# Impact of Lubrication Analysis on Improvement of AH-64D Helicopter Component Performance

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## Abstract

The purpose of this research study is to provide evidence for the further study and possible inclusion of lubricant data and analysis to common condition based maintenance (CBM) practices as a means of increasing the effectiveness of the AH-64D fleet. Presented in the paper are four different AH-64D aircraft wetted-component case studies, which aim to improve performance through the examining the effect of oil and grease on component performance and fault detection. The first case study was designed to simulate a worst case scenario regarding a leaking output seal on three different tail rotor gearboxes (TGB). The second study presents an oil feasibility experiment on the AH-64D intermediate gearbox (IGB) in which the oil replaced the grease that is traditionally used. The final case study involves two approaches in assessing the theoretical and practical approach in assessing the effectiveness of an oil analysis method to identify a failure by comparing it with the final recommendation provided by AOAP labs. The final case study also examines and compares the efficacy of oil analysis and vibration data at detecting component faults. Though not conclusive, initial correlation observations indicate that more study and research should be conducted to determine and measure the impact that lubricant has on component performance and detecting component faults.

## Introduction

The condition monitoring technologies that determine the health of a machine are crucial for implementing condition based maintenance (CBM) practices. Industrial standards for CBM focus mainly on vibration analysis, with some input from temperature signatures. However, this limited focus may overlook other potentially useful indicators, which, if incorporated into the condition indicators (CIs) that are used to predict component failure, could serve to improve fault detection performance. Lubricant and filter debris analysis is one noticeable area where potentially significant CI and CBM improvements could be made.

The two gearbox assemblies that make up the AH-64 tail rotor drive train are termed the intermediate and tail rotor gearboxes (IGB & TGB, respectively). Both gearboxes utilize NS4405-FG grease as their sole lubricant. The primary function of the lubricant is to prevent contact between components in relative motion in a mechanical system by maintaining a thin film between the surfaces. Faults in these two gear boxes are frequent and create significant problems in the field, taking time and money that may not be easily available. The TGB, for example, is prone to leaking grease near the output seal. Additionally, even newly serviced AH-64 IGBs have been found to eject large volumes of grease through the gearbox breather port which requires the aircraft to land for immediate maintenance. The Army conducts oil analysis studies in an effort to further understand the impact the lubricant has on the performance of numerous moving components on the aircraft. By understanding the relationship between lubricant properties and AH-64D wetted components, this study hopes to provide motivation for further research and studies into the impact that oil and grease analysis might have for improving tail motor performance and predicting component failures.

Industrial lubricants can be generally classified as oil or grease based. Due to the distinct properties of both classes of lubricant, different responses and damage processes are observed in practice. Historically, oil has been a popular lubricant for high-speed machinery as a result of its ability to act as both a coolant and a lubricant [3]. In addition, because oil is a Newtonian fluid, meaning its viscosity is independent of shear rate, its viscosity is easily determined with known temperatures and pressures. Finally, many oil-based lubricants contain additives to resist corrosion, contamination, and extreme temperatures and pressures.

The increase in applied stress and the range of environmental conditions under which the lubricant should work are motivating factors driving the selection of grease. Grease is the preferred choice in components prone to leaking because of its high washout resistance. Chemically, grease is composed of a three dimensional thickener network dispersed in base oil. The base oil is trapped in the thickener structure by physical and chemical forces, i.e. capillary effect and van der Waals forces. Lubricating grease exhibits plasticity, viscoelasticity, thixotropy and a complex set of rheological effects [3]. The functional properties of grease are dependent upon shear stability, mechanical stress, volume of contaminants, and variations in temperature and pressure. Grease cannot dissipate heat as well as oil which results in a higher range of peak temperatures present in an operating component. Higher peak temperatures can have noticeable effects on the chemical and physical properties of grease lubricants. For example, the base oil can bleed out of the thickener, leading to the destruction of the thickener network or lubricant starvation on the contact surface. However, in some cases, this chemical change can lead to further lubrication of the contact surface. Grease is a viscoelastic material and falls into the category of non-Newtonian fluids, its viscosity is dependent upon shear rate. Typical greases are shear-thinning fluids (viscosity decreases as shear rate increases across a certain range). Consequently, under zero-shear conditions, these lubricants can act as a sealant but will act as a lubricant at high shear rates. The non-Newtonian effects influence the local film thickness and pressures as well. Even though grease properties cannot be expressed in sample parameters as with other Newtonian fluids, apparent viscosity and consistency are characteristics that can define the effectiveness of grease as a lubricant.

Little is known about the impact that oil or grease has on vibration and temperature levels of aircraft components. Currently, Apache helicopter performance is determined by measuring condition indicators regarding temperature and vibration from mounted accelerometers and thermocouples. Therefore, it is necessary to examine the relationship between different lubricating agents and the subsequent response in CIs, in order to be able to recommend adjustments in the CIs to take lubricant characteristics into account. This will ultimately increase the understanding of the gearbox and improve fault diagnostic capabilities.

