Condition Based Maintenance Fleet Implementation and Maintenance Decision Making Through Utilization of Prognostics Data by Operational Units

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Abstract

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 Apache Attack Helicopter Project Management Office (AAH PMO) is moving forward with the implementation of a CBM enabled environment. This environment digitally integrates data on and at-aircraft, at-unit and at-enterprise to facilitate CBM, leveraging previous investment of key technical initiatives and existing enablers. To guide this effort the Apache Attack Helicopter Project Office's Logistics Modernization Division has drafted an Apache CBM+ Strategic Plan that coordinates technical initiatives and enablers with specific tasks and milestones through 2015. The Apache CBM+ Roadmap focuses on implementing a CBM enabled environment through four major objectives: reducing soldier burden, increasing operational availability, enhancing safety, and reducing operational & support costs affecting fleet management. This paper will outline the process being used by Apache to utilize the prognostic early warning of incipient failures and proactively implement CBM on the operational fleet and the benefits that have been seen by applying the concepts of CBM.

Introduction

In 2005 at the American Helicopter Society 61st Annual Forum, the Apache Attack Helicopter Project Management Office (AAH PMO) presented its plan to respond to the guidance issued from the Office of the Secretary of Defense and the Department of the Army for a Condition Based Maintenance force structure by the creation of a CBM enabled maintenance environment that holistically integrated embedded diagnostics and prognostics with maintenance operating procedures.[1] This paper included initial results from Army Aviation's CBM Proof of Principle and the initial evaluation of the Modernized Signal Processing Unit (MSPU), an on board health and usage monitoring system, coupled with other critical enablers such as the MSPU ground software, Interactive Electronic Technical Manuals (IETMs), Automatic Identification Technology (AIT), an electronic logbook, and other electrical embedded diagnostic/exceedance data from an integrated data bus to create an Aviation Platform Maintenance Environment that would support and expand the concept from CBM to CBM Plus (CBM+).

The DA G4 CBM+ Roadmap defines the "Plus" in CBM+ as the infrastructure to make use of the sensor based maintenance information. This infrastructure consisting of numerous technologies and enablers is what is meant by the "Plus in CBM+".

Since the time that paper was presented, the AAH PMO's Logistics Modernization Division has drafted an Apache CBM+ Strategic Plan that coordinates technical initiatives and five interdependent enablers with specific tasks and milestones through 2015.

The Apache CBM+ Strategic Plan outlines our roadmap to a CBM+-enabled environment through Strategic Objectives and How We Accomplish Our Objectives through Technical Initiatives. Implementation Guidelines are formed by Interdependent Enablers. Operational Guidelines

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are formed by business processes beginning from "On-Platform to the PM".

Apache CBM+ Objectives.

The Apache CBM+ Roadmap focuses on implementing a CBM enabled environment through four major objectives: reducing soldier burden, increasing operational availability, enhancing safety, and reducing operational & support costs affecting fleet management.

Technical Initiatives form action plans to achieve each objective.

Reliability Centered Maintenance (RCM) – Provides the analysis basis from which we begin CBM+; i.e., does it make sense to monitor or redesign a component for CBM+?

Diagnostics/Prognostics – Sensors provide continuous monitoring and predict incipient failure for Dynamic, Electronic, Engine and Structural Components.

Remediation/Reliability Improvement thru Failure Identification and Reporting (RIMFIRE) – Remediation extends RUL of fatigue life limited components by increasing damage & repair limits. RIMFIRE determines why components don't make their Time Before Overhaul (TBO).

Regime Recognition/Damage Summation – Provides Remaining Useful Life (RUL) on fatigue life limited components and automated data collection for Vibration Management/Rotor Smoothing. Provides actual mission usage spectrums, from which reduced Schedule Phase Maintenance is derived.

Process Re-engineering/Data Management – Identifies new processes/knowledge-base systems to optimize scheduled maintenance, proactive parts ordering based on RUL, and accurate parts forecasting.

Implementation Guidelines - Successful CBM+ implementation depends on the synchronization of five interdependent enablers: Collection of Platform Data, Transmission, Warehousing, Analysis, and Decision Support. These enablers provide the guidelines for our strategic planning and decision making.

