INITIAL RESULTS FROM THE VIBRATION MANAGEMENT ENHANCEMENT PROGRAM FOR ARMY CARGO HELICOPTERS

Jonathan Keller
US Army RDECOM
Aviation Engineering Directorate
Redstone Arsenal, AL
jonathan.a.keller@us.army.mil

Paul Grabill and Deta Adams
Intelligent Automation Corporation
Poway, CA and Huntsville, AL
paul.grabill@iac-online.com
deta.adams@iac-online.com

Stan Graves
Camber Corporation
Aviation Technical Test Center
Fort Rucker, AL
stanley.graves@attc.army.mil

The technology developed as part of the Vibration Management Enhancement Program (VMEP) is currently being demonstrated on the US Army CH-47D and MH-47G Cargo Helicopter platforms as part of a Condition Based Maintenance (CBM) demonstration. The goal of CBM is to monitor aircraft component health and predict their remaining useful life enabling maintenance scheduling, mission planning, and proactive parts acquisition. The VMEP/MSPU systems for H-47 series helicopters perform all legacy vibration-related tasks such as rotor smoothing and recurring vibration checks, monitor the condition of the drive train, and also record the Cruise Guide Indicator (CGI) signals. Initial results are discussed for the first year of the program on 5 CH-47D aircraft.

Introduction

In response to the guidance issued from the Office of the Secretary of Defense (OSD) and the Department of the Army (DA) for a Condition Based Maintenance (CBM) force structure, the US Army is aggressively pursuing safe and effective ways to incorporate the CBM concept into Army aviation platform maintenance environments [1]. The goal of CBM is to increase readiness, safety, and operational availability while reducing the maintenance burden on the soldier.

A key requirement of CBM is for an on-board condition monitoring system to actively monitor aircraft component health and predict its remaining useful life. One such system is the Modernized Signal Processing Unit (MSPU), which was developed from Vibration Management Enhancement Program (VMEP) technology. VMEP and MSPU are currently in use by the US Army Army, Army National Guard and Army Special Operations. There are over 100 aircraft equipped with the VMEP or MSPU system on the UH60 A/L & MH-60 L/K AH-64 A/D and CH-47D with additional installations in progress. The primary function of VMEP and MSPU is to provide a built-in capability to perform required maintenance functions, such as rotor smoothing and mandatory vibration checks [2-5]. The VMEP and MSPU systems provide actionable data to the aircraft maintenance team after each flight as a part of the flight de-briefing process. From this data, maintenance personnel can make informed, proactive decisions regarding the maintenance of the aircraft flight critical systems. Recently, these systems have demonstrated the capability of detecting faults in the Apache main rotor swashplate, hanger bearings and nose gearboxes and Blackhawk oil cooler fan bearings [6]. Because of these detections the VMEP and MSPU systems have been approved in airworthiness releases to either eliminate some manual inspections or increase overhaul times.

This paper discusses the adaptation of the VMEP/MSPU systems for H-47 series helicopters. Results from the first year of use of VMEP and MSPU at the Pennsylvania Army National Guard (PA ARNG) and Ft. Rucker are discussed.

VMEP and MSPU H-47 System Description

The VMEP and MSPU systems are designed for the same purpose and functionality: to provide an automated vibration monitoring and fault diagnostic tool that is composed of three primary components. The first component is a permanently installed on-board system that measures and processes vibration and parameter information. The second component is the Personal Computer – Ground Based Station (PC-GBS) software that displays recommended maintenance actions at the aircraft, aircraft status to the maintenance manager, and measurement details to the engineer. The third component is a system of web-based tools that provides data archiving, software configuration management, management reports, and an advanced engineering development test bed. While the primary purpose of the VMEP/MSPU systems is to perform routine vibration maintenance functions, such as rotor smoothing and mandatory vibration checks during routine operational flights, the system also monitors the aircraft’s flight critical systems and provides the aircraft maintenance crew with actionable information enabling them to make informed, proactive decisions. Combined, the VMEP and MSPU systems have over 20,000 flight hours of field proven experience.
The VMEP/MSPU Onboard System

The MSPU system for the H-47 has 36 accelerometers, 2 tachometers and a tracker mount on the tunnel cover permanently installed on the aircraft as shown in Figure 1. The VMEP system only has 24 accelerometers. For rotor smoothing flights, a single tracker is used to acquire blade tracking data. The VMEP/MSPU systems utilize a single tunnel mount tracker as an alternative to the two tracker configuration used in the past by the US Army Aviation Vibration Analyzer (AVA). The tunnel mount tracker provides much more accurate readings at ground and hover than the two tracker solution. A single tracker solution also has additional advantages of lower cost and weight.

