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Comparison of Bearing Spall and Fault Diagnostics using Inline Debris Monitoring

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Abstract

Wear debris monitoring and analysis are critical diagnostic and prognostic tools for modern Health and Usage Monitoring Systems (HUMS) across aerospace, industrial, defense and marine industries. Rotorcraft transmission gearboxes have relied on wear debris-based health indicators to drive maintenance action and maximize asset availability, prevent in-flight failures, and reduce operational costs. Inline wear debris monitoring technologies such as electronic chip detectors (ECD) are commonly installed in rotorcraft gearboxes. However, oil debris monitors (ODM) mainly in use in aircraft gas turbines have recently been presented as a viable alternative. These systems are used for targeted condition-based maintenance of rolling element bearings (REB) and gears within the system HUMS program. Comparative testing of the two monitoring technologies has been conducted using laboratory REB failure testing with both systems installed in simulated rotorcraft environments. Herein, REB, seeded with a minor surface defect, are loaded and rotated until raceway spall develops, discharging wear debris for the ODM and ECD systems. A total of eight tests compiled the performance metrics of the two monitoring systems against visual ground truth inspections of the bearing damage level. These scalable and translatable metrics will assist HUMS programs in decision making and reliability considerations for the critical oil wetted gears and bearings in their gearboxes. The main testing criteria of the two monitoring technologies is reliability in terms of detecting the raceway spall before significant damage is prevalent on the bearing and avoiding false alarms where the system indicates a fault prematurely. Overall, the study found strong and reliable correlation between ODM sensor condition indicators and the bearing damage, whereas the ECD showed significant variance in performance and a tendency for false alarms.

Keywords: Oil Condition Monitoring, Oil Debris Monitoring, Electronic Chip Detector, Online Sensor, Rolling Element Bearing Spall, Condition-Based Maintenance

Introduction

Accurate real time condition assessment of equipment is critical for diagnostics and prognostics as well as safety. Generally, there are two forms of condition assessment policies enacted for critical rotating equipment maintenance decisions: offline analysis vs on-equipment continuous monitoring. Periodic offline analyses, including equipment inspection, oil sample analyses, non-destructive testing, and data analysis, assist in driving maintenance decision making. To reduce maintenance costs, prevent inflight shutdowns within inspection intervals, and maximize asset availability, inflight continuous monitoring implementation has increased significantly. Vibration, temperature, acoustic, pressure, and Oil Condition Monitoring (OCM) are all forms

of continuous monitoring technologies that provide immediate and continuous notice of engine, gearbox and structural condition.

Within the last few decades, wear debris sensing has proven to be a valuable feature for continuous monitoring programs. Related products and methods monitor the metallic debris that are discharged into the lubrication system of rotating equipment including aircraft gas turbines, accessory gearboxes, and rotorcraft transmissions. Oil-wetted components with developed faults will discharge abnormal wear debris into the lubricating oil. By monitoring the discharged debris, the condition of the rotating equipment components can be approximated. This is built on the foundation of previous oil sample analysis programs which monitored Ferrous debris concentration (PPM) within a constant oil sample volume to approximate the engine condition.

The two most developed and implemented forms of continuous monitoring of wear debris are electronic chip detectors (ECD) and online debris monitors (ODM). Both are graphically represented in Figure 1.

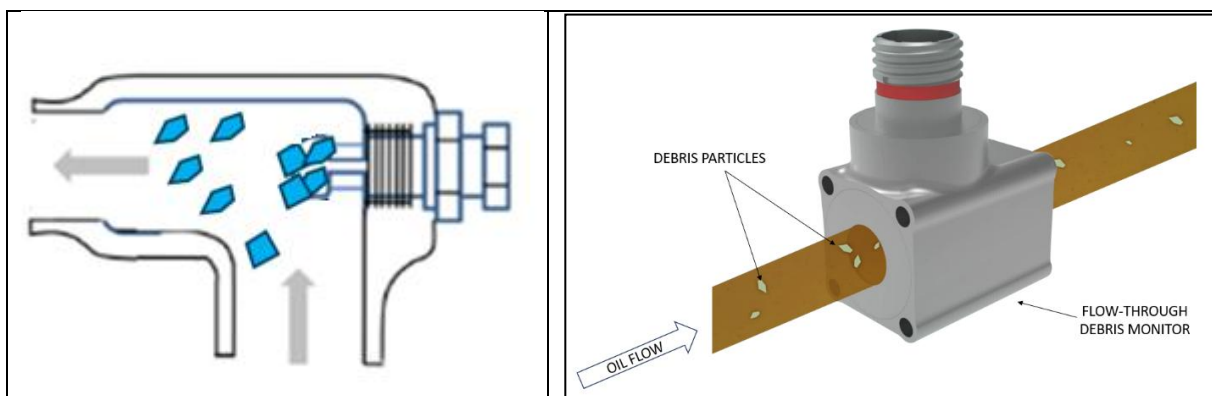


Fig. 1: Graphic showing ECD capturing passing debris along two prongs (left) and ODM detecting passing debris particles through bore within oil lines (right)

