AIRWORTHINESS RELEASES AS A RESULT OF CONDITION BASED MAINTENANCE

William D. Lewis[1], Christopher D. Perry[2], and Jonathan A. Keller[3]

Aviation Engineering Directorate
Redstone Arsenal, AL 35898-5000, United States of America
[1]e-mail: william.lewis@amrdec.army.mil
[2]e-mail: christopher.perry@amrdec.army.mil
[3]e-mail: jonathan.keller@amrdec.army.mil

Key Words: rotorcraft, condition based maintenance, diagnostics

Abstract: The current Aviation Engineering Directorate effort in condition based maintenance can be summarized in a single basic idea – the refinement of rotorcraft drive train health diagnostics which lead to tangible benefits for US Army Aviation. Refinement of a diagnostic method into a useful form requires not only instrumented aircraft, data collection systems and algorithms; but also data transfer, management, analysis, and verification. The summation of all these parts translates the raw data into a front-line maintenance decision making capability. This paper summarizes the US Army Aviation Engineering Directorate condition based maintenance program to date including examples from field units and ongoing engineering support activities.

1 INTRODUCTION

Current US Army Aviation maintenance philosophy is to perform maintenance at phased intervals, usually in terms of flight-hour usage. The longer phased maintenance intervals are supplemented by mandatory checks performed on either a shorter flight-hour usage or calendar basis. Often, completion of the mandatory checks requires the use of portable test equipment temporarily installed on the aircraft. In addition, many aircraft dynamic component retirement lives are based on flight-hour usage or calendar time and are conservatively estimated. Thus, components are often replaced regardless of their actual condition. These maintenance practices, although proven effective in terms of airworthiness and safety, actually cost aircraft availability, time and money. The Department of Defense (DoD) has mandated a shift from the maintenance philosophy of the past to a Condition Based Maintenance (CBM) philosophy [1]. The goal of CBM is to "perform maintenance only upon evidence of need" and requires Program Managers to "optimize operational readiness through affordable, integrated, embedded diagnostics".

Clearly, the ability to accurately assess the condition of the helicopter rotor system and drive train is directly applicable to the goal of CBM for Army Aviation. The most common method of rotor system and drive train mechanical health diagnostics is through vibration measurement and analysis. The legacy system used by the US Army to complete such routine maintenance tasks is the Aviation Vibration Analyzer (AVA). The AVA is a portable system, consisting of accelerometers, tachometers, cables, blade tracking camera (UTD) along with a vibration analyzer (DAU) and computer display equipment (CADU) as shown in Figure 1. The AVA is used for main rotor smoothing, tail rotor balancing, drive shaft balancing and absorber tuning, as well as mandatory vibration checks on select drive train components. The AVA, although effective, has several drawbacks. First, it is not permanently installed and requires approximately 2 man-hours installation time. This fact leads to another disadvantage in that AVA equipment can be damaged during installation or simply lost. Secondly, the AVA was only intended to be used by the maintenance crews at plane-side. After the vibration data has been acquired and used to perform maintenance on the aircraft, it usually remains with that particular AVA unit or is simply deleted. Although there are methods to transfer this data via the Internet back to engineering personnel for troubleshooting or archival, these methods are cumbersome, labor intensive and require significant computer skills. Thirdly, the AVA was designed and fielded around 1990 so its ability to perform modern vibration diagnostics is limited by its processor and available memory. Thus, the AVA does not fulfill the objectives of CBM as currently envisioned and a replacement system (or systems) is needed for Army Aviation.

