Implementation of Structural Health Monitoring for the USMC CH-53E

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Abstract

There is great concern in the U. S. Navy/Marine Corps aviation community regarding out-year operating costs. Studies and initiatives have been undertaken to reduce Operational and Support Costs, with a keen interest in Condition Based Maintenance (CBM). The Structural Appraisal of Fatigue Effects (SAFE) program at the Naval Air Systems Command (NAVAIR) has been providing structural tracking information for over 30 years. The SAFE program uses parametric data from onboard flight recorders to accrue component life consumption via actual flight data vice an assumed usage spectrum. NAVAIR has been working to implement the first rotorcraft fleet in SAFE, the Integrated Mechanical Diagnostics System (IMDS) equipped CH-53E helicopter. This paper discusses necessary tasks including regime recognition, event counting, damage rate and mapping, and various gross weight prediction tools. Mitigation strategies for obstacles such as loss-of-data and component configuration management are highlighted in this paper.

Keywords: CBM, US Navy, HUMS, Regime Recognition, Usage Spectrum, Gross Weight Estimation, Dynamic Component Tracking, Gapfill

Introduction

There is great concern in the U.S. Navy/Marine Corps aviation community regarding out-year operating costs. Maintenance activities comprise a major portion of total ownership costs for Navy weapon systems, with a majority of those being attributed to direct maintenance costs [Ref 1]. Premature and unnecessary maintenance are inflating maintenance costs and therefore overall ownership cost. The CH-53E costs more per flight hour than a number of US Navy/Marine Corps aircraft programs (Fig. 1).

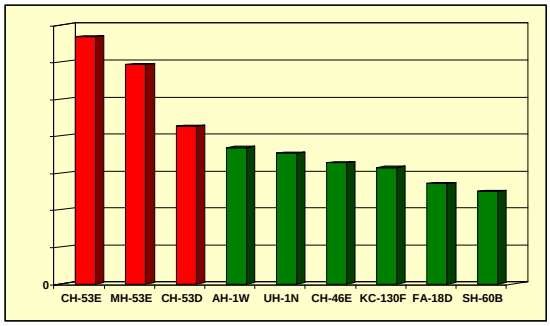


Fig. 1: FY04 Program Costs per Flight Hour, by T/M/S

Studies and initiatives have been undertaken to reduce Operational and Support (O&S) Costs, with a keen interest in Condition-Based Maintenance (CBM) and a re-structuring of the logistics infrastructure. CBM utilizes Health and Usage Monitoring Systems (HUMS) and includes maintenance processes and capabilities derived from real-time or near-real-time assessments obtained from embedded sensors and/or external tests and measurements using either portable equipment or actual inspection. The objective of CBM is to perform maintenance based upon the evidence of need while ensuring safety, reliability, availability, and reduced total ownership cost [Ref. 2 and Ref. 3]. A key artifact of CBM, Structural Health and Usage Monitoring (SHUM) is vital to the Chief of Naval Operations (CNO) vision of, "the right combat readiness…for the right cost" [Ref. 4].

Naval Air Systems Command's (NAVAIR) answer to SHUM is the Structural Appraisal of Fatigue Effects (SAFE) program. The SAFE program entails using flight data recorders to identify the severity to which the aircraft (and its components) is being utilized in comparison to how it was intended and designed. The recorded usage data is then used to monitor various fatigue critical components and/or locations on the aircraft. The program can then determine how to perform maintenance based on the specific aircraft need and not based on an assumed designed usage.

Background

In 1997, a team led by the program offices of the H-53 and Executive Helicopters (PMA-261) and the SH-60 Multi-mission Helicopters (PMA-299) were selected to implement the Goodrich Corporation's Integrated Mechanical Diagnostic – Health Usage and Monitoring System (IMD-HUMS) on the SH-60B and CH-53E aircraft under the Office of Secretary of Defense's (OSD) Commercial Operations and Support Savings Initiative (COSSI). The system evolved under the Joint Dual-Use Program Office's (JDUPO) COSSI and is now referred to as the Integrated Mechanical Diagnostics System (IMDS) [Ref. 5].

