CBM COMPONENT TESTING AT THE UNIVERSITY OF SOUTH CAROLINA: AH-64 TAIL ROTOR GEARBOX STUDIES

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ABSTRACT

The AH-64 helicopter tail rotor gearbox is a grease lubricated right-angle transmission which frequently leaks through both its input and output seals. An experiment was designed to create a worst-case scenario for a leaking output seal on three different high-life gearboxes, which were to be run for 500 hours in a seeded fault condition. The test objective was to demonstrate that aircraft with leaking output seals could continue to operate until a scheduled phase maintenance which occurs every 250 hours. Although previously considered impossible, during the study it became evident that grease freely moves from the main gear compartment into the static mast. As a result, the output seal leaks caused lubricant starvation on the gear mesh surfaces, ultimately leading to catastrophic failures of the input gear teeth. The three gearboxes tested survived 490, 487, and 573 hours after fault seeding, and numerous vibration and thermal observations were recorded as the gearboxes approached failure.

INTRODUCTION

CBM Component Testing at the University of South Carolina

Over the past decade, the University of South Carolina (USC) has held a strong working relationship with the South Carolina Army National Guard (SCARNG). During the early days of the Vibration Management and Enhancement Program (VMEP), USC played a key role in the development of early cost-benefits models which demonstrated the usefulness and effectiveness of onboard health monitoring systems for the SCARNG fleet. These efforts expanded into a fully matured CBM Research Center within the USC Department of Mechanical Engineering., which hosts several aircraft component test stands in support of current CBM objectives.

Within the USC test facility is a complete AH-64 tail rotor drive train test stand (Figure 1), which is designed to facilitate a scientific understanding of aircraft component conditions as they relate to TAMMS-A inspections, vibration signals, health monitoring systems output, and other data. These observations are necessary for the development of comprehensive and accurate diagnosis algorithms and prognosis models. The testing apparatus is also capable of being modified to test new and existing drive train components of military and civilian aircraft, including the ARH-70, CH 47, and UH-60 drive trains.

Figure 1 - USC AH-64 Tail Rotor Drive Train test stand

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The test stand emulates the complete tail rotor drive train from the main transmission tail rotor takeoff to the tail rotor swashplate assembly. All drive train parts on the test stand are actual aircraft hardware, and it is capable of handing shafts installed at the maximum allowable misalignment of over two degrees. The structure, instrumentation, data acquisition systems, and supporting hardware are in accordance with military standards, and the test stand's two 800 horsepower motors are capable of exceeding 150% of the actual aircraft drive train loading.

The test stand was designed and built to accommodate the use of multiple Health and Usage Monitoring Systems and is currently equipped with a Honeywell Modernized Signal Processing Unit (MSPU). Alongside USC's own data acquisition system, the implementation of currently fielded aircraft equipment helps validate test stand results with data from actual airframes..

AH-64 Gearbox Study Objectives

The AH-64 Tail Rotor Gearbox is a grease-lubricated right-angle transmission containing a single spiral bevel gear set with a speed reduction ratio of 2.591:1 (**Error! Reference source not found.**). Each gear is supported a set of duplex and roller bearings, and the output gear transmits torque down a ball-bearing supported quill shaft contained within the gearbox assembly (Figure 3). This region, referred to as the static mast, provides a mounting point for the tail rotor swashplate assembly and has traditionally been considered to be isolated from the main gear mesh compartment of the gearbox housing.

