagnetic debris or "fuzz".

The inductive ODM sensor, an example is shown in Figures 1 and 2, relies upon sensing the induced disturbances to an electromagnetic field created by passing metallic particles, either ferromagnetic or non-ferromagnetic. The debris is not captured by the sensor, thus requires no periodic inspection or cleaning, and is entirely "remote" in operation.

Figure 1 - Inductive ODM Sensor

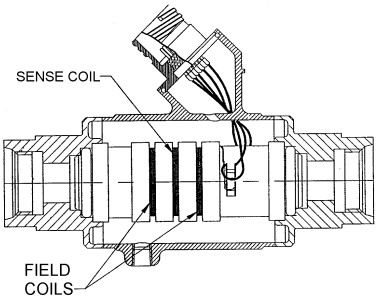

Figure 2 - Sensor Cross Section

The sensor functions by monitoring the disturbance to an alternating magnetic field caused by the passage of a metallic particle through the sensing coil assembly. The particle couples with the

magnetic field to varying degrees as it traverses the sensing region, resulting in a characteristic output signature as shown in Figure 3. The amplitude and phase of the output signature is used to identify the size and nature of the particle. The amplitude of the signal is proportional to the mass of the particle for ferromagnetic metals and to the surface area of the particle for conductive non-ferromagnetic metals. The phase of the signal for non-ferromagnetic metals is opposite to that of ferromagnetic metals allowing for a distinction to be made between the types of wear particle metal. Signal conditioning using a threshold algorithm is used to categorize the particles that pass on the basis of size. Multiple size categories can be configured which allows the tracking of the distribution of debris size. The minimum size particle detectable by the inductive ODM is a function of the sensor size, but typically ranges from 100 to 200 microns spherical ferromagnetic particles for typical aero-derivative applications.

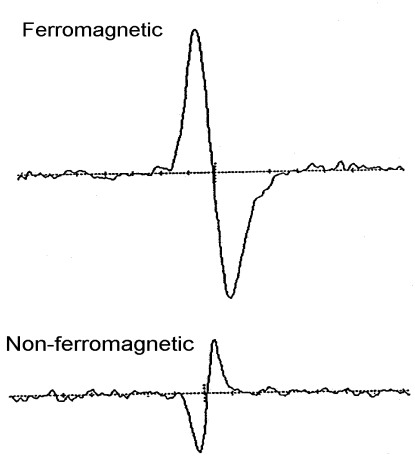

Figure 3 - Sensor Output Signal

With hundreds of engines now in operation fitted with the inductive ODM technology and with high hour units being in operation for over 50,000 hours, significant actual operating experience has been attained. Field experience has resulted in the following relevant observations:

1. An aero-derivative gas turbine with bearings in good condition with a well maintained oil system will not produce debris in the oil that is detectable by the inductive ODM. In actual field applications it is common that after a new engine or newly overhauled engine is installed, a small quantity of debris is detected over the first few hours of operation. The rate of accumulation is usually very low and goes to zero shortly after initial start-up. This debris is the result of engine build debris, or debris left over from a previous engine failure event and is usually insignificant relative to the alarm levels. Common practice is to zero out the accumulated debris after a few hours of running after the first engine start.

2. The time from initial spall to significant damage varies significantly and is dependent upon engine type, specific bearing design and operating profile of the engine. An example of a particularly rapid bearing failure on an engine is shown in Figure 4. In this case the initial spall progressed to the alarm limit value in about 80 hours (or 4 days) of continuous engine operation. A more gradual bearing failure event on another engine type is presented in Figure 5, in which case the initial spall to alarm period took about 300 hours (or 12 days) of continuous engine operation.