ECD rely on two magnetic prongs installed into the lubricating flow. Once a fault develops, the discharged wear debris is attracted to and accumulates on the prongs. Once enough debris accumulate, such as that of a failing component, a bridge is formed between the two prongs. The bridge connects the two prongs which are part of an open circuit closing the circuit. This electrical connectivity indicates a possible engine fault.

ODM sensors are flow-through inductive sensors. As wear debris passes through the sensor bore, inductive coils produce a voltage due to the particle's magnetic and conductive properties. The particle trace produced indicates whether the particle is Ferrous or Non-Ferrous which assists in identifying the failing component. Furthermore, it can also be used to size the passing particle, which can assist in the diagnostic process.

Due to the low frequency of failure, there exists ambiguity in the performance metrics of both the ECD and ODM. For this reason, empirical testing was conducted using seeded rolling element bearing failures, which are one of the most common and critical failure modes. Both systems were installed in scavenge lubrication downstream of the failing bearing to gauge the performance of both diagnostic systems for the bearings. This document will report and analyse these metrics across several tests.

Testing Overview

Several seeded fault tests were conducted within a controlled laboratory environment. Angular contact rolling element bearings with Rockwell C hardness indents to initiate a fault on the inner raceway were spun at 6,000 rpm at various loading profiles. Test durations ranged from 20 to 300 hours, and all successfully produced adequate spall. Visual inspections were conducted at various points throughout the test to provide ground truth measurements of fault levels.

In all the tests except one, a valid chip detector bridge was formed and an alarm was provided. In each test, ODM Ferrous counts were tracked via the MetalSCAN ODM system. Figure 2 shows the status of the ECD (green for healthy, red for alarm) and the progress of the ODM counts for a single test. After its first trigger, the ECD was cleaned and installed back into the system and the bearing was operated again until the second trigger at 41 hours. This was to observe how long it would take for another alarm to be initiated by the ECD. Also noted is when spall was first observed and confirmed by measurement at 12 hours. Inspections were also conducted at 32 hours, and each time there was a trigger. These are shown graphically in Figure 2.

