Dependence of Vibration Characteristics on Grease Service Levels in an AH-64D Intermediate Gearbox

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ABSTRACT

The purpose of this experiment is to determine if the intermediate gearbox (IGB) grease service level can be characterized through existing condition-based maintenance (CBM) practices, which include vibration monitoring sensors and analysis algorithms, in the IGB of the AH-64D. A secondary objective is to quantify a common phenomenon in the gearbox–the expulsion of lubrication during different times of operation. If both goals are achieved then common maintenance practices on the aircraft can be changed to reduce workload. Three different gearboxes of similar condition were used for this experiment. Each gearbox was run in a two hour test under different loading conditions five separate times. In each iteration, the gearbox contained a different volume of grease that increased in 25% increments of the standard service level (0%, 25%, 50%, 75%, and 100%). The vibration data analyzed was collected through the modern signal processing unit (MSPU) to find a trend against the different amounts of grease. To complete the secondary goal, the amount of grease ejected during the initial parts of the runs was captured and weighed. This will be used to obtain a constant number at which to service the IGB and prevent the "burping" of grease during operation. . More research should be conducted to discover whether higher-order vibrations analysis will allow this fault to be detected.

INTRODUCTION

Condition monitoring technologies that determine the health of a machine are crucial for implementing novel maintenance practices. Industrial standards for CBM focus mainly on vibration analysis, with some input from temperature signatures (Ref. 4). Vibration has been proven as a better indicator of failure because it displays a slow trend over time whereas temperature change is much more sudden and tends to occur near the very end of a component's life. To detect physical changes in the helicopter components, condition indicators (CIs) are calculated using various algorithms. However, there are limitations on the extent at which CIs can detect problems since each of these algorithms is targeted to a specific type of fault. Currently, there is no CI to detect grease loss in the intermediate gearbox (IGB).

Component Testing at the University of South Carolina

For over 15 years, the University of South Carolina (USC) has been collaborating with the South Carolina Army National Guard (SCARNG). Combined efforts between two parties led to a fully developed Condition-Based Maintenance (CBM) Research Center within the USC Department of Mechanical Engineering that hosts several aircraft component test stands in support of CBM objectives. At the USC test stands, different CIs have been tested and validated to detect faults that occur over the lifetime of various drivetrain articles including such components as the AH-64D forward hanger bearing, aft hanger bearing, IGB, tail rotor gearbox (TGB), and tail rotor swashplate (TRSP) (Figure 1).

Presented at the AHS 70th Annual Forum, Montréal, Québec, Canada, May 20–22, 2014. Copyright © 2014 by the American Helicopter Society International, Inc. All rights reserved.

Figure 1. Comparison of USC test stand to actual aircraft

TECHNICAL BACKGROUND

USC Tail Rotor Drivetrain Test Stand Overview

The test stand emulates the complete tail rotor drivetrain (TRDT) from the main transmission to the tail rotor swashplate assembly. The TRDT is comprised of actual aircraft hardware and is capable of handling drive shafts installed at the maximum allowable misalignment of two degrees. Structure, instrumentation, data acquisition systems, and supporting hardware are installed according to military standards. The test stand's two 800 horsepower motors are capable of exceeding 150% of the actual aircraft drivetrain loading. The test stand was designed and built to accommodate the use of various Health and Usage Monitoring Systems (HUMS) and is currently equipped with a Honeywell modern signal processing unit (MSPU). USC's own data acquisition results have been validated with data obtained from actual airframes. The testing facility is also capable of being modified to test new and existing drivetrain components of military and civilian aircraft, including the ARH-70, CH-47, and UH-60 drivetrains (Ref. 1).

IGB Overview

The purpose of the IGB on the AH-64D is to change the direction of the drive as well as output speed. The main components of the IGB are the input rolling bearing, input duplex bearing, output duplex bearing, and output roller bearing (Figure 2). In its current configuration on the USC test stand, it is outfitted with two accelerometers and four thermocouples. The accelerometer and thermocouple positions are identical to what can be found on the aircraft.