Figure 1. MSPU On-Board System Components

Either the legacy AVA tracker or a special tracker developed for the VMEP/MSPU program can be used. The systems also interface with the aircraft Cruise Guide Indicator (CGI), which measures actual in-flight dynamic stress loads imposed on critical flight control components in the forward and aft swashplate ridge links. The MSPU also uses a Quick Access Recorder (QAR) to provide the maintainer with quick, easy access to the data without powering up the aircraft. The system also has a 1553 interface to the Night Vision Heads-Up Display on the CH-47D or the CAAS system on the MH-47G.

PC-GBS Software

The current H-47 diagnostics consists of over five-hundred Condition Indicators (CIs) monitoring the complete H-47 drive train using high dynamic range acquisitions and measurement processing, proven measurement algorithms, proven diagnostic algorithms and a statistics based approach for Condition Indicator limits setting. A view of the PC-GBS component list for CH-47D is shown in Figure 2. The following items are included in the diagnostics:

- Rotor Smoothing - rotor adjustments are calculated using neural networks
- Forward Rotor Mechanical - swashplate bearing
- Forward Transmission - gears and bearings
- Forward Transmission Accessories – hydraulic and lube pumps
- Synchronizing Shafts - hanger bearings and drive shafts
- Combining Transmission - gears and bearings
- Combining Transmission Oil Cooler Fan - fan bearing and shaft
- Cross Shafts - drive shafts
- Nose Gearboxes - gears and bearings
- Engines - gas generator and power turbine shafts
- Aft Transmission - gears and bearings
- Aft Transmission Accessories - hydraulic pumps, lube pumps and generators
- Aft Transmission Oil Cooler Fan - fan bearing and shaft
- Aft Rotor Mechanical - swashplate bearing.
- VMEP/MSPU Built In Test - health of OBS, accelerometers, and cables

The common ground station for VMEP and MSPU is a single Windows-based software application, which can be run on off-the-shelf PC computers operating Windows 2000 or XP. The PC-GBS stores data received from the airborne system, analyzes the data to determine if limits have been exceeded, annunciates exceedances, and specifies corrective maintenance actions (either self-generated or via links to the approved maintenance manual). The ground station is able to connect to an external internet based system (iMDS-server) to receive software updates and provide collected data for archiving and trending.
The iMDS-server provides fleet wide data storage and trending for the MSPU and VMEP programs. The iMDS-server Web portal allows: fault forecasting, fleet wide data, trending, reports, alert notification, and software upgrades. The iMDS-server also provides automatic remote data backup and maintains the software integrity of connected remote system.

Current VMEP and MSPU Systems Installed

The first CH-47D aircraft to be instrumented with a VMEP system began in April 2003 at the Aviation Technical Test Center (ATTC), Fort Rucker, Alabama. This aircraft is known as “Bearcat 1” at the test center. This aircraft has recently been upgraded to a MSPU system. In June 2005, the PA ARNG began installing VMEP systems on their CH-47Ds. At this time 4 aircraft installations are completed with one more awaiting installation. In addition, one CH-47D was equipped with the MSPU system during April of 2006 at Fort Rucker’s 110th Aviation Brigade and six additional installs are scheduled to begin as aircraft become available. The 160th Special Operations Aviation Regiment (SOAR) is planning to install 10 MSPU systems on MH-47G aircraft beginning in the third quarter 2006. As more systems are installed, this will provide an excellent basis H-47 diagnostic development and maturation.

Results

Rotor Smoothing

To date, the rotor smoothing diagnostic routines have produced excellent results. In most cases one set of Hover diagnostic adjustments have produced vibrations levels that have been acceptable to allow forward flight rotor smoothing. Aircraft are routinely released from maintenance test flights after one set of forward flight adjustments. Advanced rotor smoothing algorithms also address several H-47 rotor smoothing issues such as: large track splits between the GROUND and HOVER test states that makes Hover balancing very difficult, the limited ‘authority’ of blade tip balance weights, excessive trim tab angles, and pitch link adjustments that can affect mechanical rigging (longitudinal stick position).

