U.S. MARINE CORPS CONDITION BASED MAINTENANCE CREDIT APPROACH FOR THE CH-53E HELICOPTER

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Abstract

Condition Based Maintenance Plus (CBM+) is one of six initiatives the U.S. Department of Defense (DoD) Future Logistics Agency is implementing to streamline logistics and provide the customer with end-to-end service. A CBM program is a maintenance concept intended to predict failures based on real-time assessment of equipment condition obtained from embedded sensors. CBM+ has the potential to decrease the cost of maintenance, and at the same time, to increase the operational readiness of the system (Ref. 1).

The U.S. Marine Corps is in the process of deploying the Goodrich Aerospace Integrated Mechanical Diagnostic System (IMDS) upon the CH-53E helicopter fleet. Commercially known as Health and Usage Monitoring Systems (HUMS), IMDS performs tracker-less rotor balancing, drive system diagnostics, engine performance, and regime recognition for structural usage monitoring. The combination of a heavily time-based maintenance environment coupled with the deployment of IMDS make the Marine Corps CH-53E helicopter fleet a logical proving ground for the Future Logistics Agency CBM+ doctrine.

This paper will focus on the process for improvements in cost and readiness to be enabled by IMDS. Near term plans for the implementation of health and usage monitoring techniques for the purpose of attaining CBM credits will be presented. Examples of scheduled maintenance action reduction, overhaul and removal extensions, and improved readiness are included with a systematic approach of integrating IMDS into the squadron concept of operations.

Introduction

Helicopter HUMS technologies were explored in the late 1980's and produced in the early 1990's. Initiated primarily as a safety tool, potential was soon identified for cost reduction and improved readiness. The operators quickly realized several maintenance credits, but most of the foreseeable benefits required the participation of airworthiness authorities and the aircraft Original Equipment Manufacturer (OEM) (Ref. 2). Some OEM's did not initially view HUMS as a viable business item, and operators unfortunately did not possess the resources or the leverage to connect the aircraft manufacturers to other HUMS benefits.

Naval Air Systems Command (NAVAIR) has supported and funded the development of HUMS technologies for more than a decade. These efforts led to the development of the AN/AYH-3 (IMDS), which was envisioned as a common diagnostic system for all Navy/Marine Corps helicopters. Embraced by the H-53, H-60, and H-1 program offices, the fielding of the Navy's first fully integrated HUMS in a helicopter fleet took an important step in 2004 with the successful completion of Operational Evaluation, which allowed for full-rate production procurement of IMDS on the CH-53E helicopter (Ref. 3).

The purpose of a CBM program is to reduce maintenance down time and increase operational readiness by repairing or replacing system components based on the actual condition of the assembly. It contrasts to traditional maintenance concepts, such as Reliability Centered Maintenance (RCM), which employ time based, preventive, and reactive

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maintenance schedules [Ref. 4]. These plans are critically dependent upon the often questionable quality of maintenance recordkeeping and feedback. By employing the CBM+ concept, which is driven by need, as opposed to time based maintenance procedures; unnecessary maintenance efforts can be reduced, thereby reducing the total cost of weapon system support.

In January 2005, the CH-53E IMDS Integrated Product Team re-convened for the purpose of implementing CBM principles via IMDS. Working groups for rotor balancing, engine performance and usage, mechanical diagnostics, and structural monitoring began plans to integrate IMDS and CBM into the aircraft maintenance plan. Before presenting the progress and plans for these functionalities, it is important first to discuss a few maintenance paradigms.

Marine Corps Maintenance History

In the early 1980s, Navy/Marine Corps maintenance plans were directed to employ Reliability Centered Maintenance (RCM). RCM is a process used to determine what actions must be taken to assure that a physical asset continues to do what its users want it to do in the environment that it was intended to operate. To accomplish this goal, RCM uses a logical and disciplined analytical procedure to identify what may cause an asset to fail to operate, and what adverse consequence that failure may have upon the business operations, personal safety and environment. Based upon the analysis, a plan of action is developed which may lead to revised maintenance procedures, inspections, and component redesign. RCM would be used as the basis for establishing and sustaining preventative maintenance programs for all DoD equipment and a means to justify new or modified maintenance tasks and continually evaluate existing tasks.