The first CH-53E was equipped with IMDS in 1998 and was soon followed by three additional aircraft in 1999. These initial installations served as data sources for accelerated system characterization and service suitability evaluations for the remaining fleet aircraft. In 2004 the IMDS successfully completed Operational Test and Evaluation (OTE) which allowed for the full rate procurement and production of the system on the CH-53E [Ref. 6].

The NAVAIR Aircraft Structural Life Surveillance (ASLS) branch, AIR 4.3.3.4, has tracked the structural life on Navy/Marine Corps fixed wing aircraft via the SAFE program since the 1970s. In 2006, discussion between the NAVAIR Structures Division (AIR 4.3.3), PMA-261 and PMA-275 focused on implementing SAFE on their respective rotary wing aircraft, the CH-53E and MV-22B, to meet the emerging CBM initiatives. This would mark the first time SAFE was performed for rotary winged aircraft. Implementation of SAFE poses several challenges to any aircraft program; the need for flight data, an accurate gross weight association to better increment damage and a gapfilling methodology to account for missing data. In addition to these obstacles, SAFE implementation for a rotary wing fleet introduces additional obstacles; the need to identify the serialized dynamic component history and an even more robust gapfilling methodology to account for variations in load and the fatigue contribution due to ground rotor turn time.

This paper will address the CH-53E SAFE effort, the plans to pursue its CBM benefits, and the technical challenges experienced in the process.

IMDS

The IMDS consists of an airborne system and a ground based system, both implemented with an open architecture approach. The data used by the system is obtained primarily from state sensors that are part of the basic aircraft (including buses), and specially mounted accelerometers and shaft position sensors [Ref. 5]. The major functionalities incorporated into IMDS are Health Monitoring, Usage Monitoring, and the Maintainer Interface.

Airborne System

The airborne system consists of the original manufacture helicopter fitted with additional hardware and instrumentation [Ref. 5 and Ref. 7]. During ground and flight operations, the Main Processor Unit (MPU) acquires data at sampling rates ranging from 10 to 40 hertz (Hz), storing most data as a 1-second averaged signal. The airborne system can be configured to store parametric data at a higher rate if an exceedance or event occurs. These high-rate data are referred to as a burst data set. In the case of SHUM, some parametric data are stored at a higher rate for regime recognition [Ref. 8]. A sample list of parameters required at higher than 1 hertz for SHUM can be found in reference 9. The data is written and transferred to the Ground Station (GS) via a Personal Computer Memory Card International Association (PCMCIA) card.

Ground Station

The IMDS incorporates an Information Technology infrastructure made up of a series of networked GS devices providing application user interface tools that support pilot and maintainer activities. For the purposes of SAFE, the key task of the GS is the storage, linking, and archiving of IMDS aircraft data. The maintainer is responsible for downloading the Raw Data Files (RDFs) after each flight, where the aircraft files are stored at the local level to support the IMDS application. The files are copied nightly via secure socket encryption to the Navy's fleet archive at Naval Air Station (NAS) Patuxent River (PAX) where they are distributed to customer servers such as SAFE.

SHUM Development

There are two ways to execute SHUM. The first is to implement a CH-53E SAFE program to provide a Fatigue Life Expended (FLE) metric based upon specific aircraft usage exhibited on each serialized dynamic component or airframe location. The second is to update the aircraft usage spectrum based upon fleet-wide aircraft usage and then adjust component retirement times. The CH-53E program office has funded both of these paths to maximize benefit. The following discusses the processes needed to achieve these goals.

The SAFE System

The SAFE system requires the following fleet data:

- IMDS flight data
- Pilot recorded flight records
- Aircraft dynamic component configuration records (Fig. 2).

These data are processed to perform:

- Regime Recognition
- Serialized Component Damage

The output of the SAFE system is the SAFE report, which in part contains a component life expended summary of all serialized life limited fleet component.

