Bearing Health Monitoring and Life Extension in Satellite Momentum/Reaction Wheels

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Abstract—Bearing faults in momentum/reaction wheels and control moment gyros are a significant life- and performance-limiting factor in spacecraft. Even when complete failure does not occur, problems with excessive bearing torque and torque noise can drain power and negatively impact vibration sensitive instruments. The failure mechanisms in these applications and the monitoring technologies needed are significantly different from most terrestrial and aircraft systems. This paper describes field experience and experimental data on bearing faults in satellite applications, and presents new monitoring technologies that allow optimal control of lubrication, thus extending life and preventing torque anomalies. These include a unique wireless sensor that measures cage temperature and motion, which are shown to be sensitive indicators of lubrication effectiveness. The technologies described may also be useful in aircraft applications such as hanger bearings where loss of lubrication, rather than contact fatigue, is the primary failure mechanism.

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1. INTRODUCTION

Momentum/reaction wheels and control moment gyros provide mission-critical orientation, stabilization, and energy storage for most spacecraft. These devices, referred to herein as attitude control wheels or ACWs, consist of a flywheel, a spindle that typically contains two precision angular contact ball bearings, a frameless electric motor, and control electronics integrated into a sealed housing. Figure 1 shows an exploded view of a representative attitude control wheel design.

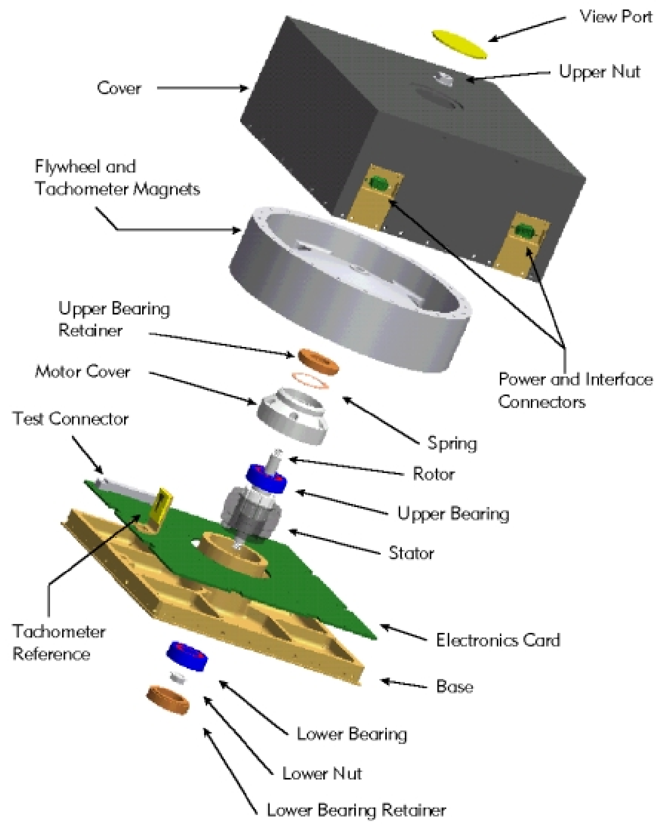

Figure 1. Representative attitude control wheel design (courtesy of NASA/JPL).

As the only wearing mechanical component, bearings tend to be the life-limiting element. In fact, bearing lubrication problems are the primary cause of premature ACW failure (Auer, 1990; Fleischauer and Hilton, 1995). In addition to causing premature wear, lubrication problems can cause cage vibration that adversely affects sensitive satellite instrumentation, for example in imaging satellites (Boesiger and Warner, 1991).

The basic sensing technologies and diagnostic approaches that have been developed for terrestrial and aircraft bearing applications are not directly applicable to spacecraft. Existing technologies focus on detecting fatigue spalls

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(vibration monitoring) or major increases in friction (temperature). Fatigue failures generally do not occur in spacecraft applications, since loads are light and debris contamination is not an issue. Monitoring race temperature in spacecraft bearings has also proven to be of limited value, since a noticeable race temperature rise does not occur until there is significant damage.

