Oil Debris Monitoring as a technique for Engine Health Monitoring and Condition-Based Maintenance

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Abstract

The collection, followed by quantitative measurement and analysis, of the wearing particles entrapped within the scavenge oil flow is traditionally used as a method to assess the health conditions of gas turbine lubricated parts (gears, bearings). The ultimate goal is to achieve early failure detection, which means that conditions of engine distress are detected before they produce secondary damages.

Several techniques have been devised to accomplish the task of oil debris monitoring, from the consolidated use of magnetic chip collectors to new devices capable to perform the operation automatically, thus reducing the maintenance burden.

The paper provides an overview of the emerging technologies, based on the authors' direct experience gained during the development of the ODMS (Oil Debris Monitoring System) for use on a military turbofan engine. The considerations related to the use of such systems are developed with care to the end-user point of view. It appears that a balanced compromise is required between the accuracy achievable by detailed particle analysis and the need to provide a clear go/no-go criterion for continued engine operation to the ground crew at first line.

1. Oil debris monitoring and Condition-based Maintenance

Oil Debris Monitoring (ODM) on gas turbine engines is the activity related to condition assessment of oil-wetted engine components via the oil system. The basic principle of oil debris monitoring is that wear of lubricated components (gears, bearings) generates particles ('debris'), which are then washed away by the oil itself and are eventually entrapped within the oil filter. Collection and analysis of these particles, in terms of quantity, size, shape, colour and material can tell a lot about the source of the incipient failure and the involved failure mode. This goal can be achieved via a combination of on-aircraft and off-aircraft equipment, with various degrees of accuracy and effectiveness. Different methods to collect and analyse these particles lead to different systems, and a great variety of devices, either well established or still under development, exist. Indeed, background knowledge about the expected debris generation is the key item to assess the performance of these systems.

Overall, lubricated engine components are maintained on condition. Therefore, the goal is to detect random failures of these components within their useful life. This requires that the oil debris monitoring system provide a fair degree of prognostic capabilities, which means that conditions of engine distress are detected before they produce secondary damages (i.e. those critical for engine operation) and become evident by means of other traditional methods (vibrations, high oil temperature). Flight safety is the major but not the sole issue, though. Engine availability and mission reliability are other items of concern.

A known problem is that in reality the currently adopted techniques for oil debris monitoring require scheduled inspections. Furthermore, they often trigger additional investigations, eventually resulting in a confirmation of the serviceability of the engine (this is ultimately a high 'false alarm rate'). It is clear that the maintenance burden is heavy and condition-based maintenance (CBM) would provide real benefit in this field.

2. Existing technologies

A broad distinction should be made between off-aircraft and on-aircraft technologies, although a combination of the two is common.

Off-aircraft oil debris monitoring systems involve lab analysis of the oil itself, of the particles entrapped within the oil filter or of those collected by magnetic plugs located on the scavenge line. These plugs (*Magnetic Chip Collectors*) are specifically designed to collect a portion of the flowing debris and allow quick visual inspection and collection of the particles.

Oil analysis is based on SOA, ferrography and colorimetric analysis; particles can be just analysed visually or by SEM, for size, shape and material composition. This approach to oil debris monitoring is conceptually simple, and lab analysis produces accurate results. Nevertheless, these methods require time and dedicated equipment, and this impacts on aircraft availability. Another major drawback is that the assessment of the analysis results (and therefore of the severity of the possible failure) has to be judged on a case by case basis, as there are no automatic rules to understand the failure mode from the debris. This means that the experience of the operators plays a major role in the assessment. The maintenance burden can be quite high, both for the frequency of the inspection task itself (10-20 engine running hours for the chip collectors), and for the time needed to perform the actual analysis. For the particles collected by the magnetic plugs, a quantitative measurement system (Debris Tester) is also adopted. This instrument has the advantage to allow a quantitative reading of the amount of collected debris, which can be compared with alarm threshold. By unanimous opinion indeed, this method is quite rough, and the results are heavily affected by the operator; it is also considered to overestimate the severity of the failure, thus leading to unnecessary additional maintenance burden. Efforts have been made to develop a system capable to perform debris analysis in an automatic way and infer the reason for debris generation. This process is developed on the basis of 'rules', derived from direct experience, which automate the failure detection process and overcome the need of skilled personnel. This system has been successfully tested on the jet engines. In any case all these methods require a scheduled activity on the engine in order to inspect the plugs or sample the oil. In most of the cases, these inspections result in a confirmation of the serviceability of the engine.