Operational Guidelines - Our CBM+ operational concept throughout the Army Integrated Logistics Architecture (AILA) begins with processes On-Platform, At-Platform and Off-Platform to the PM Enterprise. We will identify and connect the platform CBM+ infrastructure to the logistics IT systems.

The key element to this plan is through on-aircraft embedded sensor prognostic early warning of incipient failures, we have the ability to predict and react appropriately to aircraft component and system failures. The resulting impending maintenance actions that will be needed to return the aircraft to fully mission capable are minimized as a result of early warning and achieve our CBM+ objectives. Also, through on-aircraft sensor, embedded diagnostics and continuous monitoring provide automated inspections, thereby replacing and/or reducing manual labor-intensive diagnostic inspections. ***(SEE HOW TECHNICAL INITIATIVES (Embedded Sensors) ACHIEVE OUR OBJECTIVES).***

Early warning reduces soldier burden by reducing unscheduled maintenance and optimizing scheduled maintenance; enhances safety by knowing which aircraft are available to perform the next mission and avoid a precautionary landing/recovery launch; increases aircraft availability, by the early ordering of parts into the supply system (the aircraft is not down waiting for parts); and reduces operation and support costs by reducing collateral damage (trending of a failure reduces the chance of parts breaking other parts). Operationally, the end-state of the CBM enabled environment is to order a new part based on an exceeded Condition Indicator (CI) threshold or it Remaining Useful Life (RUL).

The Apache CBM+ Strategic Planning Process

In order to accomplish the aggressive CBM goals that the AAH PMO has accepted, a Strategic Planning Process was developed to guide the formation of action plans to define what specifically will be accomplished, by whom, within what timeframe, and the desired outcome with associated metrics for tracking performance.

The strategic planning process began with review of the AMCOM LCMC Commanding General's CBM+ Program Objective, from which Apache Vision and Mission Statements were derived. These defining statements establish the overall framework under which all AMCOM and PM Apache CBM+ efforts and activities evolve and provide the CBM+ destination.

Next, four major Apache CBM+ Objectives were developed to provide the Apache CBM+ Roadmap focusing on Soldier Burden, Operational Availability, Safety, and O&S Costs/Fleet Management.

Each of the objectives of the Apache CBM+ Strategic Plan is supported by interdependent key enablers that include health and usage data collection, transmission, storage, analysis and also decision support capabilities. To measure the success of these objectives, specific performance objectives were identified and translated into measureable metrics such as the goal of a reduction in the cost per flight hour of the Apache aircraft, reduction in Maintenance Man Hours (MMHs), reduced Non Mission Capable Maintenance (Unscheduled) (NMCM (U)), a goal of an increase in the operational availability of aircraft at the aviation unit level, and the increase of mission reliability and safety.

The action plans to achieve each objective are driven by technical initiatives that include Reliability Centered Maintenance (RCM), Diagnostics / Prognostics for Dynamic / Electronic / Engine / Structural Components, Fatigue Life Management (via Remediation and Usage Monitoring - Regime Recognition), Process Re-engineering, and Data Management.

A summary of the planning process can be shown as a hierarchy as shown in Figure 1.

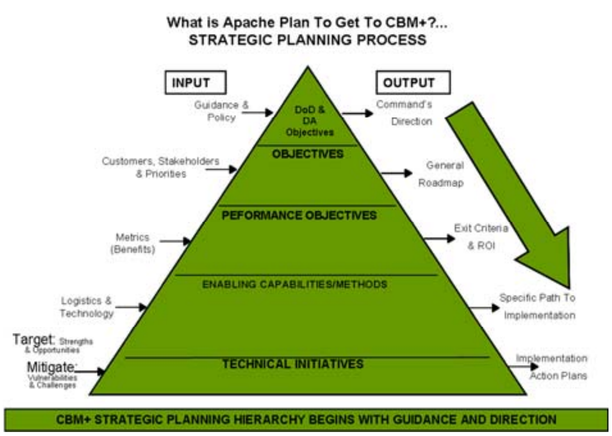

Figure 1. Apache Strategic Planning Process

The Apache CBM+ Strategic Plan

The Apache CBM+ Strategic Plan is a summary of the technical initiatives associated with developing, fielding and expanding the CBM+ enabled maintenance environment. Also included in the Apache CBM+ Strategic Plan are the supporting data analysis and engineering efforts that support the CBM+ goals. Each technical initiative is defined by the needed infrastructure and equipment that is needed to field the enabler, the Aviation Engineering Directorate (AED) engineering support needed to meet the goals, and the timeline for expected completion.