Traditional diagnostics focus on detection of damage in order to identify components that will need replacement. Since bearing replacement is impossible in most spacecraft, our objective is to detect potential problems early enough so that effective mitigation (e.g., the injection of additional lubricant) is possible *prior* to the occurrence of irreversible damage. In addition, prognostic technologies that forecast remaining life based on bearing state and remaining lubricant would be extremely useful so that eventual end-of-life can be anticipated rather than occurring unexpectedly. Predictive prognostics also enable actions to slow fault progression (such as a reduction in speed) and thereby maximize useful life. This paper describes research on ACW bearing operation and a new sensing technology that has been developed for health monitoring and life optimization in these applications.

2. ACW Bearing Lubrication

Typical attitude control wheel lifetimes are 3-7 years, and redundant ACWs are often carried on board to accommodate failures. As noted earlier, bearing lubrication is the key issue in ACW failure. Since it is difficult to keep lubricant contained within a moving bearing over long periods in a vacuum and weightless environment, grease packed bearings are giving way to newer lubrication systems that meter oil at a slow rate to make up for losses. However, there is currently no feedback of lubrication effectiveness and thus no means to prevent an over- or under-lubricated condition. The objective of this research is to develop a monitoring capability that can work in concert with these lubrication systems to optimize oil quantity. The key technical challenge is thus identifying parameters that indicate lubrication status before the bearing enters a damaging mode of operation.

An optimal lubricant quantity exists that results in both long life and low torque. Too little lubricant results in asperity interaction, premature wear, excessive noise and vibration, and possible destructive cage instability modes. Too much lubricant results in excessive bearing torque, early exhaustion of the lubricant supply, torque noise, and increased risk of lubricant contamination in other components. This optimal lubricant quantity will vary depending on temperature (viscosity) and speed. The Stribeck curve shown in Figure 2 describes the relationship between lubrication and friction. There are three lubrication regimes: Boundary, where there is some lubricant present on the surfaces but no film pressure is developed; Elastohydrodynamic lubrication or EHL, where there is a complete film developed; and Mixed, which lies between the other two states and is a combination of partial film formation and direct asperity interaction. The lubrication state resulting in the lowest friction and torque is near the transition between mixed and EHL; this also represents the minimum amount of lubrication necessary to prevent direct surface contact and wear, and is the optimal state for a spacecraft bearing to maximize life with a fixed lubricant supply.

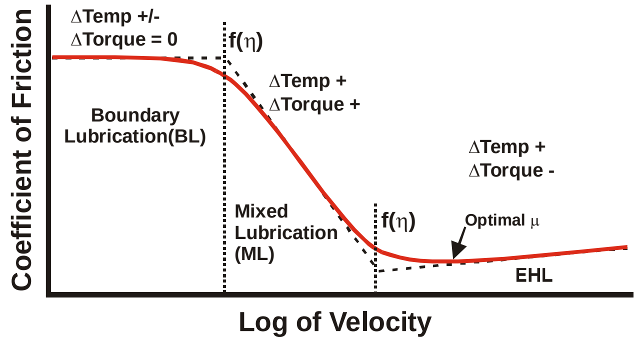

Figure 2. Stribeck curve showing the relationship between friction and film thickness in lubricated contacts.

The ball-cage interface is the critical contact in terms of bearing lubrication. While more extensive research has been conducted on the rolling ball-race contact, it is the sliding ball-cage contact that usually overheats and fails first when lubrication is inadequate. Figure 3 shows a UH-60 tail rotor driveshaft hanger bearing that failed during a lubricant starvation test. Note that the cage has bent in several places due to overheating and jammed the bearing. Figure 4 shows an ACW bearing from a similar starvation test. This bearing design uses a composite rather than a metal cage. The cage has broken in several places, and dust from extensive cage wear is visible on the bearing surfaces. The balls and race were undamaged in this test.

Figure 3. Failed UH-60 hanger bearing from lubricant starvation test.

Figure 4. Failed ACW bearing cage from lubricant starvation test. Note dust on races from cage wear.

