US Navy Roadmap to Structural Health and Usage Monitoring – The Present and Future[1]

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Abstract

The USN continues to operate under austere budgets and increased operational demands, while striving to meet the Chief of Naval Operations (CNO) vision of “the right readiness, at the right cost.” One of the cornerstones to achieve this goal of affordable readiness is the Structural Health and Usage Monitoring (SHUM) program, an initiative to leverage existing and emerging technologies to manage and maximize the structural life of the fleet, from the airframe level to the component level. It entails an evolution from a reactive maintenance plan to a proactive structural life management philosophy. This program draws on existing aircraft usage monitoring capabilities, coupled with state-of-the-art component identification technology and individual aircraft loads generation. Future advanced diagnostic/prognostic capabilities will realize our long-term goal of implementing Conditional Based Maintenance (CBM) for airframes and structural components. SHUM, in conjunction with improved processes to reduce components’ susceptibility to external damage, will minimize total life cycle costs for the fleet.

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Introduction

Continued austere budgets and increased operational demands dictate “the right cost to maintain the right readiness for the right force” [1]. With 90% of the Total Life Cycle (TLC) cost occurring after aircraft delivery, achieving and sustaining this objective presents a great challenge to the entire Naval Aviation Team, especially the engineering community.

Better tools to accurately assess structural health and recommend appropriate maintenance actions at the proper time are essential to meet this technical challenge, while ensuring airworthiness for continued operations. The Structural Health and Usage Monitoring (SHUM) program is the cornerstone of our efforts to exploit the full fatigue life of our rotary wing aircraft while minimizing cost.

The Navy has successfully tracked Fatigue Life Expended (FLE) for fixed-wing aircraft since the mid 1970s. We have used both recorded flight parameters and/or local strain measurement of selected fatigue critical locations to determine the accrued fatigue damage. We have also serialized and track numerous components of the nose/main landing gears as well as the arresting hook shank and attached fittings, and other airframe components. This has allowed the Navy the ability to plan, manage, and maintain the fleet inventory effectively. It provides an invaluable tool to quantify the Health of Naval Aviation (HONA), a Navy initiative to conduct long-term force level planning and support the development of the Naval Aviation budget.

To address the structural life management of its rotary wing fleet, the Navy performed several usage studies on rotary wing aircraft with a variety of recording systems in the 1990’s. Figure 1 shows the benefit of usage monitoring by comparing the actual AH-1W mission mix versus the design assumptions [2]. Bell-Boeing also implemented the Vibration/Structural Life and Engine Diagnostics (VSLED) system on the V-22 tilt-rotor aircraft during production. In addition, the Navy has decided to incorporate newer and more capable usage monitoring systems on all CH-53E, UH-1Y, AH-1Z, and MH-60R/S aircraft [3]. It is the Navy’s intent to install similar systems on all future aircraft as well. In this paper, we discuss the status of our fleet implementation for both V-22 and CH-53E, including planned improvements for these and future systems to enhance safety, reduce cost, and improve readiness.

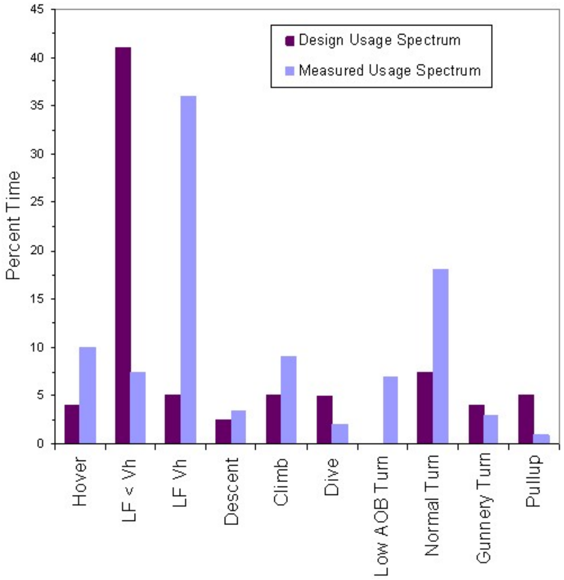

Figure 1 – AH-1W Usage Comparison [2]

While monitoring individual aircraft usage improves our fatigue damage prediction, challenges with serialization and accurate tracking of dynamic components prevents us from taking full advantage of individual usage monitoring. Without a comprehensive system to identify and track specific parts over their life in the fleet, our ability to determine damage accrued at the component level is severely limited. In addition, existing systems do not help mitigate the increasing concerns with the prevalence of counterfeit and unapproved components entering the supply system.