In 1993, General Accounting Office Report # GAO/NSIAD-93-163 identified the RCM activities being performed upon military systems with extensive histories were not cost effective due to RCM analyses cost, and their implementation did not significantly reduce maintenance requirements. This view was also shared by the Air Transport Association and FAA (the authorities whom initially encouraged the use of RCM). Though RCM continues to be mandated within DoD, logistics agencies within DoD went about identifying other means of reducing operating costs and increasing readiness.

DoD's Future Logistics Enterprise identified six initiatives to improve end-to-end customer service, one of which was CBM+. The CBM+ maintenance concept is to predict equipment failures based upon assessment of equipment condition obtained from embedded sensors. The intent to reduce maintenance down time and improve readiness by repairing or replacing components based upon their condition, vice schedule (time) based procedures. The condition monitoring provided by IMDS is a key enabler of CBM on the CH-53E helicopter (Ref. 1).

Helicopter Maintenance Model

A generic helicopter maintenance model is discussed in Figure 1. Helicopter maintenance is driven by both unscheduled events detected by the crew or maintainers and time-based (scheduled) events based on either calendar or flight hours. An aircraft is in an operational <UP> status until an exceedance event or scheduled/ unscheduled maintenance is encountered whereupon the aircraft is placed in maintenance <DOWN> status. Depending on required maintenance, the aircraft returns to operational status or requires a Functional Check Flight (FCF). Should the aircraft pass FCF it is returned to operational status; if it fails, it returns to maintenance (Ref. 5).

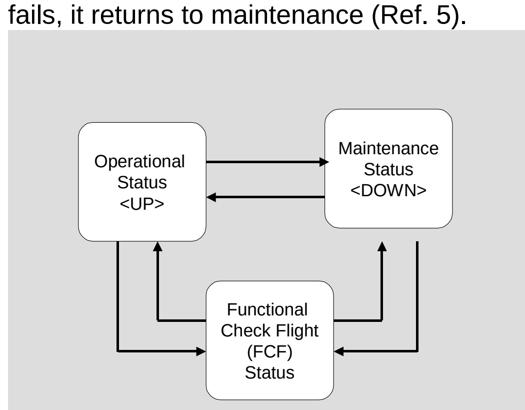

Figure 1: Helicopter Maintenance Model

The CBM IPT wishes to make Concept of Operations (CONOPS) improvements within this model, some of which are:

1. When possible, return a <FAILED> aircraft to operational status to acquire more info as to health of aircraft and corrective maintenance action, vice entering Functional Check Flight (FCF) status.
2. Move aircraft from maintenance status to <UP> status vice to FCF mode.
3. Reduce frequency of transition from <UP> status to FCF.
4. Less scheduled maintenance events required.
5. Less unscheduled maintenance events encountered.

An interesting issue within the above model is the predicament encountered when usage monitoring data is used as flight hours to drive maintenance. HUMS OEM's have long recommended the use of automatically recorded usage data for this purpose. Flight hour scheduled maintenance intervals are based on Reliability Centered Maintenance (RCM) analyses and sustained maintenance planning factors. These analyses have to this point used pilot-recorded flight hours. Because there is typically at least a +10% difference between pilot and IMDS flight recorded values, the use of IMDS usage would inadvertently wrongfully extend maintenance intervals [Ref. 6]. A study is planned to compare pilot recorded hours to IMDS tracked rotor turn time.

CH-5E CBM Process Review

Current CH-53E maintenance plans rely on aircraft time related (scheduled) maintenance including scheduled inspections, removals, and overhauls. For the purposes of CBM, scheduled maintenance can be broken into two main drivers. The first is condition- (or wear-) driven maintenance, which is performed due to wear and Time-on-Wing. The second is fatigue life driven maintenance, which is performed due to a combination of fatigue life and Time-on-Wing. The mechanical diagnostics function of IMDS will address wear driven scheduled maintenance by replacing physical inspections with health monitoring. Regime recognition and usage monitoring IMDS functions will address fatigue driven scheduled maintenance by incorporating actual aircraft usage (vice assumed usage) into the component life calculation.

