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

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ABSTRACT

Several experiments on AH-64 tail rotor drive train components have been performed, and key findings relating to the gearboxes and grease are discussed. In the first case study, an intermediate gearbox experienced three successive thermal events beyond the specified operational limits, all of which were characterized by rapid and unexplained changes in temperature at increasingly lower starting temperatures. A second study was performed to determine the effect of a severe leaking output seal on multiple tail rotor gearboxes, during which, previously unobserved grease flow dynamics showing mixing between theoretically isolated sections of the gearbox occurred. A final and ongoing experiment is attempting identify and characterize the cause of a frequently occurring intermediate gearbox grease ejections through its breather port. The studies conclude that tail rotor gearboxes have unit-level replaceable output seals, that temperature-based condition indicators may prove beneficial for health monitoring, and that poor dissemination of lubricant and gearbox information may result in significant costs in aircraft maintenance.

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 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 US Army 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.

Testing Procedures and General Observations

As on the actual helicopter, the tail rotor drive train test stand is a constant-speed and dynamic-loading power transmission system. The tail rotor drive shafts are spun at 101% aircraft normal speed, which is 4863 RPM, throughout the duration of a single test run, while the output motor changes its braking torques to produce specified load conditions, which match flight regimes as requested by the Army Engineering Directorate.

Due to memory storage limitations on the MSPU, each test run is approximately 4 hours in length, at which point the data is downloaded onto a Ground Station computer. All studies presented in this research utilized the same testing sequence as shown in Table 1, below.

Output Power (hp approx.)	Duration (min approx.)
0	3
30	10
100	50
30	10
198	50
30	10
252	50
30	10
330	50
30	10

Table 1 – Standard loading profile for a standard 4 hour test run

The MSPU collects data periodically throughout the run, and once per hour a more detailed data Survey is completed. The current standard practice is to complete a Survey in a condition known as FPG101, or flat-pitch ground at 101% speed. These surveys correspond to the 10 minute, 30 horsepower loading intervals.

A steady-state transmission of power through a gearbox would cause a constant heat generation condition, which would reach equilibrium at some temperature. As a result of the required cyclic loading conditions, the gearboxes on the test stand undergo thermal transients immediately after a load change. Because of the heat capacity of the gearbox assembly, these transients occur over a relatively long time domain, and result in distinguishable intervals on a temperature-time plot.

AH-64 Tail Rotor Drive Train Gearboxes

The two gearbox assemblies that make up the AH-64 tail rotor drive train are known as the intermediate and the tail rotor gearboxes (Figure 2). The gear ratios of each gearbox reduces the drivetrain speed in order to provide high torques to the tail rotor blades. Unlike many gearboxes at these power loads, both intermediate and tail rotor gearboxes utilze grease, rather than oil, as their sole lubricant.

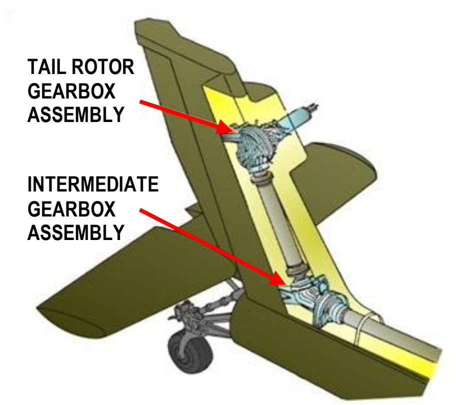

Figure 2 - AH-64 tail rotor and intermediate gearbox assembly location

The particular grease for these components is designated NS-4405-FG and consists of an ester base with a Lithium soap thickener. Ester greases are generally known for their high pressure stability and high heat resistance, and are outperformed only by the more expensive perfluoropolyether greases. In this case, NS-4405-FG has an operating temperature range of -65 °F to 275 °F.

Historically, it has been observed that some of the most common maintenance faults for AH-64 gearboxes are related to leaking or ejected grease. Some of these issues present only an inconvenience to maintenance crews, while others require extensive maintenance procedures or part removals.

Through multiple studies of AH-64 tail rotor drive train components, USC has made numerous observations and discoveries relating to the behavior of the gearbox-grease systems which have significant impact on the maintenance of the aircraft. A review of these findings is presented in this paper.