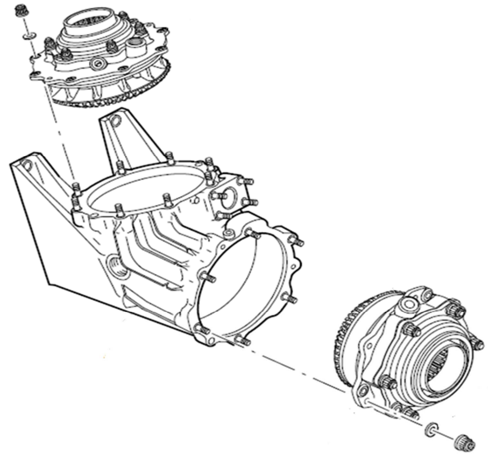

Figure 2. Internal view of the IGB

A naturally occurring fault of the IGB is the ejecting of grease from the breather port; even newly serviced AH-64D IGBs have been found to eject large volumes of grease through the gearbox breather port. This fault could require the aircraft to land for immediate maintenance (Figure 3).

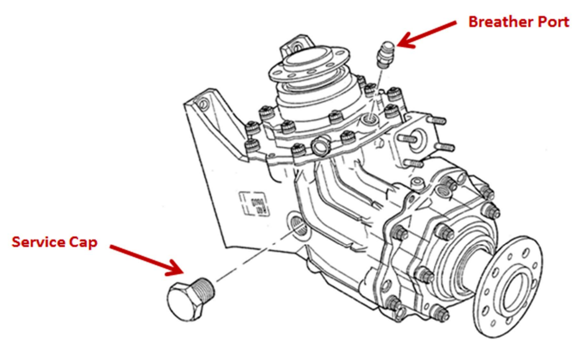

Figure 3. Diagram of Intermediate Gearbox

A common belief is that the ejection occurs when the grease exposed to the in-flight operating conditions. The physical and rheological properties of the grease change after a certain period of time even when the temperatures are within operating limits (Ref. 3). One possible mechanism responsible for this phenomenon is the simultaneous application of mechanical and thermal loads. Rheological characterization of the IGB grease samples revealed reduction in their apparent viscosities when compared to the virgin grease at shear rates tested (Figure 4).

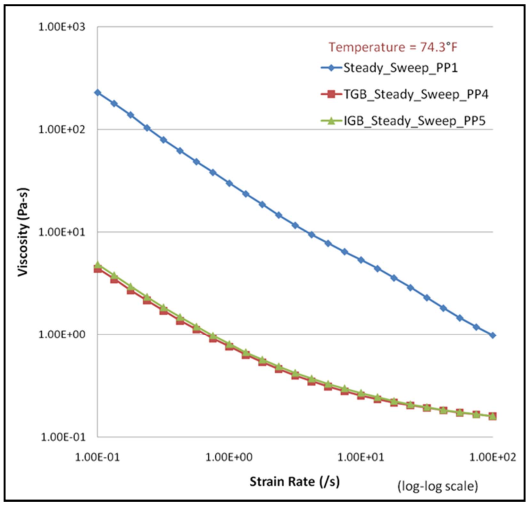

Figure 4. Sweep test results for IGB and TGB

Oil lubrication has been investigated as a possible solution to lubricant ejection. Some initial success has been found in the use of nanoparticle treated oil instead of the traditional grease. Experiments have been conducted at USC cataloguing the oil performance based on ejection, temperature, and vibration data. The experimental gearbox began by burping foamy oil during the first hour but the burping subsided and did not persist after reservicing. (Ref.4). Thus, it has been proven that both oil and grease eject from the breather port.

Detection

Presently, there is no CI value to tell the maintainer the level of the lubrication so the service level must be checked every 25 flight hours by a maintainer using a special tool designed for checking both gearboxes (Figure 5). The dipstick is inserted into the service port and then checked to determine if the lubricant is within the boundaries set on the device. Historically, it has been observed that some of the most common maintenance faults for AH-64D 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 (Ref.1).