This paper will address three different case studies: a TGB experiment with leaking output seal, an IGB oil feasibility study, and an investigation into the effectiveness of AOAP data on different AH-64D wetted components in detecting faults. The results of these studies demonstrate initial indications that further study into the impact that lubricant analysis might have on CI performance is warranted.

## Main Body

Determining correlations between lubricant analysis and component condition and CIs can either be performed using experiments conducted on actual components or through data analysis. This research utilizes both methods. Component testing of the TGB and IGB was made possible through a unique collaboration between the University of South Carolina (USC) and the South Carolina Army National Guard and the resultant test facility at USC. Data analysis utilized data supplied by the Army Oil Analysis Program (AOAP).

## CBM testing facility at USC

Over the past decade, USC has developed and maintained a strong working relationship with the South Carolina Army National Guard. USC has played a key role in the development of 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. The USC test facility possesses a complete AH-64 tail rotor drive train test stand (Figure 1), which is designed to facilitate a scientific understanding of aircraft component conditions and provide empirical understanding of various failure modes and other parameters that can be harbingers of component failure. These observations are necessary for the development of comprehensive and accurate diagnosis algorithms and prognosis models. The test stand emulates the complete tail rotor drive train to the tail rotor swash plate assembly and is composed of true AH-64 aircraft hardware. The test stand was designed and built to accommodate the use of multiple Health and Usage Monitoring Systems (HUMS) and is currently equipped with a Honeywell Modernized Signal Processing Unit (MSPU). Alongside the MSPU, another data acquisition system is employed known as the USC DAQ that operates in parallel to the MSPU. In addition to being used to run the test stand, the USC DAQ collects temperature data from thermocouples and discrete raw vibration time domain data from accelerometers mounted on the components of interest.

The availability of this test stand made possible the implementation of the first two experiments, those of the simulated leak in the TGB and the grease/oil comparison in the IGB. It also facilitated the customization of the experiments to simulate the specified conditions and to introduce additional sensors as needed.

**Figure 1 – USC AH-64 tail rotor drive train test stand**

## TGB Output Seal Leak Study

In a previous study, the output seal at the end of the static mast was investigated because of its tendency to leak due to unknown causes [1]. This study had two goals: to show that an aircraft with this condition can continue to function until the next normally scheduled phase maintenance and to identify and characterize vibration signatures that could predict the failure of the static mast ball bearings. Because this research involved specific interaction between grease and aircraft components, it was a logical choice to be included in this study and also motivated further inquiries into lubricant/component failure correlations.

For the experiment, a worst-case scenario involving a leak in the output seal was simulated to observe the impact on the two ball bearings that support the gearbox output shaft assembly. This simulated leak was performed on three different gearboxes – Articles 1, 2 and 3 – which ran for 500 hours each.

Given previously observed occurrences involving grease in the TGB, it was not surprising that Article 1 initially ejected large volumes of grease from the static mast. Following standard operating procedures, grease was added, at which time grease ejections continued. No more grease was added after this point, and when it approached the 500 hour limit of the test, temperature spikes over the acceptable limit level were recorded. After the experiment ended, the input gear exhibited severe wear due to the lack of lubricant.

No grease servicing occurred mid-run for Article 2, and this gearbox followed a similar pattern to that of Article 1, with grease being ejected into the static mast and tooth wear being observed. However, no thermal indicators were apparent before an input gear broke, and the experiment was terminated. The gear tooth wear of Articles 1 and 2 are illustrated in Figure 2.

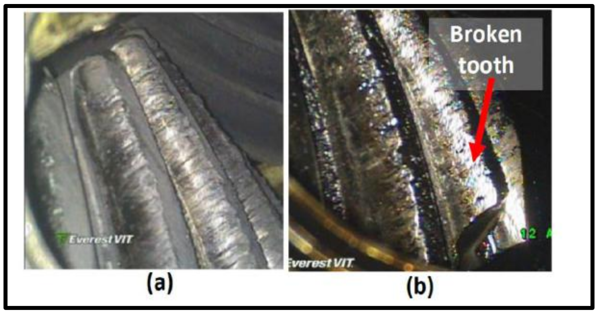


**Figure 2 – Article 1 (a) and Article 2 (b) input gears after catastrophic failure**

In order to observe the grease transfer into the static mast, a window was constructed on the static mast for the third article, and red dye was added to the grease prior to the test. Grease was observed to travel into the static mast, and slowly increasing tooth wear was evident. For this article, in addition to the standard input duplex bearing and output roller bearing thermocouples, a special thermocouple sensor was installed to be within 0.5 inches from the input gear mesh surface in order to more closely monitor gearbox core temperatures. Thermal instabilities occurred but did not appear until after the 500 hour testing limit. Thermal spikes are depicted in Figure 3.