EXPERIMENTS AND FINDINGS

Intermediate Gearbox with Severe Thermal Transients

An intermediate gearbox which had been removed from an aircraft due to unidentified vibration signatures was installed on the USC test stand for further analysis. Initially, the gearbox indicated no abnormal behavior, and the vibrations which were generated were inconclusive. At the end of the sixth test run during the 330 hp load interval, however, an unexpected rapid change in gearbox temperature was observed (Figure 3). Although, the over-temp condition of 300 °F occurred, the stand was not stopped since the test run was near completion.

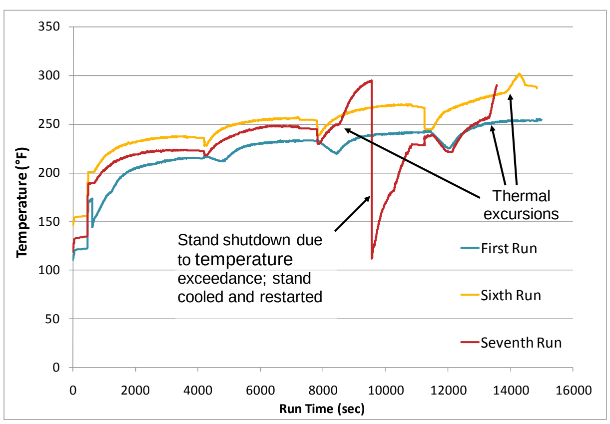

Figure 3 - Temperature-time plots of a thermally unstable intermediate gearbox

During the following run, near the beginning of the 252 hp load interval, a similar thermal excursion occurred, resulting in an emergency stop of the test stand due to the over-temp condition. The stand was then allowed to cool to ambient temperature and the run was resumed in the 252 hp load interval. Steady state temperature conditions had not yet occurred when the stand load profile was cycled to an FPG101 configuration. Almost immediately after the 330 hp load was applied, a third thermal event was observed, which also warranted the shutdown of the test and the removal of the gearbox as a test article.

This gearbox would be the first of many in which rapid changes of temperature at increasingly cooler starting conditions was observed. The sudden change in slope on the temperature plot indicates that an additional heat source beyond the normal effects of gear meshing may have been present.

Following its removal, the gearbox was disassembled and studied to identify the source of the problem. The teardown analysis findings were inconclusive and found no major damage to gear teeth surfaces or rolling element bearings. It is therefore theorized that the cause of the sudden heat generation was not due to mechanical phenomena such as friction or wear, but rather due to an exothermic chemical decomposition of the grease.

Further ongoing follow-up studies are being performed at USC to characterize NS-4405-FG when heated beyond its specified operating limits. In one experiment, unused grease samples were placed in a 300 °F oven at ambient air pressure for a period of four weeks. During that time, it was observed that the grease began to change color from tan to red and finally to black (Figure 4). In its final condition, it was further observed that the grease no longer maintained a uniform semi-solid viscosity, and had separated into solid and liquid regions.

Figure 4 - Changes in grease coloration when exposed to 300 °F temperatures

Tail Rotor Gearbox with Leaking Output Seal

In a separate study, three AH-64 Tail Rotor Gearboxes were tested to identify the survivability of the output shaft assembly ball bearings in a seeded-fault leaking output seal condition. Motivating this study was the Army required practice of replacing Tail Rotor Gearboxes at the first sign of an output seal leak. This was due to the perception that the static mast of the gearbox was sealed from the main compartment, meaning that static mast grease levels could not be observed or serviced (Figure 5).

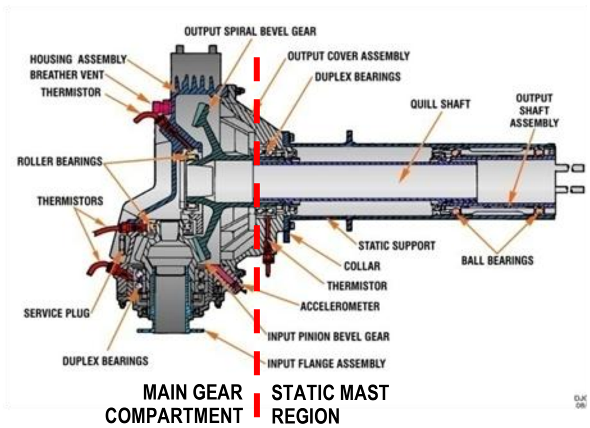

Figure 5 - Internal components of an AH-64 tail rotor gearbox

The output seals were seeded to represent a worst-case scenario leak for the gearboxes, so a large amount of seal material and the compression garter spring were removed (Figure 6). When the first attempted article was tested, it was unexpectedly found that following a sufficient ejection of grease from the output seal, the main compartment service levels were also low. Immediately following a servicing of the main compartment, the grease flow from the output seal increased in volume.

