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Delivery Order 0040: Bearing Health Monitoring Research and Development

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14. ABSTRACT
This research in support of the Air Force Research Laboratory Materials and Manufacturing Directorate was conducted at Wright-Patterson AFB, Ohio from 8 July 2005 through 1 February 2008. This task developed methodologies and performed health monitoring on advanced systems for aerospace applications to bearing materials. Coated bearings in high performance turbine engines can provide considerable advancements in engine reliability and service life extension. One coating performance indicator is the level of vibration generated by rolling elements and their cage separators at high speed bearing operation. Vibrations in engine bearings can be difficult to monitor because they are located in cramped spaces, and there is often system noise caused by other components located on the same shaft. A potential in-situ bearing health monitoring solution is a non-intrusive cage-mounted sensor that detects cage vibration and transmits wirelessly to a nearby receiver. This work describes the sensitivity of the cage-mounted sensor compared to a support-mounted accelerometer in the detection of seeded faults in coated and uncoated bearings.

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condition monitoring, Coated bearings, RF sensor

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Table of Contents

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1.0 INTRODUCTION

Currently, aircraft engine bearings are replaced based on indirect inspection techniques such as chip detection and oil analysis. Each time an engine is torn down to replace a bearing, it grounds the aircraft and costs many thousands of dollars in materials and manpower. In the case of a bearing contamination failure characterized by a spalled bearing race, the effect is even more destructive and may result in engine shut-down and degradation of flight control. In extreme cases, the entire engine may be lost, resulting in millions of dollars in damage. A reliable and direct method is needed for bearing fault detection.

Many techniques have been used to diagnose bearing faults. High frequency methods include monitoring resonance, acoustic emissions [3] and shock pulse methods [4]. Low frequency detectors include accelerometers, fiber optic [5] and incremental motion encoders [6]. The problem with current fault diagnosis technologies is that they are bulky and not easily installed into the tight spaces of the jet engine. Many would also be susceptible to the high vibration environment and surrounding component noise level, and even fewer would be adaptable to the high temperatures required. Currently, many aircraft engines have chip detectors which are used to diagnose bearing failure [7,8]. But the chips have a convoluted path to get to the detectors, which are usually located far downstream from the bearing. Even when chips are detected, they may have come from another engine component and not necessarily from a failing bearing. Regardless, by the time large chips have spalled off and been caught in the detectors, the bearing is well on its way to failure. The benefit of the cage-mounted sensor is that it can more readily detect bearing motion because of its location on the cage (Figure 2). However, it does not detect vibration like an accelerometer. Instead, it measures cage motion relative to a nearby stationary receiver, and translates this motion into vibration. The cage-embedded sensor transmits wirelessly to the receiver, and this direct method for detecting spalls has the potential to indicate a failing bearing at the first sign of trouble.

2.0 EXPERIMENTAL PROCEDURE

2.1 Test Set-Up

Trials were run on a specially-built high-speed bearing tester (Figure 3) at room temperature and pressure. The test bearing was a 25mm high speed angular contact bearing, chosen for its ease of assembly and disassembly. The phenolic cage was saturated with Pennzane® as the lubricant and all trials were run at the same temperature, load, pressure and duration. Vibration data was collected at shaft speeds of 0 to 10,000rpm every 500rpm. Sensor output was fed through a phase lock loop (PLL) demodulator to the oscilloscope. Accelerometer output was unfiltered and sent directly to the oscilloscope (Figure 4). Ten FFT averages helped to improve the signal-to-noise ratio, along with a 20MHz low-pass filter built into the oscilloscope. Finally, inner race fault frequencies were calculated using industry standard equations [9], and results from the sensor and housing-mounted accelerometer were compared to determine the minimum fault size detectable by each device.

2.2 Uncoated Bearings

An unflawed bearing was run to create a baseline vibration signals for the sensor and accelerometer. Then, flaws of 10μm, 28μm, 35μm, 50μm and 63μm were machined into the inner race of an uncoated bearing to simulate spalling (Figure 5), and vibration signatures were obtained using the sensor and accelerometer at each depth (Figure 6). Two sets of data were recorded for each spall depth to establish repeatability of the results. The spalls were machined using a precisely positioned drill bit to ensure perfect overlap, and a white light interferometer was used to measure depth in the wear track.

2.3 Coated Bearings

The inner and outer raceways of two unflawed test bearings were coated with TiCN to thicknesses of 0.4μm and 1.4μm, respectively, using a physical vapor deposition process. Each inner race was deposited with a 1/8" diameter mask to prevent coating in that area. After coating, the mask was removed during cleaning and the bearing re-assembled using the normal process. The flaw depth was the thickness of the coating; no additional spall was machined. A third coated bearing was unflawed with a thickness of ~1μm, and used for baseline testing. Two sets of vibration signatures were obtained using the sensor and accelerometer for each coating thickness. Coating thickness was measured using the white light interferometer at the site of the masked area (Figure 5).