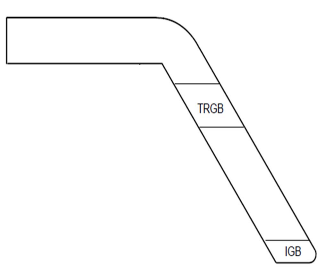

Figure 5. Gearbox service level dipstick

Experimentation is required to determine if a correlation exists between the grease service level and the vibration magnitude of the IGB. If no correlation exists, current maintenance practices are confirmed and a grease level monitoring system via vibration cannot benefit the health of the helicopter. If the correlation does exist, variation in the grease level will have an effect on CIs and monitoring this level would increase the accuracy of the fault characterization.

One of the benefits of having components run on a test stand rather than on an aircraft is that experiments can be conducted safely and are more cost effective. The safety of the testing setup has allowed USC to conduct an experiment in which three TGB were run to failure, which averaged out to 500 hours each, with no grease in the component housing. In other tests, it has been noticed that the vibration levels have changed after being serviced with grease, leading to this investigation. One example of this change due to grease addition appeared in the Tail Rotor Gearbox Vertical Bearing Energy CI (Figure 6). Grease was added on January 14 and a significant drop in vibration can be seen following that date (denoted by the vertical red line).

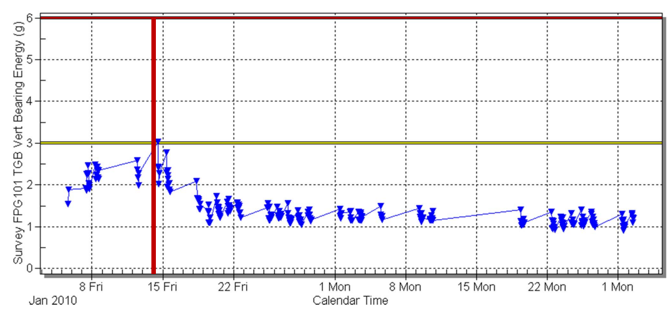

Figure 6. Tail Rotor Gearbox Vertical Bearing Energy measured over time

Though this change was noted, no further research was conducted and the correlation between grease level and vibration remains unconfirmed and uncharacterized. The expected outcome of further experimentation is that the grease level is a critical factor to the performance of the helicopter and that when the grease level decreases, the vibration will increase parametrically. By showing this correlation, maintenance practices can be changed from the current preventative maintenance scheduling to a condition-based procedure contingent on vibration levels in the gearbox. Furthermore, if the correlation is determined to be consistent between gearboxes, a standard minimum service level can be set.

PROCEDURE

This experiment was conducted using three intermediate gearboxes, each run at five different service levels of grease (0%, 25%, 50%, 75%, and 100%); these levels will be calculated based off of the Army standard for a fully lubricated gearbox (2.125 lbs. of grease). These tests totaled approximately 34 hours of testing. It was decided that all of the gearboxes start at 0% grease and increase to 100% as shown in Table 1.

Table 1. List of Tests

Test #	Serial #	Grease %
1	1	0
2	1	25
3	1	50
4	1	75
5	1	100
6	2	0
7	2	25
8	2	50
9	2	75
10	2	100
11	3	0
12	3	25
13	3	50
14	3	75
15	3	100

The test stand at USC is already equipped with standard aircraft sensors, along with a few that are unique to the facility. This includes, but is not limited to: accelerometers, thermocouples, and an infrared camera. By using both military and commercial data collection methods, techniques developed by USC were used to further analyze collected data.

Gearbox Changeout

After every fifth test in Table 1 the IGB was removed and flushed of grease. To ensure these levels are consistent the gearbox was flushed twice, first with an oil-based solution and then a second time with denatured alcohol. After being filled with the liquid the gearbox was left to sit overnight and then drained for another eight hours. To verify that an acceptable amount has been removed, the gearbox internals were checked using a borescope (Figure 7). During this part of the procedure, any damage to the gearbox could be noted.

