Implementing CBM Capabilities on the UH-60 Blackhawk Utilizing IVHMS Data Correlation and Analysis

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ABSTRACT

The ultimate goal of Condition Based Maintenance (CBM) is to know and understand the actual status of aircraft components, enabling a reduction in unnecessary maintenance and increase the operational availability of Army aircraft. The ability to accurately assess the condition of the dynamic components on the aircraft is essential to the current Army Aviation CBM philosophy. The transition to CBM for Army Aviation on monitored components has allowed the Army to perform maintenance on components that are in a degraded state, affording the maintenance manager the opportunity to do maintenance when appropriate. Documented field case studies were analyzed and correlated to identify fault modes and the corresponding corrective actions, allowing PM-UH, AED and the user community to implement a CBM Manual. This paper describes the CBM theory used to implement the CBM Manual which identifies the components, the corresponding maintenance practices, and the documented components to date that have been approved and implemented into the system. This manual bridges the gap by recommending maintenance practices on faulted and defected components until these practices can be incorporated into Army Technical Manuals.

INTRODUCTION

The US Army UH-60 Blackhawk Project Office currently utilizes the Integrated Mechanical Diagnostics-Health Usage Monitoring System (IMD-HUMS) or the Integrated Vehicle Health Monitoring System (IVHMS) On-Board Systems (OBS) on over 300 aircraft with a goal of equipping the entire fleet in the near future. The primary function of the IVHMS/IMD-HUMS system is to provide a built-in capability to perform required maintenance functions, such as rotor smoothing and mandatory vibration checks. With user feedback, the functionality of the system can be helpful to maintainers beyond this primary function, to include troubleshooting, lowering maintenance man hours, decreasing test flights, increasing readiness and better maintaining the aircraft [1].

A significant addition to monitoring the aircraft is the ability to assess the current condition of the drivetrain components on the UH-60. This includes the Main Transmission, Engine Input Shafts, Accessory Gearboxes, Input Modules, Oil Cooler, Driveshafts, Intermediate and Tail Rotor Gearboxes, and the Tail Rotor. The condition of these dynamic components is displayed as Health Indicators per Aircraft, Sub-Component, and component (Shaft, Gear, or Bearing). Each Health Indicator is a roll-up of individual Condition Indicators, which can be compared to a set of limits or statistical “thresholds.” The thresholds allow the user to view the condition of each component in either a green, yellow, or red condition. A green condition indicates that no further action is required, a yellow condition shows a need to investigate the OBS indications at the next scheduled maintenance event, and a red condition indicates a need to resolve the OBS indications prior to the next flight, especially if this indication did not progress from a previous “yellow” reading. The correlation of the thresholds to this green/yellow/red status was obtained after several thousand hours of actual flight hours. Statistical means and standard deviations were developed and in many cases correlated with actual field faults and Tear Downs of the specified components. Continuing field data collection, anomaly detection and data correlation to fault modes has allowed further investigation of identified outliers and threshold adjustment.
The successful detection of faults from field use cases has provided information for analysis and collaboration within the user community including PM, AED, OEM (Goodrich), Sikorsky, ED, and other users to identify faults and associate them with a condition indicator or signature. These finds have allowed the PM to pass the information down to the units via a CBM manual where they can be utilized in their current maintenance practices. This paper describes the theory of CBM employed on the UH-60A and UH-60L aircraft, the CBM Manual generated from the correlation of finds, and the currently addressed components included in the manual.

CBM THEORY

Initial expectations for CBM within the Army leaned heavily on an assumption that significant payback could be achieved through the extension of Time Between Overhaul (TBO) and/or Retirement Life (RL). In 2006 the Joint Aviation Logistics Command (JALC) sponsored a project to develop a process that would identify candidates for CBM that provided the best return on investment (ROI). The metric chosen for this study was Maintenance Man Hours (MMH). During the progression of the study it was found that for the UH-60 about 75% of the components that could provide a significant reduction in MMH were removed prior to achieving their TBO or RL. This piece of information resulted in a complete refocus of the UH PMO CBM efforts and goals. It was quickly realized that the most effective way to utilize our CBM processes was to take them to the field units. This was done by searching for anomalies in the field data that could be correlated to early stages of degradation of several components. As the library of component failures and correlated data expanded and engineers gained insight into these anomalies, greater confidence was gained as to how to implement this at the maintainer level. As Figure 1 depicts, the vast majority of the data collected falls within the “good signature” region of the degradation plot. The CBM WG (CBM Working Group) was able to determine when a component was starting to degrade. It was found that IVHMS could detect the initial degradation.

