# Using HUMS Data to Manage the Fatigue Life of Rotorcraft Critical Dynamic Components

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**Abstract**

This paper summarizes the experience and lessons learned from 48 years of developing and implementing methods for life cycle management of aircraft structural integrity. Specifically, it summarizes the challenges encountered in applying existing technologies to monitor and manage the life cycle of structural integrity of rotorcraft fatigue life limited dynamic components. It is based upon 20 years in pursuit of using Health and Usage Monitoring Systems (HUMS) flight recorded data to monitor rotorcraft usage, operational loads, and accumulated damage to predict material condition, maintenance actions, and remaining useful life (RUL). It is also based upon 6 years experience in support of a military helicopter Condition Based Maintenance (CBM) program. Challenges encountered in implementing rotorcraft critical dynamic component CBM using HUMS data include the failure to obtain: 1) meaningful cost/benefit metrics; 2) valid flight recorded data; 3) platform and HUMS OEM participation; and 4) airworthiness authority approval.

**Keywords:** Health and Usage Monitoring Systems (HUMS), Condition Based Maintenance (CBM), usage monitoring, regime recognition, material condition, maintenance actions, Remaining Useful Life (RUL).

## Introduction

There are challenges in the application and certification of HUMS data to support CBM of military helicopter critical dynamic components. The context of the HUMS data implementation challenges are discussed in the following topics:

- Process for determining critical dynamic component design fatigue life and operational usage fatigue life.
- Benefits of usage monitoring in managing component fatigue life through life extension and/or component remediation.
- Functions of helicopter dynamic component CBM, including:
  - Monitor usage, loads, damage accumulation, and material condition.
  - Predict maintenance actions and remaining useful life (RUL).
  - Remediate by restoring structural integrity.

In addition, observations are shared relative to the shortcomings of HUMS usage data and the on-going emphasis on regime recognition. The stakeholders in the use of HUMS data to support CBM are listed below, and their roles and participation in each of the CBM functions are discussed.

- Technical Community
- User/Operator
- Program Management Office (PMO)
- Original Equipment Manufacturer (OEM)
- Airworthiness Authorit

# Determination of Component Fatigue Life

## Component Design Usage Fatigue Life

The design fatigue lives of critical components are established with the intent of ensuring at least six-nines of reliability, or one chance in a million of a failure. As show in Fig. 1, there are three steps in establishing the design fatigue life of helicopter critical dynamic components:

- Define the operational usage regimes and conservatively establish the percent of time and/or number of occurrences experienced in each regime. This is called the Composite Worst Case (CWC) usage and accounts for one of the six-nines of reliability.
- Determine the strain in each critical dynamic component while experiencing the design flight regimes. This is accomplished by flight testing an instrumented aircraft to measure component strains. The measured strains are conservatively adjusted and account for two of the six-nines of reliability.
- Fatigue test a minimum of six articles of each critical component to establish the fatigue life. To account for unknowns (material variation, material degradation with usage, etc.) a mean minus three sigma adjustment is made to the resultant S-n curve. This accounts for three of the six-nines of reliability.

Although this process is intended to produce conservative design fatigue life values, it does not adequately quantify material degradation with usage.