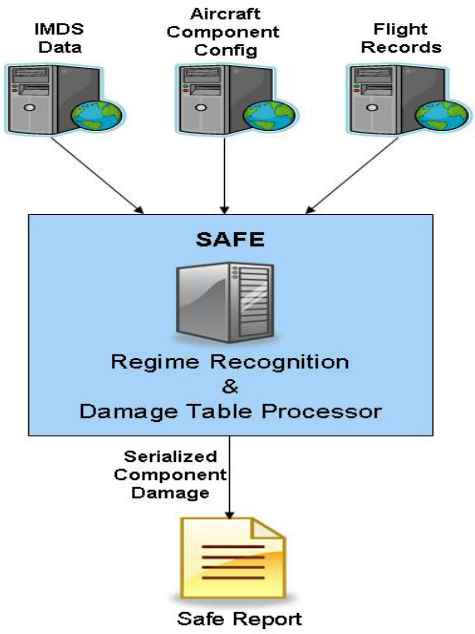


Fig. 2: The SAFE Process

IMDS Aircraft Data

Once the fleet maintainers download the data to the ground based system, the data file is then sent to the local squadron archive automatically. The data file is then sent to the IMDS fleet archive and subsequently to the SAFE server on a nightly basis. Once a file is retrieved and stored, the data are kept indefinitely in the event reprocessing is ever required.

Pilot Flight Records

The squadrons are required to provide flight records for every flight. After each flight, the pilot enters the flight date, flight duration, and other information into the flight record tracking application. These data are referred to as Maintenance, Material, and Management (3M) records. The 3M records are compared to submitted RDFs to determine if any flight data files are missing.

In the event that an RDF does not have an accompanying 3M record, or a 3M record does not have a matched RDF file, the squadron is contacted to avoid data loss. Until the discrepancy is rectified, the data is deemed missing. All missing data needs to be gapfilled to account for fatigue damage incurred on flights in which there is no IMDS data. Gapfill methodology will be discussed later in this paper.

Aircraft Component Configuration

The last piece of data provided by the squadrons is the dynamic component configuration data. These records reside in the Navy's configuration management application, the Optimized Organizational Maintenance Activity Naval Aviation Logistics Command Management Information System (OOMA-NALCOMIS) and are compiled from Assembly Service Record (ASR) cards, Equipment History Record (EHR) cards and Service Removal Component (SRC) cards. These cards document when a particular serial number of a specific part number is removed from one aircraft and placed on another aircraft, moved to storage, repaired, overhauled, and/or retired. The fleet maintainer selects preloaded part numbers in OOMA-NALCOMIS and moves them between aircraft via Work Unit Codes (WUCs).

These configuration data are entered by all squadrons and then replicated to the OOMA-NALCOMIS top tier server. These configuration data are pulled by the SAFE process nightly and quality controlled with any available data that may have been previously received. These records are then compiled to identify which serial number was installed on which aircraft for what time period. The SAFE process can then identify which RDF data to assign to which component.

It is important to note that the SAFE quality control process has uncovered occasions where the incorrect serial numbers or aircraft tail numbers were assigned to a component. The OOMA-NALCOMIS record sub-system does not have an efficient process to notify the squadrons of discrepant records. Some discrepancies identified by the SAFE quality control process are: incorrect amount of expected parts installed on one aircraft, same serialized component on two different aircraft, and time since new (TSN) data is reset to zero when a component is reinstalled on aircraft. Compiling complete and accurate component history data remains the most difficult task for tracking fatigue life of serialized components in SAFE.

SAFE Processing

With the above data at the SAFE server, processing of the three types of data is performed with the end product being damage assessments of every life limited, serialized component.

Regime Recognition

Regime Recognition (RR) is a process in which known flight maneuvers are identified from parametric flight data. These identified flight maneuvers (or regimes) have fatigue damage values associated with them depending on the parametric values. The RR code processes through 6 stages as it identifies the 356 known flight regimes of the CH-53E and categorizes them into 78 fatigue damaging regimes.

The first stage addresses the fact that most parameters used for structural tracking are recorded at different rates; some as low as 1 Hz, while others are

recorded at up to 10 Hz. Whether due to IMDS limitations or data storage concerns, some data are recorded at less than optimum frequencies for SHUM; however the minimum frequencies are met. Data that is recorded at less than 10 Hz is interpolated between the maximum and minimum values in that range to create parametric records at 10 Hz. Should an event where a data spike or dropout occur, the data is interpolated to avoid gapfilling. Most occurrences of this are no more than 2 seconds and within the limit for interpolation. The second stage in the RR process is to lump like regimes that occur sequentially together.