After multiple occurrences of these events the Army could confidently establish a maintenance management “cushion” that allowed the maintainer to defer certain maintenance to coincide with other scheduled maintenance, reducing the need to take the aircraft out of service. The payback began to show up rapidly as the Units’ Mission Capable time increased and the Mission Aborts decreased. Thus far the data supports an increase in mission capable rates of approximately 10%. Thus, if a 50 aircraft unit increases readiness by 10%, it has gained the equivalent of 5 operational aircraft.

Objective

CBM’s primary objective is to determine appropriate discriminators that identify degraded conditions or defects and trend the degradation of the defect for components and associated sub-components. Techniques and concepts have been developed for measuring mechanical conditions and assessing mechanical health based on the results of several years of extensive study. The Ground Station (GS) takes the On-Board System (OBS) HIs and associated data to provide data trending and management.1,2 In addition, Goodrich has developed an engineering software utility called Mechanical Diagnostics Analysis Toolkit (MDAT) that has been employed by HUMS analysts. This tool allows the analysts to look further into the Health of a component and utilize the condition indicators of that component and accelerometer raw data for more advanced analysis.

Z-Score

The HI concept used statistical analysis as a starting point to determine the degree of abnormality by utilizing a Z-Score transform. The Z-Score for a sample indicates how far and in what direction that sample deviates from its distribution’s mean, and is expressed in units of its distribution’s standard deviation. The Z-Score transformation is especially
useful when seeking to compare the relative standings of samples from distributions with different means and/or different standard deviations. This is the case for condition indicators used by the IVHMS to evaluate monitored components. The Z-Score is a normalized value, which provides a common scale of measure of each CI.

As mentioned before, a Z-Score is the number of standard deviations away from the mean of the measured value. This allows for a single threshold to be applied to every condition indicator. Setting a threshold on a Z-Score value provides for a statistically determined probability of false classification (Healthy vice Faulted). The Z-Score value is probability distribution dependent. Figure 2 below shows the Z-Score for a Gaussian distribution.

We have established that the amplitude measures (such as the CI values) are better modeled as Rayleigh distributions, not Gaussian. For a Gaussian distribution, it is expected that 1 value out of 1,013,594,635 measurements would be larger than 6 standard deviations (Z-Score = 6) as illustrated in figure 3. Even if the Rayleigh Distribution is three orders of magnitude different (not anticipated), we still have an expected probability of false classification of 1:1,000,000.

The first concept is to define the appropriate fault models for each monitored component type (shaft, gear or bearing). Initially, the temptation was to fuse all condition indicators together to correlate to particular fault types. A more effective methodology with new metrics such as maintenance indicators will combine predefined groups of condition indicators together to correctly identify a particular fault model. The differing fault models are normalized and clamped at appropriate levels. The worst fault model will then be promoted to become the health indicator.

For example the imbalance of a shaft can be detected using Shaft Order 1 (SO1) condition indicator. Shaft Order 1 measurement is a near 1:1 translation of the degree of shaft imbalance. The same correlation can be roughly made between Shaft Order 2 (SO2) and misalignment and between Shaft Order 3 (SO3) and looseness of the shaft. There are fleet thresholds and vibration severity charts that can be used in lieu of statistically set thresholds. This metric can be excited with or without other indicator confirmation.

In the health evaluation process, individual CIs of a component are subject to the Z-Score transform (using 6 standard deviations as the threshold) such that when the measurement CI value equals the mean value, the HI equates to 0. On the other hand, when the measurement CI value equals the mean plus 6 standard deviations, the HI is set to 1. The maximum of the computed individual CI Z-Scores is then selected as the HI of the component. This would ensure the CI with the largest deviation be the dominant driver of the HI.

For a single CI to a single HI case, the relationship between them is linear, which can be expressed as:
\[ HI = m(CI) + b \]  
(Eq. 1)

where \( m \) and \( b \) represent the slope and the intercept respectively of the above linear equation, which can be solved by using the two established relationships that \( HI = 0 \) when \( CI = \text{mean} \), and \( HI = 1 \) when \( CI = \text{mean} + 6 \text{ standard deviations} \). Therefore:

\[
\begin{cases}
  m = 1/(6\sigma) \\
  b = -\mu
\end{cases}
\]  
(Eq. 2)

where \( \mu \) and \( \sigma \) represent the mean and the standard deviation, respectively. \( HI \) can then be expressed in terms of \( \mu \) and \( \sigma \) by substituting \( m \) and \( b \) in Eq. 1 with the equations in Eq. 2:

\[ HI = \frac{CI - \mu}{6\sigma} \]  
(Eq. 3)

Finally the computed HI value is hard limited to between 0 and 1.