In the not too distant future, we plan to transition from usage monitoring to individual component damage tracking, and enhance our health assessment capability with better prediction of fatigue damage expended for each dynamic component and fatigue critical area (FCA). To achieve this objective, we will focus on the following areas: a) enhancing recognition accuracy for low speed regimes, b) improving individual aircraft loads/strain predictions, and c) increasing accuracy in serialization and tracking of fatigue life limited flight critical safety items (CSI).

In the long term, coupled with the ability of tracking each aircraft and its components in near/real time, we also need better diagnostic and prognostic tools to assess the health of the aircraft’s structural integrity and enhance our capability to determine what and when maintenance action is required. Figure 2 shows our proposed implementation concept for SHUM in order to achieve our long-term goal of Conditional Based Maintenance (CBM) [4].

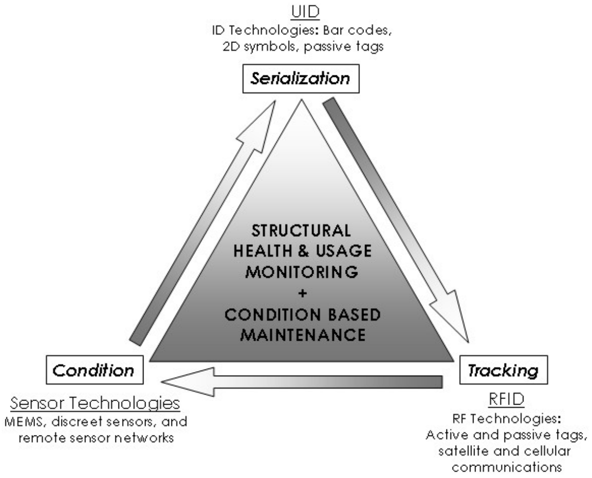

Figure 2 - SHUM Implementation Concept

In addition, we note that life-limited components are routinely retired early due to damage from external sources, such as corrosion pits, fretting, and maintenance induced nick/scratches/dents. Coupled with minimum or no rework limits, these parts are replaced for other causes far short of reaching 100% of their fatigue life. Various life enhancement alternatives will be pursued to reduce these components' susceptibility to external damage.

Structural Usage Monitoring

As noted in the introduction, structural usage monitoring has been conducted on Navy fixed wing aircraft for quite some time. The usage data from on board recorders, along with other related information, is compiled by the NAVAIR Aircraft Structural Life Surveillance (ASLS) Branch. Using the collected data, the life expended is determined for tracked aircraft and components, and the results published in a Structural Appraisal of Fatigue Effects (SAFE) report.

Implementation of structural usage monitoring for Navy rotary wing aircraft, while similar in concept to monitoring fixed wing aircraft, poses a unique set of challenges that must be overcome. These challenges include installation of Health and Usage Monitoring System (HUMS) hardware on fleet aircraft, integration of HUMS data with other information in the maintenance environment, configuration management of large numbers of dynamic components that move between aircraft, and lack of easy data access for the fleet users.

The V-22 is the first Navy rotary wing platform to have factory installed HUMS hardware (VSLED) on all airframes, and is first in-line for structural usage monitoring. The CH-53E is in the process of retrofitting its entire fleet of aircraft with HUMS hardware (Goodrich IMDS) systems, and will implement structural usage monitoring in approximately the same timeframe. MH-60R/S and UH-1Y/AH-1Z aircraft will follow along with new acquisition aircraft such as MH-53K and VH-71. The basic data flow for usage monitoring is shown in Figure 3.

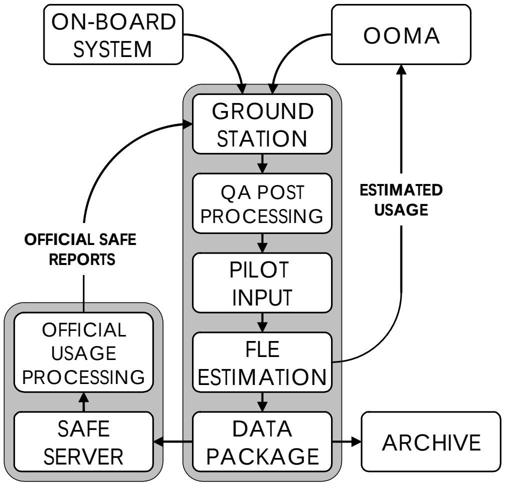

Figure 3 - Data Flow for Structural Usage Monitoring.

On Board System

The ideal concept for a HUMS system is to have raw parametric data recorded by the on-board system, and all regime recognition and post processing is done on the ground after flight [2]. The two primary benefits to this approach are configuration control and ability to reprocess the original data. In addition, if any changes are made to regime recognition or post processing algorithms, there is no need to modify on-board software.

