Failure Modes And Prognostic Techniques For H-60 Tail Rotor Drive System Bearings

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Abstract—The failure modes and diagnostic/prognostic signatures for the oil cooler and hanger bearings used in the tail rotor drive system of the H-60 series of helicopters are being researched. The overall goal is to develop a prognosis system to track and predict bearing degradation and to integrate those technologies with the open architecture IMD-HUMS. This paper summarizes the challenges and advancements that have been experienced while improving the diagnostic capabilities for the bearings. The causes and effects of bearing contamination and lubricant exhaustion are addressed, while the focus is placed on detection methods of these failure modes. Interesting and encouraging results were found for both the oil cooler bearings and the hanger bearings, but at the present time, the potential is greatest for the development of detection methods and PHM algorithms for oil cooler bearings. The anticipated system will enable fault diagnosis, damage tracking, and the prognosis of useful life remaining. [1,2]

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1. INTRODUCTION

Recently, significant research efforts have been devoted to reducing the burden imposed on the military by maintaining its fleet of aircraft. An example of this effort is the incorporation of the Integrated Mechanical Diagnostics-Health and Usage Management System (IMD-HUMS) unit for health monitoring in the H-60 series of helicopters used by both the Army and Navy.

Owing to their high rates of faults and replacement, two types of rolling bearings used in the H-60 tail rotor drive system are of particular interest for health monitoring. The first bearing type is installed in the oil cooler fan (referred to hereafter as oil cooler bearings), while the second supports the tail rotor drive shaft (referred to hereafter as hanger bearings). The locations of these bearings in the drive system are visible in Figure 1. Sentient Corporation is researching the failure modes and diagnostic/prognostic capabilities for these bearings to develop a health monitoring system that is specific to these bearings. Integrating the resulting system into the open architecture platform will complement the IMD-HUMS.

Historically, the bulk of research related to bearing condition monitoring has focused on the identification of localized fatigue spalls. A spall is formed when material flakes from a bearing surface. The rolling elements impact the spall at a frequency that is dependent on the rotation rate, the location of the spall, and the bearing geometry. As such, the fault frequencies are identifiable through vibration signal processing techniques. Many useful algorithms (as well as many not-so-useful ones) have been developed over the past 30 years for this purpose. However, bearings experience other failure modes in addition to fatigue spalling.

Maintenance records and in-house research indicate that the primary failure mode for the hanger bearings is exhaustion of lubricant, while the oil cooler bearings appear to fail as a result of foreign contaminant ingestion. Loss of lubrication is not easily identified by the analysis of vibration signals. Similarly, the ingestion of foreign contaminants can be difficult to diagnose because it does not always result in localized fatigue spalling. In this application, typical forms of damage are corrosion, hydrolysis, and distributed minor surface damage. While these conditions can be precursors to fatigue spalls, the vibration can increase to unacceptable levels well before a spall forms.

The goal of this research is to develop a Prognostic Health Management (PHM) system for the hanger and oil cooler bearings of the H-60. A significant milestone in the development process is set for improving the current diagnostic capabilities. Some of the goals are increased confidence, early fault detection, and the diagnosis of fault severity. This paper discusses the challenging circumstances surrounding fault detection and diagnosis for these applications. The concepts discussed are applicable to bearings in many settings, particularly applications where grease-lubricated bearings endure light to moderate loads.

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[1] 1-4244-0525-4/07/$20.00 ©2007 IEEE.
[2] IEEEAC paper #1122, Version 2, Updated October 19, 2006