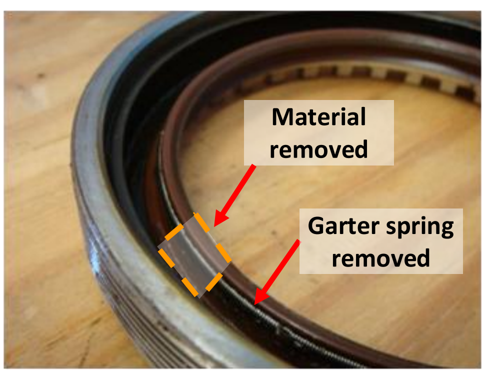

Figure 6 – Seeding procedure utilized to induce an output seal leak

Since it was thought that this behavior was impossible, the gearbox was disqualified and three more gearboxes, identified as Articles 1, 2, and 3, were selected. Article 1 showed similar behavior, causing the test plan to be modified such that the main compartment would only be serviced with the correct amount of grease at the beginning of each article test life. For all three articles, it was observed that a persistent grease leak through the output seal resulted in a loss of lubricant in the main gear compartment. Consequently, this condition ultimately resulted in lubricant starvation on the gear meshing region and catastrophic gear tooth failures (Figure 7). For Articles 1 and 3, the failure was accompanied by large thermal excursions, while Article 2 incurred a broken input gear tooth.

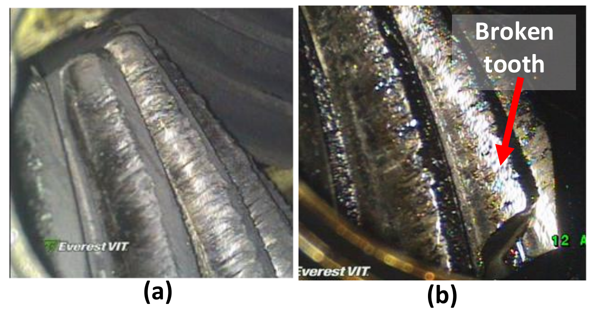

Figure 7 - Article 1 (a) and Article 2 (b) input gears after catastrophic failure

The experiment for Article 3 included a specially modified static mast, which allowed visual inspections to be made of the static mast grease levels. A special red dye was added to the main compartment, and prior to cutting the output seal, the test stand was run to observe any grease mixing. Within 120 minutes of starting the test stand, the static mast window began to show a slight red coloration and by 145 minutes, grease from the two compartments had become thoroughly mixed (Figure 8).

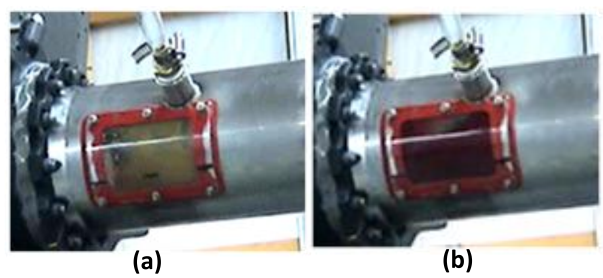

Figure 8 - Grease mixing observed through the static mast window of Article 3 after (a) 120 minutes and (b) 145 minutes of operation

From this study, various vibration signatures were collected that give some insight into the effects of lubricant condition on component vibrations. Examining the first and second harmonics of the gear mesh frequencies of Article 1 as it approached failure (Figure 9) shows noticeably cyclic behavior, despite the fact that all data points were collected in the same loading condition, namely FPG101. It is theorized that the cyclic behavior is strongly related to the gearbox temperature at the time of the Survey, and that accompanying viscosity changes in the lubricant cause the vibration signals to be affected.