Due to the length of the V-22 development program, the hardware installed on V-22 is an older generation HUMS system. As a result of memory limitations at the time, instead of continuous recording of raw parametric data, we have a less desirable periodic and burst parametric data recording combined with on-board regime recognition. Potential upgrades to improve this capability are being considered in conjunction with other avionics improvement programs.

The CH-53E, while an older airframe, has the benefit of a more robust HUMS system. The Goodrich IMDS-HUMS system has the capability to collect raw data of all flight parameters needed for the ground based regime recognition processing.

Ground Station

The second challenge is integrating the recorded usage data with other flight and maintenance related information for regime recognition, and post processing.

The HUMS ground stations are the most logical place for this streamlining. For V-22, the ground station is being integrated with the V-22 Interactive Electronic Technical Manual System (IETMS) into the Consolidated Automated Maintenance Environment for Osprey (CAMEO). Modifications to enable structural usage monitoring are being implemented as part of this development effort. For CH-53E, the plan is to implement similar capabilities for structural usage monitoring within the Goodrich ground station software.

The additional functions required to support monitoring include:

- Data QA and generation of flight summaries.
- User review of summary data, and manually enter/edit if QA identifies invalid information.
- Collection of component configurations and other maintenance data.
- Automated transfer of all data to a permanent archive and to the SAFE server for processing.

Basic QA algorithms screen the raw data to assure that all the information is accurate. Any QA failure is flagged for further follow-up and user input. After QA, flight summary data is generated, such as rotor-turn-time, weight-off-wheels (WOW) time, engine times, and number of landings.

The flight summary is then reviewed by the operational user. If the data looks accurate, the user can acknowledge and move on. If the user notes a discrepancy with the flight summary, the user can manually input ‘correct’ values as well as comments if applicable. Both the automated summary data and the pilot inputs are stored for later review.

The ground station also accesses Optimized NALCOMIS (OOMA) in order to capture a snapshot of component configuration after each flight, allowing usage to be assigned to the appropriate components. Since accuracy is essential, there are multiple levels of QA – starting with the OOMA database, continuing in the ground station, and finally at the SAFE server. Any discrepancy found is flagged for follow-up investigation.

The flight data, aircraft configuration, all post processing, QA results, and user inputs are transferred automatically to the data archive as well as to the SAFE server for processing and structural usage monitoring.

SAFE Processing

The ASLS group is cognizant for processing all Navy structural usage information. Any QA issues or user inputs from the ground station are reviewed prior to further processing. For any missing or corrupt data, such as that resulting from on-board system failures, data QA problems, or lost files during transfer, gap filling is performed using conservative usage data [7].

Regime recognition (RR) is performed to determine individual aircraft usage. For V-22, post processing identifies only certain maneuvers not captured by on-board RR. For CH-53E, we will use RR algorithms similar to the MH-60’s using post-flight processing of raw parametric data [5]. Further QA evaluation also ensures the RR output is correct for each flight [6].

Finally, damage rates are applied to the identified regimes to determine the accumulated fatigue damage for the airframe and components. The resulting FLE of each airframe and tracked component, including average usage rates, are published in the SAFE report on a periodic basis.

Providing SAFE Data to the Users

In order to provide easy access to the fleet operator, the ground station contains visualization tools to facilitate maintenance and support.

For the maintainers to provide efficient fleet readiness, the current FLE status of each airframe and all corresponding tracked components can be sorted by criticality in order to prioritize maintenance actions. For the supply community, the logistician can use the visualization tools to track consumption rate and perform spares projection for individual aircraft, specific squadrons, or arbitrary groups. This feature can also be used for deployment provisioning and scheduled maintenance. In addition, operational planners can utilize the same tools to make short term operational decisions as well as long-term force level planning and support development of the Naval Aviation budget.

Near Term Status

For V-22, the CAMEO 1.0 ground station updates for upstream data flow will be complete in early CY08. By that time, SAFE data post processing, QA processes, and fatigue damage calculations will be in place and operational. The deployment of CAMEO 2.0 in early CY09 will implement the SAFE reporting, FLE estimation and data visualization tools to the fleet users. Additional testing for validation and verification will be performed prior to each release.

For CH-53E, the generation and validation of regime recognition is underway. SAFE database and processing capabilities development will be initiated in CY08. The notional path for the Goodrich IMDS ground station is a two step process similar to the CAMEO 1.0/2.0 development for V-22. The first upgrade for upstream data capabilities will be completed in CY08 and the second upgrade for end user capabilities following in CY09.