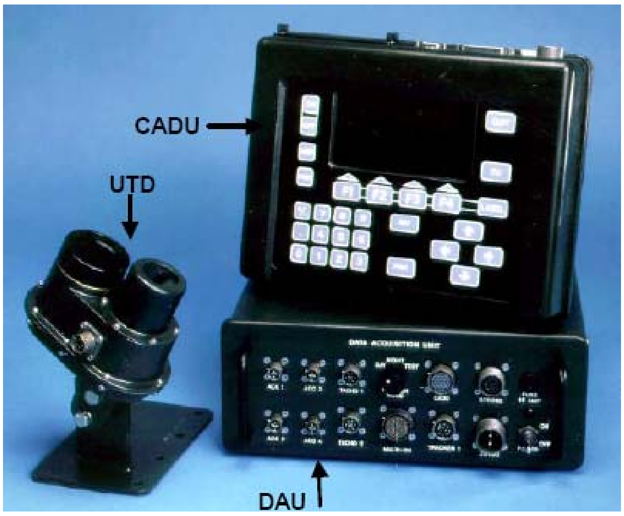


Figure 1. Aviation Vibration Analyzer

2 FIELD RESULTS

2.1 Demonstrations

The Aviation Engineering Directorate (AED) has worked with the Program Executive Office (PEO), Aviation and respective Program Managers (PMs) for Apache, Black Hawk, Armed Reconnaissance Helicopter (ARH) and Chinook on the installation of modern health and usage monitoring systems (HUMS) for the past several years. The purpose of this effort was to conduct AVA replacement and Digital Source Collection (DSC) demonstrations and to quantify the benefit of these systems specifically for Army Aviation. A limited number of Apache and Black Hawk aircraft were installed with several HUMS beginning in 2000 and a limited number of Chinook aircraft were installed with several HUMS beginning in 2005. As of this writing, there are now over 149 HUMS installed on the 3 major platforms with additional installations in progress. Currently, the Vibration Management Enhancement Program (VMEP) and Modernized Signal Processing Unit (MSPU) systems developed by the Intelligent Automation Corporation and IMD-HUMS/IVHMS developed by the Goodrich Corporation comprise the majority of HUMS installed on US Army aircraft. A few systems developed by Smiths Industries and Honeywell are also being demonstrated. The demonstrations continue into fiscal year 2008, but the Army is already beginning to see significant results in the reduction of maintenance man-hours (MMH) and an improved availability on those aircraft equipped with HUMS.

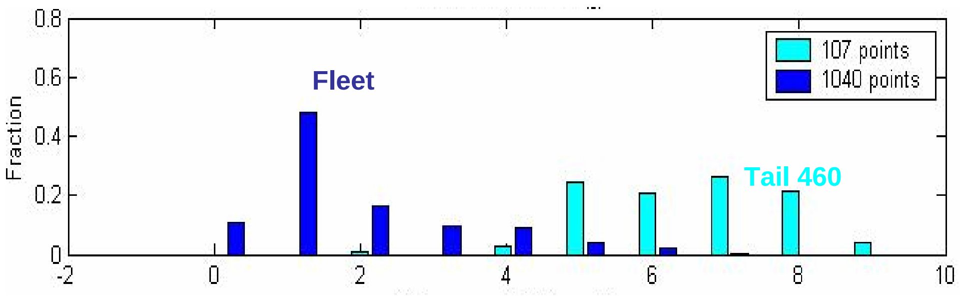
The primary function of any of the modern HUMS is to provide a built-in, permanently installed capability to perform required maintenance functions, such as rotor smoothing and mandatory vibration checks of drive train components, during routine flights. Typically, the condition of these components is expressed in terms of a single-valued condition indicator (CI) or health indicator (HI) which can be compared to a set of limits or “thresholds”. The limits express the severity of a potential fault and commonly are split into a “stop-light” paradigm consisting of a green “normal” level, a yellow “caution” level and a red “exceedance” level. Many of the vibration limits that have been developed for these maintenance activities have the benefit of years of experience with the AVA but other limits for the more modern diagnostic algorithms require the collection and analysis of a statistically significant number of samples to establish normality in conjunction with data from failed components [2].

2.2 Examples of Condition Based Maintenance

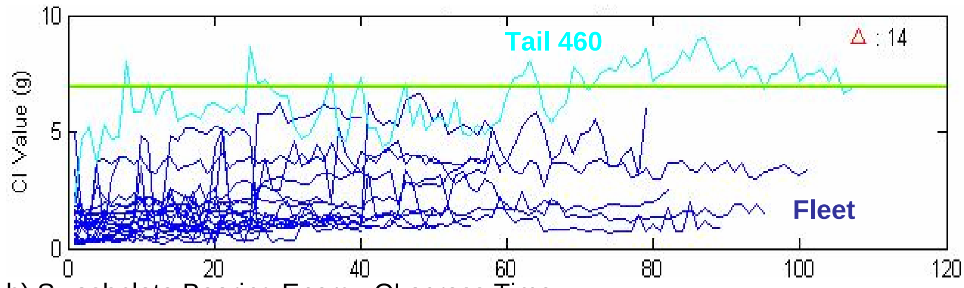
2.2.1 Apache Main Rotor Swashplate Bearing

During the South Carolina Army National Guard (SCARNG) deployment to Kosovo in 2003-2004, the main rotor swashplate component for an AH-64A Apache, tail number 87-00460, went above the yellow caution level consistently beginning in November of 2003. Concurrently, the vibration data were also being monitored by the engineering team via automated Internet data transfer tools. Unit personnel checked the bearing in accordance with the Army Technical Manual TM 1-1520-238-23, paragraph 1.137. This particular check is required every 50 flight hours and involves checking the swashplate for grease leakage; and after the swashplate accumulates 1750 total flight hours it is also required to disconnect all the pitch change links from the swashplate and rotate the outer ring, noting any abnormalities in smoothness of rotation or axial play. The unit completed this check three times and no problems were noted. The unit personnel and the engineering team agreed on a plan to continue to monitor the component for additional increase in vibration while the aircraft was deployed.