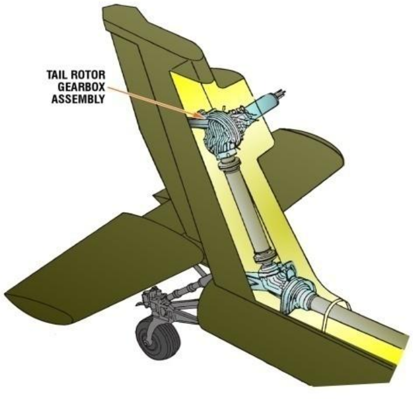

Figure 2 - AH-64 tail rotor gearbox assembly location

The output seal located on the end of the static mast has historically been prone to leaking; a fault which under current maintenance practices requires immediate removal of the entire gearbox assembly. The rationale behind this practice was the assumption that a grease loss through the static mast could not be serviced in the field, and it is not possible to determine the quantity of grease contained within the mast. It was therefore believed that a leaking output seal could cause a failure of the output assembly ball bearings, and in 2006, this fault accounted for nearly half of all gearbox removals. Furthermore, the requirement that the aircraft be immediately grounded for gearbox replacement presents a large unscheduled maintenance burden, with a high potential to disrupt aircraft readiness.

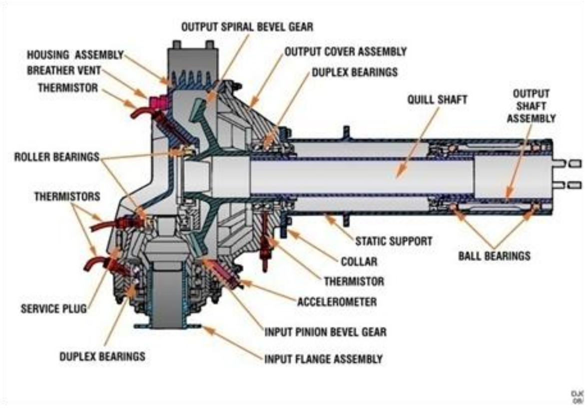

Figure 3 - Internal components of an AH-64 tail rotor gearbox

A test plan was therefore devised which would demonstrate whether or not a gearbox with a leaking output seal could be used until the aircraft reached a phase inspection, which currently occurs every 250 hours. A secondary objective of the experiment was to identify vibration signatures which might indicate the impending failure of the static mast ball bearings.

MAIN BODY

Procedure and Initial Observations

The intent of the test plan was to create a worst-case scenario for the two ball bearings that support the gearbox output shaft assembly by inducing a leak in the output seal and allowing grease to drain from the static mast. This was accomplished by removing approximately 0.5 inches of seal material on the bottom of the output seal and removing the hoop spring which compresses the seal against a rotating portion of the output assembly spline (Figure 4). The procedure was repeated for three separate gearboxes, and each gearbox was specified to run for 500 hours in the seeded fault condition.

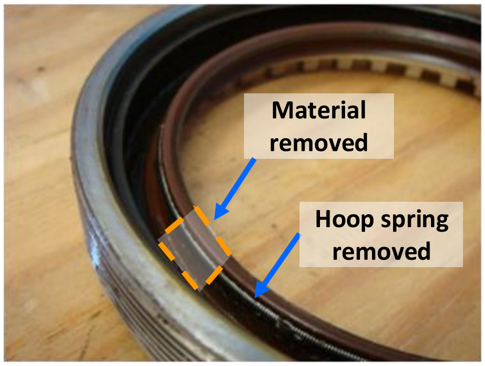

Figure 4 – Seeding procedure utilized to induce an output seal leak

The first attempt at performing the leaking output seal test was limited by problems present in the test article. Prior to the installation, it had been partially disassembled for tear down analysis, which revealed possible corrosion on some of the rolling element bearings within the main gear housing. When an unexpected transfer of grease from the main gear compartment into the static mast was observed, there was concern that the cause of this previously unobserved behavior may have been the result of the known fault condition in the gearbox. As a result, it was considered an anomaly, which ultimately led to the early termination of the test and the disqualification of the gearbox as a valid article.

The next gearbox tested, identified in this report as Article 1, originally performed as expected, with large volumes of grease being ejected from the static mast within the first 150 hours of testing. Upon inspection, the gearbox main compartment was found to be underserviced after approximately 260 hours, and grease was added in accordance with standard operating procedures.