This relationship is illustrated in Figure 4 that shows the mapping between a CI (with a mean of 1 and a standard deviation of 0.5) and its HI.

In HUMS implementation the health evaluation algorithm determines a component health based on a set of strategically selected CIs. The maximum of these computed CI Z-Scores is selected as the final HI of the component:

\[ HI = \max \left( \frac{CI_i - \mu_i}{6\sigma_i} \right) \]  
(Eq. 4)

where \( i = 1, 2, 3, \ldots \) represent individual CI indices. This operation would ensure the CI with the largest deviation from its mean be the dominant driver of the HI.

In the Currently Addressed Components Section the reader will be given multiple scenarios where this approach was applied and has resulted in significant impact to the maintainer and the operator.

**CBM MANUAL**

Through the use of the UH-60 CBM Manual many recommended procedures for implementation of CBM principles for select UH-60 components on aircraft equipped with the IVHMS/IMD-HUMS OBS have recently been made available to the maintainers. This manual highlights actionable HUMS information to the soldier in the field while allowing the Maintenance Manager the flexibility to determine when to take action. In other words, the soldier can determine when it is appropriate to do maintenance. The CBM Manual is intended to enhance the planning and execution of aircraft maintenance by providing additional tools, based upon existing field data to assist with troubleshooting aircraft faults and exceedance alerts with OBS indications, proactive maintenance planning (converting unscheduled to scheduled maintenance), reduction of unscheduled maintenance, and reduction of scheduled maintenance tasks and man hours.

The CBM Manual is a living and growing document which contains a collection of components that have direct CBM impact. This collection currently includes the Generators, Tail Rotor Drive Shafts (TRDS), Oil Cooler, Tail Rotor, Weight-On-Wheels switches (WOW), Engine High Speed Shafts and Gyroscopes as shown in Figure 5. As the CBM Manual develops, it expands the capability of the system. Software modifications to the OBS and GS are submitted to update the software in order to implement the CBM Manual information into exceedances, updates, visibility, etc into the GS and
OBS with the end goal of implementation into the applicable aircraft maintenance manual.

An example of the Tail Rotor CBM impact included in the manual is shown in Figure 6. This figure demonstrates the process where use cases are collected and correlated to allow known faults to be connected to maintenance actions to aide users in the field. It also displays the path from the CBM Manual to Software Modifications and implementation into standard Army Maintenance Manuals.

Maintainers are encouraged to utilize the procedures in the manual to maximize the advantages of the

Components currently addressed in the CBM Manual are: Main Generators, Tail Rotor Drive Shafts (TRDS), Oil Cooler Fan Bearing and Drive Shaft, Weight-On-Wheels (WOW) Switch, Engine Output Shaft/High Speed Shaft, and Gyroscopes. The following sections address the current components included in the CBM Manual. Each section follows the process of the initial goal or objective on the component, obtaining case studies, documenting them, correlating the field data to collected data, and incorporating them into the CBM Manual.

CURRENTLY ADDRESSED COMPONENTS

Main Generators

Objective:
There are two main generators on the UH-60 Black Hawk which provide electrical power to on-board electronic and avionic equipment. Until the installation of the Digital Source Collector (DSC), the health of these generators were based upon one built-in sensor to provide detection of an internal bearing fault as well as an aircraft system detection of loss of generator power output. With the DSC, the generators are monitored using the accelerometers on the Accessory Modules.

Each Generator has a shaft that is connected via a spline adapter to the accessory gearbox (AGB) as shown in Figure 7.

In the generator study, MDAT was utilized to facilitate the statistical analysis on the CIs (Shaft Order 1, Shaft Order 2, Shaft Order 3, etc.) and aide in trending the fault degradation of the part. It has been discovered that the elevated HIs are typically the result of a degraded main generator spline adapter. The basic design of the spline adapter is such that it will fail before the main generator shaft will shear. It acts as a sacrificial interface between the generator and the accessory module. It is reasonable to assume that the spline adapters begin to wear after a given time and result in a higher than normal HI.
Traditionally, the spline adapter is left alone and eventually fails resulting in the generator caution light illuminating. This will often result in a field unit mistakenly replacing the generator. One of the first steps in the replacement procedure is to replace the spline adapter. During removal, the spline adapter is normally discovered to be broken or at least cracked. This was previously attributed to the removal process. It has been found that the spline adapter will begin to display wear patterns and the HI of the generator shaft will increase before any degradation in the function of the generator.