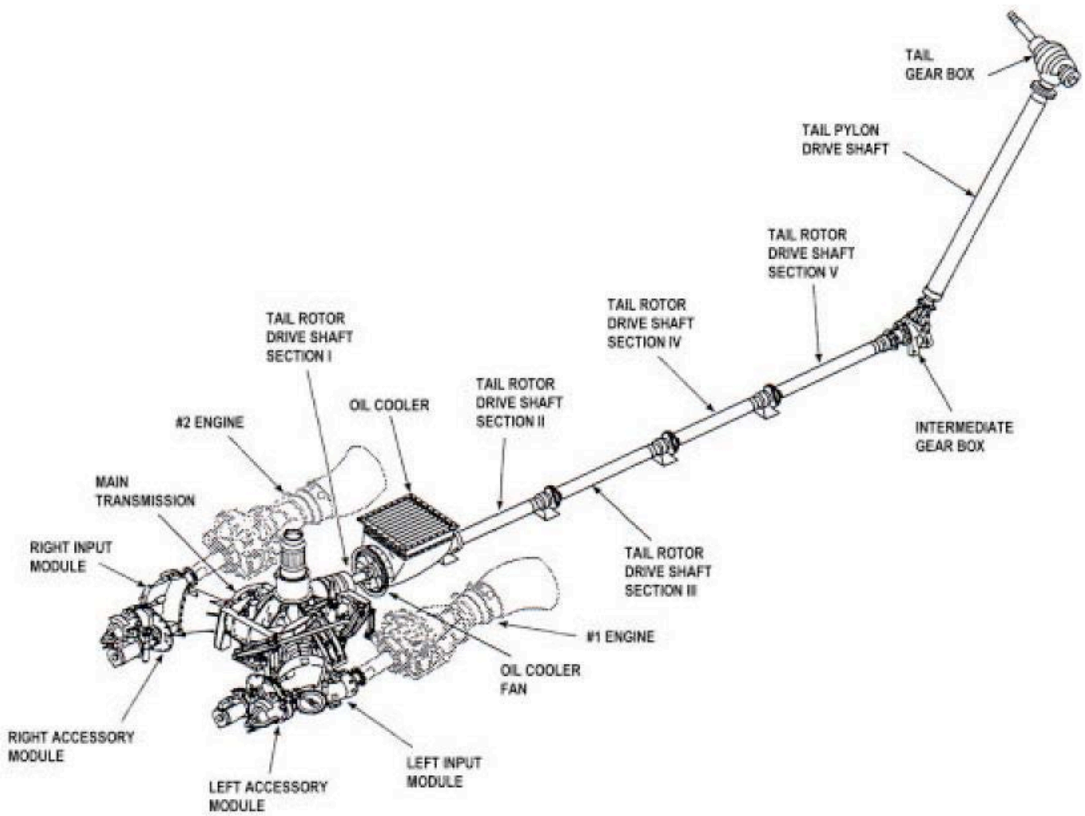

Figure 1: Drive system for the H-60 helicopter. Oil cooler bearings reside in the oil cooler fan, while hanger bearings provide support at the junctions of each section of the tail rotor drive shaft.

2. Oil Cooler Bearings

The oil cooler bearings support a fan that draws in ambient air and forces it through an oil-cooling radiator. Unavoidably, the incoming air carries contaminants such as dust, dirt, sand, water, and bits of vegetation through the system. For the most part, this is of little consequence because the air is immediately expelled after it passes through the radiator. The oil cooler bearings, however, are exposed to the flow of contamination. The bearings are shielded to minimize ingestion, but an air gap between the shield and inner race allows some of the smaller particles to enter the bearing. Figure 2 is a photograph of an oil cooler bearing (shields removed) that has taken in a large quantity of debris during normal service. The debris has been thoroughly mixed with the grease, which severely inhibits the effectiveness of lubrication. The rolling elements run over the debris and form indentations in the bearing raceways. Both the action of over-rolling and the resulting raceway damage increase vibration levels. In general, the added energy is broadband and does not create a specific fault frequency.

Water in bearings has many destructive effects on both the lubricant and the machine surfaces that it contacts. It is 2nd only to particle contamination in its damaging capabilities. Water is known to promote oil oxidation, attack rust inhibitors, and impede the formation of a load carrying elastohydrodynamic lubrication (EHL) film [1]. Additionally, corrosion by oxidation commonly occurs in contact regions between rolling elements and raceways when the bearings are idle. Evidence of this phenomenon is clearly illustrated by the black surfaces on the inner raceway of a retired bearing in Figure 3. These damaged areas are likely sites for spall initiation in the future [2]. In the condition shown here, the raceway has lost a negligible amount of material, but the surface is noticeably rougher.