Apache CBM+ Strategic Plan Enabling Capabilities

Five Interdependent Enabling Capabilities 1) On-Platform Collection systems provide the genesis for data 2) Transmission, using a wireless Enterprise Architecture, from At-Platform downloads, to At-Unit Maintenance, to the 3) CBM Data Warehouse, where storage of data is performed to support 4) Analysis and the development of 5) Decision making tools.

Apache CBM+ Strategic Plan Technical Initiatives

Technical initiatives include, but are not limited to, the fielding of embedded diagnostics systems such as the MSPU and Maintenance Data Recorder (MDR). An improved Fatigue Life Management Program using Remediation of components based on engineering analysis and the implementation and expansion of Regime Recognition capabilities within the MSPU program, are expected to increase component time-on-wing. Process Re-engineering and Data Management will be utilized to optimize maintenance processes.

Diagnostics/Prognostics

Diagnostic sensors provide continuous monitoring to detect and identify incipient failures for Dynamic (Vibrating), Electronic, Engine, and Structural (Rotor Blades) Components. Prognostics are the ability to match the fault indicators to the failure progression (Remaining Useful Life (RUL)), previously measured, or modeled, with a high level of confidence. Includes the analysis tools, processes, methods and standards to assure consistent maintenance credit validation from CBM+ data.

Modernized Signal Processing Unit

The MSPU digitally monitors the AH-64 data bus and uses 18 sensors to monitor 50 components with 174 Condition Indicators (CIs). The MSPU system uses the VMEP Personal Computer - Ground Based System (PC-GBS) as well as the Intelligent Machinery Diagnostic System (iMDS) Server data analysis capabilities. For the Apache

aircraft, the MSPU serves as a digital replacement for the analog Signal Processing Unit (SPU), since the SPU is a chronic source of field maintenance problems. Failure of the SPU system is a leading cause of unnecessary precautionary landings.
The MSPU system provides the following functions to the Apache pilot/maintainer:

1. *Basic Aviation Vibration Analyzer Functions.* This includes rotorsmooting capabilities, mandatory inspection automation, and tail rotor balancing. These functions were previous handled at the aviation unit level by the Aviation Vibration Analyzer (AVA). The MSPU completely replaces this equipment reducing rotorsmoothing time and burden.
2. *Drive Train Health Monitoring.* This includes complete drive train vibration monitoring, advanced gear and bearing diagnostics, Auxiliary Power Unit (APU) monitoring, and automated inspections. The MSPU replaces SPU functionality by monitoring the critical components of the drive train.
3. *Engine Health Monitoring.* This includes engine vibration monitoring, engine parameter exceedence monitoring (e.g. temp, torque, speed), and HIT/BASELINE HIT and MAX Power Checks.
4. *Regime Recognition.* This includes automated measurement triggering, automated gross weight calculation, regime recognition, and time in regime recording.

The MSPU system also provides the following support functions to the AAH PMO and AED:

1. *Aircraft Fault Isolation.* The MSPU provides valuable data to aid in the investigations of aircraft faults. The VMEP systems have provided valuable data and insight into AED fault investigations for the AH-64 APU clutch. If special testing is needed by AED, the MSPU software is easily configurable with a high degree of measurement capability.
2. *Aircraft Trending.* The MSPU allows for a view of the entire fleet to aid in problem investigation and early fault detection. It also supports an improved response to inadequate maintenance.
3. *Diagnostic Limit Setting.* The most challenging part of CMB is the engineering burden of placing prognostic limits on a component's life. By analyzing data at a fleet level the VMEP program has been successful in setting limits that are acceptable in operational environments. The PC-GBS software and the iMDS web server provide statistical reports and displays of CIs in order to aid in this process. The U.S. Army maintains complete control over the diagnostic limits.