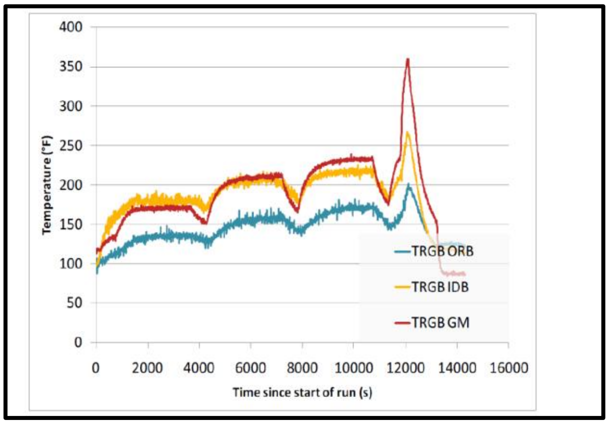


**Figure 3 – Thermal instabilities of Article 3**

As the figure shows, though neither of the temperatures recorded at the input duplex bearing and the output roller bearing rose higher than the 300°F safety limit level, significant temperature differences were recorded between the output roller bearing and the gearbox core. This indicates that, given the recorded temperatures for Article 1, it is likely that temperatures in the gearbox core rose much higher than acceptable levels, which explains the excessive gear tooth wear.

During this experiment, grease ejections into the static mast resulted in a situation of lubricant starvation for all three test articles. This loss of lubrication causes excessive tooth wear in Articles 1 and 2 and a broken tooth in Article 2. In the cases of Articles 1 and 3, significant thermal instabilities were noted around the time of the specified test-hours limit. These observations give rise to assumptions and theories being formulated as to the role of the lubricant in the condition of the component and detecting imminent component failure.

Results of the TGB Output Seal Leak Study. In order to be able to comment on the possible of effects of lubricant on the vibrations and thermal indicators that are used in CIs, some measureable interactions and/or correlations must be observed first. During this experiment, three interesting events were noted: the temperature events, a CI caution indicator during the failure of Article 1, and some specific vibration changes.

One significant thermal observation occurred with Article 3. During the normal test run hours, there were no significant thermal increases and the output roller bearing actually experienced a decrease in temperature when compared to the thermal profile of a healthy article. Because heat can be lost through convection and therefore be distributed throughout the gearbox, large thermal gradients have been detected through thermal imaging on gearboxes with low lubricant levels. The changes in viscosity that grease can experience with higher temperatures could have significant impacts on component performance and fault detection.

Another significant event of note during this experiment that warrants further investigation occurred as Article 1 began to fail. The TGB lateral bearing energy MSPU CI indicated a caution level during this period, as represented in Figure 4. Because this event was not observed on the other two article failures, it is unknown as to whether this indicates actual vibration signature changes. The high thermal levels observed during this failure, combined with the resultant changes in grease properties, are a likely culprit that should be researched further, as little is known as to the effects of the changes of grease viscosity on vibration energies.

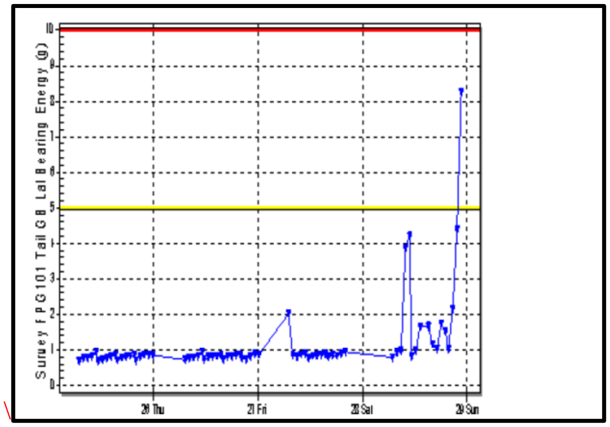


**Figure 4 – Article 1 MSPU TGB lateral bearing energy CI vibration levels**

In addition to the vibration signatures unique to the lateral bearing energy CI, the first and second harmonics of the gear mesh frequencies of Article 1 (Figure 5) showed some variation from those of the other two articles. The cyclic behavior and presence of the high second harmonic visible at the end of the run, lends credence to the idea of a correlation between the temperature behavior, viscosity changes of the grease, and the component vibration signatures.