Magnetic plugs and filters are engine mounted equipment providing material for offline analysis. A more desirable system should operate on aircraft to monitor and automatically detect the onset of a failure. For this reason, several debris monitor devices have been developed in recent years, employing a variety of detection methods. A brief overview of existing systems and emerging technologies for aircraft applications is provided here. Overall, only a few can be considered mature. A performance benchmarking and assessment is out of the scope of this paper, but the focus will be on the main issues to be considered for evaluation of such systems for CBM.

Historically, the first 'intelligent' system was the *Electrical Chip Detector* (ECD). It is the natural development of the magnetic plug, as it consists of a collective magnet with two electrical contacts, acting as a switch. The switch is closed when the collected debris fill the gap between the contacts, thus providing an electrical indication about the amount of collected particles. Although this is a good method to avoid a scheduled inspection, the accuracy of the resulting information and the related prognostic capabilities are questionable. The design factor here is that the gap size should be specified in order to be capable of detecting the minimum particle that is deemed critical. Normal sizes are anyway in the order of 2 mm. The ECDs find a major field of application in helicopter gearboxes, where generation of a big amount of fine particles is not considered critical for engine operation, while occurrence of chucks has to be promptly detected.

More sophisticated versions of the ECDs provide the capability to measure the resistance across the gap. This feature, initially introduced for testability purposes, gives the possibility to monitor the accumulation of debris and discriminate between critical and non-critical conditions. Nevertheless, a systematic attempt to correlate the resistance changes to debris type and quantity is quite difficult. A further refinement of the same approach is to quantify the size of the bridging particles from the energy required to destroy them. This is the principle of operation of the *Zapper*. In this system, when the gap is closed, a series of sparks of increasing energy is generated to try and reopen the gap. The energy required to destroy the particle is then related to the particle size. Although this system can detect debris in the micron range, a major drawback is the possible hazard related to the electrical discharge within hot oil. For this reason a protection system is needed to avoid a discharge above an oil temperature limit.

Other available systems for automatic debris detection are based on the principle of inductance variation originated by metallic particles. Three different systems are described here, which exploit the inductance effect with different approaches.

The *Oil Debris Monitor* (ODM) is a flow-through device, which means that the measuring sensor does not interfere with the oil flow. Differently from all the other systems, it is a non-collective device, thus it does not make the debris available for offline analysis, but it does not require any cleaning either. Particles are sensed as they pass through the alternating field generated by a coil around the oil line. Two coils are actually used to generate the field, in order to cancel out any temperature effects. The output information consists in a signal proportional to the mass (and indirectly to the size) of the particle. Ferromagnetic and non-ferromagnetic particles can be discriminated. Debris monitoring is performed counting the number of particles of each size.

The *Debris Monitoring System* (DMS) is the device currently adopted on the GE90. It is a collective device, measuring the arrival of particles captured by a magnet, i.e. the movement of the particle within the magnetic field. The output information is proportional to the size to the particle, but this system is too simple to allow a precise measurement of the mass. Therefore debris monitoring is performed counting the number of particles above a minimum threshold.

The authors' direct experience is with the *Oil Debris Monitoring System* (ODMS). It is a collective device, based on a magnetic sensor, but it does not detect any individual particle. Instead, it provides an indication of the mass of all the particles collected on the sensor tip. The principle of operation is that the mass of the particles generates a shift in the oscillation period of a resonant circuit. The 'integrative' nature of this method means that there is virtually no limit to the minimum particle that can be detected, i.e. the effect of a great quantity of very small particles (individually undetectable) can still be sensed. This advantage is paid in terms of environmental sensitiveness and overall measurement accuracy; in fact the system is affected by any form of bias due, for example, to initial zeroing and oil temperature.

3. The challenge

All the systems described provide, in one form or another, a quantitative measurement of the debris in the scavenge line. In order to be useful for maintenance purposes, they need to be integrated within the Engine Monitoring System with a failure detection logic. This logic should be tailored to the specific engine characteristics and failure modes, and provide a maintenance alarm whenever critical conditions for engine operation are detected. The major task is therefore the definition of the 'rules' that relate debris generation to engine distress for a specific engine. Number of particles, their mass and/or size and the rate of debris generation are the parameters used in this exercise. In principle, the more detailed and accurate the measurement, the more complex and reliable is the detection system that can be designed. Nevertheless, the real challenge lies in the definition and validation of the 'critical conditions'. From the review of the development and validation activity of the existing systems, some general considerations can be derived:

- there is no common understanding about the debris generation profile along failure progress as well as the exact relationship between the type of debris and the engine failure modes. Several interesting efforts have been done, but this field still remains more in the area on proprietary knowledge than consolidated scientific achievement
- as a consequence, there is no common approach to the definition of system requirements, such as type of output and measurement accuracy
- in third place, the approach to the validation task is not standardised. Although several interesting trials have been performed (lab investigations, rig tests, engine data collection), the definition of the criteria to assess correct system operation is left to the system supplier.