Figure 7. A comparison, from a previous experiment, of worn gear teeth (left) to healthy teeth (right)

Pre-run Procedures

The operators consider the test stand as an actual aircraft and it is treated with the same respect. Before each run, an inspection of the test stand is conducted. Additional inspection measures were implemented (i.e. grease ejection monitoring, and the removal of unnecessary equipment from the test stand since a new experiment was being conducted. Additionally, the operators carefully monitor the data collection equipment to ensure the measurements appear accurate and the ejected grease is collected.

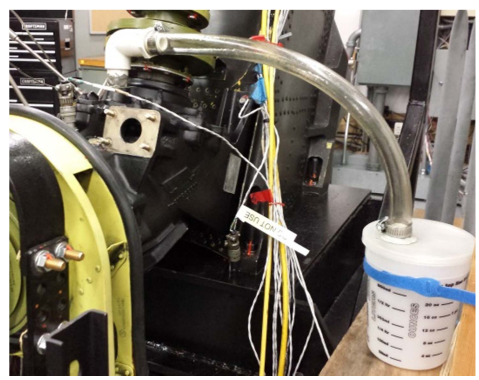

Figure 8. Breather port adapter setup

Running Procedures

The USC TRDT test stand operated with the standard test profile, shown in Table 2, built to simulate the flight characteristics of the AH-64D gearboxes. FPG 101 is when the aircraft is sitting with no pitch in the blades and the rotor running at 101% of maximum speed, approximately 4863 rpm. During this time, a survey is taken and data is collected by the MSPU and used to create a CI.

Table 2. Modified TRDT Load Profile

Load Step	Run Time	Elapsed Time	Speed	Torque	HP
FPG 101	00:05-00:15	10	4863	111	30

Normal	00:15-01:05	50	4863	371	100
FPG 101	01:05-01:15	10	4863	111	30
Normal	01:15-02:05	50	4863	979	264
FPG 101	02:05-02:15	10	4863	111	30

RESULTS AND ANALYSIS

The two biggest metrics for a CBM analysis are temperature and vibration. Vibration is the more reliable of the two indicators because it will show a trend over time for when the component is starting to fail. Temperature is a last minute indicator that will only begin to increase significantly at the very end of an article's life. Both of these indicators were utilized in this experiment and showed similar results to one another.

Vibration

The main objective of this experiment was to determine if a trend for vibration with different grease service levels exists across multiple gearboxes. This analysis was done for three different gearboxes using two different CI values: input and output bearing energy. These values were taken directly from the PC-GBS program used by the Army. This program displays filtered data that is collected from accelerometers on the aircraft using the MSPU. Gearbox #3 was the only article to exhibit the predicted behavior, of vibration decreasing as grease amount in the gearbox increased, making the results inconclusive.

The vibration plots are displayed to put emphasis on the trend for each gearbox through all the grease level changes. The figures below (Figure 9-Figure 11) each show the data for one run broken up by CI. These plots show the overall trend across runs. During the course of a run, the vibration is expected to decrease because the grease has a break-in period and then after that time the changing conditions will not affect the grease performance. For reference, the graph labeled IBE denotes input bearing energy and the plot with OBE is output bearing energy.

In gearbox #1 this expected trend in the input bearing energy is only seen in the 25% grease run, and only in the 25% and 100% runs is it noticeable in the output bearing energy. In the overall trend graphs the increase in grease was expected to lead to a decrease in vibration, due to less friction in the gears leading to a downward trend. This trend is not evident in most of the graphs (Figure 9).