Existing sensory parameters in attitude control wheels are quite limited. Motor current/torque is often the only parameter available, and past research has shown that by itself motor current gives limited information on bearing lubrication status until a significant problem has developed (Fleischauer, 1997; Marble and Sadeghi, 2001).

One of the most comprehensive collections of general work in this area is contained in NASA's *Space Mechanisms Lessons Learned Study* (Shapiro, et al., 1995a & b). This publication describes a number of examples of spacecraft tribological failures (both mechanisms and rolling bearings), and summarizes many of the related papers. Fehrenbacher (1991), Fleischauer (1995), Kalogeras and Didziulis (1995), and others have also investigated tribological issues in spacecraft.

3. BEARING CAGE SENSOR

During an earlier study [Marble and Sadeghi, 2001], several types of commercially available sensors were tested for diagnosing ACW bearing lubrication state. None of them proved useful. A novel wireless sensor for cage temperature and instability was then developed by the authors and has proven highly effective for identifying the transition between EHL and mixed lubrication regimes. Depending on the bearing design, this may be indicated by cage temperature, instability, or both. Detection of this transition is the critical indicator that more lubrication is needed, and yet it occurs well before any damage occurs. In the ACW application, this could be used to trigger injection of a small amount of additional lubricant. In other applications (such as a sealed hanger bearing), it could be used as a fault indicator to signal the need for bearing replacement.

The unique cage telemetry sensor used in this project consists of a passive transponder circuit mounted on the bearing cage and an active excitation/measurement circuit mounted on a stationary circuit board adjacent to the bearing. The system is similar in concept to the RFID tags commonly used for security and identification of store merchandise. The resonant frequency of the cage circuit is dependent on both temperature and cage position; thus, slow variations in frequency are due to cage temperature and rapid variations are due to cage motion. The output signal is fed to a separate signal processing system that demodulates the signal and separates the temperature and motion components. The cage telemeter can thus be used to measure cage temperature and also to detect cage instability, and can even determine the frequency at which the cage instability is occurring. Figure 5 shows a bearing instrumented with the cage circuit portion of the system. The transponder weight is only 0.1g and is embedded in the composite cage.

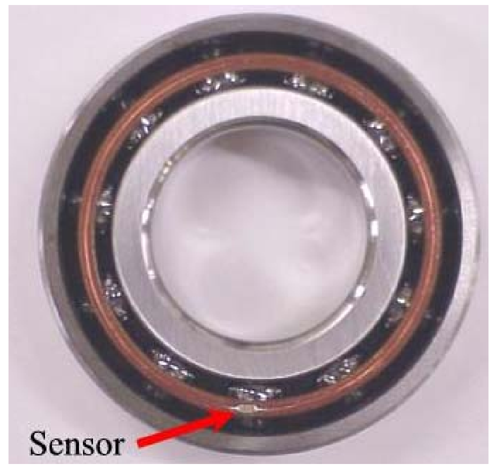

Figure 5. ACW angular contact bearing with transponder installed in cage.

The excitation/measurement circuit mounts adjacent to the bearing (where a seal would normally be located) and does not contact the moving components. The receiver acquires the signal from the cage sensor and transmits it via wire to a remote data collection system. The complete system is shown in Figure 6.

Figure 6. Instrumented bearing with cage transponder, excitation/measurement circuit, and signal processing unit.

Data from the cage sensor can be processed to obtain information on the lubrication regime (boundary, mixed, or EHL), as well as indication of an over-lubricated condition. This state information can then be combined with a prognostic model of cage operation, taking into account the bearing speed and ambient temperature of the system.

4. EXPERIMENTAL RESULTS

Sentient Corporation has a unique bearing test rig designed to emulate ACW operation and environmental conditions. The rig uses two angular contact ball bearings driven by a frameless brushless DC motor at up 6000 RPM. The frameless motor permits accurate bearing torque measurement via motor current, since there are no support bearings in the system other than the two test bearings. This method is also used in real ACWs. The bearing housings have a liquid thermal control system that permits a wide range of ambient temperatures. The bearings are instrumented for race temperature, optical cage and shaft speed, vibration, and the cage transponder described above. The entire system is contained inside a vacuum chamber to emulate space conditions. Air is actually an important convective cooling medium for internal bearing components and thus vacuum testing is required for accurate data. The rig is shown in Figure 7.