For other platforms after V-22 and CH-53E, the concept will be similar as discussed above, but the specifics of HUMS implementation have not been completely defined at this time.

Refinements to Automation in Structural Usage Monitoring

Currently the Navy is focusing on automating data flow and QA efforts. In the mid-term, we seek to expand capability for partial recovery of flight data if certain parameters are incorrect or inoperative. The final objective is to obtain a robust QA process with high data utilization and little or no manual intervention required.

Automated flight matching for gap-fill identification is another potential area for improvement. Currently, the gap-fill determination has limited automation capability and ultimately requires manual intervention. One alternative is to use an interface to the NAVFLIR system through the ground station to allow the pilot to fill out his or her flight records as part of the flight download/debrief. To reduce the pilot's workload, most information available in the ground station can be used to pre-populate the NAVFLIR forms. If the HUMS CONOP requires the pilot to input flight record data directly to the ground station, the system can capture the information and automatically match to the associated flight records. In the event of missing HUMS data, the system will insert a placeholder for automated gap-filling so that the pilot would no longer need to create a manual record in the ground station. These improvements not only support the needs of the Navy users, but also provide a benchmark for data quality assurance in order to obtain maintenance credits.

Refinements to On-Board Recording Systems

The planned refinements to existing on-board systems include optimizing data acquisition rate, integrating crash survivable recording, and providing growth capability for future wireless technology.

Our development work with regime recognition has shown that sampling rate for only a few key flight parameters needs to be increased in order to capture some of the highly transient events that may cause significant fatigue damage. For aircraft with newer HUMS systems such as CH-53E, MH-60R/S, and H-1Y/Z, the impact to overall system memory requirements would be insignificant, because other parameters would remain in their normal range of 1 to 10 Hz.

For the V-22, refinement to the on-board system is a bigger challenge due to the VSLED's limited memory capability. An upgrade or replacement of the entire system would be required to make the V-22 as capable as the other platforms. There is an ongoing study to consolidate avionics systems that may allow an opportunity to incorporate a more capable HUMS system, such as the Goodrich IVHMS.

The Navy also desires to have crash survivable data recording capability on all of its aircraft. The HUMS system collects a wide variety of parameters that are of interest in mishap investigation, but the recording media is not designed to be crash survivable. Creating an interface to pass some or all of the HUMS data to crash survivable memory would be a valuable asset for mishap investigation.

In anticipation that future plans may call for wireless sensors within the aircraft, any HUMS upgrades should include an interface compatible with this technology. For HUMS systems currently under development, the general recommendation is to reserve an expansion slot in the hardware, and maintain an open systems architecture that will allow this technology to be inserted when it is available.

Individual Component Damage Tracking

In order to successfully transition from usage monitoring approach to individual component damage tracking, we would need to improve significantly in these areas:

- Regime Recognition
- Loads / Strain Prediction
- Component Serialization and Tracking

Improved Regime Recognition

Some maneuvers that cause significant fatigue damage occur during rapid descents, hover, rearward flight, approach, and weapons deployment. Due to rotor downwash, turbulence, and lack of pressure differential at low speeds, traditional pitot-static sensing equipment on rotorcraft are not very accurate below 40 knots [8]. Current state of the art flight instrumentation with low speed capability still has many limitations including cost, weight, size, and power consumption [9].

The Navy is actively pursuing affordable, three-axis data sensors that could provide more precise information on airspeed and direction. The sensor developed by Tao Systems using hot-film and constant voltage anemometer technology has shown promise, but will need to overcome challenges such as sensor fragility, and damage susceptibility due to insects and dust [10].

Also of interest is the ability to obtain actual gross weight and center of gravity information in real time.

Improved Loads/Strain Prediction

To fully appreciate major factors that could impact fatigue life, it is important to briefly review the basic damage calculation methodology as shown in Figure 4.

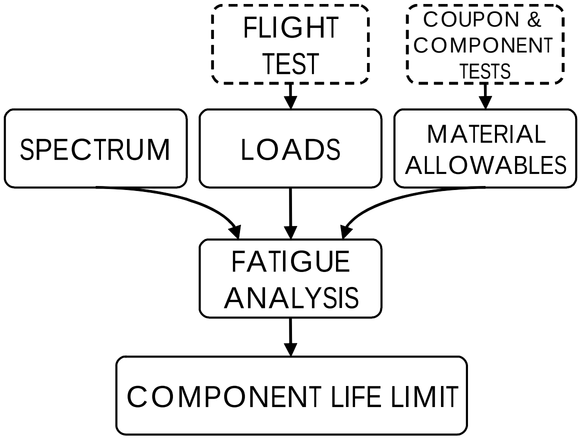

Figure 4 - Basic Fatigue Life Methodology

Similar to the effects of usage spectrum variation, a small change in loads/strain level could result in an large reduction in life. Consequently, the Navy seeks to improve the accuracy of loads/strain prediction by directly measuring data in flight.