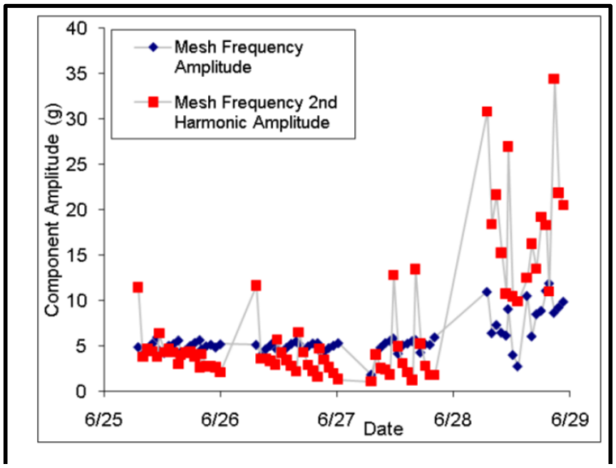


**Figure 5 – Article 1 gear mesh harmonic amplitudes**

Though limited in scope, this isolated TGB study presented several interesting events that raise questions about the impact of grease properties on the vibration levels apparent in the component. To assume that no correlation exists without further study would be needlessly eliminating the opportunity to discover new information that could be critical to the CBM effort.

### IGB Oil-Grease Study

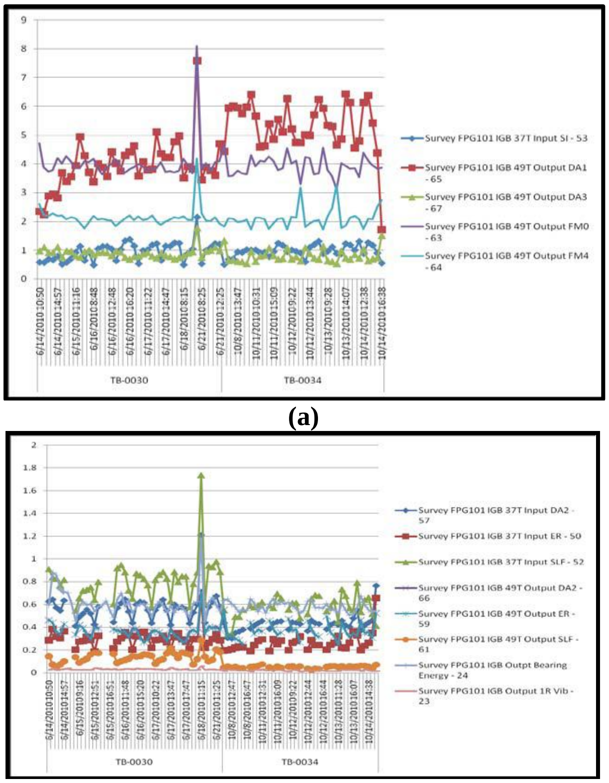
The second case study was originally designed to investigate the phenomenon of the IGB burping grease out of the breather port, which is depicted in Figure 6 [2]. However, some interesting observations occurred that warrant its inclusion in this study. Though traditionally a grease-lubricated component, this experiment strove to compare the effects that using oil in the place of grease in the AH-64D IGB had on factors such as the ejection of grease, temperature, and vibration signatures. To that effect, both temperature and vibration data was collected from the oil-whetted article and compared with grease-lubricated baseline data to determine what, if any, effect and differences could be detected.

**Figure 6 – IGB breather port**

For this experiment, the component was first run with grease to establish baseline measurements. It was then flushed and serviced with oil. At the beginning of this test run, the gearbox burped foamy oil for the first hour, but the burping subsided and did not persist after re-servicing. The article was then run for the remainder of the test, while temperature and vibration data were collected. Following the experimental test run, the gearbox was sent back to the Army for a tear-down analysis, at which time it was noted that there was no abnormal wear on the gear or bearings.

Results of the IGB Oil-Grease Study. In an effort to measure the difference between oil and grease as the lubricant of choice for the intermediate gearbox, two main pieces of data were examined: vibration/CI levels and temperature behavior. Differences noted attest to the fact that lubricant choice, and ergo the lubricant itself, has an impact on the vibration levels and therefore the ability to detect faults on the component.

With regards to the IGB CIs, few major differences were observed, though several CIs did change when oil was used on the article. These differences are plotted and visible in Figures 13a and 13b, a comparison between the TB-0030 grease baseline to the TB-0034 oil measurements. The IGB 49T Output DA1 CI experienced the most significant and observable increase; however, this did not affect the stability of the component. The IGB 37T Input SLF and IGB 49T Output SLF CIs experienced a decrease in vibration level, which may be contributed to the dampening effect of oil as compared with grease. Though these vibration variations are slight and did not affect the performance of the IGB, they do serve to highlight the fact that lubricant does have some measureable impact on the vibration levels of the component.



(a)

(b)

**Figure 7 – TB-0030 vs. TB-0034 FPG101 Survey CIs**

Temperature is a large factor in lubricant and component performance and is therefore a major component of data analysis for CBM. For this experiment, the particular properties of grease versus oil resulted in observed thermal differences, which are highlighted in Figures 8 and 9. Thermal measurements are typically collected in four places on the IGB: the input duplex bearing, input rolling bearing, output duplex bearing, and output roller bearing. Because oil is a Newtonian fluid and does not significantly react to external stresses, it maintained a lower and more streamlined thermal profile than that of the grease-lubricated component. The steady operational temperature of the oil-lubricated component was around 175°F, compared to that of grease at 225°F. Because grease is a thixotropic, or non-Newtonian, fluid, it reacts more noticeably to stress – loading, in this case – which explains the wider temperature bands, higher average temperature, and cyclic behavior of the thermal graph. Given the impact that temperature can have on the performance of an aircraft component, the observation that oil can have an effect on the temperature profile of the IGB is significant and should be investigated further to more fully understand the significance of this finding and what it means for the future of aircraft fault detection.