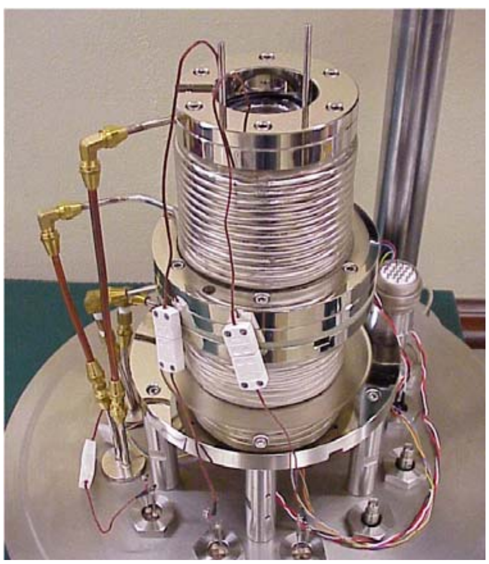

Figure 7. Attitude control wheel simulator test rig.

Figure 8 shows a set of test data collected using the cage temperature and motion transponder. The light green trace is the cage data, while the dark green is the race thermocouple and the blue trace is the motor torque. The bearing was initially lubricated with a very small amount of oil and then run for several hours prior to the test shown. Between 200 and 300 minutes into the test, the bearing transitions from the EHL to the mixed lubrication regime. This is evidenced by the high frequency signal that becomes superimposed on the cage temperature data. This is actually the unstable cage motion resulting from the increase in friction between the ball and cage. Note that neither the torque nor the race temperature show any indication of this transition.

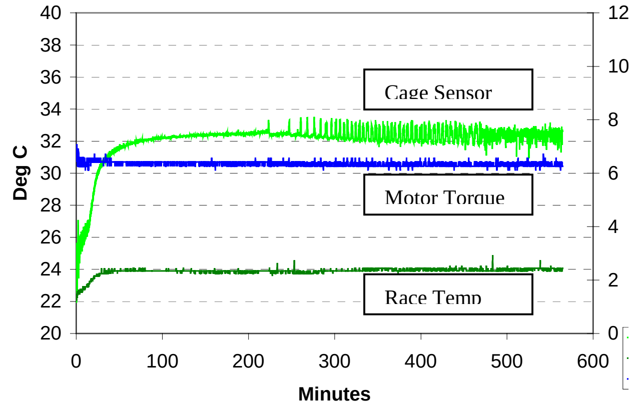

Figure 8. Test data showing transition to mixed lubrication.

Figure 9 shows data from another starved test where the cage was already operating in an unstable mode. In this figure, the red trace is the cage transponder data, the dark red trace is the cage thermocouple, and the blue trace is the motor torque. The unstable cage motion at the beginning of the test is indicated by the high frequency signal from the cage sensor. At 40 minutes, a small amount of oil was injected into the bearing. The oil immediately eliminates the cage instability and also causes a temporary rise in torque and race temperature due to the additional viscous drag. This confirms that that bearing has transitioned back into the EHL regime. Stable operation continued for approximately 1 month of additional testing.

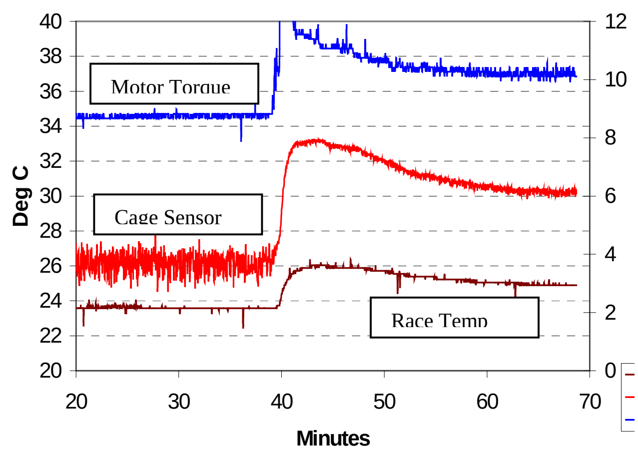

Figure 9. Oil injected at 40 minutes causes transition back to EHL regime, eliminating cage instability.