In order to overcome the burden of complex instrumentation such as slip rings, power consumption, and wiring installation, our emphasis has been focused on wireless sensors and power harvesting technology. However, there are several technical issues that must be addressed prior to practical implementation. Size and mounting method of the sensor package must not degrade fatigue life nor change dynamic response. Sensors also must be rugged enough to survive harsh operating environments. Capabilities such as recording rates, on-board data storage, and transmission requirements must be optimized and balanced with limited harvested power available. Lastly, the data collected must remain protected and secured while stored and transferred. The Navy is currently working with two SBIR companies; Microstrain Inc., and International Electronic Machines Inc. (IEM) to develop these enabling technologies.

Microstrain has produced a compact wireless sensor suite that relies on piezoelectric energy harvesters capable of measuring strain, temperature, and acceleration. Microstrain's sensors offer a powerful combination of real-time sampling rates up to 4 KHz and on-board data storage. The sensors are configured to be very efficient when using energy to sample, record, and process strain data, as well as communicate over a bi-directional radio link. The company is also studying other methods of energy harvesting that include vibration, electromagnetic, and solar cells. Recently, Microstrain has successfully demonstrated a prototype loads/strain measurement system on a Bell 412 helicopter pitch link in February 2007 as shown in Figure 5 [11].

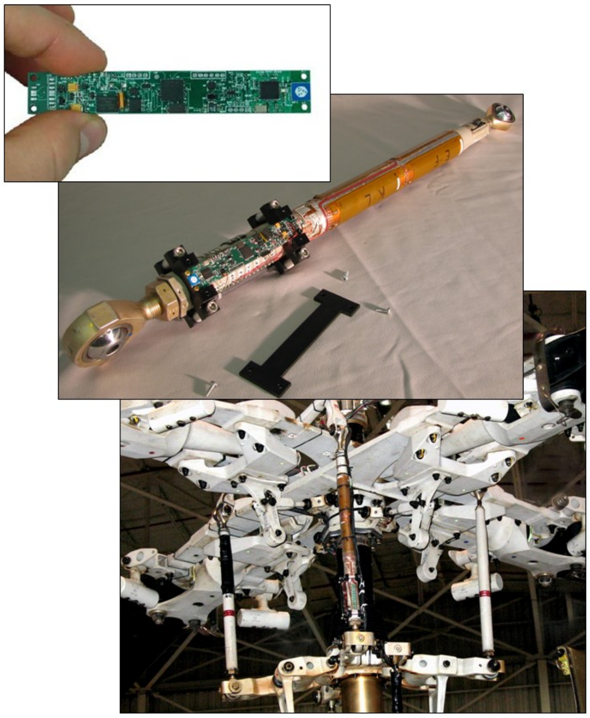

Figure 5 - Microstrain Wireless Sensor Package Installed On Bell 412 Pitch Link

Concurrently, IEM is developing very small 2-D, temperature compensated strain gages and transmitters using micro-electro-mechanical systems (MEMS) technology (Figure 6). Potentially, the sensor suite could also harvest energy through vibration and transmit data to a small central collection unit. IEM has manufactured a prototype of their system that shows the MEMS technology to be feasible with minimum power consumption [12].

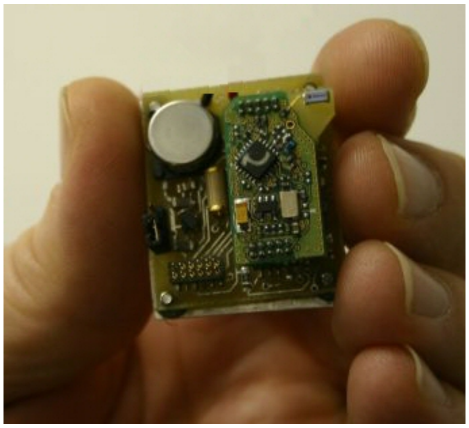

Figure 6 – IEM's Proof of Concept MEMS-Based Prototype Sensor Node

Component Serialization

UID is a cornerstone for data driven migration from reactive fleet support to proactive, predictive fleet readiness. Department of Defense (DoD) per USD (AT&L) Memo of July 29, 2003 dictates the implementation of UID on all new acquisition programs to provide life cycle data visibility.