After getting the ground track split into acceptable limits, generally under 1-inch, many H-47s then experience a large track split in hover. This large track split makes it very difficult to achieve acceptable hover lateral vibrations because of the limited number of tip weights that can be applied. The MSPU uses an advanced neural network for Hover diagnostics to optimize the hover track and balance solution to produce acceptable results with a minimum number of adjustments. For problematic aircraft, operators can select the best diagnostic solution for that particular aircraft. Options include a pitch link only solution derived from track split, a weight only solution, a combined pitch link and weight solution with no track data, and a combined pitch link and weight solution with track data. Nearly instantaneous predicted results and polar plot displays are available from within the ground station to check the effectiveness of these user selected solutions. If the default solution cannot be applied for some reason the ‘Options’ section gives the operator complete control over the solution. Operators can limit the solution to a prescribed number of moves, calculate a solution that just reduces the vibration levels to within the goal instead of zero (Resolve to Vibration Limits), or he can calculate a Manual Solution. In any case the predicted results of that custom solution can be viewed at the Vibration Values or Vibration Plot tabs. Individual adjustments or adjustments to a blade can be turned off if desired or individual adjustments and be incremented up or down by the minimum adjustment value, one weight, one mark of the pitch link. This is especially useful for weight adjustments that are in many cases limited by the current blade weight configuration. In some cases default diagnostics call for the addition or removal of more weights than can be changed in that blade. Users can select the maximum weight change that can be applied to a blade and modify the weight change to opposing blades and check the results.

The VMEP system was installed in the first CH-47D, tail number 87-00110, at PA ARNG during routine phase maintenance in July 2005. After phase was completed, the rotor smoothing procedure was initiated. The track split on the ground was acceptable. But in hover the track split on the aft rotor was 1½-inches, which is over the recommended limit of 1½-inches. The resulting HOVER diagnostic adjustment window is shown in Figure 3a. Diagnostic solutions can be modified to assist in flight control mechanical rigging (longitudinal cyclic stick position) or to help correct auto-rotational RPM issues. The default solution shows two relatively large positive adjustments to the aft pitch change links on the green and yellow blades. At the time, the aircraft was within flight control rigging limits but the longitudinal cyclic stick position was at the aft limit. The PA ARNG maintenance officer felt that the default pitch link adjustments would have caused the Hover stick position to move further aft to an out-of-rig condition, which would force maintenance to “roll the heads”. The maintenance officer de-selected the green pitch-link which changed the primary adjustments from primarily positive pitch link moves to both positive and negative link moves to hover the track split on the aft rotor was 1¾-inches, which is over the recommended limit of 1½-inches. The resulting HOVER diagnostic adjustment window is shown in Figure 3b.
b) Altered Hover Diagnostic Solution

The predicted lateral vibrations of this move were then checked on the Vibration Value and Vibration Plot tabs. The predictions looked very good as shown in Figure 4, being reduced from 1.1 IPS on the aft pylon to below the goal of 0.2 IPS. This solution was then applied to the rotor system by the maintenance crew.

Operators are encouraged to use the default rotor smoothing solution if possible which has shown very good results to date. The operator does, however, have complete control over the diagnostics which was very valuable in this example. In some cases reducing the number of moves still produces acceptable results and reduces the chances of introducing an error by making an improper adjustment. Every adjustment can be controlled by the operator. This is very useful when
dealing with blades that have excessive trim tab angle bends or tabs that will not hold a bend or blades that have max weights or zero weights. Predicted results are always available by clicking the Vibration Values and/or the Vibration Plot tabs. A record of all adjustments can be stored by selecting the “Save Current Solution” button. This benefits the program by providing developers actual field data to check the results of default and custom solutions.

Once the hover adjustment and hover lateral vibrations were acceptable, the aircraft was taken into flight mode. Blade track and lateral and vertical rotor vibrations are acquired in 3 states in the FLIGHT mode: hover, 100 knots level airspeed, and 130 knots level airspeed. The vibration measurements for this flight are shown in Figure 6a. The largest vibration value measured was 0.49 IPS lateral on the forward rotor head, considered to be above the caution level set at 0.4 IPS. Based upon the track and vibration measurements, adjustments are calculated currently with a linear rotor smoothing routine. In this case, the maintenance office chose to limit the number of adjustments to 4 as shown in Figure 6b. The predicted vibration values for these 4 adjustments are shown alongside the measured values in Figure 6a. The predicted vibration values were all reduced to near of below the goal of 0.20 IPS. So the maintenance officer chose to have those 4 adjustments applied.