The third stage in RR is the consolidation logic. This portion of the code looks at the recently lumped regimes and determines how long the maneuver lasted. This allows compression and better damage mapping so that instead of 20 records stating the same regime, there is one 2 second record with the flight regime. Another benefit of the consolidation code is when parametric data of certain maneuvers border the threshold limits. Since it is possible that the RR code could identify different transient regimes for one maneuver based on where the parametric thresholds are set, the consolidation code has logic built in that identifies the actual maneuver occurring and lumps the like data together. For instance, this would cause a maneuver sequence to be counted as a 30 degree angle of bank turn for 3 seconds, even if the parametric data causes the RR code to identify it as a 30 degree turn followed by a 1.1 g pullup followed by a second 30 degree angle of bank turn. The fourth stage in the RR code is to identify all control reversals, their start time and duration. A control reversal is when a pilot inputs control completely in one direction, then fully reverses the input to the opposite direction. The aircraft weight is also used here to determine the damage increment incurred by the control reversals. The control reversal damage increment is only counted once and is not double counted when the RR process is complete.

The fifth stage is to identify all other damaging maneuvers that are counted based on the number of occurrences and not duration. Examples of such maneuvers are Ground-Air-Ground (GAG) cycles, hook loads, and torque cycles. The final stage for the RR code is the log file. The log file provides basic results on the quality assurance program. The log file records takeoffs, landings, rotor start and stop conditions, and the cause for flight rejection, if applicable.

The RR code was validated against flight test data, known as the ‘HUMS flights’. The HUMS flights were a number of flights in which pilots flew to a known sequence of regimes at specific times. Once the RDF file is processed through the RR code, an output file is generated and a regime identifier is assigned to all regimes located in the file. This output file summarizes all the regimes that occurred in the RDF, as well as the time and duration of the regime.

Gross Weight Estimation

Component damage rates are impacted by aircraft gross weight (GW) and density altitude. Without accurate gross weight estimation, the most conservative damage assumption must be utilized. In order to accurately monitor gross weight, IMDS requires crew input before a flight. This is deemed an impractical increase to pilot workload as well as a source of potential inaccuracy. This initiated the program to fund the Naval Surface Warfare Center (NSWC) Carderock to develop a novel GW Virtual Sensor, similar to the one developed for the SH-60B [Ref. 10], based on recorded parametric HUMS data. In order to accomplish this task, NSWC Carderock gathered flight control system data, weight and balance reports, Naval Aviation

Training and Operating Procedures Standardization (NATOPS), and OEM reports. The GW Virtual Sensor is a second generation sensor developed to predict aircraft gross weight at take-off once the aircraft has climbed to 30 ft above ground level (AGL) and has a working range of 19,545 kg (43,000 lbs) to 24,773 kg (54,500 lbs). Additional test flights are scheduled for early 2011 to expand the weight range above 24,773 kg (54,500 lbs). These data were validated using fleet weight and balance sheets.

Due to the current lack of required gross weight range, the program has decided to use a torque based gross weight estimator. The estimator uses the simple relationship of power required to hover for a given thrust, i.e. weight value [Ref. 11]. The limitation with this approach is that the aircraft must be in a hover regime to obtain the weight. This approach is also dependent on having an accurate fuel quantity reading from the IMDS.

The Carderock estimation is one method for utilizing artificial neural networks. An artificial neural network is a data driven deterministic estimation method in which data input and output pairs are used to train on a set of data. Neural networks allow for the ability for the data the "learn" by modifying the connection weights in response to the inputs. A downside to artificial neural networks is that the data must be rigorously trained and is dependent on available data. Another downside is that no mathematical model can account for all scenarios.

Another method is using Kalman filters. Kalman filters use a discrete linear system, a helicopter for example, and the representative state variables for the system, the helicopter's dynamic model, to calculate a state or variable. Kalman filters make use of probabilistic values for given parameters. The algorithms then estimate the state of a dynamic system from a series of incomplete or noisy measurements. This process makes use of the systems dynamic model and measurements from sensors. Although it has benefits for real-time estimates, the dynamic models must be fully defined (Ref. 12).

Component Damage Table Generation

The component damage tables are a key component for SHUM. The tables are from the Original Equipment Manufacturer (OEM), in this case, Sikorsky Aircraft, and represent the amount of fatigue damage each component exhibits for a particular amount of time spent in a flight regime. The table also contains damage information for those maneuvers that are not time dependent, but rather the number of occurrences an event is recorded.