The MSPU data flows from the aviation unit level to the AED managed iMDS web server allowing for a fleet level view both at the unit level and at AED. MSPU data flow is aided by the JTDI and CASI enablers and the data flow schema is adaptable according to the environment in which the aircraft is operating.

Improved Fatigue Life Management

By coupling remediation analysis with recorded aircraft usage and health data (i.e. from MSPU regime recognition capabilities), the AAH PMO has created a Fatigue Life Management Program with the goal of safely increasing the time on wing for fatigue life limited components based on actual accumulated damage versus a worst case scenario design usage spectrum.
Remediation - Extends the RUL of fatigue life limited components through improved inspection, damage tolerance analysis/test, and repair procedures.
Regime Recognition/Damage Summation – Provides Remaining Useful Life (RUL) on Life Limited Components based on actual usage, time in flight regime, associated analysis tools, processes, methods and standards to determine loads and accumulated damage fraction.
Fatigue life limited components are defined by components that incur metal fatigue stress or strain and accumulated physical damage. The need for the effort is the result of the finding that 77% of Apache DA Form 2410 tracked components do not meet their expected life on wing due to knicks, dings, scratches, or corrosion. The removal criteria for these defects were set using the assumption of the worst case scenario design usage spectrum. This effort focuses on extending a component's useful life on the aircraft while monitoring that component's cumulative damage using regime recognition. By extending a component's time on the aircraft, the soldier's burden is reduced, and aircraft operational availability is increased, leading to a reduction in operational and support costs.

Process Re-Engineering and Data Management

Identifies new processes to improve scheduled maintenance, proactive parts ordering, and accurate parts forecasting. Includes data transport and storage processes, methods, and standards that move platform and maintenance data to the 'PM/Enterprise' for wholesale analysis and fleet management. Process Re-engineering and Data Management also utilize diagnostic and prognostic data to support increased situational awareness for the commander, early warning for the maintenance team, improved fleet management, and a collaborative maintenance environment where AED can provide real time advice on complex maintenance decisions and avoid catastrophic incidents. AED also reviews MDR exceedance amplitude and duration diagnostic data for adjudication. Otherwise mandatory hardware removal is replaced with an inspection for such events as engine overtorques and rotor underspeeds [2]. The resulting benefits are avoided hardware replacement costs, avoided maintenance man hours (associated with the avoided hardware replacement), and avoided downtime (associated with the avoided hardware replacement).

How Technical Initiatives Achieve Our Objectives

Through on-aircraft embedded sensor prognostics, early warning of incipient failures, we achieve the objectives below:

- Reduced 'domino effect' collateral damage is achieved as parts are not breaking other parts. E.g, A Nose Gear Box (NGB) bearings fail prior to its gears and gears fail prior to the NGB housing. When the prognostic indication of bearing failure occurs, the NGB can be optimally scheduled for removal (NMCM (S)), and a new part ordered early from the supply system.
- Increased Availability is achieved by anticipating parts requests in the supply system, aircraft not down waiting for supply as the part was ordered early.
- Reduced Unscheduled Maintenance (NMCM (U)) is achieved through anticipation of the incipient failure, identification of the part's Remaining Useful Life (RUL) and proactively scheduling its maintenance.
- Reduced Maintenance Man-hours are also achieved through increased component time-on wing through Fatigue Life Management of our Limited Components. Remediation extends Component Time On Wing by increasing damage & repair limits (component's are not removed as often for damage). Regime Recognition/Damage Summation/loads based RUL as opposed to Time Before Overhauls (TBO) for Life Limited Components.
- Lower Inventory Costs are achieved via the ability to forecast demand rate.
- The probability of catastrophic accidents are reduced as the early warning of impending failures are identified before the occurrence of mission affecting failures and mission aborts.
- Increased situational awareness enables a commander to better understand which aircraft are available to perform the next mission, how severe an aircraft was damaged, where it is, and what is the maintenance time needed to get the aircraft ready again.