The ball retainer, or cage, often receives the least amount of attention in the design and engineering of bearings because it is not a load-bearing element. As a result, its material may be less resistant to corrosion. This is indeed the case in the oil cooler bearings. Figure 4 shows the obvious rust that has formed on the inner surface of the cage in the contact region between the cage and the ball. The geometry of the cage forms a pocket that is capable of trapping water and promoting corrosion. The balls are also affected by this corrosion, albeit to a lesser degree. Upon rolling, the damaged surfaces of the balls continuously interact with the cage and the raceways and increase vibration. Corrosion of the cage could also lead to the release of macroscopic particles from the affected area, further contaminating the grease and likely leading to damage on the raceways.

Figure 2: Debris-filled oil cooler bearing

Figure 3: Oxidation of oil cooler bearing inner raceway

Figure 4: Corroded inner surface of the cage in the ball/cage contact region

The cumulative effects of debris, debris indentations, water, and corroded surfaces can substantially increase friction, drag, surface interactions, and vibration. Until localized fatigue spalls form, there is no specific fault frequency that can be used for diagnosis. Figure 5 illustrates this effect. Here, raw vibration signals are shown for bearings in three distinct conditions. The blue signal was recorded from a used bearing that was retired from service. The green signal was recorded from the same bearing after it was completely degreased and repacked with fresh grease. The red signal was recorded from a brand new bearing. Refurbishing the bearing with fresh grease had a minimal impact on the amount of energy in the signal, which is quantified by the root-mean-square (RMS). In fact, the RMS only decreased by 5%. As expected, the new bearing ran the smoothest, with an RMS that was a small fraction of the previous cases. This demonstrates the large amount of damage that can be incurred in normal usage.

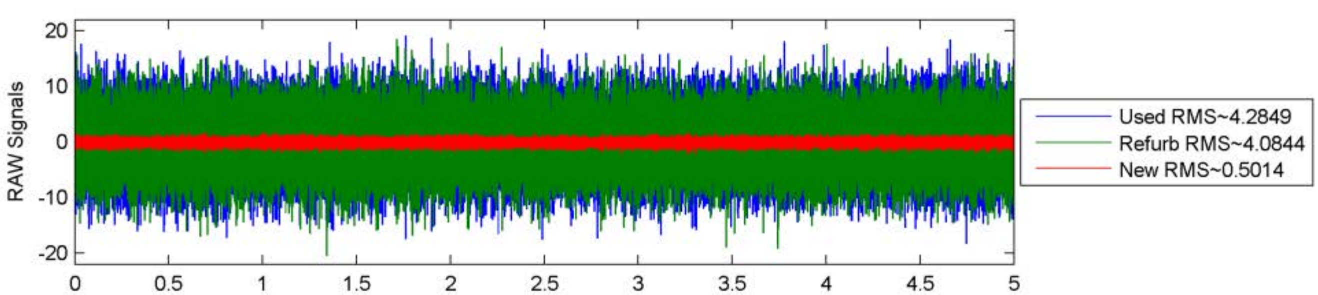

Figure 5: Time series vibration signals for used, refurbished, and new oil cooler bearings

From analysis of multiple bearings retired from service, it appears that the oil cooler bearings generally accumulate damage in three phases. First, foreign contaminants (debris particles and/or water) enter the bearing and reduce the effectiveness of the lubricating grease. The contamination then leads to corrosion, oxidation, and minor damage to the bearing surfaces. This damage creates stress concentrations that can evolve into fatigue spalls over time.

The ideal health monitoring system for oil cooler bearings would be able to identify, track, and predict the progression of all three phases of damage. The results to date suggest that this could be possible with a single accelerometer, which is already installed on the aircraft. Contaminated grease and minor surface damage can both be identified by increases in RMS, and frequency analysis may be able to differentiate between them. This approach has been validated in industry. In fact, testing machines are commercially available that use frequency analysis to evaluate the cleanliness of grease [3]. When/if localized fatigue spalls form, other vibration signal processing techniques have proven to be successful at identifying them by examining specific fault frequencies.