CBM Approach to Condition Driven Maintenance A broad approach to the implementation of CBM was initiated by instituting an Integrated Product Team (IPT) composed of propulsion, structural, and reliability engineering, maintainers, fleet support team, Original Equipment Manufacturers, and airworthiness activities. The IPT was divided into working groups based upon functional activity, i.e. Rotor Systems, Mechanical Diagnostics, etc.

The working groups then gathered and reviewed all scheduled maintenance pertaining to their competency with the following tasking:

- Identify reasons for scheduled maintenance, i.e. what are the degraded modes the inspection/overhaul is identifying or preventing
- Compare component degradation with IMDS capabilities. Identify if the degraded modes are detectable by IMDS

If the degraded modes are believed to be detectable via IMDS, then a CBM Credit Worksheet is authored for the maintenance action, and a CBM analysis is begun which includes the following tasks:

- Document current maintenance and proposed changes
- Risk analysis
- Cost/benefit analysis
- RCM analysis (to assist in extending life/inspection intervals and establish "on condition" life)
- Diagnostic Evidence and Requirements (IMDS system improvements and seeded fault tests may be needed)
- Airworthiness assurance issues related to credit.

- Introduction to service plan (including training and publications) and continued monitoring

All credit activities are recorded in the Credit Worksheet, which remains a living document until CBM activities pertaining to the credit are concluded.

During documentation review, it was determined that Daily Maintenance actions would not be reduced, and in certain areas may be modified. Daily maintenance provides good man-in-loop coverage and can identify corrosion and impact type defects which are often included in Special Maintenance Cards.

CBM Approach to Fatigue Driven Maintenance Current practices for the determination of component retirement times are a combination of institutional fatigue life calculations and reliability studies. For the CH-53E airframe and dynamic component fatigue life, this determination is made up of three components. The first is material properties based upon metallurgical handbooks, coupon and component fatigue tests. The second is a loads survey, where an instrumented aircraft is flown in different flight regimes and respective loads are measured, typically the highest load for a regime being the one used for life calculations. The third item is the assumed usage spectrum, usually determined by expected mission requirements. The IMDS usage monitoring function attempts to make adjustments to the fatigue life determination process by incorporating actual usage into the usage spectrum calculation. Because the assumed spectrum is thought to be conservative, the OEM has projected considerable fatigue life extensions should actual usage be properly implemented. Margins of safety are maintained (six-9's, or "one-in-a-million" probability of catastrophic failure) historically embodied in the original safety goals by making adjustments to the material properties values to regain the reliability lost by using a usage monitor.

The structural usage activities for the CH-53E is a process with several steps:

1. Verify that IMDS can accurately record regime recognition parameters. Status: Substantiated during Operational Evaluation.
2. Perform stand-up of a central IMDS data repository. Status: Complete and in use.
3. Provide a means to move fleet data to the repository. Status: Complete and in use.
4. Design and deploy a structural usage database that calculates aircraft component lives using IMDS recorded data. Status: In concept development.
5. Provide a real-time means to connect re-calculated component life limits to squadron assets. Status: In concept development.
6. Provide a means to identify and "gap fill" flights for which there is no IMDS data. Status: In Requirements Definition.

At the completion of these tasks (and the collection of enough flight data) the Structural Usage Working Group will re-calculate the assumed usage spectrum and retirement times for the entire fleet. Studies will then investigate the assignment of an assumed spectrum to a given squadron. This is useful as certain squadrons have particular regimes that are flown more or less than the norm, i.e. takeoffs and landings for a training squadron. The final iterative activity would be the calculation of life expended subsequent to each flight locally at the squadron. This granularity will probably require IMDS system upgrades and may not be required based upon the rates in which component lives are expended.

IMDS Requirements for CBM

To reduce scheduled maintenance via IMDS, a means of performing continuous monitoring must be attained. The key to achieving the diagnostic and prognostic goals of a CBM program is a data collection and analysis system that is reliable and automated to the greatest degree attainable. It is equally important that a continuity of data acquisitions be maintained in order to develop evolving CBM threshold values.