Immediately following the servicing, grease ejections from the static mast once again became heavy and regular. Coupled with the observations made from the disqualified article, it was concluded that grease added to the main compartment was moving into the static mast and would interfere with the original objective of the experiment, specifically: a loss of lubricant on the static mast rolling element bearings. The test plan was modified to disallow any further addition of grease during the test life of the gearbox, and after 490 hours of operation, the Article 1 exhibited thermal instability and found to have severe wear on its input gear resulting from the loss of lubricant.

For the next gearbox, Article 2, grease servicing was performed only at the beginning of the experiment, and a similar behavior was observed. By 300 hours of testing, the main compartment of the gearbox was severely underserviced and tooth wear was evident. At 487 hours, without any thermal indicators, a tooth on the input gear broke and the test was terminated.

Since the observed grease transfer between the compartments was a previously unobserved phenomenon, the final article in the experiment, Article 3, was specially modified to include a window on the static mast so that grease levels in this region could be observed directly. Furthermore, a vendor-supplied red dye was added to the main gear compartment so that grease from the two regions could easily be distinguished.

Prior to cutting the output seal on Article 3, it was allowed to run for approximately 50 hours to observe grease movement rates. After 120 minutes of operation a red discoloration was evident in the static mast grease, and by 145 minutes, it had been thoroughly mixed with the dyed grease from the main compartment (Figure 5). During this pre-seeding phase, grease levels were also observed to rise within the static mast.

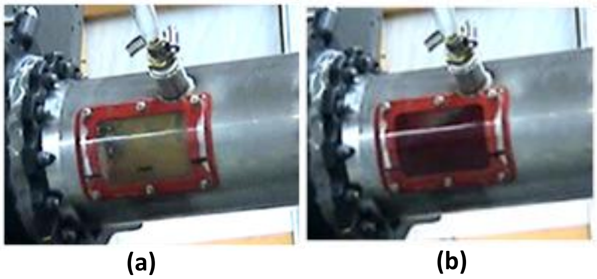
(a) (b)

Figure 5 - Grease mixing observed through the static mast window of Article 3 after (a) 120 minutes and (b) 145 minutes of operation

At the time that seeding was performed, additional grease had to be added into the main compartment due to lubricant transfer into the static mast. The article showed a similar slowly increasing tooth wear, but exhibited no thermal instabilities or catastrophic breaks until 573 run hours.

Although the original objective of the experiment was not met due to the premature failure of Articles 1 and 2, the tests open the possibility to even greater benefits that originally anticipated, namely, the replacement of leaking output seals in the field. Furthermore, the experiments generated large quantities of previously unobservable data that occurs during gear mesh failures. A detailed description of the failures and a summary of the key observations are described in the following sections.

Gear Tooth Failures

During the final day of testing for Article 1, two thermal events outside the designated operating temperature limit of 300 °F occurred while the test stand was operating at the maximum power level of 330 horsepower. These temperatures were recorded using thermocouples inserted into the standard thermistor location for the output gear roller bearing. After the first event, the gearbox was given approximately one hour to cool before restart, and nearly eight hours of operation passed before the temperature peaked again. The second event occurred more rapidly than the first, with the temperature rising approximately 20 degrees Fahrenheit in less than five minutes.

Video analysis of these events shows the gearbox was venting either a mist or smoke through the breather port immediately prior to shutdown on both occasions. Post run inspection found the teeth on the input gear to be noticeably textured, and the output gear was found covered with a layer of coarse carbon deposits.

Further inspection using a borescope revealed catastrophic wear nearly every tooth on the input gear and discoloration of the metal surfaces (Figure 6). The damage is consistent with failures caused by high friction and high heat metal-to-metal contact.

Figure 6 - Article 1 input gear after catastrophic failure

Because the failure was first noticed from temperature readings, additional thermocouples were moved into two of the other standard thermistor locations for Article 2. Since the greatest damage had been observed on the input gear, the input duplex bearing and input roller bearing locations were selected for temperature monitoring.