Cage dynamics have been studied by a few researchers, notably by Gupta (1991), who developed a commercially available dynamics modeling package known as ADORE, and by Boesiger, Donley, and Loewenthal (1992) who conducted experimental studies of cage instability by controlling the amount of lubricant applied to the cage ball pockets. Most other researchers are in agreement that cage instability occurs when a critical threshold of sliding friction is reached between the cage and ball. The value at which this will occur is dependent on bearing and cage design. Hoeprich (1996) conducted an experimental study of bearing rolling element temperatures.

The authors' tests have shown that there are multiple modes of cage instability. The instability observed in Figures 7 and 8 is a relatively benign mode that does not cause damage to the bearing. If the starved condition is allowed to progress, eventually the bearing will reach a higher friction state that results in a more destructive mode of cage instability. For example, Figure 10 shows motor current anomalies due to cage instability as observed by Fleischauer (1997). This test ended with bearing failure and the pre-failure instability has a strong effect on motor torque, in contrast with the relatively benign mode of instability that does not affect motor toque (and is thus not observable using motor torque). It is therefore suggested that at least two critical cage-ball friction thresholds exist, and that discriminating between them would improve knowledge of the lubrication status of the bearing. Clearly, by the time the second (destructive) instability mode is observed, the bearing is already accruing damage and may only be a few hours from failure.

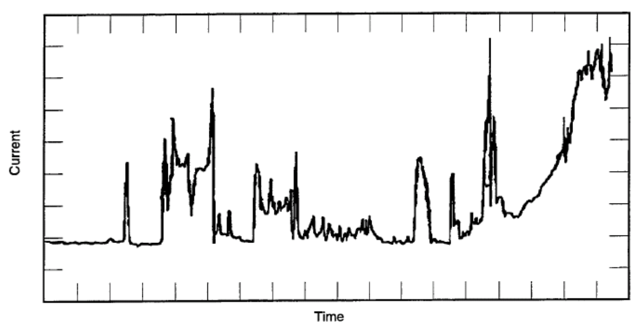

Figure 10. Motor current with periodic cage instability anomalies and eventual failure (from Fleischauer, 1997).

The cage temperature is also an important state indicator. Figure 11 illustrates the steady-state cage temperatures reached (for two test bearings) during a series of identical tests over the course of approximately 2 months. The bearings were initially lubricated and then run during this period with no additional lubrication. With the outer races held at a constant temperature (22° C), the steady-state cage temperature was relatively constant across a number of tests, and then started increasing. The trends suggest that around test 24, the lubrication regime transitioned from EHL to mixed. Prior to test ~24, temperature/friction is constant or even decreases slightly as total runtime increases, while after that point, temperature increases with additional runtime. Mode 1 instability occurred in test 33 and continued for all subsequent tests. Mode 2 instability, as distinguished by torque anomalies similar to those observed by Fleischauer (1997), occurred from tests 40 onward.

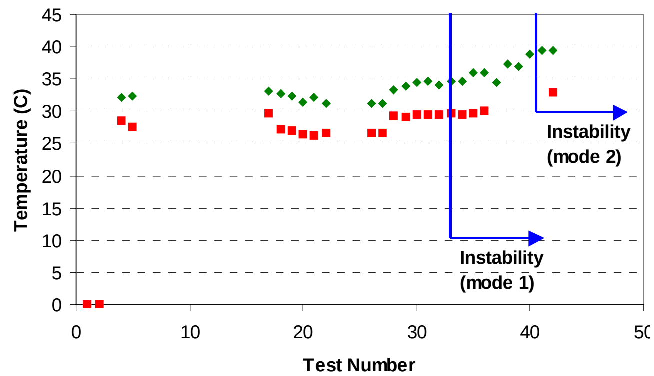

Figure 11. Steady state cage temperature reached during a series of long-term tests (data for two bearings is shown).