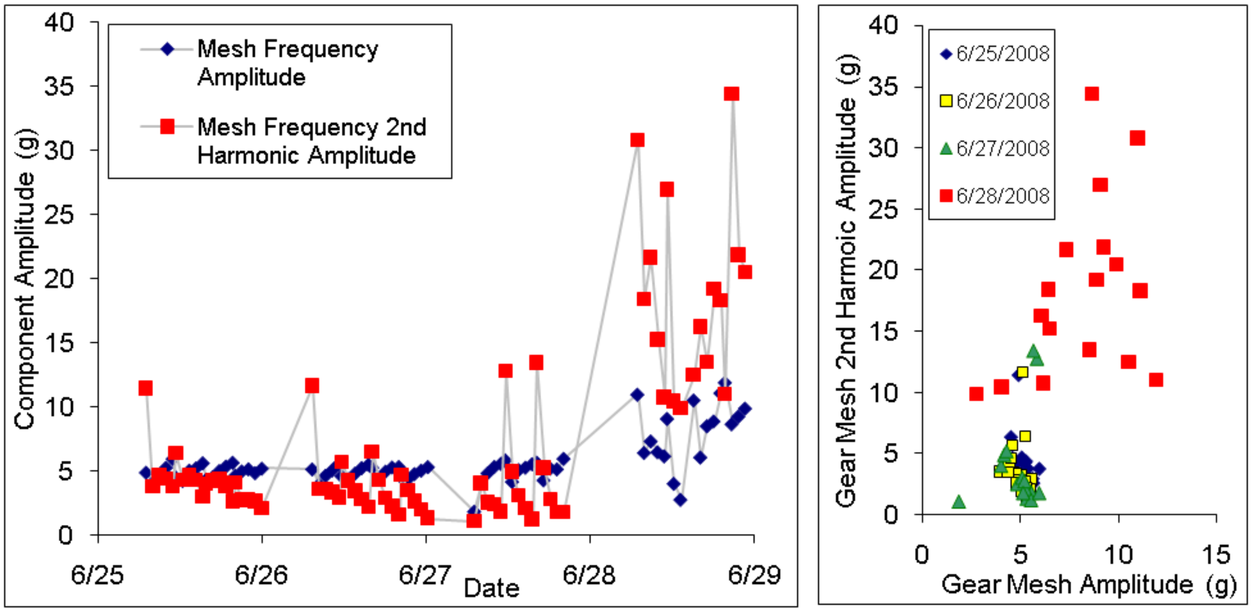

Figure 9 – Article 1 gear mesh harmonic amplitudes in the final four days of testing

This is evidenced even more when utilizing joint time-frequency domain analysis of the vibration signals for the same gearbox (Figure 10). In the days leading to the failure, the cold-start conditions show significantly less high-frequency noise than two hours into the run. Such noise is often associated with shock energy and indicates that in a lubricant-deficient gearbox, high temperatures cause a final protective layer of grease to become thinner and less effective.

During the experiment, several key observations about the thermal characteristics of a low-lubricant tail rotor gearbox were also observed. Contrary to the predicted behavior that a loss of lubricant would result in elevated temperatures due to increased friction, it was found that the heat generation regions of the gearbox maintained a consistent temperature profile until the point of failure. On Article 3, temperatures were monitored at three different locations: the input duplex bearing, the output roller bearing, and through a modified service plug which allowed a thermocouple to be placed very close to the gear mesh location.