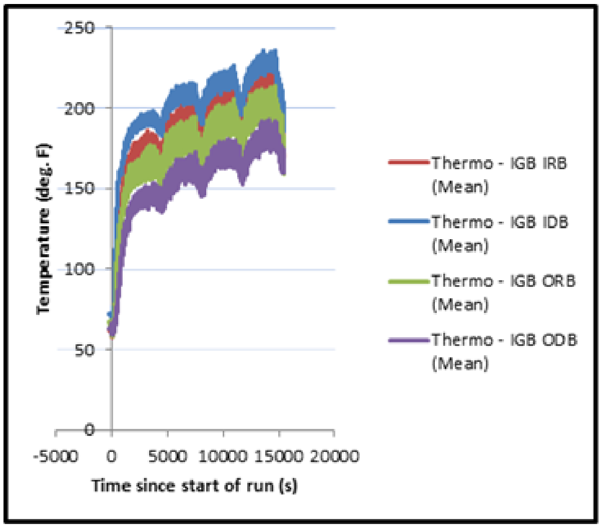


**Figure 8 – Grease baseline thermal plot, single run**

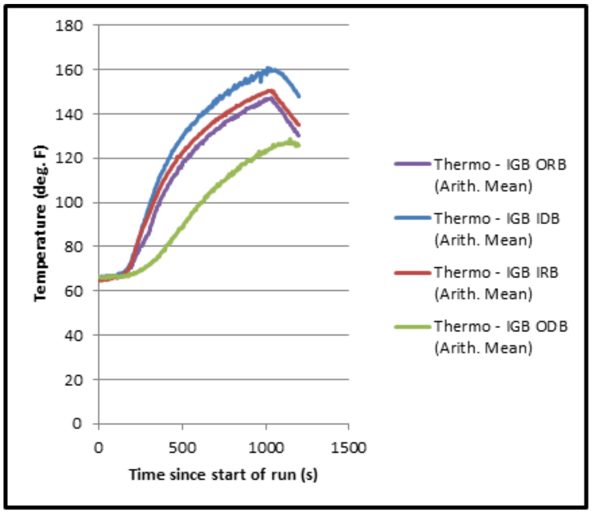
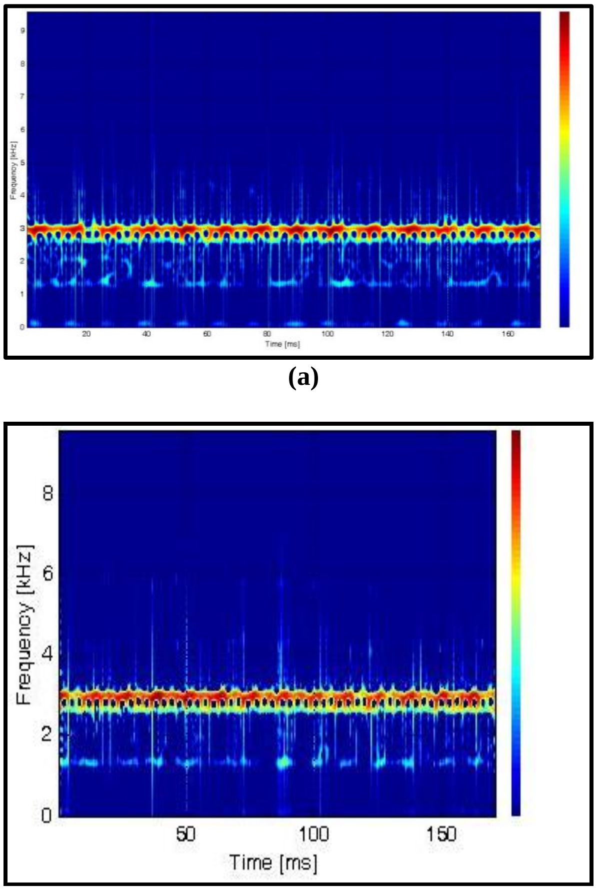


**Figure 9 – Oil temperature data post-service**

In addition to temperature and CI measurements being made, a time-frequency analysis using the Choi-Williams (WV-CW) kernel function was also conducted on the oil-whetted component a couple of hours into the run and again at the end to detect any transient faults arising during the test run. The analysis concluded that the oil did not have any negative effects on the article and that the component was healthy throughout the test run. Because the oil did not bring on any adverse effects, the possibility of the use of oil for gearbox lubrication should be investigated further. This analysis also lends credence to the assertion that, because the oil did not introduce any faults into the article, the changes in vibration signatures between the grease and oil components must be a direct result of lubricant impact. Results of this study are presented in Figures 13A and 13B.