From our structures perspective, past experience has shown that records are lost, components get on the wrong aircraft, and unapproved components find their way into the supply system. To accurately track component history, we require proper marking of components and the ability to retain configuration and maintenance service records.

Life limited components are sensitive to invasive marking methods such as mechanical etching. Furthermore, the marking must be durable enough to survive harsh operating environments throughout its life cycle. Currently, the only MIL-STD-130M approved marking method that could meet these criteria is laser bonding. The Navy is working with industry to implement laser bonding technology for dynamic components.

Figure 7 and Figure 8 show the laser bonded markings remain readable after being subject to severe environmental testing. Using this method, Intermec Technologies has successfully marked flight critical components for the US Coast Guard (USCG) on their Aerospatiale Dauphins and Lockheed C-130s [13].

Figure 7- Laser Bonding after 24 Hours in Paint Stripper

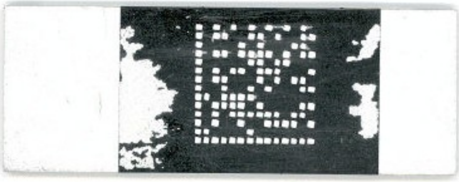

Figure 8 - Laser bonding that has been dipped, blasted, and scraped still remains readable.

Component Tracking

To provide in-transit visibility and supply chain management, DoD requires implementation of RFID tagging for all shipping pallets and their contents.

We need similar capability for tracking flight critical components on aircraft throughout their life cycle. Our requirements for durability, data integrity, signal bandwidth, and electrical requirements are more stringent and demanding than that for supply chain management. Data security, including encryption, is also required to protect component information from being accessed by unauthorized parties. In addition, RFID transmissions must not cause aircraft to become vulnerable to detection. The severe electromagnetic environment aboard Navy ships also poses a great technical challenge to overcome.

In the future, the Navy plans to develop an integrated package that would combine all three key elements of SHUM as shown in Figure 2. This capability could also satisfy requirements for supply chain management and in-transit visibility.

Achieving Condition Based Maintenance

In addition to individual component tracking and usage monitoring, better diagnostic and prognostic tools are required to realize condition based maintenance for structures. Furthermore, reducing components susceptibility to external damage will allow full utilization of its fatigue life.

Prognostics

The Navy's vision for the future is a robust prognostic suite that would not increase the risk of failure over the current FLE methodology. Our general concept is to develop a micromechanical model to predict damage accumulation from crack incubation through nucleation to initiation. In-situ or off-aircraft sensors with the capability of detecting precursors prior to crack initiation could be used to assess the health of the dynamic components. The data from the sensors would then be fed back continuously to refine the damage model. This will result in better estimates of when and where maintenance action will be required.

Diagnostics

For helicopters subject to high cycle loading, traditional NDE/NDI methods are not, nor will be in the foreseeable future, reliable enough to detect small cracks less than 0.01". Our approach to develop better diagnostic tools is a paradigm shift from attempting to detect small cracks to identifying precursor(s) of crack initiation. Change in bulk mechanical properties, residual stress, and surface strain are excellent candidates as precursors.

JENTEK has demonstrated that their Meandering Winding Magnetometer (MWM) system can find small damage by detecting changes in the material conductivity as shown Figure 9 [14], [15], [16].

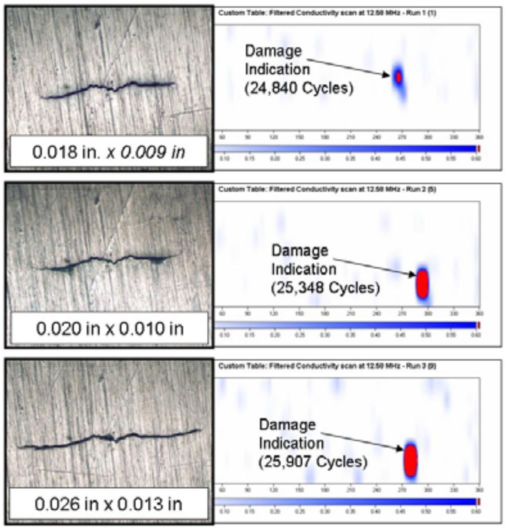

Figure 9 - Example of damage detection using Jentek's MWM sensors & GridStation software.

The presence of tensile surface residual stress is a known indicator of impending fatigue cracking. Proto Manufacturing, Inc.'s X-Ray Diffraction (XRD) techniques allow direct measurement of the state of residual stress at life-limiting locations of the part. Components which exhibit residual stress levels beyond a set threshold can be identified for rework or retirement [17].