The following system requirements must therefore be met:

- The IMDS system components that perform the monitoring function must be in an operational mode at all times, if possible. This may lead, in time, to the system being added to the Mission Essential Subsystem Matrix (MESM). Failure of a MESM component places the aircraft in a Maintenance <DOWN> status and requires repair to return to operational status.
- A frequency of valid data acquisition must be performed to assure CBM target component health. The frequency (acquisitions per flight hour) is determined by the component's existing scheduled inspection interval and statistical analyses.
- Diagnostic evidence must be demonstrated for the degraded mode. Ground or flight testing to demonstrate diagnostic capabilities may be required.
- Naval Aviation Maintenance Program (NAMP) changes and process improvement cycle implementation to maintain safety and cost avoidance efforts.

Additionally, some targeted scheduled maintenance may be beyond existing capabilities. In these cases, IMDS upgrades could be implemented. It is hoped the fleet wide deployment of IMDS will identify previously unidentified vibrations that may be leading to premature aircraft failures. For example, the CH-53E helicopter has three scheduled maintenance actions to inspect airframe locations for cracking. On one aircraft, IMDS has detected a high tail rotor 1/rev lateral vibration in forward flight which was previously undetectable by the portable RTB gear. It is reasonable to expect that maintaining an overall lower level of rotor vibration will reduce vibration-induced failures in unrelated systems.

IMDS as Mission Essential

Since the fielding of monitoring systems, a debate has existed regarding their classification as mission essential. The trade-off between monitoring system reliability and benefit has been the issue. In reality, mission essential diagnostic systems already exist on some aircraft in the form of chip detectors and blade pressure indicators. [Ref. 4]. The benefits of monitoring must however far outweigh the maintenance, readiness, and logistical burden of the systems' mission classification. One must return to the CBM Credit forms to determine if the accumulated benefits provided by the monitoring functionality justify MESM status. If the answer is positive, then the IMDS LRU's that support this particular function (components required for this functionality to execute) must be scheduled for the proper logistical Equipment Operational Codes.

Reliability and maintainability (R&M) values during Operational Evaluation were 1.5 hours mean corrective maintenance time and 113 hours mean time between failures. Though these values are acceptable for a MESM implementation, they were recorded under a more benign training squadron environment. The IPT plans to monitor the IMDS R&M indicators whilst the system undergoes more strenuous deployments to stateside training sites and overseas.

Rotor Systems CBM

The CH-53E Special and Conditional Maintenance Requirement Cards (MRC) contain minimum requirements necessary to assure the aircraft is safe for flight (Ref. 7). The cards are comprised of tasks that do not fit into the phased maintenance package due to conflicting intervals and are therefore performed at time-based durations between phase maintenance. Pilot recorded aircraft flight hours are used to track accumulated aircraft flight hour usage. The phase cycle consists of four inspections (A through D) performed every 150 hours. The cycle includes a total of 222 flight-hour-based special maintenance activities pertaining to rotor systems. The working group reviewed the entire MRC Special and Conditional volume and identified the four rotor system maintenance activities in Table 1 as CBM candidates, totaling 60 activities per phase cycle. The main rotor Pitch Change Rods (PCR) will be discussed in this report, with the PCR bearing condition being the key component that drives inspection.

Table 1: Targeted CBM Activities

Component Inspection	Time Interval	MMH
Main Rotor Outboard Damper Bearings	25 flight hours	4.0
Main Rotor PCR's	50 flight hours	4.0
Tail Rotor Pitch Links	50 flight hours	1.5
Main Rotor Inboard Damper Bearings	100 flight hours	6.0

Figure 2 illustrates the time based maintenance activities for the Main Rotor Pitch Change Rod (PCR) bearings. Every 50 hours of flight time the PCR bearings are inspected for looseness, corrosion, and bearing wear (by feeler gauge). Any bearings identified to be worn or degraded beyond limits are replaced. A Functional Check Flight (FCF) is not required to bring the aircraft back into service.