3. Hanger Bearings

The hanger bearings support the tail rotor drive shaft of the H-60. There are a number of examples from both military and civilian rotorcraft where failure of a hanger bearing has resulted in breakage of the driveshaft and loss of the aircraft. The hanger bearing application is unusual (as compared to many other bearing health monitoring applications) in several respects. First, the bearing is grease-lubricated and permanently sealed, so lubrication problems cannot be detected directly (e.g. through low oil pressure or level). The ball-race contact is four-point contact rather than the more common two-point contact found in radial or angular contact ball bearings. The bearing is not subject to substantial loads that would initiate contact fatigue. Finally, the bearing is mounted in an oil-filled urethane damper assembly that is designed to attenuate vibration due to a slight shaft imbalance or misalignment. This is beneficial for the operation of the system, but quite unfavorable for vibration signature visibility. The mounting of a hanger bearing within the viscous damper is shown onboard a UH-60 in Figure 6. The orange seal makes the bearing easily identifiable.

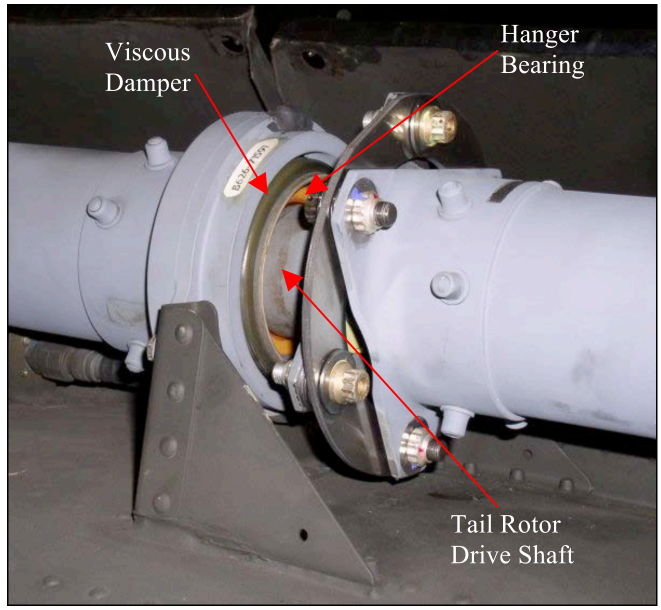

Figure 6: Hanger bearing installed on a UH-60

Sentient Corporation has conducted research to identify and/or develop better ways to sense impending hanger bearing failures, with greater prognostic lead-time as compared to existing approaches. With the current monitoring configuration, it is quite likely that the accelerometer would not detect a problem until it had progressed to a severe, possibly safety critical state.

Testing of the viscous damper has shown its drastic level of signal attenuation. This was accomplished by collecting vibration data from accelerometers mounted in two locations on the damper housing: one was located on a fixture attached to the bearing side of the damper (denoted the "internal" accelerometer), while the other was on the external housing of the damper (denoted the "external" accelerometer – this is the present accelerometer location for the H-60 IMD-HUMS). The internal accelerometer collected the vibration before transmission through the damper, while the external accelerometer collected the damper-attenuated vibration. Figure 7 shows these two signals for a bearing with a seeded fault, where the external accelerometer signal is severely attenuated. This seriously reduces the ability to observe hanger bearing faults with an accelerometer in the current mounting configuration of the H-60.