A progressive defect in the generator spline adapter can be identified and corrected. If corrected at the proper vibration level, the spline adapter could potentially extend the life of the generator. If uncorrected, the spline adapter defect becomes a fault and could result in structural damage to the generator. This capability allows the user to avoid unscheduled maintenance and prevent avoidable degradation to the generators.

**Case Studies:**

An example of a faulted Generator Spline Adapter still installed in the AGB drive is shown below in Figure 8.

![Figure 8: Example of a failed Spline Adapter still installed in the AGB drive](image)

Using the CIs (SO1, SO2 and SO3) developed from the AGB Output Accelerometer data and the parametric sensor of the chip detector of the AGB, the ability to ascertain the health of the generator and drive components has been demonstrated.

In Figure 9, the spline adapter remained in service for an extended period of time with elevated CIs and HIs. Eventually, the AGB Chip Detector caution light illuminated.

![Figure 9: Example of a Generator Spline Adapter chipped](image)

The unit replaced the AGB first due to the chip light illumination. With MDAT, it was then determined by evaluating SO1, that the generator was also damaged and required replacement. After the generator was replaced, all three CIs returned to normal. The sudden increase in SO1 can be utilized to develop a trend model and employed to alert the maintainer to strongly consider replacing the generator before the AGB is damaged.

In Figure 10, the CIs were able to alert the maintainer that there was a gradual increase in SO1 of the generator. After inspection, it was determined that the spline adapter was not only cracked but also the wrong part number for the generator. This find revealed a wide-spread maintenance error that resulted in the substitution of a shorter spline adapter used for the APU rather than the generator.

![Figure 10: Example of a Generator Spline Adapter Cracked](image)

**CBM Implementation:**

From the generator spline adapter analysis it was found that there were three major failure modes: a
cracked spline adapter, a chipped spline adapter, and an incorrect spline adapter. Below, in Figure 11, are examples of each of the three faults. Each Fault was indicated by SO1 exceeding the 2 IPS level. This level was also confirmed using statistical analysis.

![Figure 11: Spline Adapter Fault](image)

Generally speaking a cracked spline adapter typically produces a “split trend” characteristic due to the effect of torque applied to the generator drive shaft. It has been found that the SO1 vibration is typically higher at higher torque but lower for SO2 and SO3 for a cracked spline adapter. This is because more mass imbalance is produced with higher torque, while the coupled shaft has become more misaligned/loose when it is subject to a lower torque.

Defining whether the generator has failed, the spline adapter has faulted, or the AGB needs replacement has been demonstrated with actual field data and incorporated into the CBM Manual.

**Tail Rotor Drive Shafts**

**Objective:**
IVHMS/IMD-HUMS offers the maintainer the ability to continuously monitor the tail rotor drive shafts (TRDS) for increased vibration of each individual drive shaft. Previously, there was a limited ability to isolate the specific drive shaft attributed to the increased vibration of the entire tail drive shaft. The primary goal for CBM is to minimize the TRDS / Viscous Bearing Assembly vibration levels responsible for the accelerated wear of these components. This will reduce the requirement for early replacement and other associated unscheduled maintenance on TRDS drive train components.

There are a total of four TRDS from the Oil Cooler to the Intermediate Gearbox (IGB), see Figure 12. Each TRDS is connected via a flexible coupling and supported by a viscous bearing assembly. The monitoring accelerometer for that particular TRDS and viscous bearing is mounted on viscous bearing mounting bracket.

![Figure 12: Tail Rotor Drive Shaft](image)

**Case Studies:**
It has been determined that when the vibration level of Shaft Order 1 is greater than the six sigma threshold with an increase in Shaft Order 2 and 3 that a mis-shimming is a common fault associated with the increase in vibration levels. In this example, drive shaft vibration levels had increased in the Viscous Bearing #3 accelerometer, shown in Figure 13 below.

![Figure 13: Health Indicator of TRDS Section #3](image)

After further investigation, it was confirmed, using the MDAT software (see Figure 14), that Shaft Order 1 had increased above 1.5 ips with all three Shaft
Orders (SO1, SO2, and SO3) over the limits of six sigma from the population mean.