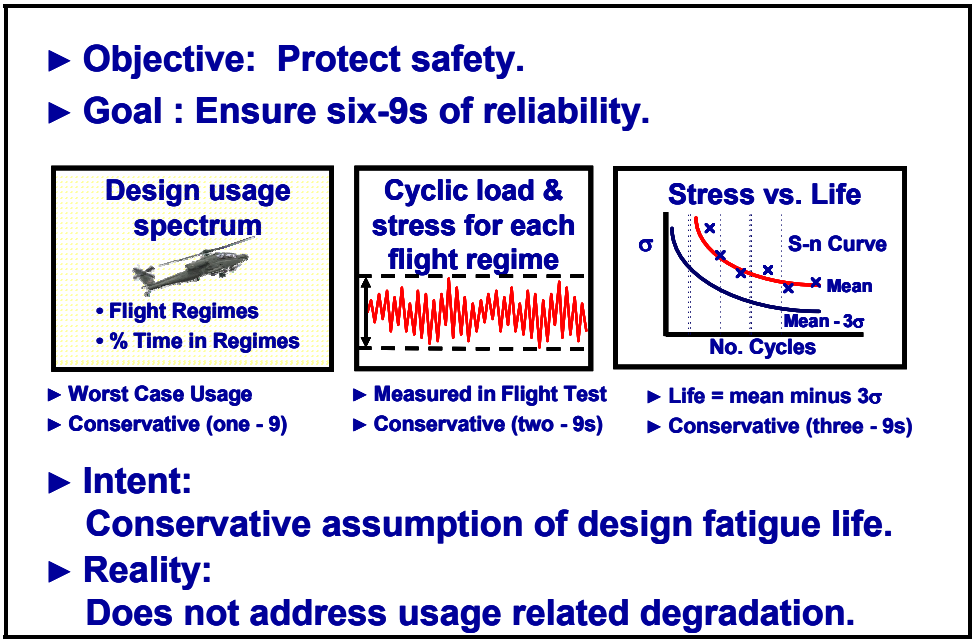



*Fig. 1: Process for Determining Component Design Fatigue Life*

## Component Operational Usage Fatigue Life

Individual component operational fatigue life can be determined by monitoring actual regime usage to determining the resultant accumulated fatigue damage as show in Fig. 2. If operational usage results in a component experiencing fatigue damage at a rate greater than the predetermined CWC design damage rate, it will expend 100% of its fatigue life prior to achieving the design flight hours. To continue flying the component until it reaches the design flight hours would create a safety issue.

Conversely, if operational usage results in a component accumulating fatigue damage at a rate less than the CWC design damage rate, which is the normal condition, it will have expended less than 100% of its fatigue life upon reaching the design flight hours. This creates the potential for extending the flight hours beyond the Component Replacement Time (CRT), which is the design flight hour limit. However, material degradation should be accounted for in establishing a new flight hour limit.

In addition, the usage of critical components that are removed and replaced before reaching their design lives can be evaluated to determine usage-related reasons for early removal. This evaluation can be supplemented with knowledge of the operational environment that the component has experienced.

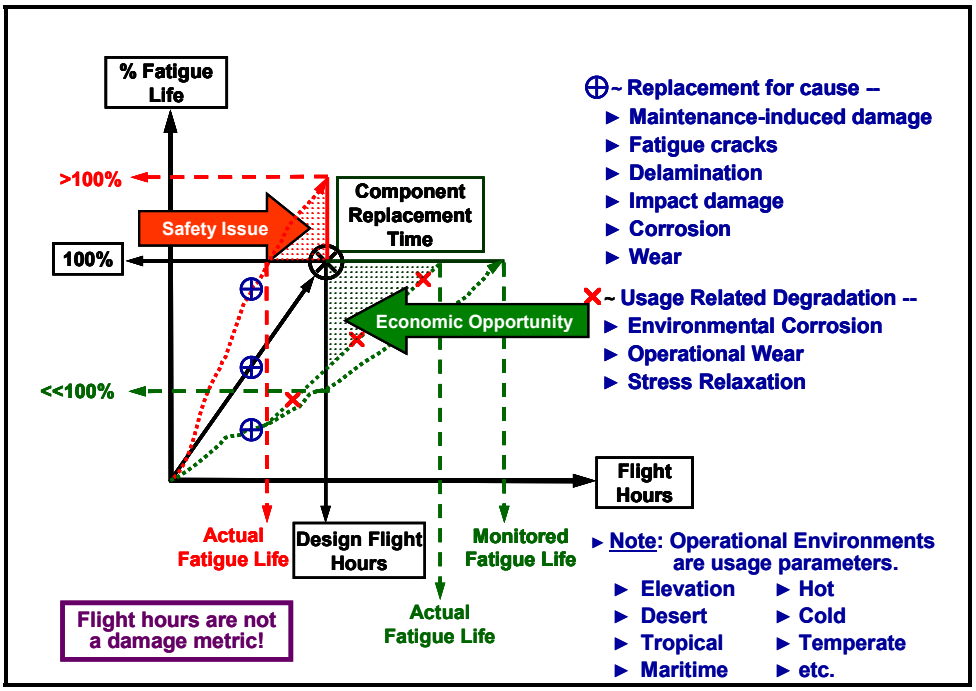



*Fig. 2: Process for Determining Component Operational Usage Fatigue Life*

## Management of Component Fatigue Life

Helicopter dynamic components are designed with CRTs based upon CWC usage. In reality, many components are retired at flight hours far short of the CRT. Many components are retired “on condition” using conservative criteria for wear, corrosion, maintenance-induced damage, and other defects. Other components that achieve the CRT are retired without knowledge of how they were used and whether the usage can be safely extended. As shown in Fig. 3, the opportunity of achieving a higher percentage of the design fatigue life prior to “on condition” replacement is “remediation”, and the opportunity of safely extending usage beyond the CRT is “usage extension”. It should be noted that the most “bang for the buck” is obtained by remediation. In both the remediation and usage extension cases, actual knowledge of component usage and material condition is required to ensure continuing cost-effective structural integrity.