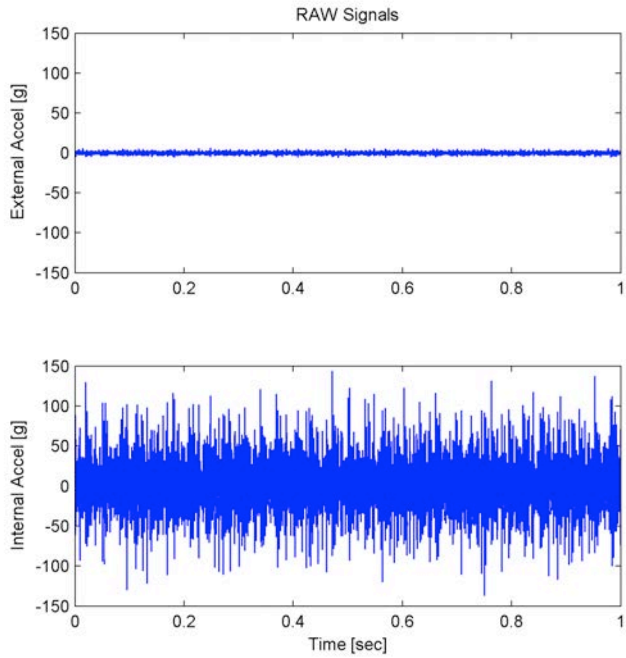

Figure 7: Drastic signal attenuation by the damper

The primary failure mode of hanger bearings is exhaustion of lubrication. As exemplified by the seized hanger bearing in Figure 8, lack of lubrication failures can be very sudden and dramatic. Except for visible leakage, grease loss is extremely difficult to track, since even a small fraction of the original grease is sufficient for proper bearing operation. Of course, there is a point where insufficient lubrication does begin to affect bearing operation and diagnostic indicators are more easily identifiable. At this point, a vibration signal will typically show an increased RMS, but this approach often does not provide sufficient lead-time before failure. A degreased hanger bearing was intentionally run to failure in a laboratory experiment. The results are shown in Figure 9, where the RMS began to increase only 10-20 minutes before the bearing seized. Similar to the oil cooler bearing application described in Section 2, there are typically no specific frequencies that can be used to identify the faulted state.

Figure 8: Degreased hanger bearing that seized in a lab test

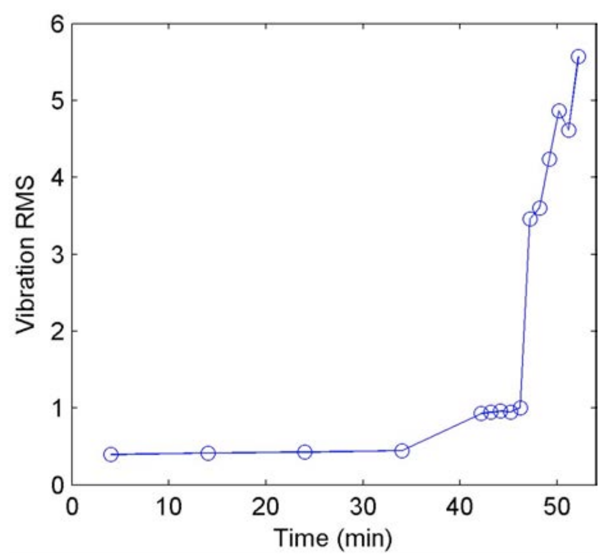

Figure 9: Failure of a degreased hanger bearing in a test rig. RMS increases before failure, but with a small diagnostic window

Given the limited usefulness of the accelerometer due to the attenuation by the viscous damper and the low probability of spalling or debris ingestion, bearing temperature was investigated as a diagnostic indicator of grease level. Tests were conducted with hanger bearings at various grease levels, ranging from 0.1 to 5 grams. The rig was run at least long enough for the bearing to reach a steady-state temperature at each grease level. The temperature of the outer race was recorded throughout the testing.

As a general trend, bearing temperature increased with grease level. This relationship is demonstrated in Figure 10. The lowest grease levels consistently resulted in the lowest bearing temperatures. In all tests, the temperature increased drastically between 3 and 4 grams of grease. This is most likely the upper bound where the grease occupies all of the free volume within the bearing that is not in the swept path of the cage/ball train. Drag, churning, and shearing of grease then generate high friction and temperature until the excess grease can be forced past the seals and out of the bearing.

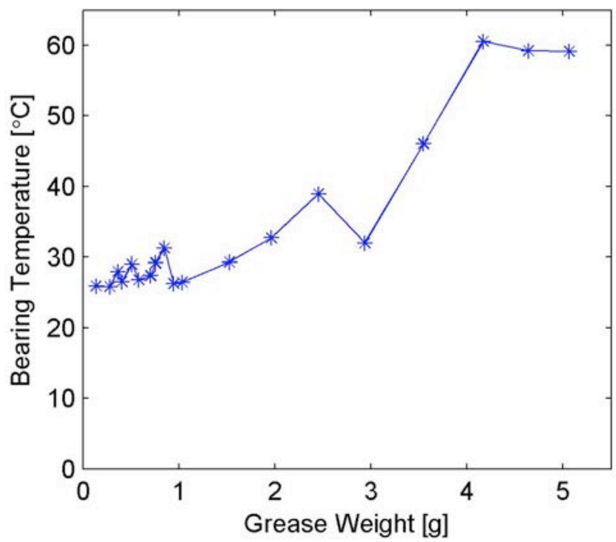

Figure 10: Generally, hanger bearing temperature increases with an increasing quantity of grease

A second bearing was "along for the ride" throughout the battery of varied grease tests. It was mounted in a damper assembly on the same shaft as the aforementioned bearing. This was a factory new bearing with its original grease; it was not modified in any way. During the test, the grease was allowed to naturally purge, leak, evaporate, or otherwise leave the bearing. The quantity of grease loss and outer race temperature were measured at many points during the testing.