After discussion with the maintainers, it was agreed to do a visual inspection on the Viscous Bearing. It was found that the bearing was against the snap ring and improperly shimmed (see inset in Figure 14 and see Figure 15). The shims should be equal in number and thickness installed on the fore and aft ends of driveshaft flex coupling. In this case, there were more washers on one side of the flex coupling.

The maintainer verified that the shaft needed to be re-shimmed. The re-shimming was scheduled to be completed at the next opportunity. After the re-shimming, the vibration levels returned to a nominal level. The early detection of this fault saved the maintainer unscheduled maintenance and potentially a more extensive maintenance evolution in the near future. This early detection may have also reduced or eliminated further degradation or additional faults of related components.

The system is also beneficial in determining whether a viscous bearing is faulted. There have been several cases where the health indicator increases but the drive shaft and the shimming are found to be correct. In the example below (Figure 16), the replacement of the viscous damper bearing assembly was due to a low level of damping fluid within the viscous damping tube. The viscous damping tube was serviced with fluid and the vibration levels returned to normal.
CBM Implementation:
Using the CIs (Shaft Order 1, Shaft Order 2, and Shaft Order 3) developed from the raw data of the accelerometer, the ability to determine whether the shafts are unbalanced, misaligned, incorrect maintenance performed, or a viscous bearing has a fault has been demonstrated using actual field data and incorporated in the CBM Manual.

Other fault findings including elongated mounting bracket holes, viscous bearings with lock ring inverted, cracks in the brackets/structure near the viscous bearings, as well as several unbalanced or misaligned drive shafts, have led to the development of various maintenance actions to determine the source of the vibration and the associated repair. These actions have been incorporated into the CBM Manual to guide the maintainer in the field.

Tail Rotor (TR)

Objective:
Tail Rotor vibration measurements are automatically taken during every flight and ground turn. The OBS regime recognition capability is utilized to determine when the aircraft is in the proper flight regime to collect meaningful TR vibration data. These measurements are presented to the maintainer and allow early detection of tail rotor faults. Vibration data acquired on the ground and in-flight has proven useful in detecting a variety of failure modes. These faults include loose/cracked TR components, FOD damage and improper maintenance procedures. The vibration data is acquired using two accelerometers. One measures the balance of the TR in the plane of rotation while a second measures the vibration normal to the plane of rotation as shown in Figure 17.

Case Studies:
One of the most common component failures is cracking of the TR De-Ice Bracket. The on-ground automated vibration checks will create and exceedance whenever the in-plane SO1 vibration exceed established limits. Such exceedances prompted the decision to inspect the TR assembly for loose / broken components. The TR De-Ice bracket (Figure 18) was found to be severely cracked. If allowed to continue operation with a cracked bracket, the bracket can separate causing additional damage to the TR paddles.

Figure 18: TR De-Ice Bracket Crack Resulting In Erratic TR Vibration

The traditional measurement of tail rotor vibrations is limited to ground observations of vibrations in the plane of rotation. But experience has shown that there are imbalance conditions that are aggravated by transitioning into forward flight. Such a case is presented in Figure 19. In this case the forward flight data is roughly 0.3 IPS higher than the ground data.

The figure also includes a plot of HI which is similar to the screens that are available in the Ground Station. In this case, HI greater than HI=0.75 will cause a CBM warning to be annunciated on the Ground Station. Note that the Ground and Flight data trends in the Ground Station HI screen are very similar to those presented on the MDAT SO1 graphic. The increase in the in-plane vibration levels shown here as a function of time are unusual and alert the maintainer to the need to inspect the tail rotor to determine if there is damage that is being exacerbated by usage. All of this information is useful when scheduling CBM maintenance actions.

Figure 19: TR HI History and Vibration History of TR Vibrations Measured in the Plane of Rotation by the TGB Output Accelerometer; UH-60L 90-26291 between 1-2-07 to 4-1-08
Experience has shown that the SO1 vibration level as measured by the TGB Input Accelerometer is not sensitive to increases in airspeed when the tail rotor is rigged correctly and free of material defects. An example of this “Normal” performance is shown in Figure 20. In this case, the vibration does not exceed 0.3 IPS and averages less than 0.2 IPS from hover through 140 knots. Experience indicates that it is reasonable to expect the SO1 vibration (as measured by the TGB Input Accelerometer) to remain less than 0.5 IPS following a comprehensive servicing of the TR.

![Figure 20: TR Vibration Levels of Properly Maintained TR Assembly: UH-60L 00-26872 Between 1-29-07 to 5-17-07](image1)

However, if the TR Pitch Change Rods are not properly rigged, it will result in an out-of-track condition of the TR paddles. The vibrations produced by this out-of-track condition are normal to the plane of rotation and increase as airspeed is increased from a hover.