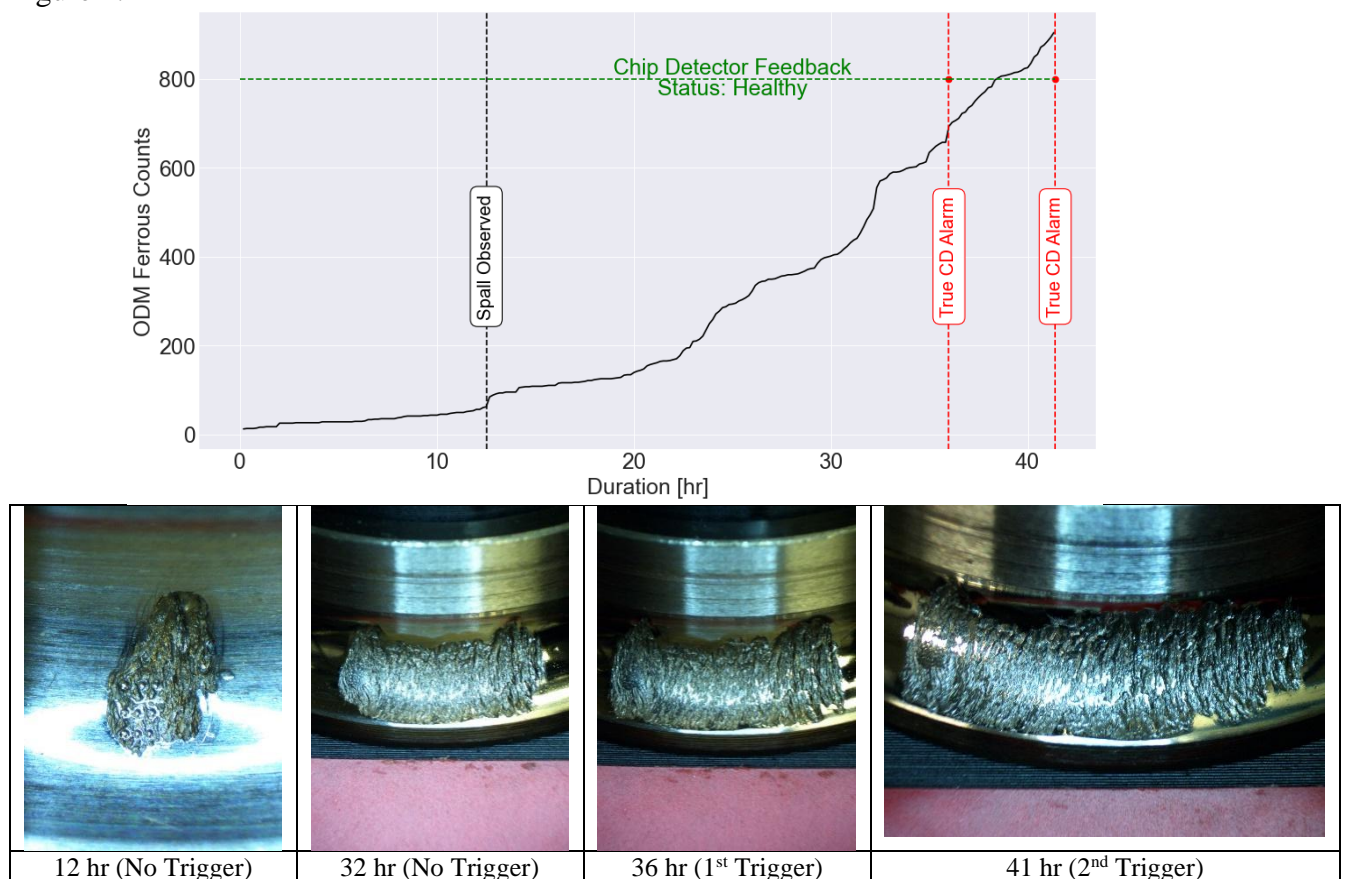


Fig. 2: Single Test overview showing ODM counts observed over time and the ECD status (top) and the visual damage inspections (bottom)

Testing Results

In 7 out of 8 tests, the ECD triggered at least one true alarm. False alarms accounted for about 20% of all triggers. In this case a single long particle was able to form the bridge rather than the accumulation of several particles. Per the instructions associated with this ECD's use, these alarms were considered false. These large flake-like particles are generally associated with break-in or run-in wear and offer no insight into component condition. The single test where the installed ECD was unable to form a bridge despite active bearing spall was abandoned after 200 hours.

ODM counts increased progressively in each test in a similar fashion to Figure 2. However, within this application domain, ODM counts generally are fitted into a three-tiered diagnostic model. Essentially, based on the number of total observed counts by the ODM, the component condition falls into one of the following stages:

Stage 1 – Healthy: component is of good working condition. A few particles may be seen due to residual running wear, or break-in wear.

Stage 2 – Warning: After crossing the ODM warning threshold, a fault is reported by the ODM system. This indicates the presence of a true fault. Maintenance should be scheduled, and proactive maintenance practices can be enacted. Degradation and subsequently produced counts continue to occur steadily while the asset's operation continues.

Stage 3 – Alarm: After crossing the ODM alarm threshold, degradation can be severe and rapid. Catastrophic failure by bearing seizure or fault propagation is possible. This is tied to the spall knee within bearing degradation curves (well documented in literature) and is when the degradation progresses from steady to severe [1]. Bearings should typically not be operated beyond the alarm stage.

In 4 out of the 8 tests, the ECD indicated a fault within the warning stage of the ODM diagnostic system. In the remaining 4, the ECD did not detect, or detected well after the alarm stage was reached, indicating a late diagnosis. In all eight tests, the ODM warning stage was diagnosed indicating fault presence before the ECD alarm. In one test, the ECD did detect a fault in close proximity after the warning was provided by the ODM and both sensors performed adequately. In the remaining tests, the ECD detected a fault well after the ODM warning status was reached. On average, the ODM provided fault notice 40 hours or 14 million revolutions before the ECD. Furthermore, on average, the ECD provides notice after 70% of the bearing life is used up before the spall knee. A single test showcasing the performance of both the ECD and ODM diagnostic systems is shown in Figure 3.