The bearing initially purged a significant amount of grease. This is shown in Figure 11, where the seal is orange and the purged grease is red. This photograph was taken after only one hour of run time. The high rate of grease purging persisted for about 11 hours. The rate was dramatically slower thereafter, as seen in Figure 12. Note that the loss continued throughout the 340 hours of run time. This suggests that the bearing would continue to lose lubrication in future usage. In actual service, the rate of loss would most likely be exaggerated by the more severe environmental conditions.


Figure 11: Grease purged from a new hanger bearing after 1 hour of run time in a test rig

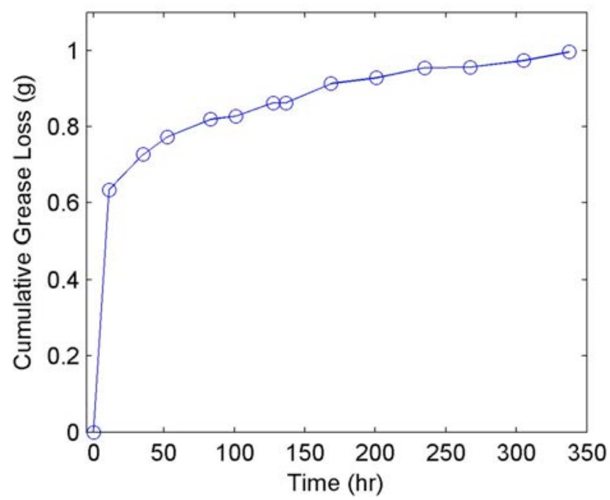

Figure 12: Grease purge from hanger bearings is initially rapid and gradual thereafter

These results all agreed with reports and studies obtained from the Army and Navy. According to reports provided by the Army, the factory grease fill is 3.3-4.4 g, and tests conducted by the Navy on the same bearing indicated that about ½ of this will escape. The same study showed that overfilled bearings tend to purge the majority of excess grease in the first 10-30 hours and end up with about the same quantity of grease remaining after 100 hours as properly filled bearings [4]. This shows that overfilling the bearing with grease will not extend its life.

In addition to the amount of purged grease, the temperature of the bearing was also tracked. Figure 13 shows that the temperature varied throughout the testing. These results can be aligned with the purged grease plot in Figure 12 for comparison. As expected, the initial spike in temperature coincides with the initial 11 hour-long grease purge. Following this period, the temperature is highly variable. It is interesting to note that the temperature spike that began near 100 hr did not coincide with a noticeable increase in purged grease. At times, the bearing temperature fell nearly to room temperature (~20 °C). Perhaps most interesting to point out is that the temperature fluctuated even though the grease level was adequate and only slowly decreasing throughout this plot.

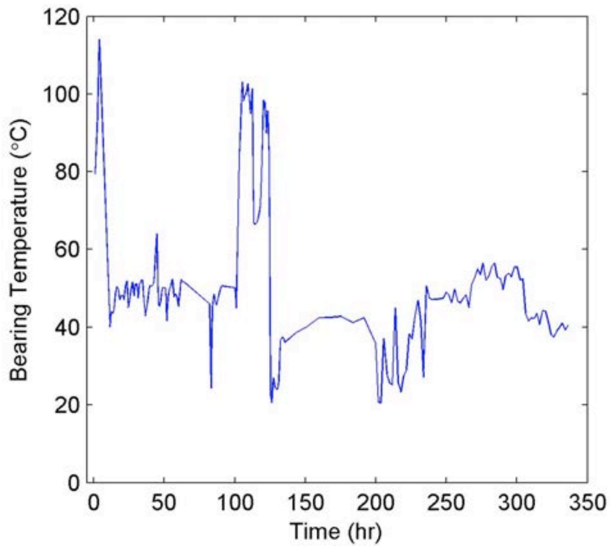

Figure 13: Temperature fluctuations of a properly lubricated hanger bearing in constant operating conditions. The bearing was factory new at 0 hr and allowed to purge naturally