The vast majority of all monitored UH-60 TR’s have exhibited SO1 vibration histories that never exceed 1.0 IPS as measured by the TGB Input Accelerometer. A noteworthy exception is shown in Figure 21. Here the SO1 history covers roughly 6 months of continuous operations in Iraq.

![Figure 21: TR Vibration History of Improperly Rigged TR Assembly acquired by TGB Input Accelerometer; UH-60L 90-26291 from 10-2-07 to 4-2-08 (TR Vibrations are Normal to the Plane of Rotation)](image2)

Concurrent Tail Rotor Defects:
The In-Plane Imbalance addressed above (Figure 19) was introduced at about 180 hours and was corrected at about 210 hours rotor turn time. Prior to and overlapping this 30 hour period, an aerodynamic imbalance was introduced at about 140 hours rotor turn time (see Figure 22). The suddenness and magnitude of this change in tail rotor vibration suggests that the defect was the result of a maintenance action. This defect was corrected about 240 hours later. The time required to achieve the appropriate corrections was due to the learning process and the time it took to develop the CBM Manual.

In summary, two completely separate types of rotor imbalance defects were present concurrently. Both required CBM corrective actions and the CBM manual guidance instructs the maintainer to schedule the corrections for the first available CBM opportunity as well as the most probable defects to expect.

The vibrations caused by these faults have the potential to cause collateral damage to the tail rotor gearbox, mounting structure and other tail rotor components. With the OBS these problems can be identified early resulting in less damage to the entire system.

In summary, the maintainer had discovered what appeared to be two completely separate imbalance defects. Both required CBM corrective actions. The
CBM manual guidance suggests the most probable defects to expect and instructs the maintainer to schedule the corrections for the first available CBM opportunity.

At about 140 hours rotor turn time the Aerodynamic imbalance was suddenly introduced (see Figure 22A). This suggests that the defect was the result of a maintenance action. This defect was corrected about 240 hours later.

The In-Plane Imbalance addressed above was introduced (see Figure 22B) at about 180 hours and was corrected at about 210 hours. The time required to achieve the appropriate correction was due to the learning process and the time it took to develop the CBM Manual.

CBM Implementation:
Trend plots provide a quick summary of recent in-plane balance acquisitions. Shaft Order 1 (SO1) vibration levels are acquired during ground operations for comparison to balance criteria established for ground acquisitions. Exceedances are generated when the ground data exceeds a threshold. (Advisory >.15 IPS, OverGoal >.40 IPS, OverLimit >.80 IPS) This capability allowed for automation of the 120 Hour Vibration Check.

The maintainer can easily construct a Trend Plot (see Figure 23) to determine if the balance is stable or increasing with usage. In addition, erratic readings or scatter in the data during a single operation are indicative of a TR component defect.

Evolving GS Functionality:
Ground Station Screen formats are evolving and will provide more and more diagnostic information that can be acquired by the maintainer and used to interrogate the CBM manual for CBM corrective maintenance strategies. Figure 24 is a characterization of evolving Ground Station functionality for the display of Mechanical Diagnostics.

When a high HI causes the Component Icon “Tail Rotor Shaft” to be colored orange the maintainer is trained to click on the Icon to obtain detailed Mechanical Diagnostics information. When the Icon is selected, two subassemblies of the display are opened. One addresses inplane vibrations while the second addresses vibrations normal to the plane of rotation.

Once the maintainer selects the Tail Rotor Shaft Icon, two alternatives appear (see Figure 25). The Orange Icon identifies the most serious defect requiring attention. Selecting the “Aero Balance” (AB) Icon a Mechanical Diagnostics screen is opened. Two choices are next available: Forward Flight HI Only and Ground Data Only. Note that the Forward Flight
Data Screen is Colored Orange. Almost all of the HI data are at HI=1, which is a clear indicator that the tail rotor is experiencing very high vibrations in forward flight. In contrast, the Ground HI data presentation is “green”, confirming that the vibration level is low on the ground.

The maintainer now uses the following information to enter the CBM Manual for specific tasking to correct tail rotor Aerodynamic Balance faults.

The Aero Balance (AB) tab is orange. The orange color indicates the need to inspect the tail rotor as soon as practical. The maintainer has noted:
1. The Flight HI data has been at HI=1 for some time.
2. The ground data is increasing as a function of usage, this is unusual.
3. The ground data is about to rise above HI=0.75.