**(a)**

**(b)**

**Figure 13 – WV-CW time-frequency distribution after the initial survey of the oil experiment and (B) WV-CW distribution 4 hrs. before the termination of the oil experiment.**

Though conducted to address the concern about grease being ejected from the breather port on the IGB, this study also served to examine the differences that could be detected when using oil in the place of grease as lubrication on the component. While major differences were not observed, the differences that were detected – those of the CIs and the temperature – demonstrate that choice of lubricant does indeed affect the aircraft component and warrant further testing and research to obtain a quantifiable and measured impact.

## Army Oil Analysis Program (AOAP) Study

The AOAP labs have been assisting various army units in conducting tests on oil samples extracted from components and in assessing the condition of that component. This process has led to the collection of a large volume of data related to various types of rotorcrafts. This data is invaluable in determining the effectiveness of oil analysis as a tool for fault detection, which was the purpose of this study. Analysis of this data, the aggregation of the test results, and the combination of this data with vibration and maintenance data serve to draw conclusions as to the role that oil analysis should play in CBM, as well as to demonstrate correlations between oil and component vibrations.

The tests conducted by AOAP labs on oil samples include Atomic Emission Spectroscopy (AES), Fourier Transform Infrared Spectroscopy (FTIR), LaserNet Fines (LNF), Karl Fischer (KF), Viscometric, and Titration tests. For a given sample, depending upon the need and availability of instruments, some or all of the tests are performed, and a final recommendation is provided based on the analysis of the results of the individual tests. To further improve effectiveness of oil analysis in realizing CBM, the AOAP and the USC research facilities have collaborated to analyze this historical data ranging from July 1999 to August 2009 for the AH-64 fleet [3]. Meanwhile, an independent assessment was also performed by the U.S. Army Aviation Engineering Directorate (AED) [4] in response to disenrolling aircraft components from the AOAP. The data obtained for both analyses from oil analysis records include aircraft and component details as well as information about the date the sample was received, the tests performed, results obtained, and the recommendation from the lab expert. Because both IGB and TGB systems are predominantly lubricated with grease, they were excluded from the AOAP and the USC analysis of approximately 277,000 test results; however, there was some limited data available in the AED Study [4], for the IGB and TGB, and was used in the AED review. Additionally, the AED study also reviewed the AOAP results for the Engine Nose Gearbox and Main Transmission.

Figure 10 shows that the AES test has been performed on all test samples. Additionally, Figure 10 shows that AES and FTIR are performed in conjunction more often than any other two tests (82% of the data), followed by AES and LNF (80% of the data). The relative share of these tests is important, as it has an impact on the recommendation of the results which are presented in the next section. Figure 11 indicates that around 77.7% of the test results were normal and only 3.8% of the total tests indicated abnormal results. This is perhaps due to frequent, regularly scheduled sampling during times of healthy component life.

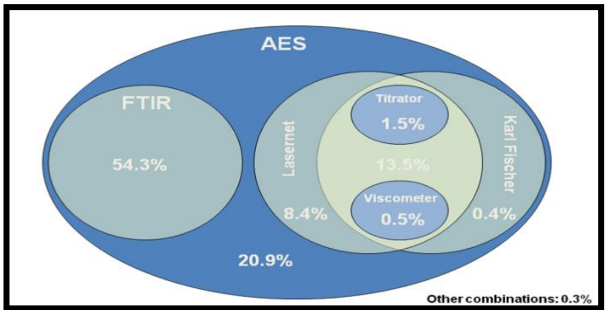


**Figure 10 – Historical test data summary**

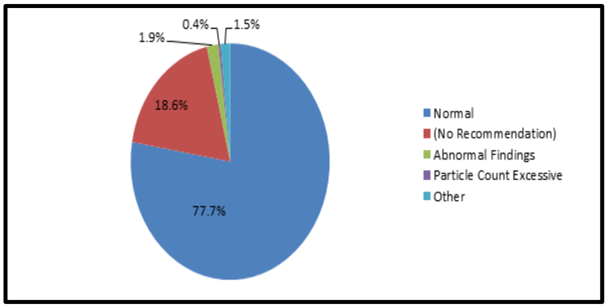


**Figure 11 – AOAP test results summary**

After an analysis of the data as a whole, the outcomes of the individual tests for a given sample were compared against each other, as well as against the ultimate outcome of the test, to determine correlations between tests and between the individual tests and the final recommendation. This helps in comparing the recommendation provided by the lab expert with the outcome computed from the first principle.