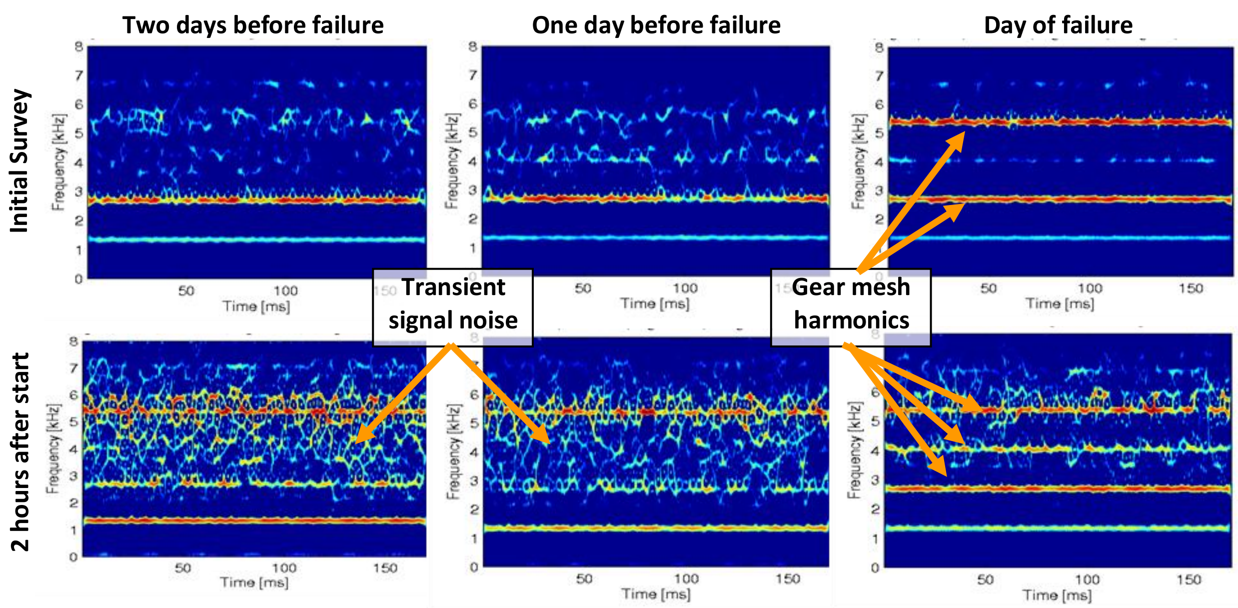

Figure 10 – Time frequency domain analysis of Article 1 lateral accelerometer as it approached failure

Comparing the temperature profiles of Article 3 in original fully serviced condition with its imminent-failure condition, it can be observed that two of the locations saw no significant changes in thermal behavior while the output roller bearing actually experienced a decrease in temperature (Figure 11 and Figure 12). It is theorized that this effect is due to the loss of a convective transfer mechanism which distributes gear mesh heat throughout the gearbox. It is predicted that gearboxes experiencing low-lubricant conditions will typically exhibit large thermal gradients, as illustrated by the use of infrared imagery ().

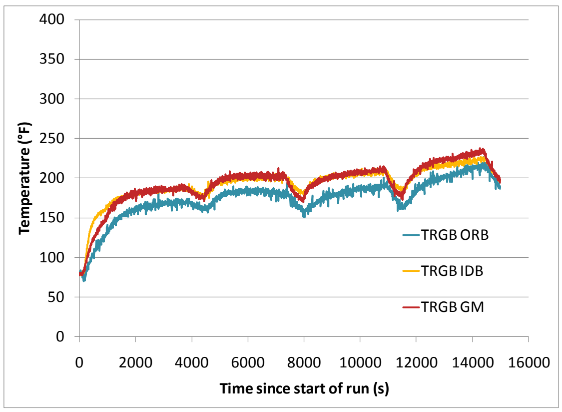

Figure 11 - Temperatures of the three measured locations on Article 3 prior to fault seeding

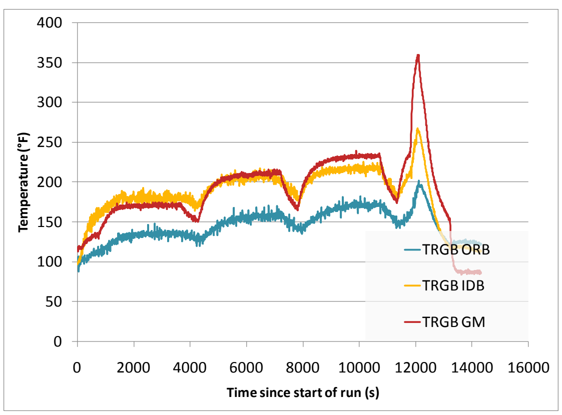

Figure 12 – Temperature of Article 3 as it experienced rapid heating from gear mesh lubrication starvation

As observed previously, Article 3 experienced three over-temp conditions each at successively cooler initial temperatures. Examining the first of these events, it is clear that the magnitude of the thermal gradients increases severely during the thermal transients, and that the gear mesh region can reach temperatures approximately 100 °F hotter than the highest monitored location on the actual aircraft (Figure 12). This indicates the possibility that in certain scenarios, a gearbox may reach temperatures beyond the operational limits of the grease without indicating this information to the flight crew.

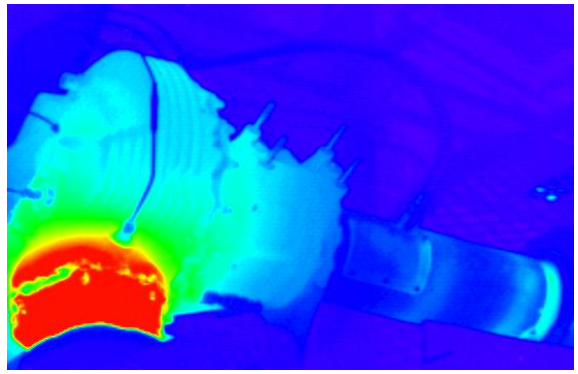

Figure 13 - Infrared thermal imaging of Article 3 after main compartment grease loss through the output seal

Intermediate Gearbox with Grease Ejections from Breather

One presently ongoing investigation by USC has been to characterize and identify the cause of intermediate gearbox grease ejections, which frequently occur through the breather port. In this study, two articles that were removed from actual aircraft for this behavior are being utilized.