For these reasons, none of the devices above can be considered a mature off-the-shelf product; in fact, there is still a certain difficulty for the system designer to choose a technology for a particular engine application. Nevertheless, extensive flight testing is being achieved, and for military jet engine use some systems are currently in a standard configuration. In the following, it will be shown how the questions above have been addressed during the ODMS development and validation. This will be the starting point for some considerations related to performance assessment of the oil debris monitoring and its relationship to condition-based maintenance.

4. The ODMS experience

The development and validation of the failure detection logic for the Oil Debris Monitoring System has involved the authors during the past five years. The ODM function is one of the Engine Monitoring System features, and is composed of the debris monitoring device (i.e. the ODMS) and the failure detection logic. A summary of the system operation and validation activity is provided here.

The whole ODM function design is based on the characteristics and performance of the ODMS. The actual measurement consists in a continuous indication of the current mass collected on the sensor; this information is heavily affected by the environment, e.g by oil temperature variations. To derive useful information about the debris generation process, the function has to perform the following tasks:

- smooth the mass measurement to cancel out short term variations
- identify mass increases
- measure the corresponding debris mass accumulation rate
- compare the accumulation rate with warning thresholds

This approach is based on the following two major assumptions:

- all types of ferromagnetic particles (whatever their size) are significant to identify the onset of a failure
- the mass accumulation rate is the key parameter for engine health monitoring

The first goal was therefore to ensure that sufficiently high capture efficiency could be achieved by the collective device, in order to base the analysis on the biggest possible debris quantity. This was obtained with the use of a centrifugal separator within the scavenge line. An example of the capture capability is shown in Fig.1, which is a photo of the sensor tip (about 2 cm in diameter) completely covered by particles, following a gearbox breakdown.

Fig.1 - Debris collection

The need to distinguish significant events (i.e. high debris generation rates) from environmental noise was a major problem during the function validation. The difficulty arises from the high temperatures which are experienced in the scavenge line of a military engine. The idea was to introduce a thermal compensation mechanism, based on oil temperature measurement. In addition, as debris accumulation is a long-term phenomenon, this compensation should cope with slow thermal changes, while short term variations (lasting a few minutes), due either to temperature transients or other environmental changes, should only be smoothed. Thermal compensation is therefore an essential factor to achieve satisfactory ODMS performance and a big effort was required to refine it. Fig.2 shows the desired compensation for an output variation due to a temperature step change, with a clean sensor (i.e. the output should be zero), compared with the result of a poor compensation. The residual variation, if lasting not more than 15 min, is left over to the smoothing.

A typical example of the temperature compensated output from the ODMS (red line) and its smoothing or 'filtering' (blue line) is shown in Fig.3. It can be noted how the 'essential' information related to the mass accumulation is extracted from the background noise by this process and can be used to identify sudden variations due to debris accumulation.

Although the problems noted above generated some technical difficulties, the real challenge was the definition of a failure detection logic. Having based the operation of the oil debris monitoring function on the mass accumulation rate, is appears logical to define some thresholds for this parameter. How to choose this warning threshold and, even worse, how to validate it were the questions.

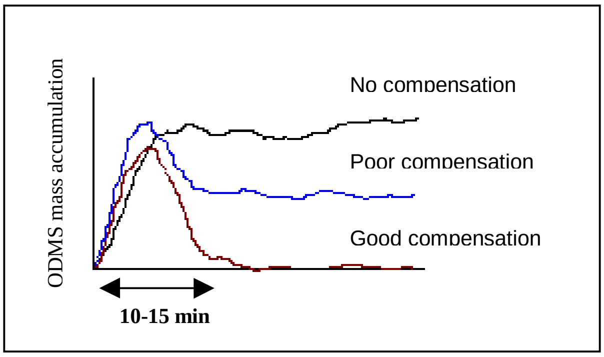

Fig.2 - The effect of thermal compensation (clean sensor = zero indication)