While the aircraft was still deployed, the data was investigated further. The component caution was being driven by a CI associated with the accelerometer bonded to the underside of the non-rotating main rotor swashplate. This particular CI measures the vibration energy within a frequency band from 100 to 5900 Hz, which contains the fundamental and several harmonics of the main rotor swashplate bearing fault frequencies. This CI is also only calculated while the aircraft is on the ground in flat-pitch at full rotor speed to eliminate variations in the CI due to aircraft loading and drive train torque. The statistical review of the CI for tail 460 compared to the rest of the CBM-equipped aircraft is shown in Figure 2. The top plot shows a histogram of the data by CI level, while the bottom plot shows the value of the CI for each aircraft by acquisition number. Note that there were a total of 1147 acquisitions of this CI (107 for tail 460 and 1040 for the rest of the fleet), which encompasses a period of approximately 4 years and 32 aircraft. The majority of the fleet has a CI of about 1, while the CI for tail 460 was above the caution limit of 7 for the last 30 acquisitions which covered the period from November of 2003 to January of 2004. The aircraft accumulated approximately 250 flight hours during the period it had been monitored.



a) Swashplate Bearing Energy CI Histogram



b) Swashplate Bearing Energy CI across Time

Figure 2. AH-64A Main Rotor Swashplate Energy CI

Once the aircraft returned to South Carolina, raw time-domain vibration data was collected during ground runs from tail 460 and two other aircraft chosen at random. Somewhat serendipitously, tail 460 was also scheduled to be turned-in to Boeing Mesa for conversion to an AH-64D Longbow. Coordination with SCARNG and the Apache Program Management Office enabled the removal of the entire swashplate for teardown analysis by AED. At the time of removal the swashplate had accumulated 1961 flight hours, out of a maximum life of 2250 hours. The swashplate assembly was shipped to Redstone Arsenal and the duplex ball bearing was removed per the Depot Maintenance Work Requirement (DMWR) and finally cut apart and inspected. The upper row was in good condition; however, the lower row had a broken cage, corrosion and pitting on the inner and outer races and blackened grease shown in Figure 3.


a) Broken Cage


b) Corrosion and Pitting on Inner Race

Figure 3. AH64A Swashplate Bearing Teardown

2.2.2 Apache Nose Gearbox

In the summer of 2003, HUMS systems were installed on AH-64A Apaches at the Western Army National Guard Aviation Training Site (WAATS). During the standard installation checkout procedure, tail number 90-00315 was noted to have an extremely high vibration reading for the #2 (right) engine "nose" gearbox causing the component to be in the red exceedance condition. The vibration spectrum for tail 315 compared to an average spectrum for 7 other "normal" aircraft is shown in Figure 4. The spectrum for tail 315 appears to be drastically different than normal and has a very high noise floor. The largest peaks in the spectrum for tail 315 correspond to the first three harmonics of the cage fault frequency (CFF) of 69 Hz and the second harmonic of the ball spin frequency (BSF) of 892 Hz for the duplex ball bearing supporting the output bevel gear while the only peaks of note for the average aircraft occur at the engine power turbine shaft speed of 348 Hz and the nose gearbox output shaft speed of 164 Hz. During next test flight the crew noted that the #2 nose gearbox chip detector signaled that the gearbox had a chip, which caused the flight crew to land the aircraft at an off-site location. The chip detector inspection criteria called for the replacement of the nose gearbox. After unit personnel replaced the gearbox, the chip detector light went out and the CI returned to a normal level. The vibration spectrum immediately after gearbox replacement is also shown in Figure 4. Note the drastic reduction in vibration.