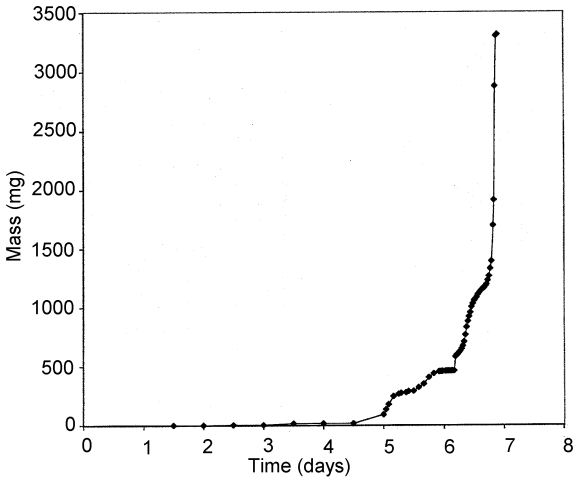

Figure 4 - Rapid Engine Bearing Damage

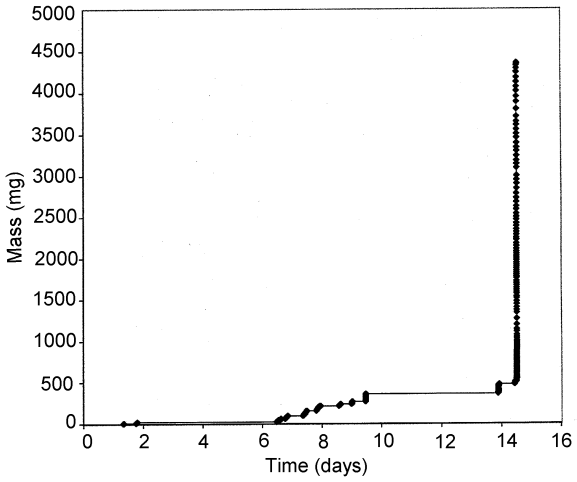

Figure 5 - Gradual Engine Bearing Damage

3. The inductive ODM technology is effective at identifying other engine component problems including gear failure, spline failure, shaft/seal rub and erosion. In some cases these failures have their own identifiable "debris signatures" which may be characterized by particle size distribution and/or particle type composition.

This field experience demonstrates that this oil debris monitoring technology does indeed provide reliable early warning of bearing and gear damage well before "failure" occurs.

The Benefits

Gas turbine operators benefit from ODM via improved plant Reliability and Availability (both key performance parameters for most operators); and significantly lowered operating costs. Each benefit is analysed in detail below.

Reliability Improvement

Reliability is usually defined as:

$$R = \frac{P - F}{P}$$

where:

P = Number of hours the unit is expected to be running in a given period

F = Number of hours of unplanned outage in the same period.

ODM affords operators the flexibility to maximize corrective action planning. Without ODM, an operator typically runs to failure, then orders a lease engine. With ODM the operator can assess the degree of damage on-line and order a lease engine well in advance of when the engine must be taken out of service. For example, if it normally takes 72 hours for a lease engine to arrive on site, the application of ODM would then be attributed to eliminating those 72 hours (3 days) of potential lost production. If we assume that an engine change takes 18 hours, then without ODM fitted $F = 72 + 18 = 90$ hours while with ODM fitted, $F = 18$ hours.

Therefore, for an engine without ODM fitted that operates 600 hours per month and suffers a bearing failure during that period.

$$R_{without} = \frac{600-90}{600}$$

$$= 85\%$$

For that same engine with ODM fitted:

$$R_{with} = \frac{600-18}{600}$$

$$= 97\%$$

In this scenario, ODM is attributed with improving Reliability by 12%.

Availability Improvement

Availability is usually defined as:

$$A = \frac{P-F-S}{P}$$

where:

S = Number of hours of planned outage during a period.

Given base-load 24/7 operation and 1,000 hours of planned outages (S = 1,000), P = 8,760 – 1,000 = 7,760 hours. As presented earlier without ODM fitted and the engine suffers a bearing failure during that period, F = 90 and:

$$A_{without} = \frac{7{,}760 - 90 - 1{,}000}{7{,}760}$$

$$= 86\%$$

For that same engine with ODM fitted, $F = 18$:

$$A_{with} = \frac{7{,}760 - 18 - 1{,}000}{7{,}760}$$

$$= 87\%$$

In this scenario, ODM is attributed with improving Availability by 1%.

In fact, Reliability and Availability will be further improved if one considers the reduction in downtime for inspection due to elimination of false alarms that are common with the chip detector systems that are usually fitted to these engines. A conservative estimate is one false alarm per year leading to an engine outage for inspection lasting about 4 hours. This would be accounted for in the above analysis by increasing F from 90 to 94.