As mentioned briefly, the lubrication environment in the bearing test rig for the ECD and ODM is ideal, however, aerospace lubrication systems can include aeration and turbulent flow rates. Therefore, tests were conducted using aircraft simulated lubrication environments on a flow test rig and the ECD performance suffered, requiring sometimes thousands of particles rather than hundreds to form a bridge. Furthermore, it was revealed that the capture efficiency within these environments was generally 25%. This was approximated by placing the ECD in between two ODM sensors to see the difference in observed counts in between them. In some high aeration and flow rate environments, this dropped to 10%. This indicates that the vast majority of particles that pass the ECD are generally uncaptured by the two magnetic prongs.

The ODM counts were also found to closely align with the actual damage observed via inspection. The number of counts closely correlates to the actual damage area, as reported in previously published literature for both rolling element bearings and gears [2]. There is little error in the stage identification. Generally, if an alarm is reported by the ODM, the area of damage on the bearing is very close in proximity to the area that will initiate the spall knee. This area has been found in several previous publications. Overall, there is little variance within the ODM diagnostic system in correlation to the actual damage on the bearing raceway [3].

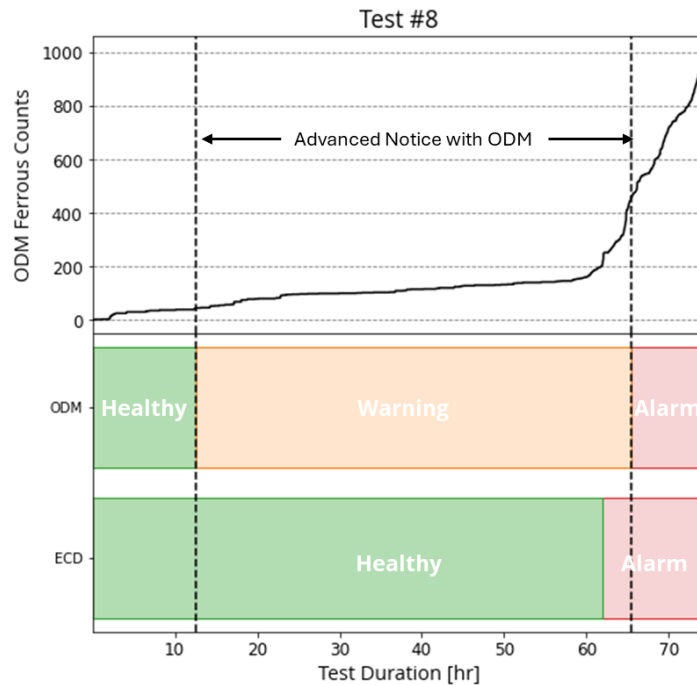


Fig. 3: Single Test showcasing diagnostic status provided by each system along with the ODM counts across the test duration.

Results Discussion

Industry has commonly reported a false alarm issue with ECD, where a single or few particles form the bridge between the two prongs, and there is no engine/component damage. These experiments have validated this issue with 20% of all triggers being false positives. This can be application and scavenge lubrication environment dependant.

ODM diagnostic systems offer earlier and more reliable fault notice. Consider the example of the single flake forming a bridge for the ECD creating a false positive. Within ODM systems, it would simply count as one particle, and warning and alarm levels generally require a significant number of particles. This quantity sets the foundation for the ODM's reliability as it depends on the total quantity, and is unaffected by high flow rates, noisy environments and aeration.

The early notice is also based on its observance of more counts. The capture efficiency of ECD generally being between 10-30% means there are significantly more particles detected by the ODM. Therefore, the warning count threshold will be crossed quickly once a fault develops, and the close correlation between the discharged counts and actual damage indicates that further damage will be detected immediately by the ODM system.

The ODM's three-tier diagnostic system also assists in maintenance decision making. Rolling element bearings are critical equipment, however, they can operate for millions of cycles with a detected fault. The differentiation between warning and alarm stages coinciding with steady and severe spalling levels provides operators with invaluable insight into the component condition. This can assist in deciding whether to perform an emergency landing, return to base, or complete the flight, and removes the burden from operators.

Conclusions

Continuous monitoring is a critical aspect of the maintenance program for both fixed wing and vertical flight applications. This document shows empirical evidence highlighting the improved

fault notice and reliability of ODM for condition assessment of rolling element bearing failures. Issues with false alarms and high variance in ECD alarms were found in this study, and the high correlation between accumulated debris counts and damage area proved valuable towards the ODM multi-tier diagnostic model.

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