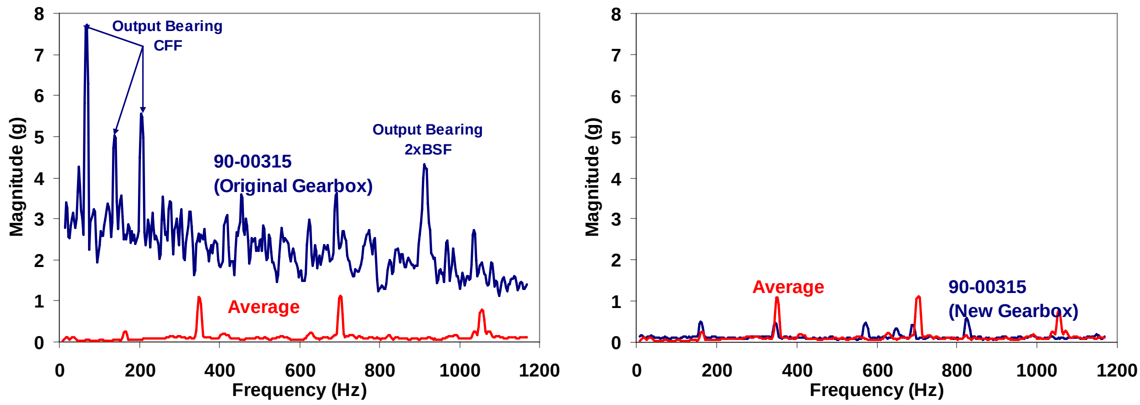


Figure 4. Original and New Nose Gearbox Vibration Spectra

The original gearbox was sent to CCAD for overhaul. Teardown revealed the primary cause of failure was spalling of the inner race of the duplex ball bearing supporting the output bevel gear. Secondary damage then also occurred to the other parts of the gearbox. The input gear had a deep groove on the seal surface and metal breakout on the gear teeth; and the output gear had stress pitting on the teeth as shown in Figure 5.

a) Normal and Damaged Balls

b) Damaged Input Pinion

Figure 5. Spalled Duplex Output Bearing and Input Pinion

Since that time, several additional examples of Apache AH-64A and AH64D nose gearbox problems have been detected with the VMEP/MSPU systems. In some cases, the gearbox was removed due to high vibration readings and a chip light, in other cases the gearbox was removed due only to high vibration levels because the aircraft was at a convenient maintenance interval prior to deployment. Follow-on vibration acquisitions after the gearboxes were replaced show that the new gearboxes have been operating normally as shown in Figure 6. Note a normal condition indicator level is about 0.1 to 0.2 per the figure. The red "exceedance" level is currently set at 1.0 and in 2 instances the gearbox had a value of 1.7 to 1.9 prior to illuminating the chip light. Additionally, in one case the unit was given approximately 80 days warning of an impending chip light; in the other case it was 160 days warning. From this information, there have been 2 additional nose gearboxes that have either entered the yellow "caution" condition or red "exceedance" condition that were changed at a convenient maintenance interval prior to the illumination of the chip light, so they are not depicted in Figure 6.

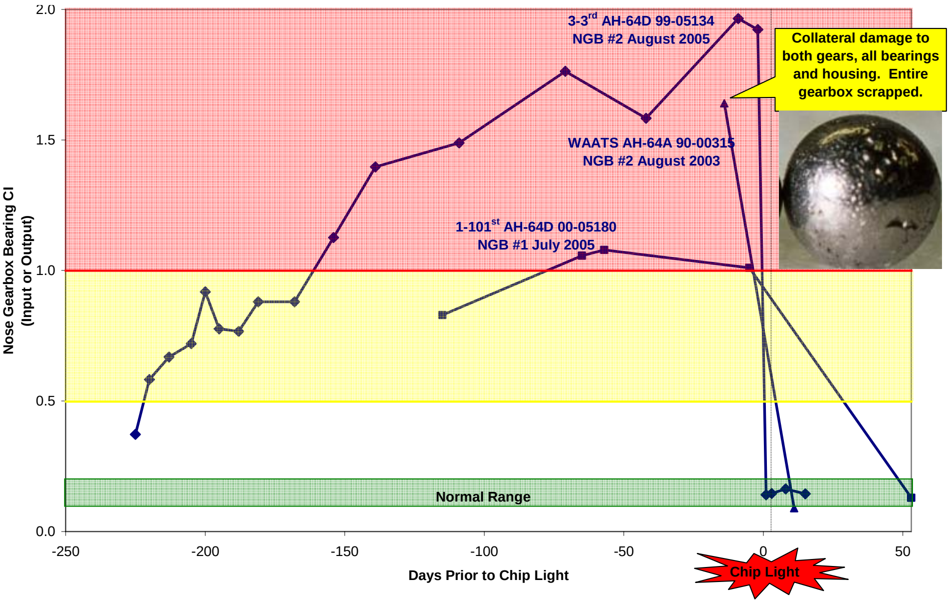
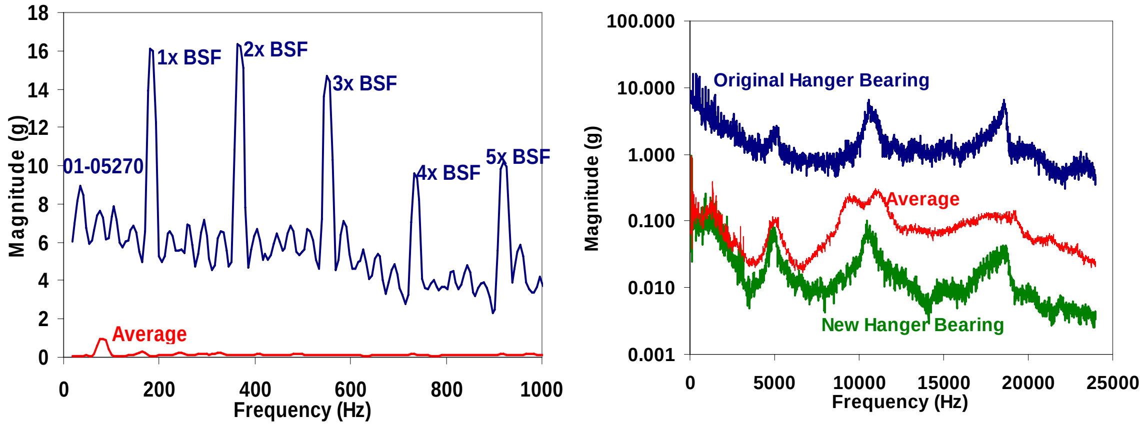