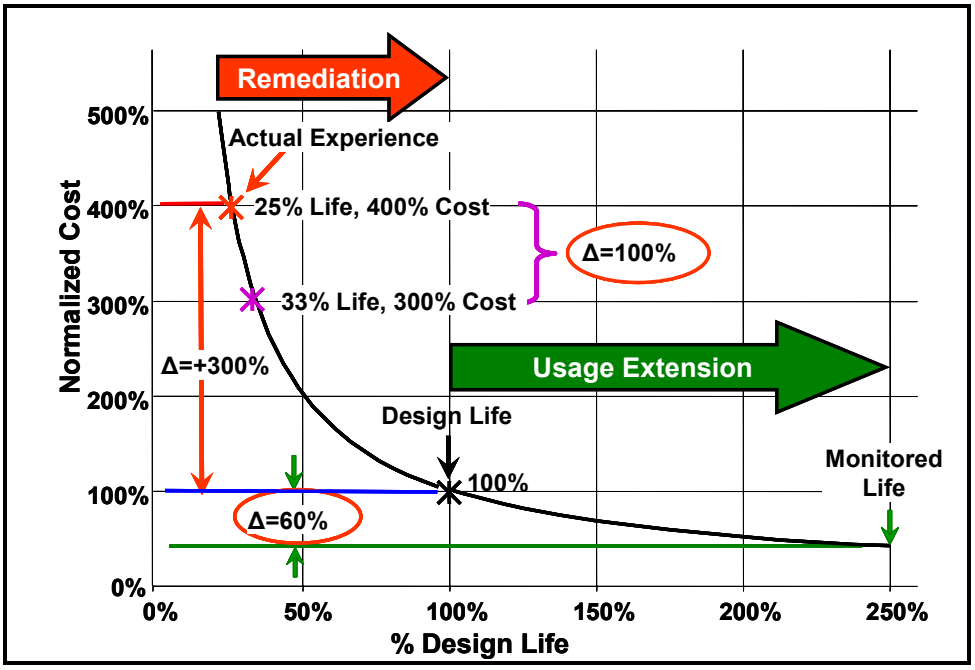



*Fig. 3: Relative Cost Saving Benefits for Remediation and Usage Extension*

## Application of HUMS Data in Support of CBM Functions

HUMS data are used to support the CBM functions that are required for life cycle management of rotorcraft dynamic components. These CBM functions consist of monitoring aircraft usage, accumulated damage, component loads, and material condition; predicting maintenance actions and remaining useful life (RUL); detecting structural anomalies; and remediating component structural integrity. The functions listed below are those identified in the pursuit of applying HUMS flight recorded data to helicopter critical component CBM.

### Monitor

*Aircraft Usage*

It is necessary to monitor aircraft usage in order to determine the accumulated fatigue damage in dynamic components. Aircraft usage monitoring consists of monitoring the number of occurrences of, and/or the amount of time spent in, damaging regimes. This is accomplished by employing the process of regime recognition. Some of the challenges in achieving the potential benefits of regime recognition are discussed in a subsequent section of this paper.

*Accumulated Damage*

Regime recognition information is used to calculate the fatigue damage accumulated in each fatigue life limited dynamic component and the actual fatigue damage is compared with design fatigue damage. This information, in combination with knowledge of the operational environment, can be used for potential fatigue life extension, to predict impending maintenance actions based upon empirical correlations, and to isolate, evaluate, and correct damaging events. Component usage information has the potential to replace flight hours with valid metrics to improve maintenance by progressing toward a CBM-based program.

*Component Loads*

There are benefits in monitoring actual load sequences in dynamic components as a means to refine and improve upon the results of regime recognition. Although regime recognition models 1) produce a conservative estimate of the fatigue damage experienced by critical dynamic components during each flight regime and 2) produce results that are superior to the adoption of fixed flight hour maintenance intervals and replacement times, simply recognizing the regime occurrence and duration is insufficient to determine the true fraction of life expended for a component. Existing statistical methods (such as neural networks, genetic algorithms, regression analysis, and holometrics) can be utilized to develop algorithms that relate fixed-system parameters and strains to loads and strains in rotating dynamic components. Direct methods for monitoring component loads include wired and wireless strain gages.