It appears that temperature fluctuations are normal for a properly greased bearing. This could be due to grease constantly shifting within the bearing, heating up due to friction (which causes the grease to release more oil), followed by an overall cooling of the now better-lubricated bearing. In contrast, temperatures may tend to stabilize as lubrication becomes deficient. Grease becomes less mobile as it loses oil. Hence, the shifting of grease will decrease, along with decreases in the oil available to lubricate the surfaces. Eventually, the lubrication will become insufficient and friction will increase. At this point, a thermal runaway is initiated in which temperatures continue to rise gradually until a short period before failure, when the temperature rises at a much faster pace until the friction is so great that the bearing seizes. Figure 14 is a plot of a test where the bearing's initial grease fill was barely sufficient for proper lubrication. The bearing was then allowed to run continuously until failure. In this barely-adequate state of lubrication, the temperature is quite stable until about 450 hr, after which it increases slightly over the next 100 hours. The temperature abruptly spikes a few minutes before failure.

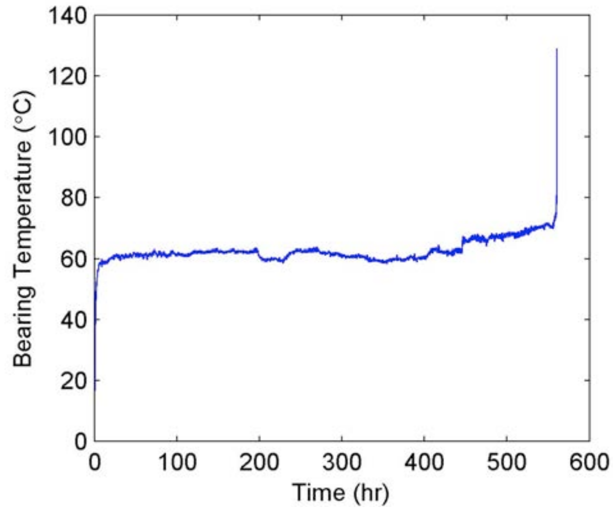

Figure 14: At low grease levels, bearing temperature is relatively constant until a thermal runaway is initiated, at about 450 hr here

Although the results presented herein are promising, further testing is necessary to explore the relationship of bearing temperature and lubrication status in sealed greased aircraft bearings.

4. CONCLUSIONS

Improved PHM algorithms for tail rotor drive system bearings in the H-60 are being developed, with encouraging results thus far. The development process is particularly interesting due to the unusual and challenging circumstances of fault detection and diagnosis.

The oil cooler bearings fail in a three-phase process, and there is great potential to differentiate all three phases using the current IMD-HUMS accelerometer. The three phases of damage are: (1) Grease contamination, (2) Minor surface damage, and (3) Fatigue spalling. The first two phases can be identified by increases in RMS, and frequency analysis looks very promising for differentiating between them. If the third phase (spalling) occurs, existing signal processing techniques can confidently identify the condition.

The hanger bearings fail primarily due to lubricant loss. Early identification of insufficient lubrication is difficult with an accelerometer due to a vibration dampener and the lack of distinct fault signatures. The effectiveness of bearing temperature as a diagnostic indicator of lubrication status was explored to overcome the shortcomings of the accelerometer. Temperature tended to increase with increasing grease quantities. Large temperature fluctuations were found to be a sign of a properly lubricated bearing, while stable temperatures may indicate a lower grease level. Temperature consistently spikes immediately before failure, but the lead-time window at this point can be as short as a few minutes.

The oil cooler bearings appear to be the more promising candidate for PHM, and the majority of future research will focus this application. Sentient Corporation will analyze at least 20 used H-60 oil cooler bearings from Corpus Christi Army Depot (CCAD). This will provide a statistically significant sample size for better determination of the primary failure mode and the extent of damage incurred in the field. Extensive additional testing with these bearings will further solidify the ability to identify, track, and predict the progression of damage.

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