Once an RDF has been processed through the RR code and a gross weight identified for each regime, the results are then mapped to the damage tables for all experienced regimes. The damages from a flight of regimes are then summed to provide a unit of damage on the components for that flight. With no additional reliability adjustments, an FLE of 1.0 corresponds to end of life for the component. This process is carried out for all flight data to determine an FLE for all life limited dynamic components.

Gapfill Methodology

Gapfill is a process in which statistical data are used to fill in missing or corrupt data. Data that are gapfilled are assumed to be more severe than average

operations to account for the unknowns of the flight. Since the weight and regimes are unknown, worst case damage rates are used. The updated usage spectrum will be discussed later in this paper.

Gapfill is also used when the historical component configuration data are incomplete or inaccurate. Install and removal records are only sought for components from when IMDS was installed. The starting FLE will be based on the number of landings and flight hours to that point. Should a serialized component have missing install or removal records, the SAFE process assumes the worst case for that time and cannot use the IMDS data to map a fatigue damage.

Due to the six-nines reliability requirement (probability of failure of a dynamic component at the retirement life does not exceed one in a million, i.e. a reliability level of 0.999999), the gapfill methodology will need to be revisited when the new usage spectrum is released. One thought is to use the 99th percentile instead of 95th percentile to account for the perceived reduction in reliability. Many parties in industry, government and academia are evaluating different methods to address this notion [Ref. 13 and Ref. 14].

Components to be Tracked

The CH-53E has thirty-one components that are identified to be prime life limited components, or components with a fatigue life of 10,000 flight hours or less. Once the SAFE process was developed, the first items to be tracked needed to be determined from the existing thirty-one. Seven of the thirty-one life limited components were selected to be inducted into SAFE first, based on criticality, perceived benefit, and expense. The components selected were: main rotor sleeve assembly, main rotor hub lower plate assembly, main rotor hub upper plate assembly, main rotor blade extender, main gear box housing, main gearbox shaft, and the main rotor spindle/sleeve assembly.

Usage Spectrum Update

Another way to gain benefit from SHUM/SAFE is to update the aircraft flight spectrum. The initial design spectrum is usually developed in a few different ways; derivation from specifications such as Aeronautical Requirement 56 (AR-56), pilot surveys, data on similar T/M/S or the Navy/Marine Corps-provided requirements to the OEM. These requirements illustrate what the expected mission and mission mix will be for the aircraft. These requirements yield a design spectrum that drives component usage based on aircraft mission, weight, and mission frequency. During operation, it is common that any one of these aspects change, resulting in an inaccurate portrayal of maintenance requirements and component life. A flight spectrum based on actual aircraft usage, the usage spectrum, provides a more accurate account of what the dynamic components and aircraft structure are experiencing. From these data, fatigue rates and maintenance intervals could be adjusted accordingly. In order to maximize SHUM benefit, the CH-53E program will update the usage spectrum, in addition to providing SAFE FLEs.

As of the writing of this paper, the CH-53E usage spectrum method is still under development, however the process will be similar to that used on the Navy AH-1W in the 1990's to update their usage spectrum, using statistical cumulative

frequency distribution of the usages [Ref. 15]. Traditionally, the usage spectra updates have been through usage surveys conducted using a paper questionnaire, which is filled out by the pilots for information on mission type, gross weight, altitude, velocity, flight maneuver and associated time, flight duration, and other information. As with the H-1's in the past, pilot surveys were not used for two main reasons, the pilot's account is not always a clear representation of the actual mission flown, and the availability or an established regime recognition algorithm to identify the experienced flight regimes [Ref. 15]. The CH-53E will be using the IMDS data and their regime recognition software to identify which regimes were flown, the durations, and remaining information to accurately model the usage.

Conclusions

SAFE is a large part of SHUM and the overall CBM program being pursued by the US Navy/Marine Corps. With the implementation of SAFE, the CH-53E program hopes to achieve cost savings while ensuring safety is not compromised. Other studies have shown that smaller programs have been able to achieve 50% increase in component life using SAFE. Initial analysis has shown that if the CH-53E program achieves 25-50% savings in retirement time or maintenance burden, the program could save in the neighborhood of $20.56M AUD ($20M USD) per year.

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