Upon the first evidence of tooth damage, daily pictures of the fault progression were taken using a borescope. On several occasions when attempting to take pictures of tooth wear, a gray-blue grease vapor was observed to fill the main gear compartment at the end of completed test runs. It is believed that this mist was the same material that was observed venting through the gearbox breather during the Article 1 failure. A separate hand-held temperature probe also found that the gear tooth surfaces as well as the air inside of the main gear compartment had significantly higher temperatures than those measured from the bearing thermistor locations.

Article 2 never experienced a complete loss of lubricant on the gear tooth surfaces. When an unexpected tooth breakage occurred after 487 testing hours, the gear teeth, although severely worn, maintained a thin layer of grease, and temperatures showed no instability (Figure 7).

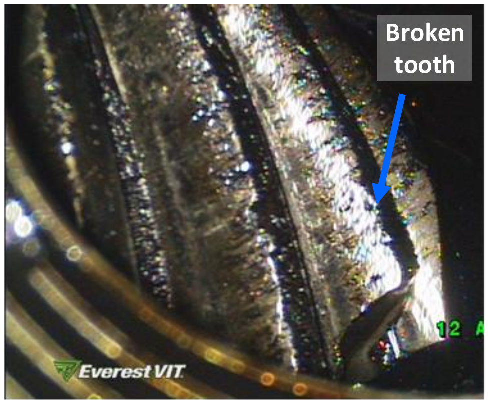

Figure 7 - Article 2 input gear after gear tooth breakage

Based upon the observations that the gearbox core temperatures were noticeably higher than could be measured at the standard thermocouple locations, Article 3 utilized a specially modified service plug which allowed a thermocouple to be inserted less than 0.5 inches above the input gear surface.

In a similar fashion to Article 2, borescope pictures were taken daily after the first signs of tooth wear were evident. When the gearbox successfully reached 500 test hours, it was decided that testing should continue until it reached a failure state in order to provide a more complete understanding of the vibration characteristics of degraded gear teeth.

After 534 run hours the gearbox core exceeded the specified cut-off temperature of 300 °F, and borescope images revealed a sudden increase in the surface wear on the input gear. At 569 run hours, another thermal excursion occurred at the start of the peak loading condition of 330 horsepower, which resulted in rapid core temperature rises. The stand was shut down and allowed to cool, and pictures showed only a slight increase in wear from the previous run.

In the following two runs, temperatures again rapidly peaked above the specified safety limit, and at 573 run hours, testing on the article was terminated. The stand was allowed to run for several minutes above the safety limit so that a final set of vibration measurements could be made, and core temperatures of 325 °F were recorded.

It should be noted that neither the input duplex bearing nor the output roller bearing thermocouple locations exceeded the safety limit, and during the final run, differences as great as 150 °F were recorded between the gearbox core and the originally recorded output roller bearing. This may indicate that during the failure of Article 1, the gearbox core temperatures may have reached as high as 450 °F. As a result, the damage caused to the gear teeth of Article 3 is significantly less severe than the previous two articles (Figure 8).

Figure 8 - Article 3 input gear after gearbox core temperature instability

Condition Indicators and Mesh Harmonics

As Article 1 began failing, one of the MSPU condition indicators transitioned from a normal to a caution level. This indicator, denoted as the TRGB Lateral Bearing energy, showed notable changes during the two thermal excursions (Figure 9). Whether this is indicative of actual changes in vibration signature or is merely a reflection of the influence of temperature on vibration energies has yet to be determined.

Examination of the Lateral Bearing Energy prior to the observed thermal events shows a consistent magnitude of 1 g or less. Typical values for this CI on actual aircraft are less than 2 g, and it is likely that reducing the threshold levels for the Lateral Bearing Energy caution and exceedance will result from these findings. Several other indicators were observed to have changed on the day of the failure, none of which had experimentally determined threshold limits. A thorough examination of these condition indicators on the other two test articles as well as a comparison to typical fleet aircraft should also result in an enhanced set of threshold limit values.