Figure 6. Original and New Nose Gearbox Vibration Spectra

2.2.3 Apache Hanger Bearing

In the fall of 2004, 8 HUMS systems were installed on AH-64D Longbow Apaches assigned to the 3-3rd ARB. Tail number 01-5270 was noted to have an extremely high vibration for the aft hanger bearing during the standard installation checkout procedure causing the component to appear in the red exceedance condition. Concurrently, AED engineering was reviewing the vibration data. The vibration spectrum for tail 01-05270 compared to the average spectrum for the 7 "normal" 3-3rd AH-64D aircraft is shown in Figure 7. Inspection of the low frequency region reveals large peaks corresponding to the hanger bearing ball-spin fault frequency (BSF) of 183 Hz and higher harmonics. After inspection of the vibration measurements, it was recommended to the unit perform the driveshaft and hanger bearing inspection in accordance with Army Technical Manual TM 1-1520-238-23, paragraph 6.1. Included in this check is a visual inspection for damage or looseness in the mounts, driveshaft and bearing support. No obvious damage was found. Additionally, the hanger bearing is also inspected for damage, grease leakage or roughness of rotation. Here, it was noted that the hanger bearing rotation was rough. No roughness is allowed per the TM, so the bearing was removed. A new hanger bearing was installed on the aircraft and another set of vibration measurements were acquired during a ground run. The results, shown in Figure 7, demonstrate the new hanger bearing actually has lower vibration levels than the other 3-3rd Apaches. The drive shaft component returned to a green condition and the aircraft was released for flight.



a) Low Frequency Region (Linear Scale) b) Full Spectrum (Log Scale)

Figure 7. Hanger Bearing Vibration Spectra

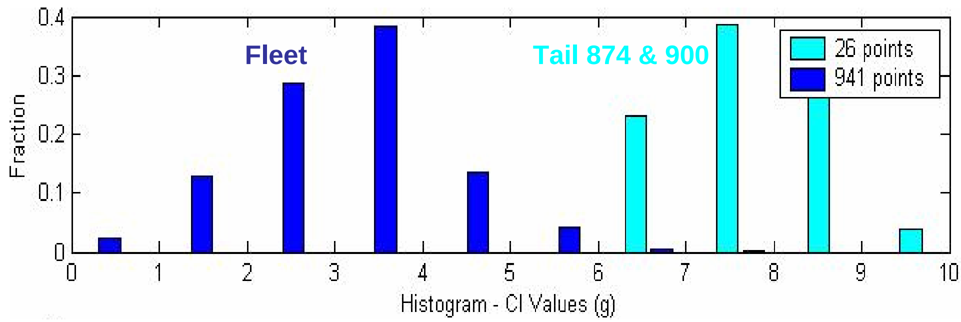
When the original bearing was disassembled, it was noted that the grease adjacent to the ball bearing retainers appeared dark and over heated and had a high presence of dirt. The bearing was then cut apart and the AID investigators discovered that the failure was initiated by a single corroded ball bearing which was actually reduced in size due to spalling as shown in Figure 8. The spalled ball then caused secondary damage to the other balls and raceways.