3.0 RESULTS AND DISCUSSION (ALSO, 3.2 SENSITIVITY TO COATING FAILURE)

3.1 Sensitivity to Spalling

Both the sensor and the accelerometer detected the seeded faults in the uncoated bearing, but the accelerometer detected smaller flaws at a broader range of shaft speeds. The BPFI (inner race spall frequency) did not reliably appear in the sensor data until the spall was 28μm in depth (Figure 7). The sensor detected the 28μm flaw in just 38% of the tested motor speeds, and had a 60% detection rate for the 63μm spall. Therefore, although the amplitude of the BPFI did not increase with spall depth, it was detected at more shaft speeds, and was therefore more reliable as the spall size increased (Figure 8). However, the BPFI was often difficult to spot because its amplitude was often not much greater than the noise level.

The housing-mounted accelerometer exhibited a clear BPFI at most motor speeds, even for the smallest tested 10μm spall (Figure 9). Both the detection rate (Figure 8) and the BPFI amplitude remained nearly constant for each spall depth tested. The accelerometer was just as reliable in detecting the 10μm spall as the 63μm spall. The sensitivity limit of the accelerometer was not tested, but it detected the coated bearing flaw at 0.4μm and the average roughness of the coated bearing was 0.15μm, so the lower detection limit of the accelerometer is assumed to be close to 0.4μm. The detection rate of the accelerometer was not a perfect 100% because neither the sensor nor the accelerometer detected the flaws at the higher speeds near 10,000rpm, and the accelerometer detected best at the lower speeds around 1000rpm-4000rpm.

3.2 Sensitivity to Coating Failure

The accelerometer successfully detected the missing coating on both the coated flawed bearings (Figure 10). It also was slightly more reliable in detecting the 1.4μm coating failure than the thinner coating (Figure 11). However, the cage sensor was unable to detect the coating flaw in either bearing and exhibited only healthy signatures (Figure 12). The large values in the 0.4μm and 1.4μm flawed bearings are probably a harmonic of the cage rotation rate and not detection of the spall.

Increasing the coating thickness beyond 1.4μm was not considered due to space and durability restraints. Previous studies report that bearing coatings thicker than 2μm tend to delaminate and flake off during operation [10]. In addition, too thick a coating will increase stiffness and wear rates and decrease the life of the bearing. Therefore, the sensor was judged ineffective in detecting coating failure, not surprising since the sensor did not identify a spall in the uncoated bearing until it was 28μm deep.

3.3 Signal Conditioning

In an attempt to optimize the sensor output, first and fifth-order Butterworth low-pass filters were built to amplify the small sensor signal and minimize high-frequency noise. Both successfully boosted the signal to the oscilloscope. However, they also increased the noise level by acting as a magnifier of electricity and room noise. The sensor signal was amplified, but consequently drowned out by the similarly amplified noise. This was determined not to improve the effectiveness of the cage sensor and the filters were removed.

Separately, a low noise amplifier was installed on the sensor output to boost the small signal from the sensor before it is demodulated. In theory, this would increase the output from the demodulator while keeping the noise level the same. The result was a complete loss of output from the demodulator. The low noise amplifier (LNA) was unable to transmit the 30MHz output from the sensor to the demodulator. Even though the signal of interest, the BPFI, is on the order of 1kHz, the output from the sensor is in the MHz. Without the full input from the sensor, the demodulator was unable to output the BPFI, so the LNA was removed.

3.4 Future Work

Future work will include installing a high-frequency low-noise amplifier which will boost sensor power after telemetry but before demodulation to increase the sensor signal-to-noise ratio. Also, additional trials are needed to establish repeatability, including changing the diameter of the spall. Additional sensors are being fabricated and it will be important to determine repeatability between sensors. The circuitry on the receiver is very susceptible to input power and has been overloaded several times. Comparing the results from a new circuit board with the one used in these trials will be very helpful in determining robustness and whether this sensor used in these trials was fully functional.

4.0 CONCLUSION

The smallest spall on an uncoated bearing that the sensor detected was 28μm with a reliability of 38%. The sensor was unable to detect the coating failure at all. In contrast, the accelerometer reliably detected all levels of flaws, the smallest being 10μm on the uncoated bearing and 0.4μm on the coated bearing, with a minimum reliability of 78% for the uncoated bearing and 53% for the coated bearing. This research successfully demonstrated that the sensor could detect bearing spalls and established its sensitivity level. In the next generation of sensor, the receiver temperature capability will be increased. With further advances in miniaturization, sensitivity, temperature and transmission ranges, the cage-mounted sensor may become a reliable and direct approach for engine bearing health monitoring.

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