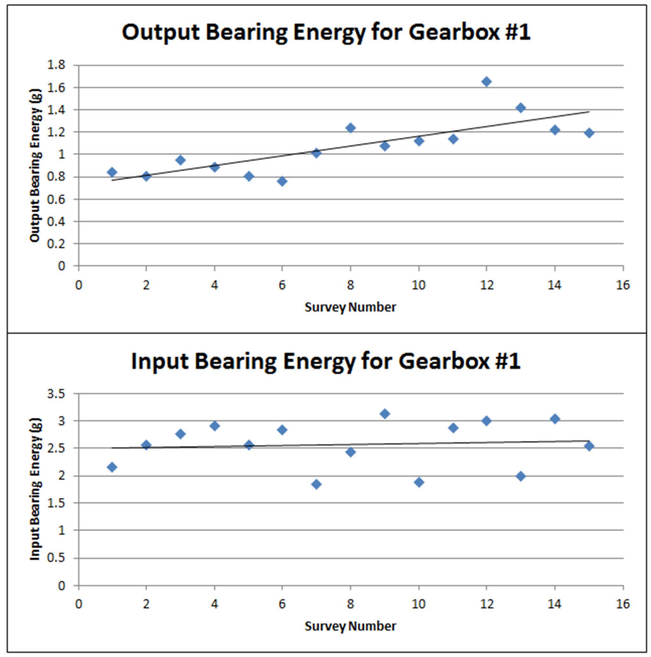

Figure 9. CI values for Gearbox #1

The vibration magnitude of gearbox #2 is closer to the expected trend but there are still some unexpected qualities (Figure 10). There was only one grease level for both the input and output bearing energy that had a positive trend. When all of the runs were graphed together the trend was negative for the input bearing energy and positive for the output bearing energy.

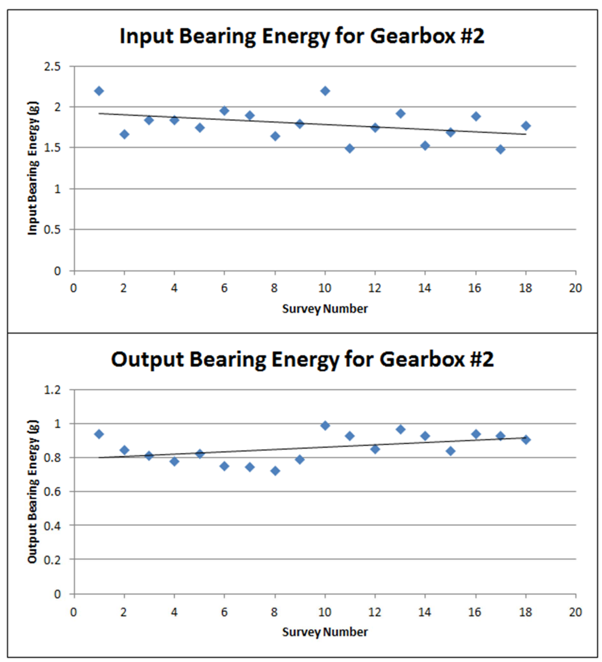

Figure 10. CI values for Gearbox #2

The final gearbox exhibited nearly all of the expected characteristics in this experiment (Figure 11). When changing grease levels from run to run all of the resulting trends from the input and our bearing energy had negative trends. Although the gearbox mostly matches all of the expectations when conducting vibration analysis it is still unclear if a trend that can be applied to this type of data right now.