The same FLIGHT measurements were acquired after the adjustments and the results are shown in Figure 7. The greatest effect was reduction of the aft lateral from 0.29 IPS to 0.08 IPS in hover, forward lateral from 0.49 IPS to 0.34 IPS at 100 knots, and forward vertical from 0.24 IPS to 0.04 IPS at 130 knots. Based upon these measurements the maintenance officer was satisfied and released the aircraft.

The H-47 incorporates a Cruise Guide Indicator (CGI) system gives the pilot a visual indication of actual loads imposed on critical components of the helicopter dynamic system. The system allows the pilot to achieve maximum helicopter utilization under various conditions of payload, altitude, airspeed, ambient temperature, and center-of-gravity. The system consists of strain gages bonded to fixed links in the forward and aft rotor controls, a signal processor unit in the aft pylon, a signal conditioner unit in the forward pylon,
interconnecting wiring and a cockpit indicator. The CGI system measures alternating stress loads at each rotor and displays the larger of the two signals. The pilot views the measurements with the Cruise Guide Indicator, a gauge on the instrument panel with three bands colored green, yellow and striped red-and-yellow. The purpose of the monitoring system is to alert the pilot so corrective actions are taken to reduce stress when in the red-and-yellow striped band. This is accomplished by lowering the THRUST CONT lever, reducing airspeed, releasing back pressure on the cyclic stick, or by reducing the severity of the maneuver.

A requirement for the VMEP and MSPU CH-47D HUMS systems was to provide the function to monitor and indicate CGI exceedances. Since both the VMU and MSPU have the capability to measure low DC voltage inputs, the signal to the CGI gauge was connected to the high impedance inputs on the VMU. Flight tests were performed at the PA ARNG on aircraft 87-0110 to verify the monitoring capability. The software was configured to measure the CGI voltage during the background monitor mode. In this mode the VMU will trigger measurements on a time base once the aircraft rotor RPM crosses the 90% Nr threshold. The time base is programmable, and for this test was set to measure every 10 seconds. The CGI values are calculated and stored on board the VMU and are downloaded at the end of the flight. The PC-GBS processes the flights data and calculates a CI that is the maximum over the flight using a programmable length median filter to eliminate noise spikes. A plot showing the output from the first flight at PAANG is shown in Figure 8.

The CGI monitor plot shows for the first flight were a startup transient was indicated in the first few minutes after the rotors were at 100%. This transient is attributed to the generators coming on-line and is normal operation where the gauge will quickly go to full “red” and back. The first flight is shown where the aircraft was flown in the normal rotor smoothing states. After this test the aircraft was flown to a location to pick up a sling load with the purpose of flying with the CGI in the yellow to low red area. This flight is shown at the end of the monitor flight with the higher CGI voltage outputs. It was noted during this flight how the data displayed at the meter was more transient than expected with the needle in the gauge jumping from green to yellow to red very rapidly. Subsequent ground tests were performed to collect CGI data with the CGI test button depressed to determine the voltage when the meter was in the red region and this data was used to set the limit at its current value of 4.0 Volts. Even the startup transient is larger than the limit, it is removed by the 5 point median filter.

The PC-GBS now includes a CGI component which will change status color based on the most recent flight data. Figure 9 shows the Component List and the CGI component as presented to the flight line maintenance personnel.

**Figure 8. CGI Recording during a Flight**

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**Figure 9. Aircraft Component Tree with CGI**

**Hanger Bearing Monitoring**

After phase was finished on CH-47D tail number 87-00110 at PA ARNG, the Survey FPG100 mechanical diagnostic acquisition was completed several times within the first few flights to check the condition of the drive train. When the data was downloaded, it was noted that the vibration level measured at hanger bearing #3 was abnormally high relative to other hanger bearings on the aircraft. This was causing the hanger bearing energy condition indicator (CI) to range from to yellow to red. This particular CI is the root-sum-square of the vibration from 500 to 5500 Hz in the averaged asynchronous vibration spectrum, with notch filters around the forward and aft transmission input bevel and lower stage planetary gear mesh frequencies. This
particular window was configured such that the first four fundamental fault frequencies of the hanger bearings were included within the window. Condition indicators configured in this manner have previously demonstrated success in detecting pitting, spalling and corrosion in gearboxes and bearings on the Apache and Blackhawk [6].