For the AOAP and the USC study, the AOAP oil analysis data was compared with Army TAMMS-A data – which provides information involved with controlling and managing aircraft, aviation-associated equipment, mission-related equipment and maintenance – in conjunction with data from the PC Ground-Based System (PC-GBS) database – which provides processed vibration data from Army aircraft. Relevant events were determined by cross-checking related maintenance actions with the 20-day window of vibration data prior to that maintenance action. Four case studies were used in reference to the AOAP and combined TAMMS-A and PC-GBS (termed simply "VMEP" Vibration Management Enhancement Program) data: where both indicated a need for maintenance, where only one correctly identified the fault, and where neither was successful.

Results of a Joint AOAP and USC Study. Two types of conclusions can be drawn from the results of the AOAP data analysis study. The first consists of conclusions about the oil analysis tests themselves and their consistency with the final recommendation. As Table 1 shows, FTIR and KF tests have a stronger influence on the final result than any of the other individual tests. Knowing the test capabilities of KF and FTIR tests, it can be surmised that contamination due to water, fuel or soot, or the possibility of oxidation, nitration, and sulfation are major problems that are responsible for possible damage to a particular system and the maintenance action. Also, a strong relation has been observed between AES and Viscometer. The AES data constitutes a significant percentage of test data, which suggests that perhaps changes in viscosity could be one of the primary reasons responsible for the fine wear particles identified by AES. This change in viscosity may not be due to only temperatures changes but could also be induced by other modes like contamination by water, fuel or oxidation, etc. Because oil analysis is the only means of detecting particles and measuring viscosity, these individual tests might be prioritized in the future to make oil analysis a more feasible option for inclusion in the CBM process given the resource-intensive nature of the oil analysis process.

**Table 1 – Summary of statistical analysis of test results comparison**

| Comparison Type | Number of Samples | Mean (µ) |
|---|---|---|
| AES vs Final | 225248 | 0.30707 |
| FTIR vs Final | 115604 | 0.79357 |
| VISC vs Final | 1848 | 0.08820 |
| KF vs Final | 42843 | 0.99260 |
| AES vs FTIR | 151109 | 0.32651 |
| AES vs VISC | 1876 | 0.77132 |
| AES vs KF | 44796 | 0.25107 |
| FTIR vs VISC | 264 | 0.90152 |
| FTIR vs KF | 359 | 0.15599 |
| VISC vs KF | 1843 | 0.08681 |

The results from the joint AOAP and USC study of the integration of the oil analysis data with the VMEP data produced little overlap in the joint success of the two analyses. This suggests that each system is successful at detecting distinct types of faults. Although case studies show that VMEP is historically more likely to identify a fault than AOAP, with this data set, there is a 21% increase in the number of correctly identified faults due to the addition of the AOAP system (Figure 12).

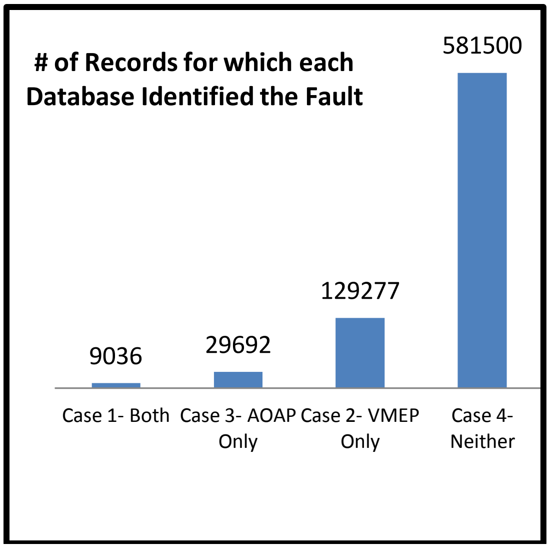


**Figure 12 – Distribution of oil analysis and VMEP results of individual case studies (AOAP and USC)**

This suggests that AOAP may expand the capability of the CBM system beyond what was provided by VMEP alone [3] and the addition of oil analysis may play an important component of CBM analysis. However, the research conducted under the AED study detailing the impact that oil analysis has on the efficacy of the CBM system at prediction failures and slightly contradicts the overall AOAP success.

<u>AED AOAP/RIMFIRE Review Results</u>. For the AED study, a separate data set was used in reviewing the effectiveness of the AOAP result. The AOAP recommendations and results provided were compared to the component condition captured under the Reliability Improvement through Failure Identification and Reporting (RIMFIRE) program at the Corpus Christi Army Depot (CCAD) overhaul facility. At the time of the review, the RIMFIRE data base contained 341 Main Transmissions. Of these, 82 had sufficient data in RIMFIRE and LIW (Logistics Information Warehouse). Only 1 removal out of 82 gearboxes examined, could possibly be attributed to a successful AOAP analysis and recommendation. 3 gearboxes were also "false positives"; meaning, they were returned due to recommendations provided by the AOAP labs and found to have little to no damage present. 7 gearboxes were also "false negatives"; meaning, they were removed with various levels of severe damage and all AOAP history immediately prior to return showed no indications of abnormalities.