The in-plane balance (IPB) Icon is colored yellow. This yellow color indicates the need to balance the tail rotor during the next scheduled CBM period. The maintainer has noted:
1. Both the ground and the flight HI trends are increasing with time (usage). This is unusual and may be serious.
2. The flight HI trend is higher than the ground data.
3. The flight HI are closely approaching HI=1.

Weight-on-Wheels Switch

Objective:
There are two Weight-On-Wheel (WOW) Switches monitored by the system, one located on each of the main landing gear drag beam of the aircraft. The WOW switches let aircraft systems know it is in flight. Proper operation of the WOW switches is required to ensure the proper functioning of critical systems such as the Back-up Hydraulic Pump and Aircraft Survivability Equipment (ASE), including the Common Missile Warning System.

One of the most functional and often used tools provided by the IVHMS/IMD-HUMS Ground Station is the Strip Chart, a graphical display of parametric and state data plotted across operating time. All parameters and aircraft state data from an operation can be plotted, from the initial APU start through each landing and eventually to the final shutdown of the day. The GS allows the user to monitor and evaluate the health of input and output signals for pressures, temperatures and values associated with all monitored aircraft operating systems. Parameters are recorded at varying rates between 1 Hz and 20 Hz depending on the system requirement specification. The fidelity of the data and the ability to zoom in to view each individual data point on the strip chart has become a time-saving troubleshooting and signal verification tool. There are currently 160 different parameters that are collected by the IVHMS/IMD-HUMS system.

Case Studies:
Using the Strip Chart describe above, the maintainers learned that they could easily determine if the switch had failed open, failed closed or if the switch is sticking periodically. Figure 26 shows an example of a WOW Switch malfunction with the WOW Sensor exceedance annotations highlighted. The IVHMS/IMD HUMS utilizes the discrete signal from the WOW along with state data from the torque, radar altitude, and main rotor speed (Nr) sensors to determine the point of landing or take-off.

Figure 25: Four Mechanical Diagnostic HI Screens Available to the Maintainer

Figure 26: WOW Switch Parametric Data Strip Chart
CBM Implementation:
The OBS Configuration was updated to implement a WOW Sensor exceedance that detects a sticking or failed open condition. Upon release of the updated configuration, nearly 50% of the monitored fleet had WOW Switches that were “sticking” often unknown to the maintainer. This implementation enables the maintainer to determine if the faulty WOW Switch needs to be cleaned (sticking) or replaced (failed open or closed). The system displays an exceedance which is transferred to the maintenance management information system and identifies the faulty switch to the maintainer.

Engine Output shaft/ High Speed Shaft

Objective:
There are two High Speed Shafts (HSS) one located on each aircraft engine. They are continuously monitored using the Input Module Input accelerometer. Legacy methods required a single engine data collection to determine the proper balance of the HSS at each 120 hour inspection. The objective was to determine the HSS vibration during normal operations, which would eliminate the need for a dedicated maintenance run up to collect the vibration data during single engine operations. Monitoring the HSS vibration levels minimizes the possibility of vibration levels that would result in accelerated wear of components and potentially catastrophic failure of the HSS assembly.

Case Studies:
Historically, it was believed that there was “cross-talk” between the Left and Right HSS when both engines were operating at 100% RPM. Normal aircraft operating procedures do require enough single engine operating time to allow for an automated data collection. Therefore, to gain approval for continuous monitoring, testing was required to determine if “cross talk” affected measured vibration levels. Testing did indeed disprove the existence of “cross-talk,” and authority to eliminate the single engine data collection was granted by AED. It was also necessary to determine which Capture Window (CW) provided the best correlation to the legacy single engine vibration levels. Watch Lists were developed to extract the SO1 vibration levels at various CW’s. This information was provided to field maintenance personnel to compare with single engine readings taken at the next 120 Hour vibration check. The low torque Mechanical Diagnostic acquisitions proved to be an accurate indication of SO1 vibration levels. An Example the GS HI trend of an unbalanced HSS is shown in Figure 27, below. In this example, the HI increased to the .75 Advisory limit upon completion of a balance event. Then, upon completion of the next 120 Hour vibration check and another balance event, the HI returned to a nominal level.