Through on-aircraft embedded sensors, automated inspections replace and/or reduce manual labor-intensive diagnostic inspections and we achieve continuous monitoring. The objectives below result:

- Reduced Soldier Burden (Maintenance Man-Hours) is achieved as the sensor continually conducts the inspection vice the soldier conducting periodic inspections.
- Reduced Maintenance-Induced Collateral Damage – Since there are less manual inspections, the likely-hood of less parts damage is increased, therefore less demand rate/inventory costs. Also reduced maintenance man-hours (again) via reduced parts breakage.
- Increased Mission Reliability (MR) and Enhanced Safety are achieved through a Higher Diagnostic Confidence (from the sensor conducting the inspection) and reduced No Evidence Of Failure (NEOF).
- Increased Availability (Aircraft is not down for manual inspections).
- Reduced even-driven (unscheduled) maintenance is achieved through continuous monitoring. Event driven/Unscheduled maintenance results from Exceedances,

Regular Inspections, Pilot reports, and/or Maintenance Test Flights (MTFs). As a result of monitoring, the amplitude/duration of an exceedance is identified, revealing exactly which parts require inspection vs. erring on the side of caution and suspected replacement, thus also increasing component time on wing, reducing inventory costs, demand rate.

- Increased Safety/Reduced Parts Inventory/Demand Rate – On-board Rotor Vibration Monitoring (Rotor Track Balance) provide continuous rotor vibration state assessment. From this information, adjustments to the rotor system to reduce 'once-per-rev- vibration are computed on a regular basis. Application of these computed adjustments on a routine basis will maintain a lower overall vibration environment and is known to reduce component failures and crew fatigue.

Fatigue Life Management – Using both Remediation and Regime Recognition affects the following Apache CBM+ Objectives.

- Reduced Maintenance Burden occurs as reduced failures due to Remediation relaxed tolerances may result in increased inspection intervals.
- Enhanced Safety results as Remediation processes analyze and repair potentially catastrophic defects, thus mitigating mishaps.
- Reduced Inspections (Maintenance Man-Hours) also result from Regime Recognition/Damage Assessment.
- Reduced Scheduled Phase Maintenance results from Regime Recognition software that measures actual flight profiles and environmental conditions. Previous Scheduled Maintenance tasks were based on an assumed worse case mission profile as opposed to the actual usage spectrum as measured by the RR software.
- Improved fleet management is achieved for understanding the actual structural usage profiles and environments that the aircraft has experienced. This enhances the ability to forecast demand rates based on actual usage, understand OPTEMPO, location, asset visibility, and aircraft configuration.

At-Aircraft - Prognostics Early Warning At-Aircraft tells us when to order a new part and when to replace it. Enhanced safety is achieved as you'll know which aircraft are available to perform the next mission and avoid a precautionary landing.

At-Unit - Prognostics Early Warning At-Unit Optimizes Scheduled Maintenance, allowing us to reduce unscheduled maintenance. An exceeded threshold, allows the soldier to 'tickle the supply system' and order the part early, avoiding down-time associated with waiting for supply (reduced NMCS). Increased availability regarding operational status is the resultant. Fatigue Life Management via Usage Monitoring and Regime Recognition allows us to revise the way we schedule maintenance based on actual accumulated damage vs. based on time on wing (determined by worst case assumed usage spectrum).

At-Enterprise - Prognostics Early Warning At-Enterprise supports a collaborative maintenance environment where recommendations are provided back to the unit. Aircraft Exceedance data is provided to the training managers and identifies areas of concentration. Regime recognition allows us to understand how we're flying the aircraft and the environments in which we flew. Actual usage data provides information for new aircraft initial provisions, training exercises, supply and sustainment, Go To War push packages, engineering re-design "what-if" scenarios, readiness-based sparing, and tactical redeployment.