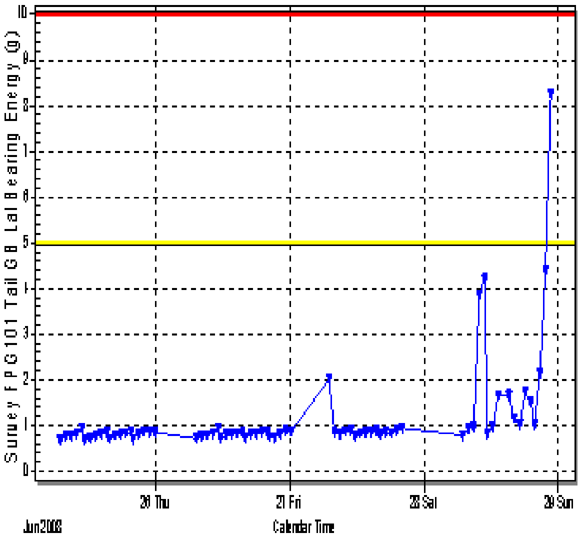

Figure 9 - Article 1 MSPU TGB Lateral Bearing Energy Condition Indicator prior to failure

Extracting the gear mesh harmonic amplitudes from the frequency domain data as Article 1 approached failure reveals the transition from stable operation to imminent catastrophic failure occurred relatively rapidly. Plotting the first and second harmonics over the final four days of testing illustrates a regular cyclic pattern of mesh amplitudes, possibly indicating a strong dependency of component amplitudes on system temperature (Figure 10). Local amplitude maxima are also observed to occur during the first measurement survey of a given run, and steadily increasing as the gearbox approaches failure.

Plotting the amplitudes of the two harmonics against each other reveals strong data clustering prior to the failure and wide dispersion on the date of the failure. There is presently no physical interpretation of these results, particularly the large increase in the second harmonic of the gear mesh frequency amplitude. Gearbox tooth wear is not conventionally diagnosed through simple frequency domain analysis, therefore warranting the need to investigate more advanced processing techniques such as joint frequency time domain analysis.