The results for the Nose Gearbox were similar to those found for the Main Transmission. 68 gearboxes had an adequate amount of data to determine if any correlation was possible. Only 2 gearboxes were found that could be considered "detected" by AOAP (additionally, it appears in both cases the final samples prior to removal were supplementary samples taken by the unit in an attempt to confirm a failing gearbox, not indications from regular samples that indicated an unknown abnormality. However, since they did give a sign of abnormalities, they were counted as "True Positives"). There was 20 "False Negatives" out of the 68 examined with severe damage that should have been detected.

The TGB and IGB data reviewed, were limited to only a handful of gearboxes that could be used for correlation. All of the AOAP results ranged from "Marginal" to "Critical", but the condition of the gearboxes overall showed very little evidence of wear.

**Table 2 – Summary of the components reviewed in the AOAP analysis (AED Study).**

| Airframe | Component | QTY |
|---|---|---|
| AH-64A/D | Intermediate Gearbox (IGB) | 2 |
| AH-64A/D | Tail Gearbox (TGB) | 5 |
| AH-64A/D | Nose Gearbox (NGB) | 68 |
| AH-64A/D | Main Transmissions | 82 |

The VMEP or MSPU (Modernized Signal Processing Unit) Accuracy is a compilation of seeded fault testing conducted at the USC CBM Facility, RIMFIRE, and field articles with data submitted under the Army's Product Deficiency Reporting System (PQDRs). The AED reviews the Tear Down results of a component, scores the component's health, and asses the performance of the CIs. In summary, the accuracy of the VMEP/MSPU system can be seen in Table 3. Overall the system performs very well. The IGB score is lower than desired; however, this is marked with an "*" because of the way the accuracy is calculated. Several components may affect the IGB CIs (input flange, driveshaft, couplings, mounting torque, and diffuser. Unfortunately during tear down evaluation, very seldom are any of the above mentioned components sent with the IGB for review; which, are most likely the source of the vibration. This leads to a "No Evidence of Failure" and a lower accuracy score.

**Table 3 – AED VMEP/MSPU Accuracy.**

| Airframe | Component | Accuracy |
|---|---|---|
| AH-64A/D | Intermediate Gearbox (IGB) | 66.7%* |
| AH-64A/D | Tail Gearbox (TGB) | 83.3% |
| AH-64A/D | Nose Gearbox (NGB) | 91.4% |
| AH-64A/D | Main Transmissions | 94.4% |

*Score is lower due to methodology – see paragraph prior to table.

## Conclusions

The three described studies each examined different aspects of the interaction between lubricant and aircraft components. Though not conclusive or readily quantifiable, initial correlation observations resulting from the three given case studies indicate that more study and research should be devoted to determining and measuring the impact that lubricant has on component performance and fault detection.

As a result of the TGB output seal leak experiment, it was determined that both thermal and vibration levels were influenced to some degree by the lack of sufficient grease lubrication on the component. This study also pointed to a marked correlation between lubrication and temperature, which is a typical CBM measure. During the IGB oil feasibility study, differences in temperature and CI behavior between a component lubricated with grease and one with oil indicates that lubrication choice should be considered in the algorithmic design of CIs, and that further study of the interaction could yield measurable ways of improving CI performance and detection capabilities.

Results from the AOAP case study could provide an insight into common modes of damage to the components. Based on analysis times and test effectiveness, the AOAP testing needs improvement to give effective recommendations. The correlation study between oil analysis and vibration data indicates that oil analysis reports need more research and development to be a valuable inclusion to the CBM fault detection process.

In all studies, the data continues to indicate that there are strong relationships between temperature, viscosity and vibration signatures. Additional study would serve to provide the conclusive assessments necessary to quantify the impact of lubrication within CBM and indicate how the CBM system could be adapted to best incorporate this new method of detection. Ultimately the end goal is to have enhanced, multi-sensor condition indicators that could be more reliable and meaningful to assist the current vibration-based systems and lead to an enhanced application of CBM practice. Follow-up research projects at the CBM Research Center will further study and assess the operational and rheological characteristics of the tail rotor drive train gearboxes and its effect on vibration signatures. Additional controlled studies are recommended in order to fully understand the tribological behavior of oil and grease.

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## References

1. Goodman, N., Bayoumi, A., Blechertas V., Shah, R., Shin, Y. J. "CBM component testing at University of South Carolina: AH-64 gearbox grease studies", American Helicopter Society, 65th annual forum, Texas, May 2009.
2. "Test article summary report: AH-64 IGB oil based study." USC CBM Center Internal Report, July 2011.
3. "Condition indicator evaluation report: AOAP Test and GBS/AOAP comparisons." USC CBM Center Internal Report, July 2011.
4. Chris Hirstein, "AOAP Effectiveness on Aircraft Transmissions and Gearboxes." Redstone Arsenal, U.S. Army Aviation Engineering Directorate, 9 June 2008.