The Affordability Challenge

ODM technology has been available now for close to 10 years and over these years it has become apparent that most operators appreciate the benefits but many still struggle with satisfying the financial affordability questions posed by management to justify any expenditure of capital. These questions are even more demanding in times of economic downturn such as the current situation in the North American power generation market. This has resulted in fewer dollars available to spend and those resources that are available are applied to expenditures that

demonstrate less than a two-year payback period, if not less than a one-year payback! Traditionally, monitoring systems have been considered to have a longer payback period, and thus often do not make the cut. The challenge, of course, is to demonstrate that this is not necessarily so and if all the numbers are analyzed properly there can in fact be acceptable paybacks, and well within the desirable 2 year period.

Operating Cost Reduction

The operating cost for an engine can be considered the sum of the recurring costs (labour, fuel, taxes, mortgages, insurance, scheduled maintenance, etc.) and the event based costs (hurricanes, tornadoes, engine failures, etc.). Clearly the recurring costs are readily predictable and the event based costs less so, which is why insurance is purchased. Unfortunately insurance coverage is limited and in the cases referenced above, only covers a small fraction of the total costs (and little or no lost profits) associated with an engine failure, and in some cases none of the costs associated with the damage such as those due to severe weather. In reality it is the operator who still bears much of the risk.

The fitment of ODM to an engine affects both the recurring and event based cost items; the effect on the event based likely being the more obvious. For the following analyses we assume a typical aero-derivative engine in the 40 MW class.

Consider a bearing failure event where C_{Event} is defined as the aggregate of the cost savings in the event of a bearing failure associated with having ODM fitted to the engine. These items are numerous and may vary from incident to incident but there are significant cost items associated

with a bearing failure that occur consistently for any event. Table 1 summarizes these significant cost items, including estimated magnitudes based on the 40 MW engine example. (Dollar values are in US$ for this analysis).

Cost Item	Cost Savings with ODM	Notes
a) Secondary Damages	$500k	Conservative estimate taken as an average. Main bearing failures can result in over $1.5M repair while gearbox bearing failures may be much less.
b) Lease Engine	$200k	Assuming depot repair time is reduced by approximately 60 days (replace bearing versus repair engine) and a weekly lease engine rate of $25k.
c) Lost Profit	$60k	3 days lost on production while waiting for lease engine to arrive.
d) Penalties	$15k	Penalties paid to customer for degradation of reliability and availability.
Total Savings per Event:	$775k	

Table 1 - Bearing Event Cost Savings Attributed to ODM

$C_{Recurring}$ is the aggregate of cost savings attributed to ODM that can be considered ongoing that do not relate to a single event. Table 2 summarizes these significant cost items magnitudes based on the 40 MW engine example.

Cost Item	Cost Savings with ODM	Notes
a) Insurance Premiums	$5k	Premium reductions of 5% are achievable by installing proven protection systems.
b) False Alarms	$3k	Costs shown are associated with a 4 hour lost production period once per year.
c) Fault Isolation and Troubleshooting	$3k	ODM enables faster troubleshooting and fault isolation, often eliminating the need to shut down the engine. Costs shown are associated with 4 hour lost production period once per year.
Total Ongoing Annual Savings:	$11k	

Table 2: Recurring Annual Cost Savings Attributed to ODM

The third cost savings element that is capturing the interest of operators is extending the engine overhaul intervals. Many gas turbine operators typically follow manufacturers' recommendations for hot section replacements and major overhauls. For many aero-derivative gas turbine engines, the hot section replacement is recommended at 24,000 hours, and a major overhaul at 48,000 hours.

Some operators have already pushed the maintenance intervals to 30,000 and 60,000 hours respectively by combining the regular maintenance routines such as 4,000-hour borescoping and fitting ODM to provide effective on-line bearing condition monitoring. ODM supports this condition-based philosophy since the engine manufacturers may warn that the bearings may exceed their useful life. With ODM fitted, the operator is provided with all the warning required to plan and execute an engine change at minimum cost in the event of a bearing failure.