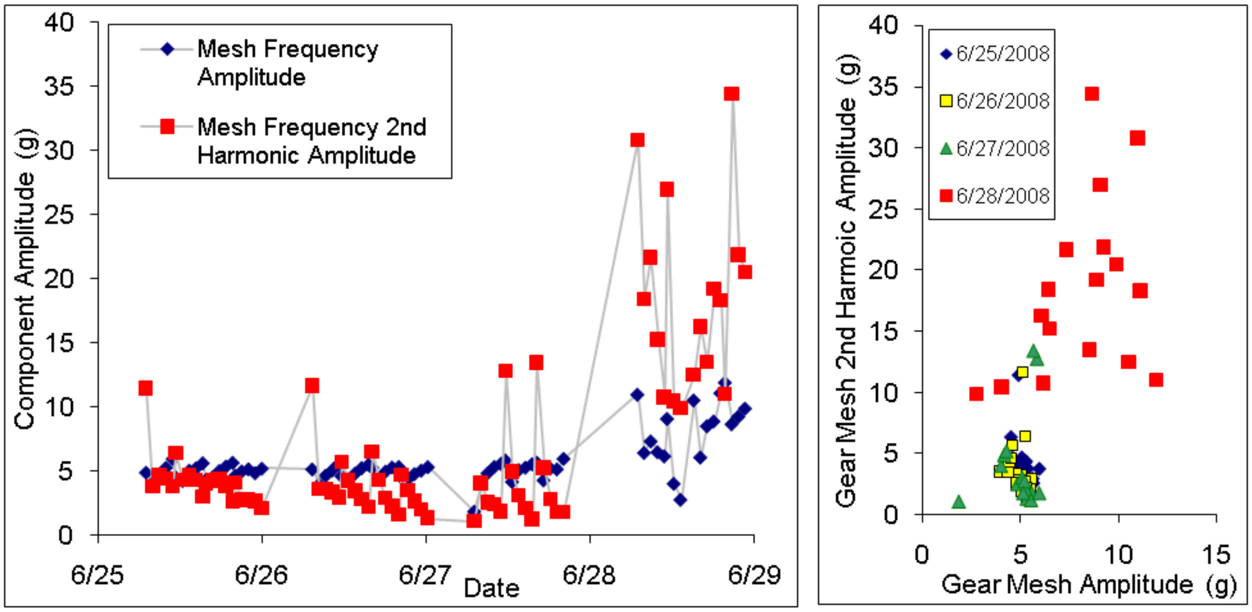

Figure 10 – Article 1 gear mesh harmonic amplitudes immediately prior to failure

Joint Time-Frequency Domain Analysis

A more advanced analysis was performed on raw vibration data using the Zhao-Atlas-Marks kernel for joint time-frequency distribution. Much like the commonly used spectrogram, this distribution shows time domain and frequency domain content of a signal simultaneously using the same fundamental principles as a short-time Fourier transform. A repeated computation of the transform was performed over several short time intervals creating a distribution of time and frequency content, thus providing a higher sensitivity to and resolution in the change of signal components over time.

These results confirm the oscillating behavior of signal characteristics observed in the gear mesh frequency plots. The first surveys taken on the days before the failure show a reduced signal noise in the 3 to 6 kHz range when compared to samples taken later in the day (Figure 11). On the day of gearbox failure, higher-order gear mesh harmonics become prominent, and the noise band is reduced.

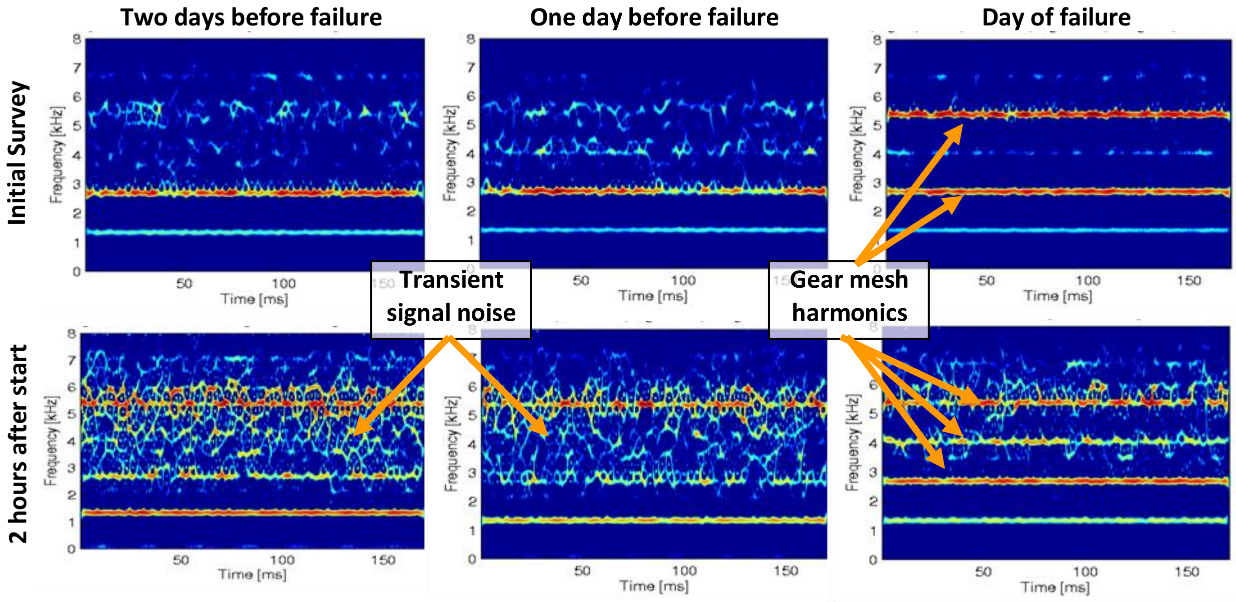

Figure 11 – Time frequency domain analysis of Article 1 lateral accelerometer as it approached failure