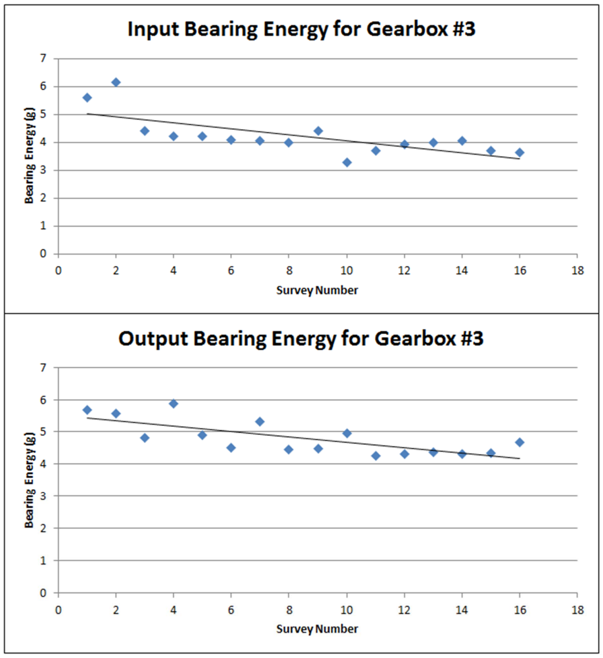

Figure 11. CI values for Gearbox #3

Temperature

On the aircraft, temperature plays an important role as an indicator for the health of a component. The purpose of temperature readings throughout testing were to make sure that the article was not being damaged due to running in a state with a low grease service level. Like vibration qualities, each gearbox has a different standard operating temperature. When that value starts to increase rapidly, it is a good indicator that the component is going to fail shortly. Since there is more friction on the internal components of the gearbox, it is thought that the 0% grease run will have the greatest temperature average. There are four places on the IGB where thermal readings are taken: input duplex bearing, input rolling bearing, output duplex bearing, and output roller bearing. For visual purposes these values where averaged together and plotted for each run conducted on a gearbox (Figure 12-Figure 14).

After analyzing the results from gearbox #1, it can be seen that there is not a very noticeable change from run to run. An interesting result is that the temperature actually increased as the amount of grease increased, from 130.8°F average temperature to 139.7°F (Figure 12). It is important to note that the torque affects the temperature of the grease. This is seen at the beginning of the run when the torque is at 371 ft.-lbs. and goes back down around the one hour mark because a survey is taken at 11 ft.-lbs. It increases again at the last value of 979 ft.-lbs.

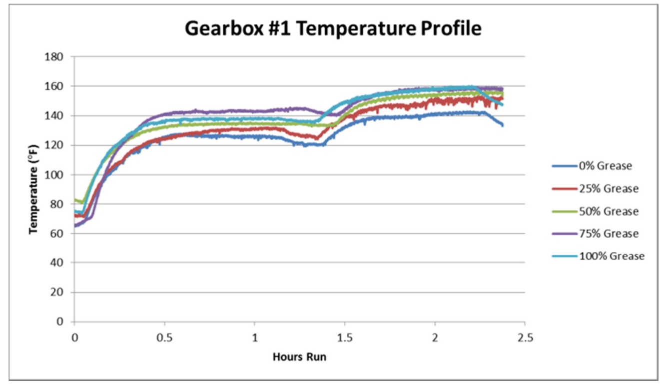

Figure 12. Temperature results for the different runs conducted on Gearbox #1

The temperature profile for gearbox #2 shows similar results to the first test article. The gradient increases with the service level, but it is not by a great amount (Figure 13). The average temperature for the 0% grease run was 125.1°F and for 100% it was 143.8°F.

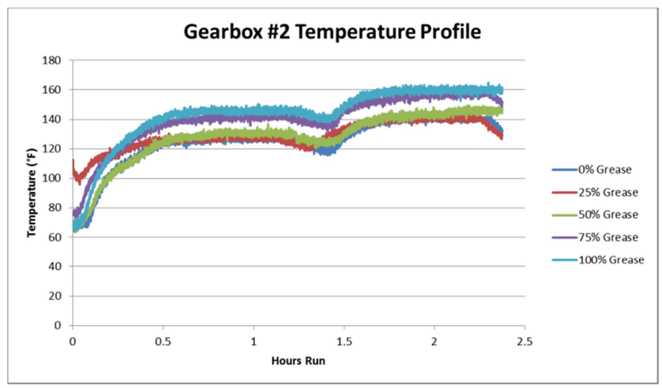

Figure 13. Temperature results for the different runs conducted on Gearbox #2

Similar to the vibration analysis, gearbox #3 shows some of the characteristics of an expected trend for a gearbox with different grease levels (Figure 14). Although the 100% grease is the second highest average temperature value, the largest is the 0% grease value. The lowest average temperature for this article was at 25% grease at 160°F and has a maximum average value of 198°F with the gearbox running on no grease.