The first step in characterizing this fault was to attach a transparent pipe to the breather port so that the static pressure head of the grease could be determined. During the first 4 hour test run, grease was ejected out of the breather to a maximum height of approximately 14 inches (**Error! Reference source not found.**). Based upon the density of the grease at room temperature, this would indicate an internal gearbox pressure of approximately 0.5 psi. The source of such a relatively low pressure has not yet been verified, but may be the result of centrifugal fluid dynamics of the grease or by thermal expansion of trapped air within the gearbox.

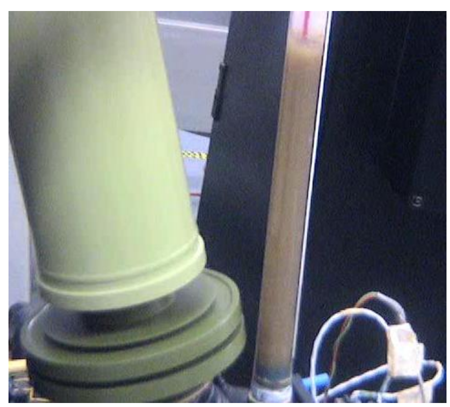

Figure 14 - Ejected grease column observed on intermediate gearbox test article

Another interesting observation is that the grease ejection only occurred during the first day of testing. At the end of the day, the grease settled back into the gearbox, and since then no further ejections have been observed coming from the breather. It is theorized that this may be due to rapid changes in grease properties such as a decrease in viscosity, thus changing the dynamics of air pocket and foam generation.

Future work will seek to quantify if such changes are, in fact, occurring and to determine what implications it may have on the operational practices of the intermediate gearbox. Other possible follow-up investigations may attempt to modify the breather such that grease ejections are less severe.

CONCLUSIONS

1. Repair of Leaking Output Seals

The most practical conclusion that results from the findings presented is that unit-level replacement or repair of AH-64 tail rotor gearbox output seals is feasible. Since grease has been observed to mix and transfer freely between the two gearbox compartments, there is no longer an immediate need to ground aircraft with minor output seal leaks. Since the observed rate of ejection was relatively low compared to the flight duration on an actual aircraft, properly servicing the main gear compartment is sufficient for maintaining static mast grease levels.

2. Condition Indicator Improvements

A new thermal signature has been identified which can be related to lubricant service levels within a gearbox. A future health monitoring system could utilize measurements of thermal gradients rather that solely relying on over-temp limits to identify faulted conditions.

Furthermore, the data continues to indicate that there are strong relationships between gearbox temperature and vibration signatures. From this information it may be possible to use temperature to normalize condition indicator levels. Enhanced, multi-sensor condition indicators could be more reliable and meaningful than the current vibration-based systems and lead to an enhanced application of Condition-Based Maintenance.

3. Temperature and Lubricant Issues

The thermal transients observed in the first two studies indicate the high possibility of thermal conditions within the AH-64 gearboxes, which exceed the operational limits of the lubricant, and that these events may occur without detection. Furthermore, changes in gearbox behavior observed during the third experiment indicate that the lubricant currently in use may be subject to rapid changes in physical properties, even at normal operating conditions. Follow-up research will be needed to further assess the operational characteristics of these gearboxes, and whether or not the grease has an appropriate specification for its current use.

4. Needed Improvements in the Dissemination of Information

The accepted practice of removing AH-64 tail rotor gearboxes for output seal leaks strongly illustrates a poor understanding of the operational characteristics of this component, and shortcomings in the dissemination of information between the manufacturer and customer. Anecdotes which have persisted during the life of the aircraft explained this maintenance practice by insisting that the static mast of the gearbox was sealed from the serviceable main compartment; however, also throughout the life of the aircraft there have been manufacturers and overhaul sites which would have been aware that such a seal never existed.

Improved dissemination of facts between the Army, overhaul facilities, and the aircraft and component manufacturers would have prevented such costly misinformation from persisting for so long. In this particular case, the problem was confounded by the fact that the purported part was not accessible or visible to aircraft users. It is therefore recommended that maintenance practices based on unobservable components, which are also high cost drivers, be investigated to ensure that such policies are, in fact, needed and cost-effective.

ACKNOWLEDGEMENTS

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