Thermal Observations

Installed on every AH-64 tail rotor gearbox are four thermistors, which activate the cockpit gearbox over-temperature indicator when temperatures between 274 to 294 °F occur. This activation range barely includes the maximum operational limit specified for the gearbox lubricant, which is 275 °F, leaving a high possibility that the grease can be heated beyond its limits without detection. Previous research at USC shows that in normal operating conditions, these upper limits are seldom encountered, but when overheating does occur, it can be very rapid and instantaneous.

Temperature readings taken from Article 3 prior to fault seeding show that even in a properly serviced gearbox, slight thermal gradients exist between various regions in the assembly (Figure 12). Plotting these values over the course of the four-hour run intervals illustrates the effect that torque loading has on overall gearbox temperatures. The four wide regions of increasing temperatures correspond with the approximately 50 minutes of loading, while periods of cooling are caused by the 10 minute load reduction during MSPU survey measurements.

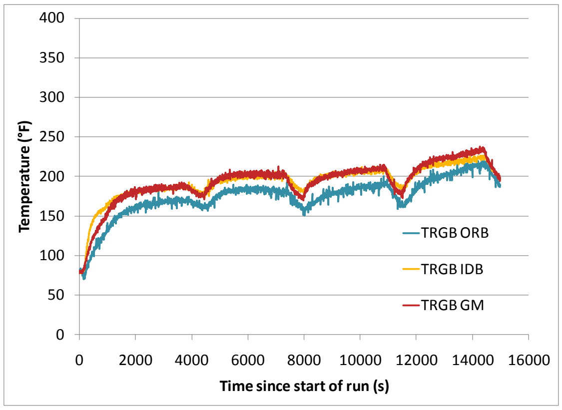

Figure 12 - Temperatures of the three measured locations on Article 3 prior to fault seeding

After 216 hours of seeded fault operation, the majority of the total grease had been purged from the gearbox. This corresponded with an overall reduction in temperature measured at the output roller bearing location (Figure 13). Since the primary heat generation occurs on the input gear mesh surface, this indicates that heating at the output roller bearing is partially due to convective heat transfer of the lubricant within the gearbox. Infrared imaging confirms that large temperature gradients occur on the surface of the gearbox when there are insufficient levels of grease within the main compartment (Figure 14).

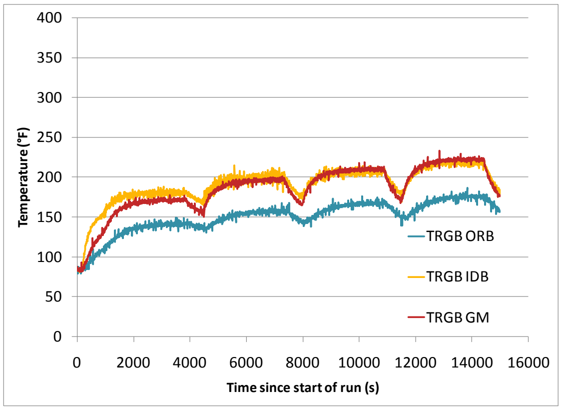

Figure 13 – Temperatures of Article 3 after main compartment grease loss through the output seal