Figure 8. Spalled Hanger Bearing

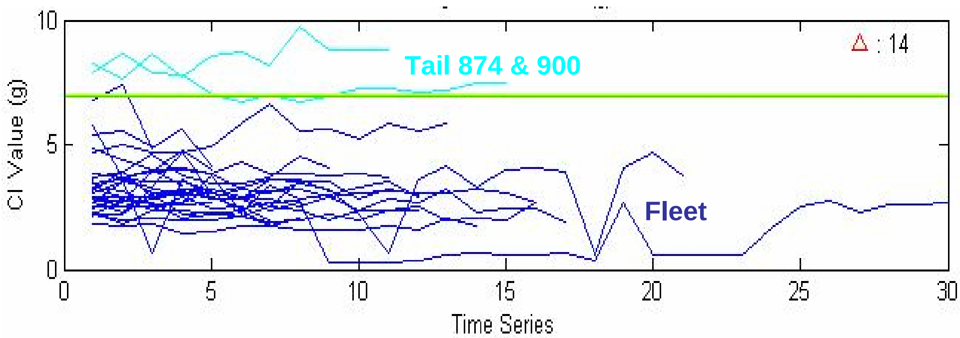
2.2.4 UH-60 Oil Cooler Fan Bearing

During the fall of 2003 to spring of 2004, CBM systems were installed on 15 UH-60A Blackhawks at the 1-52nd Aviation Regiment in South Korea. Since then, the CBM systems identified 2 aircraft, tail numbers 83-23874 and 83-23900, with oil cooler fans that were in the yellow caution condition. Both of the oil coolers in question passed the US Army mandatory 120-hour vibration check, with axial vibration levels of approximately 0.25 IPS for the tail rotor driveshaft 1R compared to a limit of 1.0 IPS. The particular CI that drove the oil cooler component into the caution level measures the axial vibration energy within a frequency band from 50 to 950 Hz, which contains the fundamental and several harmonics of the oil cooler fan bearing fault frequencies. This CI is also only calculated while the aircraft is on the ground in flat-pitch at full rotor speed to eliminate variations in the CI due to aircraft loading and drive train torque.

The statistical review of the CI for the two oil coolers in question compared to the rest of the CBM-equipped aircraft is shown in Figure 9. The top plot shows a histogram of the data by CI level, while the bottom plot shows the value of the CI for each aircraft by acquisition number. Note that there were a total of 967 acquisitions of this CI (26 acquisition for tails 874 & 900 and 941 acquisitions for the rest of the fleet), which encompasses a period of approximately 4 years and 33 aircraft. The majority of the fleet has a CI of about 3.5, while the CI for tails 874 & 900 were above the caution limit of 7 for all acquisitions since the HUMS was installed on the aircraft in February of 2004.



a) Oil Cooler Energy CI Histogram



a) Oil Cooler Energy CI across Time

Figure 9. Oil Cooler Energy CI

Even though the CI was only slightly above the caution limit, further investigation of the vibration spectrum was cause for greater concern. The vibration spectrum for tail 874 compared to an average spectrum for 7 other “normal” aircraft from the same unit is shown in Figure 11 The vertical error bars for the “normal” aircraft are one standard deviation, σ. The vibration spectrum for tail 874 aircraft contains large peaks at the oil cooler fan bearing inner and outer race fault frequencies. Note the “normal” aircraft has very little vibratory magnitude at the fault frequencies, but does have a few peaks at 69, 197, 348 and 989 Hz. Those peaks are naturally occurring and correspond exactly to the tail rotor driveshaft once-per-revolution speed (1R), accessory drive 1R, engine high speed shaft 1R and the fundamental planetary gear mesh.