CBM Implementation:
The Z-score transform for the HSS was configured to force the HI value to 0.75 (Yellow – Advisory) when the HSS SO1 vibration was at .5 IPS. An HI value of 0.90 (Red – Warning) was configured to trigger when the SO1 vibration levels reach 1.0 IPS. An exceedance for both the Advisory and Warning levels was programmed into the OBS and GS configuration. The Advisory level requires that maintenance action to reduce the vibration level be taken at or before the next 120 Hour inspection. The Warning level requires that maintenance action be taken at or before the next 40 Hour inspection. Utilizing new methodologies, the OBS can monitor the balance state and health of the HSS during normal dual engine operations. The system eliminates the need to install portable vibration monitoring equipment and additional dedicated maintenance run-ups to verify HSS balance, which is a significant benefit to the maintainer. These inspections are now fully automated, eliminating the requirement for manual checks for IVHMS/IMD-HUMS equipped aircraft.

Gyroscopes

Objective:
The Strip Chart capability to provide valuable troubleshooting information has already proven useful as describe in the WOW section of this paper. The same type of information has also proven useful in troubleshooting Automatic Flight Control System (AFCS) malfunctions. Application of the same techniques will reduce or eliminate the need to
pursue time consuming traditional troubleshooting techniques.

Case Studies:
There are three rate gyroscope (gyro) signals (Pitch Rate, Roll Rate, and Yaw Rate) that are monitored by the OBS. Each can be displayed as a strip chart to assist in troubleshooting AFCS faults. Since these signals are monitored on the #2 Digital AFCS units, proper functioning of these gyros indicates that the fault is in the #1 Analog AFCS components. The gyro signal amplitudes vary in response to changes in pitch, roll, and yaw attitude during flight. Strip charts display these variations from a no-change (null) state to the maximum change in degrees-per-second resulting from aircraft maneuvers. Gyro signals that do not show correct null or rate variations in response to attitude changes indicate signal source malfunctions and allows the maintainer to identify the problem in a few minutes, compared to several hours of troubleshooting time.

Below is an example of a Strip Chart that identifies a faulty gyro in Figure 28. In the case shown here, the vertical gyro signal clearly depicts that the aircraft was maneuvering in pitch attitude with no corresponding indication from the pitch rate gyro.

CBM Implementation:
The CBM Manual was updated with step-by-step instructions for plotting gyro data and example strip chart plots that highlight the most common failure modes of the gyros. It also refers the maintainer to the appropriate maintenance procedure to remedy the situation. Previously, many gyros were incorrectly diagnosed and replaced using traditional troubleshooting only to find out the problem remained. This capability provides the maintainers with more accurate information for troubleshooting faulty gyros and saves valuable maintenance man-hours.

CONCLUDING REMARKS
Implementation of the IVHMS/IMD-HUMS along with the CBM Manual has given the maintainer the ability to troubleshoot more effectively, lower the required maintenance man-hours, decrease dedicated maintenance run-ups and maintenance test flights, reduce unscheduled maintenance, and better maintain their aircraft. All of these improvements have led to an increase in aircraft readiness and a reduction in mission aborts due to maintenance failures, key factors to all unit commanders, especially those who are currently deployed supporting the Global War On Terror. The expanding knowledge of CBM concepts that is permeating the Army Aviation community will lead to an increasing number of detection and field use cases. Analysis of these cases and implementation of best maintenance practices into the CBM Manual will continue to expand the utility of IVHMS/IMD-HUMS.

The bridge between vibrations/parameters collected from the aircraft to known faults has been accomplished and implemented in the field. The CBM Manual is the launching point to implement CBM enabling technology into Army Aviation. The ability to view the health of components and aircraft parameters has alerted the maintainer of faults and has provided new insight into the current status of the aircraft. Instead of replacing components based upon an event written up by the crew in the aircraft log book, Maintenance Managers can now rely on accurate data to determine the appropriate course of action.

One of the key objectives of CBM is to reduce the unnecessary maintenance burden on field units. In these cases, the first steps to CBM are being accomplished. Along with charter members of the CBMWG, PM-UH is striving to continue improving CBM capability and integrate new technologies into the system. Investigation continues into field reported use cases involving engine parameters being used as verification of engine exceedances. Numerous instances of data review resulting in preventing the replacement of engines and/or transmissions has been reported from the field. Without the ability to review these parameters the maintainer would be required to replace components based on the interpretation of an event written up by the pilot in the maintenance log book.
CBM technology has the potential to monitor health of components thru the use of onboard diagnostics and On/Off-Board Prognostics which will lead to component reliability improvements, reduced maintenance man-hours, improve readiness and improve flight safety.

REFERENCES

7. Figure 2 courtesy of http://www.cs.princeton.edu