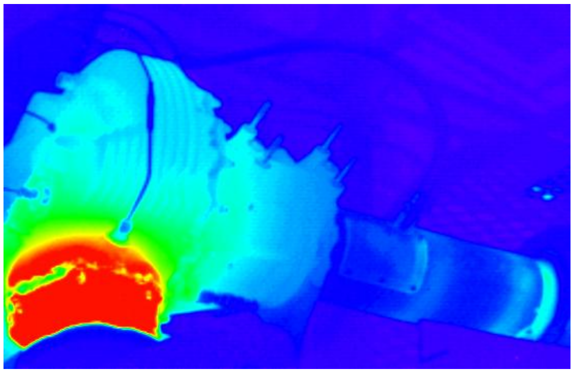

Figure 14 - Infrared thermal imaging of Article 3 after main compartment grease loss through the output seal

Examining the thermal plots of Article 3 prior to and after the grease loss, the temperature difference between the output roller bearing and the gearbox core increased from approximately 15 to 50 °F. The input duplex bearing temperature very closely corresponds to the chamber temperature, though measurements performed with a hand-held sensor at the end of a run indicate that gear tooth surface temperatures may be up to 30 °F hotter than the compartment air.

The greatest temperature gradients were observed at the end of the gearbox life. During the second thermal runaway event, the gearbox core suddenly began rising at approximately 10 °F per minute, peaking at 350 °F before the test was suspended (Figure 15). This was 150 °F hotter than the output roller bearing and 90 °F hotter than the input duplex bearing, which is the hottest measureable region on the actual aircraft. It is predicted that low lubrication conditions have the potential to generate gear surface temperatures in excess of 425 °F without detection, risking lubricant breakdown or tooth material degradation.

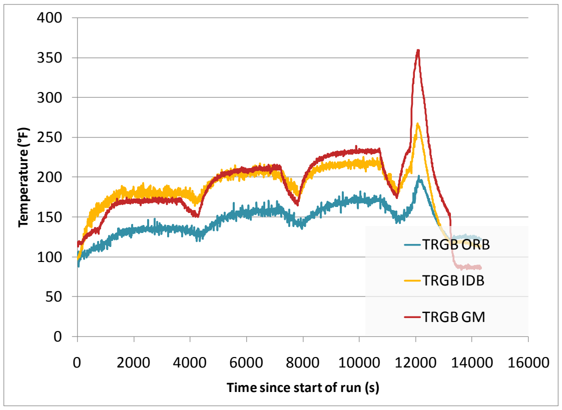

Figure 15 – Temperature of Article 3 as it experienced rapid heating from gear mesh lubrication starvation

CONCLUSIONS

1. Repair of Leaking Output Seals

The most significant finding of this study is the previously unknown grease movement between the two compartments of AH-64 tail rotor gearboxes. Although this discovery does not produce any advancements in the field of condition monitoring, it does give maintainers a more concise understanding of the actual health of a particular critical aircraft component.

A leaking output seal ultimately causes gearbox failure only if the main compartment lubricant levels are not appropriately maintained; however, if the seal is replaced or, more simply, grease is constantly added to the gearbox, it will continue to operate in a nominal and safe manner. This allows the current requirement of immediate gearbox replacement via an expensive and burdensome unscheduled maintenance procedure to be replaced with a less expensive and scheduled seal replacement.

2. Condition Indicator Threshold Evaluation

Although the experiment failed to meet the original test objectives of characterizing a failure on the output assembly ball bearings, it did provide an opportunity to evaluate the performance of many of the currently implemented Condition Indicators for gear health monitoring. Changes observed in the Tail Rotor Gearbox Lateral Bearing Energy indicator, along with several others, corresponded well to observed wear and failures in the gear mesh region. From these results, it will be possible to more appropriately define caution and exceedance threshold levels.

3. Temperature and Lubricant Issues

The thermal behavior of the AH-64 tail rotor gearbox during the observed gear mesh failures demonstrated the very real possibility of gearbox temperatures rising above the specified grease operational limits without detection by the current aircraft monitoring systems. Further study in this area should be performed to characterize the heat signatures of over-temperature gearboxes which are properly lubricated, as well as recording thermal data from actual aircraft in flight.

ACKNOWLEDGEMENTS

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