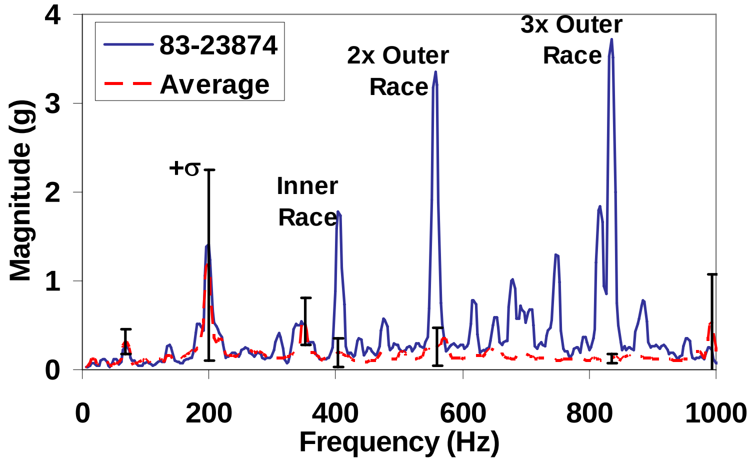
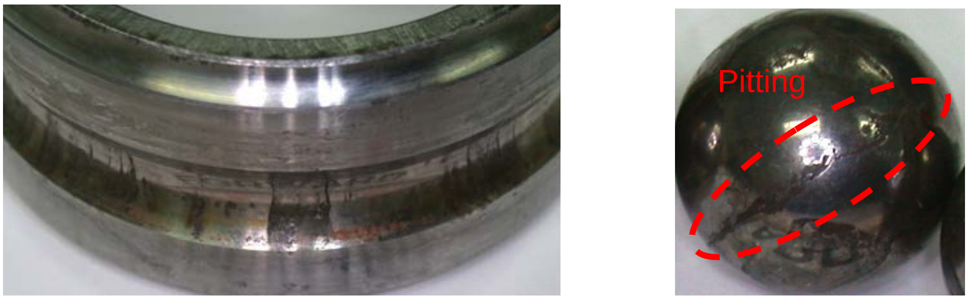


Figure 11. Oil Cooler Bearing Vibration Spectrum

Coordination with the unit and the Blackhawk Program Management Office enabled the removal of the oil coolers from tails 874 and 900. The oil cooler assembly from tail 874 was then sent to Corpus Christi Army Depot (CCAD) where it was disassembled and inspected by the Analytical Investigation Division (AID). At the time of removal the oil cooler has accumulated 1600 flight-hours, while the maximum service life of the oil cooler fan bearings is 2000 flight-hours. Compared to the suspect oil cooler, the rotation of a new oil cooler fan was noticeably quieter and smoother. The suspect bearings were then removed from the fan. The bearings and bearing grease were weighed, and the bearing dimensions were measured with no anomalies. Both bearings were then disassembled and visually inspected and exhibited significant corrosion pitting and spalling, examples of which are shown in Figure 10. The AID investigators stated that the fan had likely sat idle for a significant amount of time with moisture present in the bearings. It was possible to see a pattern on both races due to corrosion that had developed between the ball-to-race interfaces. The cages from each bearing also revealed corrosion pitting. Balls from both bearings showed evidence of spalling and deformation. The AID investigators stated that once the corrosion had developed, spalling then resulted when the fan was operated which exacerbated the poor condition of the bearings. It was the opinion of the AID investigators that it was a wise decision to remove the oil cooler fan from service.



a) Oil Cooler Fan Bearing Race b)Oil Cooler Fan Ball Bearing

Figure 10. Oil Cooler Fan Bearing Teardown

Once new oil coolers were installed on both aircraft, new measurements were acquired to determine the effect on the vibration and condition indicators. Figure 12 shows the energy CI before and after the oil cooler replacement for tails 874 and 900 only. The condition indicator for the original set of oil coolers was relatively constant for the entire eight month period they were being monitored. After the oil coolers were replaced, the CIs for each aircraft immediately returned to the fleet median of 3.

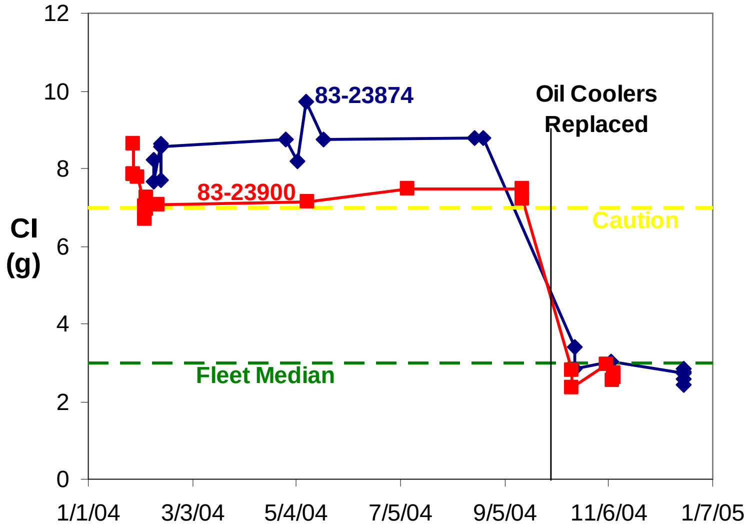


Figure 12. Oil Cooler Fan Energy CI

2.3 Airworthiness Releases

Due in a large part to the examples of CBM discussed in the previous section, the data collected allowed the AED to issue Airworthiness Releases (AWR) in June 2006 resulting in reduced inspections and maintenance man-hour (MMH) savings for CBM-equipped aircraft [3]. The benefits listed below are in addition to the MMH savings related to AVA-replacement (i.e. rotor smooting) functionality. The AWR returns on investment to date include:

- AH-64 A/D Main Rotor Swashplate – Avoids an inspection event which occurs every 50 flight hours after the swashplate accrues 1,750 total flight hours, and also avoids the associated maintenance operational check (MOC). The MMH saved per aircraft per inspection is 7.4 hours. The downtime saved per aircraft is 5.9 hours.
- AH-64A/D Auxiliary Power Unit (APU) Clutch – Eliminates vibration checks at APU installation and phase maintenance intervals. Extends APU mount inspection from 250 hours to 500 hours. The MMH saved per aircraft per inspection is 28 hours. The downtime saved per aircraft is 9 hours.
- AH-64A/D Forward and Aft Hanger Bearings – Extends the Time Between Overhaul (TBO) from 2,500 hours to 2,750 hours.
- UH-60A/L Oil Cooler Axial Fan Bearing – Automates a recurring 120-flight hour inspection with the permanent application of CBM monitoring. Extends time between overhaul of the axial fan assembly from 2,500 hours to 3,000 hours. The MMH saved per aircraft per inspection is 0.75 hours. The downtime saved per aircraft is 0.6 hours.
- UH-60A/L Engine Output Drive Shaft – Automates a 120-hour inspection requirement with the permanent application of CBM monitoring. The MMH saved per aircraft per inspection is 3.3 hours. The downtime saved per aircraft is 1.8 hours.

3 CONCLUSIONS

Since the Army began installing HUMS systems on selected US Army and Army National Guard aircraft in 2000, a large database of helicopter drive train machinery diagnostic condition indicators has been compiled. Analysis of the drive train vibration data has been facilitated through use of automatic data transfer tools via the Internet and allows real-time troubleshooting between engineers and field units. In the past two years, periodic investigation of outliers has uncovered several mechanical faults in gearboxes, bearings, and drive shafts. The faults discovered were often on critical areas of the drive train and include a swashplate bearing, hanger bearing, engine nose gearboxes, and oil cooler fan bearings. In some examples, the components passed the current Army Technical Manual field checks, which often rely on subjective measures. In some cases, unit personnel conducted maintenance and based their decisions solely on their interpretation of the vibration data presented to them in the ground software. In other cases, coordination between government engineers and the unit facilitated the correlation of vibration measurements both before and after part removal with the teardown analysis of the part. Through these efforts, the machinery diagnostic algorithms and condition indicators can be improved for earlier and/or more definitive detection of future faults; and the thresholds to which the condition indicators are compared can be adjusted in an iterative process. Successful discovery of these drive train faults has demonstrated the value of having a permanently installed vibration monitoring system on Army aircraft and provided valuable information towards the goal of transitioning to a condition based maintenance program. Due to demonstrated successes, airworthiness releases have been issued which give relief from some manual inspections and some time between overhaul extensions to the HUMS equipped aircraft.

4 FUTURE WORK

The majority of the current work is on fixture development to complete seeded fault testing of CBM components. This will allow AED to gain the required knowledge much faster than anticipated and in turn will allow AWRs to be issued sooner which provides benefit to soldiers as promised at a much quicker pace. Specifically, two separate efforts are underway. The first effort is in the construction of an AH-64A/D Apache Auxiliary Power Unit (APU) COSSI clutch test stand. This stand will have the capability of inserting degraded primary duplex bearings into the APU clutch and running them at full operational speed and monitoring with the MPSU vibration monitoring system as well as with temperature gauges. The second effort is in the construction of a tail rotor drive system test stand for the AH-64A/D and UH-60 at the University of South Carolina. The test stand will be constructed of the drive system from the output of the main transmission to the tail rotor of both aircraft. Damaged hanger bearings, intermediate and tail gearboxes, tail swashplates, and the oil cooler fan of the UH-60 will be tested.

5 REFERENCES

1. Defense Acquisition Guidebook, http://akss.dau.mil/dag/Guidebook/IG_c5.2.1.2.asp, Dec. 2004.
2. Keller, J.A. and Grabill, P., "Examples of Condition Based Maintenance with the Vibration Management Enhancement Program," American Helicopter Society 61st Annual Forum, Grapevine, TX, May 2005.
3. Pillsbury, James H., "Condition Based Maintenance for Army Aviation," *Army Magazine*, January 2006, pp. 27-30.