The gains in Availability and reduction in operating costs associated with extending the hot section and major overhaul are very significant. Typical direct costs of an engine overhaul for a 40 MW aero-derivative engine are as follows:

Hot Section Replacement:	\$800k after 24,000 hours
Major Overhaul:	\$1,800k after 48,000 hours
Total Overhaul Repair Costs:	\$2.6M over 48,000 hours

Assuming the operating profile from the previous example of 7,760 hours per year the 48,000 hours would extend over a 6.2 year period. The annualized cost would be \$419k per year. By fitting ODM, an overhaul extension programme is enabled such that \$2.6M in repair costs are amortized over 60,000 hours (rather than 48,000) and direct overhaul repair costs would now be amortized over 7.7 years. The annualized cost would then be \$338k for a saving of:

$$C_{Ext\,O/H} = \$419k - \$338k$$

$$= \$81k \text{ per year.}$$

Looking at the total cost savings on an annual basis one simply needs to add the three cost elements:

$$C_{Annual} = f_{Event} \bullet C_{Event} + C_{Recurring} + C_{Ext\,O/H}$$

The term f_{Event} is introduced because the cost savings associated with bearing failure clearly is only recognized when a failure event occurs. This probability term typically causes some debate

in any group of operators. Firstly, it is useful to define what is a failure event particularly in light of the fact that we have chosen the very conservative average engine repair cost due to secondary damage of $500k. By this definition an event is any failure that would cause some secondary damage to the engine including failure of:

- main rotor bearings,
- radial drive train (bearings, gears, splines), or
- gearbox drivetrain (bearings, gears, splines).

Damage to any of these components, if detected early in the damage progression, would be contained to the component itself, and not cause a secondary damage condition within the engine.

The source of data to help define the value of f_{Event} includes the engine manufacturers (reporting at user's conferences), overhaul service providers (reporting at user's conferences), large fleet operators and personal experience. The frequency will be influenced somewhat by type of engine, maintenance practices, operational demand, hours operated per year, load, number of starts, etc. Experience in the industry suggests that a reasonable industry average that applies to the more common aero-derivative gas turbines is about one event in 10 years of operation, or f_{Event} = 0.1.

For the example presented above the total annual cost savings are:

$$C_{Annual} = 0.1 \times \$775k + \$11k + \$81k$$

$$= \$170k$$

Payback Analysis

The requirement to spend money responsibly is a requirement in all businesses and the common methodology for ranking each potential expenditure is through payback analysis. Having concluded the total annual cost savings, the payback period is calculated simply as:

$$PBP = \frac{Capital\ Expenditure}{C_{Annual}}$$

Total expenditures to fit ODM to an engine can vary, but for the class of engine under analysis, all costs including equipment and services should not exceed $70k. This analysis therefore shows that for most engines the payback period for fitting an effective condition assessment monitoring tool such as ODM can be less than 6 months. Clearly the example may not exactly reflect every operator's situation but one only has to tweak the numbers in the above formulas to get the right fit. For example, an operator might challenge the frequency of events (one in 10 years) and instead chose one in 20 years. The payback period will still be less than 12 months. If an operator chooses not to exercise the ability to extend overhaul intervals the payback period will still be less than 18 months.

Condition Assessment and LTSAs

Some operators may have long term service agreements that cover some of their financial exposure in the event of failure but certainly not all, and in particular, very rarely will the agreement cover lost production profits. Some argue that the service providers should be fitting these technologies as part of their service, and indeed some already do so. It also can be argued that those operators who do transfer some of the cost risk to service providers through long term service agreements should be concerned with the scope of the condition monitoring tools that are

being applied to their engine. Money that the service provider saves by applying effective condition monitoring should eventually trickle down to the customer and furthermore, this is a good a sanity check on whether the service provider really can deliver on what he has signed up for.

Conclusions

It is already accepted in industry that effective condition monitoring tools such as ODM do provide significant benefits in terms of improved plant Reliability and Availability. What might be novel for some operators is that if the financial benefits are considered fully, such technologies can be shown to provide financial payback in less than one year. The analysis is simple... and compelling.