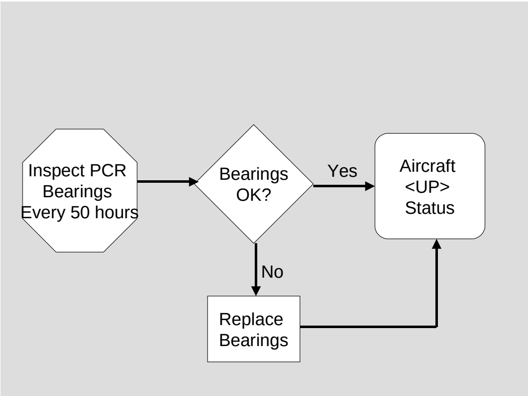

Figure 2: Current PCR Maintenance CONOPS

In order to transition the PCR inspection to CBM, the component degradation for which the Table 1 maintenance activities are designed to identify must be detectable by the IMDS Rotor Tuning Functionality. A CONOPS could then be defined to monitor component health via IMDS and reduce its scheduled maintenance. CH-53E IMDS flight test results have determined this to be the case for the Pitch Change Rod and Outboard Damper Bearing components. The Rotor Tuning function has identified degradation of these components via gradual increases in main rotor 1/R vertical vibrations. As discussed earlier, any health monitor which can identify component degradation already targeted by time based scheduled maintenance can be used as a means to forego the subject scheduled maintenance. A CBM credit activity was therefore initiated for the 50-hour main rotor PCR inspection.

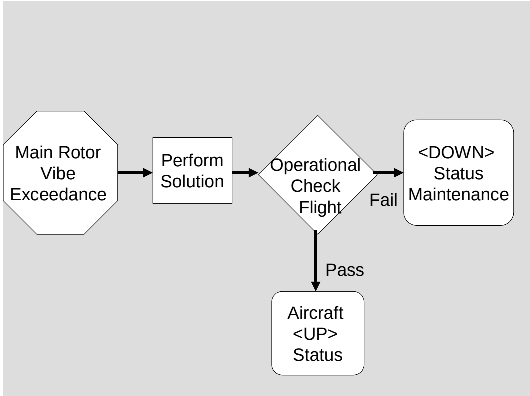

Figure 3: Conventional Rotor Smoothing CONOPS

The implementation of rotor system smoothing provides the user the ability to monitor the health of the rotor system and to perform system adjustments using weights, PCR's, or trim tabs. Though the Navy had never instituted this Concept of Operations, conventional wisdom suggested the Figure 3 activities would take place in the event of a Main Rotor vibration exceedance. It was assumed a between phase rotor system vibration exceedance would initiate a balance solution and subsequent check flight.

Subject Matter Experts (SME's) overseeing IMDS use took another approach. Knowing a system adjustment under current rules would require a subsequent check flight and that bearing degradation often coincided with higher rotor vibrations, the maintainers were first directed to perform visual inspections on the rotor system. A more thorough inspection could be performed, dependent upon the results. Investigation revealed that in most cases either the PCR or outboard damper bearings were found to be in need of replacement, and operational flights subsequent to repair exhibited acceptable vibration levels *without* the need of a rotor system adjustment and/or check flight. In this instance bearing degradation manifested in vibration data provided the key CBM connection between component condition and IMDS data. Rotor system monitoring could be used to change these items from time-based to condition- based maintenance, utilizing the Figure 4 CONOPS.