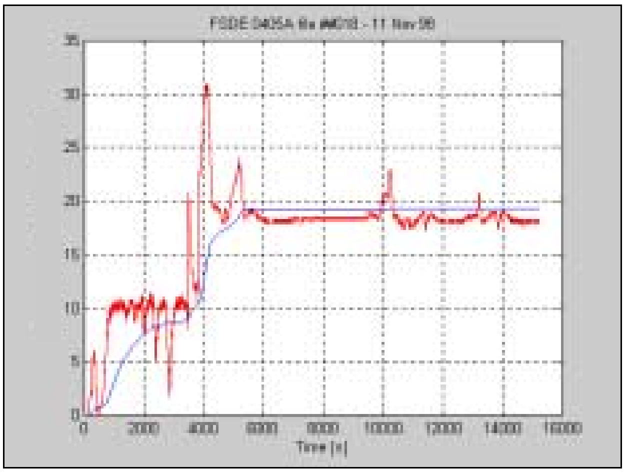

Fig.3 - Mass accumulation

The first problem was solved with an ad-hoc bearing destruction test. The test used a rig simulating the operating conditions of a shaft bearing on engine. The bearing was damaged prior to start the test, in order to induce a failure, and the rig was run up to bearing destruction. An ODMS was fitted on the scavenge line, in order to collect the produced debris, and data were collected and processed as it happens on engine. The test lasted 105 hours, when the bearing failed. Fig.4 shows the type of results that are obtained from data processing. The debris mass accumulation rate is plotted and checked to observe when it increases above a warning limit. This happens a few hours before the bearing breakdown. This event, like the warning raised by an Electrical Chip Detector, is the trigger for a maintenance operation. A more detailed view of the results is given in Fig.5, which shows the time plot of the mass accumulation at the beginning and towards the end of the test. The difference in accumulation rate can be appreciated visually, thus indicating the failure progress.

The experience gained from the rig testing was very useful to define a validation method on engine. Here the issue is that no validation benchmark exists, as there is really no way to know whether the oil debris monitoring function is working correctly or not during normal engine operation. In fact, the actual debris quantity produced by the engine cannot be measured and it is not possible to know in advance when a failure is approaching. It really appears that significant validation can only be done over a long period, along with normal engine operation, based on data collection and analysis. Therefore, the adopted validation approach was based on these key items:

- the background for validation is obtained from lab testing; these results are used to define some 'guidelines' for oil debris monitoring
- the 'guidelines' will be checked during engine development testing for confirmation or further refinement; traditional oil debris monitoring (i.e. via magnetic chip collectors) will be used in parallel to avoid the occurrence of undetected failures.
- occurrence of false alarms should be kept to a minimum and possibly avoided, in any case unnecessary maintenance burden due to warnings from the automatic oil debris monitoring should be lower than using the traditional methods
- of course, occurrence of engine failures, although undesirable, would help a lot in the validation process

As a result of this validation activity, when sufficient confidence in the automatic oil debris monitoring function will be achieved, then it will be possible to discard the traditional inspection techniques and rely on the ODM function alone. This validation process is currently ongoing with flight testing.