The nature of the instability modes is currently being explored in greater detail. Figure 12 shows the cage sensor output spectrum for a typical mode 1 instability. The cage rotation rate is 20 Hz. Note that the primary frequency content is at the cage rotation rate and its first few harmonics. This signature appears to be relatively consistent for this mode, and might be used as another diagnostic indicator of the transition between lubrication regimes.

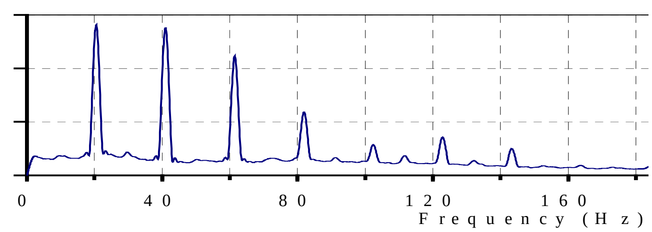

Figure 12. Cage sensor output spectrum. The cage rotation rate is 20.4 Hz.

One interesting observation under some starved conditions is the appearance of a phantom outer race anomaly, as indicated by the demodulated envelope spectrum from an accelerometer. This technique is commonly used to diagnose spalls in bearings for terrestrial and aircraft applications where fatigue is the primary concern. Figure 13 shows an accelerometer demodulation spectrum. Note the spike at about 225 Hz; this typically indicates an outer race spall. However, no spall was present in the bearing. This phenomenon has been observed in other starved tests and disappears when lubricant is added. Further research is under way to determine the cause.

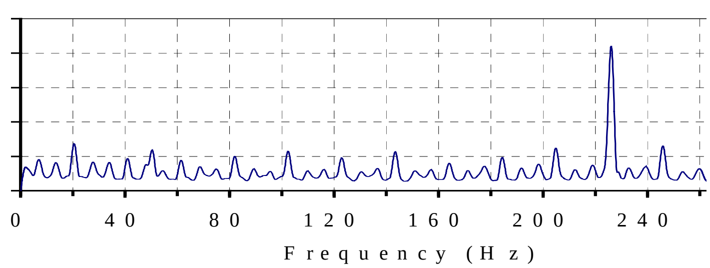

Figure 13. Accelerometer demodulation spectrum.

5. CONCLUSIONS

Bearing lubrication in spacecraft momentum/reaction wheel bearings was studied experimentally. A novel cage transponder which measures cage temperature and motion was developed both as a research tool and as a potential on-board diagnostic sensor. Cage temperature and instability modes under different lubrication scenarios were studied. Over a number of similar experiments with different test conditions, several general observations were made:

1. In air, cage temperature is nearly the same as race temperature. In a vacuum, cage temperature is significantly higher due to the lack of convective cooling.
2. Race temperature remains approximately the same in either environment.
3. Temperature rise of the cage was more sensitive to speed than load, as would be expected.
4. After running for some time without having lubricant added, cage instability was observed in both bearings. This was a low frequency instability mode and did not affect torque; an addition of oil eliminated the instability.
5. For tests where the mode 1 instability was allowed to continue for some time, this eventually progressed to a mode 2 instability which occurred in parallel with torque fluctuations.

This research highlights some of the differences in bearing fault signatures between the more widely known fatigue failure mode and lubrication related failure modes. It is hoped that this insight will lead to new and more effective health monitoring approaches for applications where lubricant loss drives bearing failure.

The cage sensor appears to be extremely promising as a diagnostic tool for these applications. Future work will include demonstration of a complete monitoring system including sensors and signal processing and diagnostic software. This system could be incorporated into future ACW designs to provide automatic management of lubricant application, thereby maximizing spacecraft life and minimizing torque anomalies and bearing related vibration.

Other similar applications may also benefit from this technology. For example, rotorcraft hanger bearings are a sealed grease lubricated design that typically fails due to lubricant exhaustion. Traditional vibration based diagnostic approaches have not performed well in this application. A derivative of the monitoring system described herein may be useful as a diagnostic indicator.

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