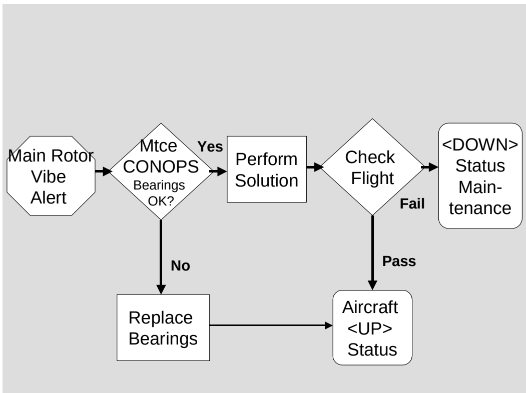

Figure 4: CONOPS with Bearing Inspection

The problem with this CONOPS is an FCF is still required after an RTB solution is applied to the rotor head. This requirement is due to safety of flight concerns as a rotor system must be maintained in a state that will enable a safe autorotation (Ref. 8). Pitch Change Rod (PCR) adjustments can result in moving the aircraft autorotation main rotor speed to an unsafe envelope. This accumulation of adjustments is possible in a CONOPS where several main rotor-smoothing adjustments can be applied between Phase maintenance. To mitigate the autorotation hazard the IMDS system will be upgraded to track applied PCR adjustments in the groundstation. Any combination of adjustments which would lead to an unsafe condition would be prohibited in the solution calculation. An aircraft can thereby be safely returned to operational status subsequent to a rotor smoothing adjustment without the need for an FCF.

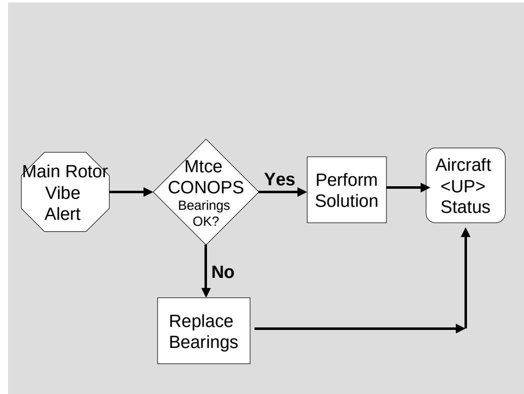

Figure 5: CONOPS with PCR Controls

Figure 5 exhibits the rotor smoothing CONOPS for CBM credit implementation for the main rotor PCR bearings. Several of the aforementioned CBM goals are accomplished in this CONOPS and discussed in Table 2.

Table 2: CBM Goals and Examples

IMDS CBM Goal	CONOPS Example
When possible, return a <FAILED> A/C to operational status to acquire more info as to health of aircraft and corrective maintenance action, vice entering FCF.	Subsequent to an RTB vibration exceedance, the aircraft is returned to service to collect more data, vice placed in <DOWN> status. Maintenance Control and QA make the judgment, within published guidelines.
Move aircraft from maintenance to <UP> vice to FCF mode.	No FCF required after PCR adjustment.
Reduce frequency of transition from <UP> to FCF.	CONOPS to encourage adjustments at 0.3 < ips <0.4 allows users to make adjustments at convenience.
Less scheduled maintenance events required.	The PCR bearing scheduled maintenance has been foregone in lieu of monitoring.
Less unscheduled maintenance events required	Improved defect identification reduces troubleshooting.

Within the vibration alert object a widely used commercial RTB process is employed. When vibration levels above 0.3 ips are reached, the squadron is encouraged, but not required, to perform a rotor smoothing action. Values above 0.4 ips require that on the following operational flight an RTB data be accomplished in the regime that failed the previous flight to verify an out-of-limits condition. If the alert does not re-occur, no further action is required. If an alert occurs again, the crew must acquire data in all regimes and acquire adjustment solution information. The aircraft is then placed in a Maintenance Status and a check flight is required (Ref. 9)

Transmission Systems CBM

Another cost and readiness issue for the CH-53E is the relatively low Time Between Overhauls (TBO's) for transmission system components (Table 3).

Table 3: CH-53E Gearbox TBO

Component	Overhaul Interval
Intermediate Gearbox	1,800 hours
Nose Gearbox (2 per aircraft)	2,600 hours
Oil Cooler Blower	2,000 hours
Main Gearbox	1,600 hours
Tail Gearbox	1,500 hours

The main driver for this low time interval on the CH-53E is the gearbox housing corrosion encountered while in-service, particularly due to the marine environment on ship exacerbated by high operation tempo during detachment. Overhaul inspection typically finds the internal dynamic components in satisfactory condition (which are returned to service), whereas the magnesium housings often require repair or are sometimes scrapped at great cost.