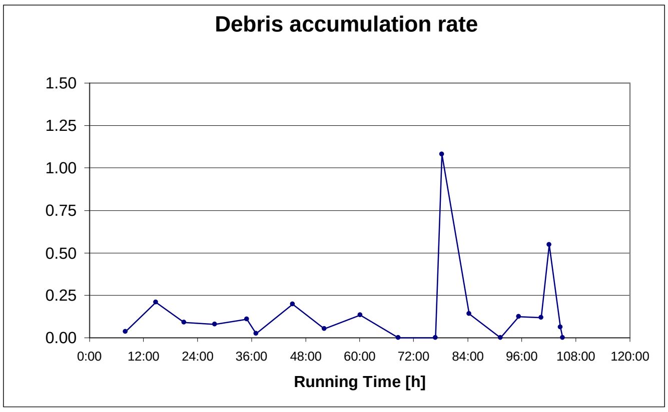

Fig.4 - Bearing destruction test results

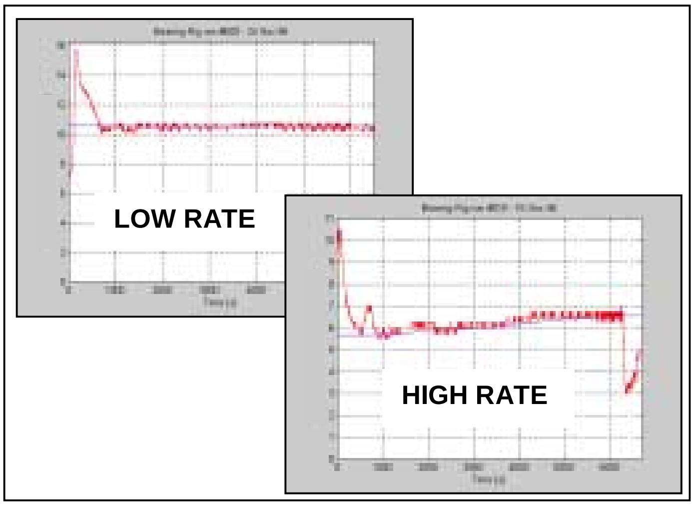

Fig.5 - Mass accumulation rate variation

5. The engine company perspective

The development and validation activity of the ODMS, briefly described in the previous paragraph, provided useful considerations that can be applied to the problem of oil debris monitoring and the selection of a suitable device to accomplish this task.

The temperature compensation issues posed serious limitations to the achievable measurement accuracy. In the end, it is acknowledged that the performance of the ODMS in terms of minimum detectable particle is not impressive and probably less than similar systems. Also, the type of measurement that is performed (mass accumulation of all the captured particles) is indeed quite simple, even rough, compared with the detail achievable with individual particle analysis. Nevertheless, the remarkable aspect lies in the simplicity of the failure detection method, which on the basis of warning thresholds provides a go/no-go indication for maintenance crew. This is quite similar in principle to the warning indication provided by the most common of the automatic debris monitoring devices, the Electrical Chip Detector, but the details and accuracy required to the ODMS are much higher than the ECD.

In the end, this appears as the major lesson learned from the ODMS development, that the aim of on-aircraft oil debris monitoring should not be a detailed analysis of the particles with complex detection logic. The proposed approach, at the basis of the engine ODM function development, is to provide a simple and reliable criterion to warn the maintenance crew about the arising of critical conditions for the engine. This will trigger all the required additional investigations and analysis which can be better performed offline in a lab environment. Due to the relatively infrequent arising of failures detectable via debris generation, the point is to try and avoid false warnings or unnecessary maintenance actions just to confirm the serviceability of the engine. The maintenance crew at first line should only be informed about their major concern i.e. whether it is safe to continue to operate the engine or not. Of course the big challenge lies in the transition from a relatively 'safe' approach, based on regular checks, to the intrinsic risk associated with an on-condition warning system. Therefore the reliability of the failure detection logic has to be well-proven through a series of back-to-back testing with the current methods, before sufficient confidence is achieved. Another consequence of this validation approach is that the system will be benchmarked against the performance of the magnetic chip collectors which, despite all their limitations, still represent the adopted system on several in-service engines.

From the considerations above, a proposal for an integrated oil debris monitoring function, supporting engine condition-based maintenance, can be derived. The function will be composed of:

- *an automatic online debris measuring device*, capable to provide some quantitative indication of the amount of debris
- *an online failure detection logic* that will use the debris measurement to define the occurrence of critical conditions and provide a go/no-go criterion to the maintenance crew
- *additional methods for oil debris analysis* (inspections of magnetic chip collectors, oil sampling) combined with the availability of offline analysis tools, possible integrated within the Ground Support System. This will be used on-condition to confirm the warnings detected by the online system, identify the source and the reason for the arising failure and drive the consequent maintenance actions

A major advantage of this design is its modularity, which will allow selecting, developing and refining each component to various degrees of complexity, on the basis of the required accuracy, prognostic capabilities and available budget. The underlying concept indeed is that it will lead to condition based maintenance for the failures detectable via debris generation.

6. Conclusions

The existing technologies for oil debris monitoring have been reviewed and the direct experience gained in this field during the ODMS development has been described. The challenges posed by the validation of the ODM function on a military engine suggest that the design of the monitoring logic should focus on the end-user perspective and avoid unnecessary online complexity. Therefore, the aim is to provide some criteria to define whether the engine can be operated safely or additional maintenance actions are required. In the latter case, additional, more detailed investigations can be performed offline. Given the burden derived by scheduled inspections (which currently most often confirm the engine serviceability or trigger unnecessary warnings about the engine health), this technique appears a good compromise between the complexity of the task and the reliability required for an online logic. Therefore it appears as a way to achieve condition based maintenance for failures detectable via oil debris generation.

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