In addition to storing UID information, Direct Measurements Inc.'s (DMI) 2D mark can also be used to measure surface strain. DMI has successfully employed its optical-based technology to detect crack initiation. Figure 10 shows their 2D mark and the SR-2 reader unit [18].

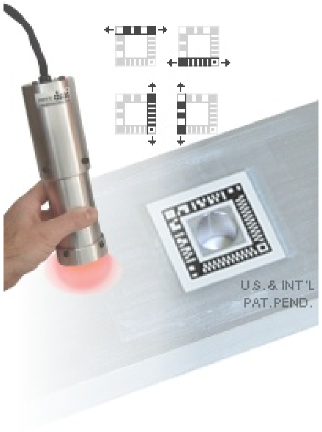

Figure 10 - DMI 2D Mark and SR-2 Barcode Reader

Concurrently, the Navy is also pursuing NDE/NDI technology to perform large zonal area diagnostics. Aero Union has successfully implemented Airborne Acoustic Integrity Monitoring System (AAIMS) developed by Ultra Electronics on their P-3 Orion fleet. With proper instrumentation, cracking in metal or composite structure can be detected and localized within a 10cm diameter. Flight trials have also been conducted on an Airbus A340 [19].

Reducing Susceptibility to Damage

The Navy expects to reap the economic benefits of a condition based maintenance program; however, components are often retired due to external damage. In Figure 11, the US Army has shown that it could save up to 75% per year for its critical safety components by realizing the full fatigue design life [20].

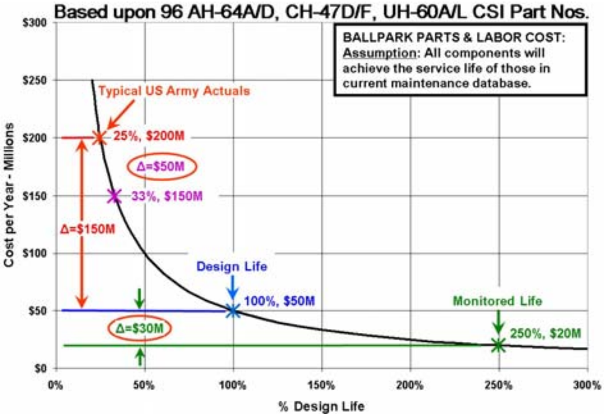

Figure 11 - US Army Cost vs. Design Life

High Velocity Oxygen Fuel (HVOF) Thermal Spray Coatings

HVOF is a wear and corrosion inhibiting coating used mainly for high strength steel applications such as landing gear struts and actuators where hard chrome has been traditionally used. The legacy chroming system has been deemed highly hazardous to health and the environment, so HVOF is replacing it. Qualification testing for helicopter dynamic components and fixed wing landing gear is in progress [21], [22]. Figure 12 shows an example of HVOF application.

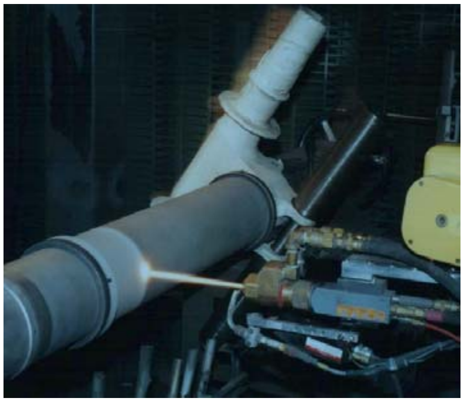

Figure 12 - Application of HVOF Coating on a Main Landing Gear Cylinder

Laser Shock Peening

Laser shock peening is a method for creating a residual compressive stress layer on the surface of metal components. The residual compressive surface stress delays the propagation of fatigue cracks and provides improved fretting and joint fatigue performance [23]. Laser peening has advantages over traditional shot peening with increased magnitude of compressive stress and the ability to tailor the depth of the compressive layer [24], [25].

Force Mate Bushings

The previously discussed durability enhancement technologies are more useful for line-of-sight applications. Fatigue Technologies Inc (FTI) offers the ForceMate bushing process as a cold-working method to increase damage tolerance and fatigue life around holes and lugs. Furthermore, ForceMate products can also minimize damage due to fretting and corrosion. Figure 13 shows example locations that ForceMate bushings can be applied on Sikorsky H-60 [26].