Confidence in mechanical diagnostic detection has been demonstrated both in test stand and flight testing (Ref. 10). However, using existing transmission systems maintenance practices and IMDS mechanical diagnostics to monitor dynamic component health to assist in extending the overhaul interval would not be practical. A TBO extension would allow corrosion rates to continue and probably increase unscheduled removals due to corrosion found during on-wing inspections. Similarly, housing scrap rate at overhaul will presumably increase. TBO extension could also lead to undesirable corrosion damage to *internal* components. As illustrated in Figure 6, cost avoidance benefits in moving the overhaul duration to the right can be nullified by increased corrosion damage as the component Time on Wing increases. Therefore, achieving a cost effective extension of TBO's for the CH-53E requires a separate means to control component corrosion while IMDS monitors the health of internal dynamic components.

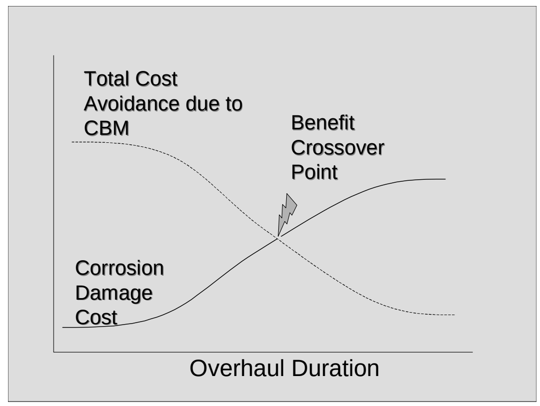

Figure 6: TBO Extension Benefit Crossover

Upon closer examination, an opportunity exists to meet this challenge. The problematic corrosion areas for the Nose and Tail Gearboxes are in benign, low stress areas. Inspection and repair criteria for these areas will be investigated and improved in order to reduce unscheduled removal and scrap rates. Concurrently, TBO extension requests for these gearboxes may be made by the operators and must be accompanied by records of sufficient diagnostic data indicating satisfactory component health. For the remaining gearboxes, corrosion prone areas will be addressed on an individual basis with the intent to support TBO extension. For all cases, age exploration efforts including Engineering Investigations of high time gearbox overhauls shall be performed to correlate component health with IMDS data.

Another IMDS benefit is its ability to identify internal component degradation prior to chip detector indications. This tool will help deployment planners better manage their assets by being proactive rather than reactive. For instance, an IMDS indication of bearing degradation can be a precursor to a chip light and requirement for gearbox removal. If this scenario would occur prior to an aircraft deployment, the maintenance planners would have the option to remove the gearbox at the home base thereby relieving burdens to logistics and maintenance systems.

Difficult to Quantify Benefits

Some IMDS benefits will be difficult to quantify; nevertheless, they are reasonable expectations. For example, the implementation of rotor smoothing will reduce rotor system induced vibrations and reduce wear upon components. Non-IMDS aircraft using the portable track and balance systems balance the aircraft after Phase maintenance. These aircraft observe an increase in rotor system bearing removals towards the end of their 150-hour Phase period (presumably aggravated by an increase in rotor system vibration). A study investigating the effect of reduced rotor induced vibrations was performed upon the H-3 helicopter (Ref. 11). Two squadrons of the same type model were studied. One squadron main rotor vibration was maintained at levels half the other. Improvements of 48% in reliability and 38% in maintenance were observed with a 10% reduction in life cycle costs.

The prompt and accurate IMDS identification of flight limit exceedances has reduced both troubleshooting and unscheduled maintenance. Improved troubleshooting has led to fewer unscheduled removals and cannibalization from other aircraft. Finally, any reduction in maintenance reduces the possibility of new maintenance-induced failures.

Conclusion

The Department of Defense considers CBM as a key enabler to streamline logistics and improve customer support. The installation of IMDS on the CH-53E helicopter fleet will lead to the integration of CBM into the aircraft's CONOPS. The authors have illustrated the use of IMDS to reduce scheduled maintenance and improved readiness. The implementation roadmap for CBM specific to rotor smoothing, mechanical diagnostics, and structural monitoring has been discussed, with the Maintenance Credit Worksheet being the airworthiness assurance record keeper of all CBM activities. IMDS holds great promise to enable CBM practices for the CH-53E fleet, and future papers will discuss progress of these competencies, as well as engine monitoring and life usage.

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