*Material Condition*

Critical component material condition can be periodically monitored to measure and trend the condition of component material to identify whether to 1) continue safe component usage, 2) remediate the component to insure continued structural integrity, or 3) retire the component. There are two available technologies that can be employed to monitor and trend material condition:

- *Residual Strain:* Use Digital Image Correlation (DIC) to monitor and trend dynamic component material plastic deformation and predict accumulated fatigue damage as indicated by the zero load residual strain in the surface of the component.
- *Residual Stress:* Use x-ray diffraction (XRD) to measure, map, and trend changes in component surface residual stress to assess adverse trends produced by usage-related material degradation, and predict impending rework or retirement.

**Predict**

Prognostic Health Management (PHM) tools are used for predicting dynamic component maintenance actions and RUL. Dynamic component PHM is based upon knowledge of operational usage, observed detrimental symptoms, historic maintenance requirements, and an understanding of component failure modes. PHM is facilitated by diagnostic and prognostic algorithms that are based on operational usage and sensor information. The algorithms provide for metric-based analyses and trade studies to evaluate and resolve dynamic component CBM issues by predicting maintenance actions and RUL.

RUL can be directly predicted by monitoring aircraft usage and the resultant critical component damage accumulation. A normalized damage index can be developed to determine the fraction of the total CWC usage fatigue life that has been expended due to actual operational usage.

**Remediate**

Component remediation can be accomplished in either of two ways: 1) review and revise the criteria for critical component maintenance and removal, and 2) improving component structural integrity. This paper focuses on two proven methods for improving the structural integrity as discussed below.

*Reintroduce Surface Residual Stress*

Portable ultrasonic peening provides the capability to improve component surface condition to restore the benefits of compressive stress; including resistance to fatigue cracking, stress corrosion cracking, chemical corrosion, hydrogen embrittlement, fretting, galling, and erosion. Ultrasonic peening in the following manner: 1) a generator sends an electric current to a sonotrode, 2) the sonotrode produces a mechanical wave that vibrates at a low amplitude, 3) the mechanical wave is acoustically amplified and vibrates homogeneously, 4) balls are energized at the surface of the sonotrode, and 5) balls remain in the housing between the sonotrode and the surface of the part being treated. Ultrasonic peening can be computerized and automated for use at depot and other rework facilities, or, in some cases, be used in situ in the field to provide high quality, repeatable, clean, quiet and easy to control peening to provide maximum fatigue life improvement.

*Cold Expand Holes*

Structural integrity of fatigue-susceptible holes in dynamic components can be improved by cold expansion (Cx). Cx rework is accomplished by split sleeve cold expansion or force fit bushings to forestall fatigue crack initiation, crack growth, and extend the safe usage life by a factor of at least 3:1. Cx is a process used to generate compressive stresses in structural holes to prevent cracks from initiating and/or to prevent existing small cracks from propagating. Cx is a cost effective solution to problems associated with fatigue cracks in holes in metal components and is accomplished by pulling a tapered mandrel, pre-fitted with 1) a lubricated split sleeve, or 2) a force-fit bushing, through a hole in aluminum, steel or titanium. Each application is designed to ensure correct radial expansion of the hole to attain the desired benefits. The Cx process is a cost effective alternative to redesign; adds no weight to structure; provides simple, one-sided operation; works on all common aerospace materials; and is applicable in both production and rework.

## Usage Data and Regime Recognition

Usage data normally consists of more parameters at a higher sampling rate than is necessary to identify damaging ground and flight regimes. However, important parameters that are necessary to relate the regimes usage to component damage are many times not available. These missing parameters commonly include aircraft gross weight, center of gravity, and external store configuration.

Helicopter usage databases are seldom used on a routine basis. As a result, erroneous data is not discovered and the causes for errors are not corrected.

Much emphasis is placed on recognizing 100% of identifiable flight regimes 100% of the time. This emphasis is misplaced, because many regimes produce little or no damage in any of the critical dynamic components that are being monitored. In addition, there is a tendency by the technical community to create new regimes, such as transitions from one steady state regime to another, for which no loads have been measured and no damage rates are available. Also, there are some very damaging events, such as droop-stop pounding, that are not identifiable from the parameters in the usage database.