The Apache CBM User Working Group

Internally within the AAH PMO, the development and expansion of the CBM enabled maintenance environment is guided by a CBM User Working Group (UWG) that includes members of the Aviation and Missile Research Develop Engineering Center (AMRDEC) functional groups and systems engineering, the Integrated Materiel Management Center (IMMC) item managers and technical publications, the vendors for key CBM enablers, support from the AMCOM G3 CBM office, participation of field units who have been fielded CBM enablers, and the oversight of the Apache Logistics Modernization Division.

The analysis and decisions of the UWG are guided by data from key enablers that include an on-board condition monitoring system, the

Modernized Signal Processing Unit (MSPU), to actively monitor an aircraft component's health, usage, and predict its remaining useful life, the integration of CBM maintenance practices into Interactive Electronic Technical Manuals (IETMs), the inclusion of Automatic Identification Technology (AIT) working with an electronic logbook for component tracking and identification, and other electrical embedded diagnostic/exceedance data from an integrated data bus.

Data flows to the UWG using advanced wireless and satellite technology from U.S. Army aviation units and operational battlefields such as Operation Iraqi Freedom. This aircraft health and usage data is coupled with data from teardown analysis, Quality Deficiency Report (QDR) investigations, and engineering knowledge to offer informed advice on improving the At-Aircraft and At-Unit maintenance processes to make them more proactive and agile.

Conclusion

Even though the Apache CBM+ Strategic Plan includes initiatives and milestones spanning to 2015. Apache has realized the benefits of CBM technical initiatives like embedded diagnostics since 1998 with the installation of the MDR and the MSPU in 2005.

For the time period Aug 2007 through February 2008[2], AED recommended waiving hardware replacement for nine exceedances, based on analysis of MDR data, resulting in MMH, Hardware, and Downtime benefits/cost avoidance as bulleted below:

- Avoided Maintenance Burden on the Solider:
  - 359 MMH Avoided (at a cost of $60/Hr = $0.215M)
- Avoided Operational & Support Costs:
  - Total Hardware Cost Avoidance = $3.713M.
- 148 hrs Avoided Downtime (not in $) associated with avoided hardware replacement.

For the time period Oct 2005 through December 2007[3], Apache has measured benefits resulting from 184 aircraft equipped with MSPU diagnostic sensors. These sensors conduct (or extend interval) inspections for the soldiers, thus avoiding the inspection. If the avoided inspection also required a Maintenance Test Flight (MTF), then MTF hours are also averted. The resulting MMH, MTF hours, Downtime (associated with avoided inspection time) and Readiness benefits/cost avoidance as bulleted below:

- Avoided Maintenance Burden on the Solider:
  - 9,853 MMHs Avoided (at a cost of $60/Hr = $0.591M).
  - 1,192 MTF Hrs Avoided (at a cost of $3,802/Hr = $4.532M).
- 3,001 hrs Avoided Downtime (not in $) associated with avoided inspection time.
- 1% - Readiness Increase

As the Apache CBM+ Strategic Plan progresses the expected Future Benefits are summarized below:

- Avoided Maintenance Man-Hours
- Increased Readiness
  - Reduced Scheduled & Unscheduled Maintenance and Non Mission Capable Supply
- Avoided Downtime
- Reduced Maintenance Test Flights
- Avoided Hardware Costs
- Increased Mission Reliability (MR)
  - Reduced Mean Time Between Mission Essential Function Failure (MTBMEFF), Mean Time Between Mission Affecting Failures (MTBMAF), Mean Time Between Maintenance Actions (MTBMA)
- Enhanced Safety:
  - Early Warning Reduces Mission Aborts and Accidents.
  - Detection of Faulty Components before Failure
- Reduced Demand Rate
- Reduced No Evidence Of Failure (NEOF)
- Demand Rate Forecasting

In summary, the collaboration of the Apache CBM-enabled environment, the associated business, technical and logistics analysis processes, and infrastructure being developed to support the Army CBM+ Enterprise Architecture, will facilitate these transformational capabilities through the use of prognostics data:

- Reduced Maintenance Burden
- Proactive Mission Planning
- Anticipatory Logistics/Proactive Parts Ordering/Accurate Parts Forecasting/Interactive Training
- Increased Safety/Inherent Reliability
- Enhanced Fleet Management

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