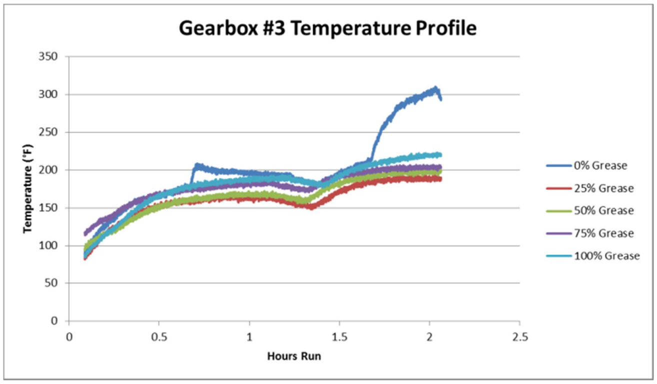

Figure 14. Temperature results for the different runs conducted on Gearbox #3

Grease Ejection

As previously stated, common phenomenon on the AH-64D is that the gearboxes have a tendency to eject lubrication when they are considered 100% serviced. During testing, the gearboxes displayed the same characteristics as on the aircraft, even once at 75% of the standard service level. The results displayed in the table below quantify the amount of grease ejected during each run. Some of the gearboxes were run multiple times to see if the amount of grease the gearbox ejected was the same each time. It is important to note that after a gearbox ejects grease it is common practice for that new amount to be considered the 100% service level. The results agree with this rationale because there was only one gearbox, gearbox #1, that ejected the same amount of grease as the previous run, which was still 65% of the 2.125lb recommended service level. The results from all of the components tested seem to indicate that the amount of grease ejected is a random amount and is unique to each gearbox.

Table 3. Total amount of grease in each gearbox

Tail #	Test #	Grease Level	Grease Amount (grams)	Ejected (grams)	Net Amount (grams)
Gearbox #1	1	0%	0	0	0
Gearbox #1	2	25%	241	0	241
Gearbox #1	3	50%	482	0	482
Gearbox #1	4	75%	723	102	621
Gearbox #1	5	100%	964	341.6	622.4
Gearbox #2	6	0%	0	0	0
Gearbox #2	7	25%	241	0	241
Gearbox #2	8	50%	482	0	482
Gearbox #2	9	75%	723	0	723
Gearbox #2	10	100%	964	131	833
Gearbox #2	10	100%	964	272	692
Gearbox #3	11	0%	0	0	0
Gearbox #3	12	25%	241	0	241
Gearbox #3	13	50%	482	0	482
Gearbox #3	14	75%	723	0	723
Gearbox #3	15	100%	964	396.4	567.6
Gearbox #3	16	100%	964	511.5	452.5

CONCLUSION

The operational characteristics of the gearbox drivetrain components on the AH-64D are very unique to an individual article. Throughout this paper, nearly every metric used to quantify a quality of the gearbox has been different. The magnitudes of vibration are different from gearbox to gearbox as well as how the values respond to changing grease levels. Temperature is another aspect in which their unique qualities are shown because, although the general qualities are the same, the operating temperature is still different between them. Even something as simple as gearbox grease service level is not standard for the component. Each gearbox should be theoretically over serviced and then allowed to find its own 100% service level.

Future Work

The experiments thus far are insufficient to establish a correlation between the CI magnitude levels and the grease levels. However, the correlation may exist and be undetectable if the correlation is not strong enough to be noticed in such a small sampling population. The two objectives for future work are to increase the diversity of analysis algorithms and increase the number of different gearboxes used in sampling. The two algorithms used in this paper are standard on the MSPU but as mentioned before are not tuned to detect grease leakage. Using less processed data, such as the raw frequency information, custom CIs could be created. Furthermore, research into other factors in gearbox vibration response may help eliminate variables from our consideration. How different faults affect the gearbox, and its response to other problems is not entirely characterized and so further research into this area would help determine how much of the response is due to grease and how much is due to the historic faults of the that gearbox reacting to the different loadings and conditions of the test stand.

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