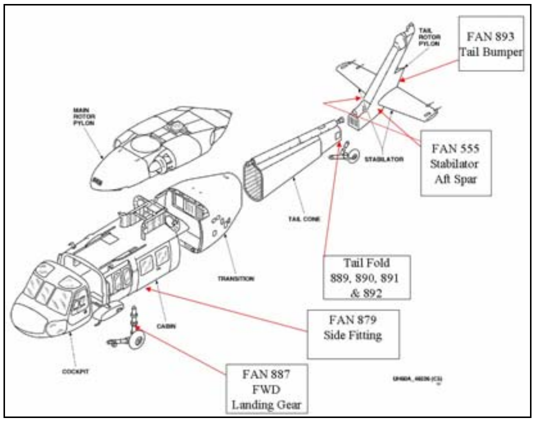

Figure 13 - Example of ForceMate Applications

Innovative Materials

New generation aluminum alloys, such as 7249-T76, are now available as a one-to-one replacement for the corrosion-susceptible 7075-T6 material. These new alloys have demonstrated superior mechanical properties combined with significantly improved corrosion resistance [27]. For high strength steel applications, Questek has developed Ferrium S53 with mechanical properties equal to or better than 300M. Ferrium S53 also has the added benefit of general corrosion resistance similar to 15-5 PH without the need for protective coating [28].

Conclusions

The Navy is proceeding full steam ahead with the implementation of structural usage monitoring for rotary wing aircraft and their dynamic components. The short-term plan includes tracking implementation on V-22 and CH-53E aircraft, with the MH-60R/S and H-1Y/Z to follow. All future Naval rotorcraft will have structural usage monitoring of airframes and dynamic components. As shown in Figure 14, the Navy plans to compile a toolbox of capabilities to support future condition based maintenance.

Acknowledgment

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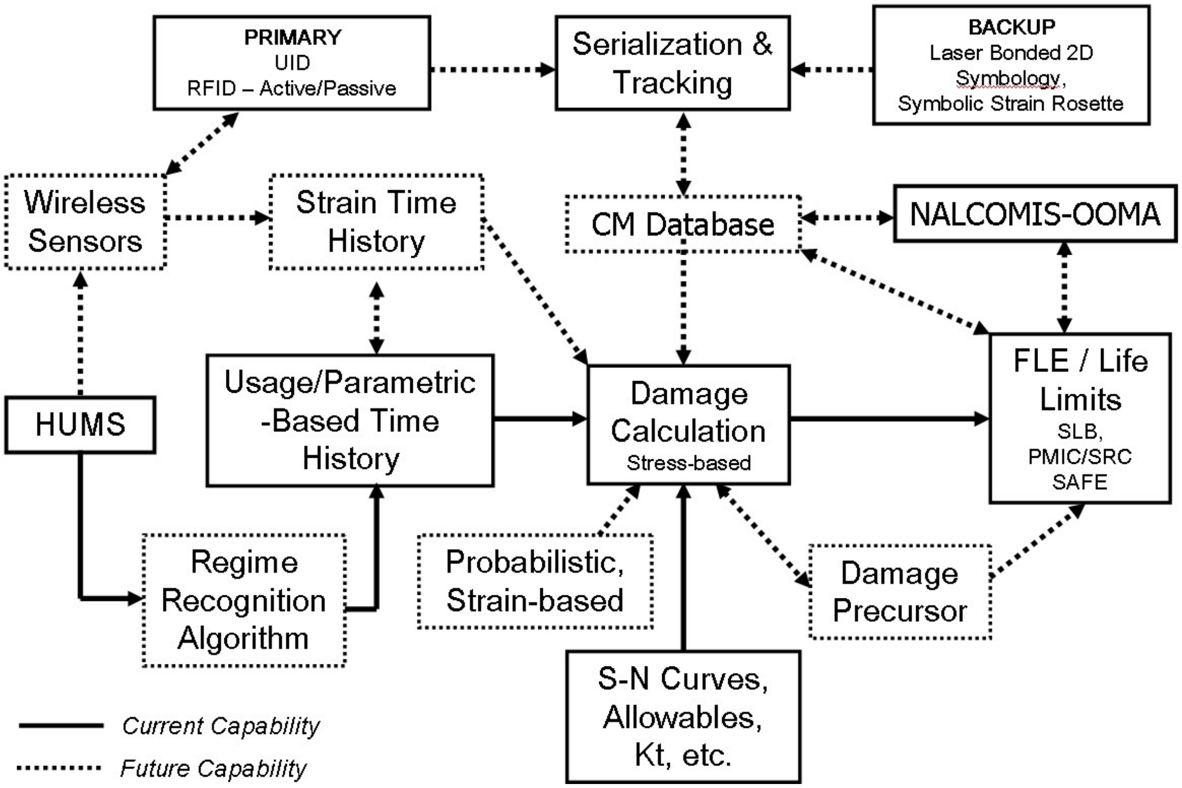

Figure 14 - Navy SHUMS Roadmap

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