The asynchronous vibration spectrum for the suspect hanger bearing along with a normal hanger bearing is shown in Figure 10. For the suspect hanger bearing, there are large frequency components at the fundamental train frequency (FTF) and the ball-pass frequency for the outer race (BPFO) along with an elevated noise floor. Comparing to the next hanger bearing the vibration level is much lower.

At a convenient maintenance opportunity in mid-October 2005, the PA ARNG chose to replace the 3# synchronization shaft and hanger bearing. When removed from the aircraft, there was roughness noted when the hanger bearing was rotated by hand. The hanger bearing CI trend over time before and after the replacement of the suspect hanger bearing is shown in Figure 11a. Note that the CI dropped from over 100 g, to slightly under 10 g and has been operating at that level for the past 6 months. The hanger bearing CI trend across the 4 VMEP-equipped aircraft at PA ARNG is shown in Figure 11b. After replacement, 87-00110 has the lowest vibration level of the 4 aircraft. A normal vibration level is about 20g.

Synchronization Shaft Imbalance

The VMEP system was installed on the second CH-47D, tail number 91-00250, at PA ARNG during routine phase maintenance in October 2005. After phase was finished, the Survey FPG100 mechanical diagnostic acquisition was completed to satisfy the recurring 50-hour combining and aft transmission cooling fan assembly vibration check requirement IAW TM 55-1520-240-23. The measurements acquired from the accelerometers mounted on the combining and aft transmission fans passed all specified limits. Part of the 50-hour check requirement is the measurement of the synchronization shaft once-per-revolution (1P) vibration level as measured by the lateral and longitudinal accelerometers mounted on the combining transmission oil cooler fan. These measurements were 0.2 IPS and 0.1 IPS, respectively, compared to a limit of 0.7 IPS. Naturally, this is only a general indicator of the imbalance of the synchronization shafts. If this
measurement is above specified TM limits, it would not be clear which shaft is the source of the problem. Upon looking at the PC-GBS, it was noted that the Synchronization Shafts component was in the yellow caution condition because of the synchronization shaft 1P vibration level as measured by the accelerometer mounted at hanger bearing #3. The vibration measured there was over 6 IPS. The average 1P vibration level measured at the hanger bearings themselves is normally 2 to 3 IPS. Thus, even though the aircraft passed normal vibration checks, it was clear that either the #3 synchronization shaft (in front of hanger bearing #3) or the #4 synchronization shaft (behind hanger bearing #3) was well above normal vibration levels. The vibration level at hanger bearing #4 was a normal level of 3.2 IPS, so it was suspected that the #3 synchronization shaft was the source of the problem.

In February 2006, the unit located a spare shaft and replaced the #3 synchronization shaft. The vibration history before and after replacement are shown in Figure 12a. Note that the vibration level dropped from 5.5 IPS to 2.2 IPS as a result of the new shaft and has remained at that level for the past 3 months. For comparison, the current synchronization shaft 1P vibration level measured at hanger bearing #3 for the 4 VMEP-equipped Chinooks at PA ARNG is shown in Figure 12b. Three of the four aircraft have normal vibration levels between 2 and 3 IPS, while the fourth aircraft 90-00199 is actually very well balanced under 1 IPS.

Conclusions
The technology developed as part of the Vibration Management Enhancement Program (VMEP) is currently being demonstrated on the US Army CH-47D and MH-47G Cargo Helicopter platforms as part of a Condition Based Maintenance (CBM) demonstration. The VMEP/MSPU systems for H-47 series helicopters perform all legacy vibration-related tasks such as rotor smoothing and recurring vibration checks, monitor the condition of the drive train, and also record the Cruise Guide Indicator (CGI) signals. Currently, the VMEP system is installed on 4 CH-47D aircraft at the Pennsylvania Army National Guard with a 5th aircraft scheduled for installation; while the MSPU is currently installed on 2 CH-47D aircraft at Ft. Rucker, Alabama. Additional installations are planned on both CH-47D and MH-47G aircraft at other locations. The VMEP/MSPU systems have shown positive results for rotor smoothing where the maintenance officer has the ability to choose the best set of adjustments to both smooth the rotor system and satisfy flight control rigging requirements. The system has also identified two hanger bearings suspected of having corrosion or pitting damage, and one imbalanced synchronization shaft.

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References