## HUMS Data Stakeholders and CBM Implementation Participants

The use of HUMS data in support of helicopter critical dynamic component CBM can not be implemented without the active support of key stakeholders and participants. Airworthiness approval for changing maintenance schedules and retirement times based upon component operational usage must have acceptance and support from the following organizations:

- Technical Community
- User/Operator
- Project Management Office (PMO)
- Original Equipment Manufacturer (OEM)
- Airworthiness Authority

The perceived support of each of the CBM functions by each of the participant and stakeholder organizations are summarized in Fig. 5. Their roles and interactions are not clearly defined, emphasizing the fact that the use of HUMS data to support dynamic component CBM acceptance and approval process presents a challenge to achieving CBM implementation.

The Fig. 4 matrix of dynamic component HUMS/CBM functions and the participants and stakeholders is color coded based upon the following criteria:

- Grey: Support not required.
- Green: General active support.
- Yellow: General indifference. .
- Red: General opposition.

Each cell, or merged cells, contains key words that describe the author's perception of each participant's level of CBM functional support. These perceptions are briefly discussed below.

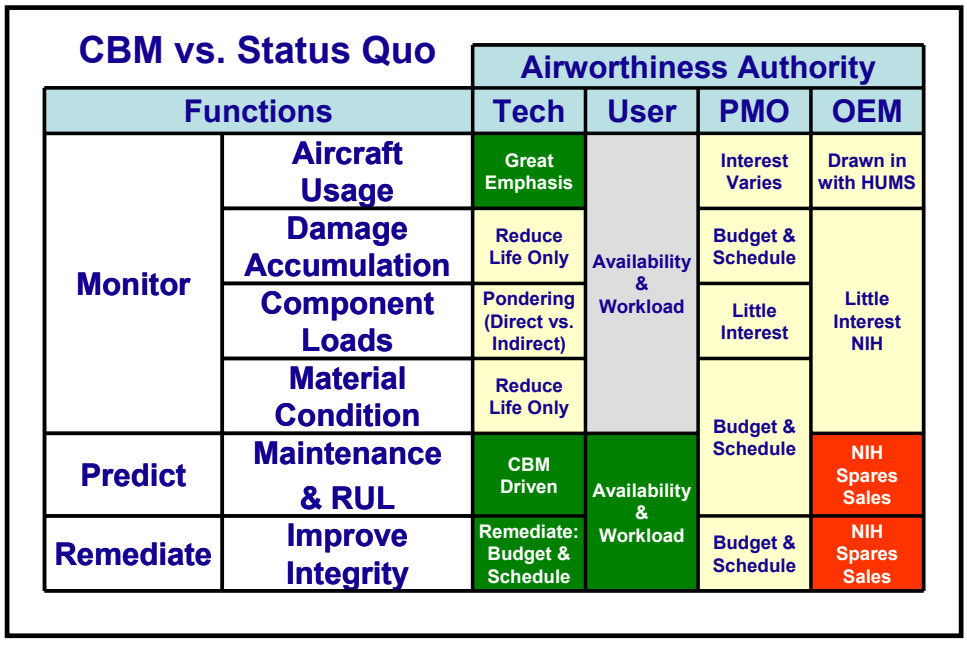



*Figure 4: CBM Functional Support by Participants and Stakeholders*

**Technical Community**

*Monitor*

- Aircraft Usage: As previously discussed, the technical community places great emphasis on recognizing 100% of regimes 100% if the time whether or not the regimes produce damage in any flight critical dynamic component.
- Damage Accumulation: There is some interest in critical component damage accumulation, but not to the extent that individual component damage tracking has been implemented. In the few cases where damage accumulation has been monitored, the results were used to reduce, but not extend, operational usage.
- Component Loads: There have been research activities related to indirect methods and direct methods for monitoring critical component loads.
- Material Condition: The technical community will use perceived material condition to reduce, but not to extend, the operational life of critical components.

*Predict*

In some cases, funded CBM programs have given the technical community the incentive to address the potential for using HUMS information to influence maintenance schedules and RUL determination. However, no dynamic component maintenance schedules or RULs have yet been affected.

*Remediate*

Much emphasis is placed on component remediation if and when the PMO perceives the potential for having to ground aircraft due to the lack of replacement spares. This situation is driven by adequate lead time and/or sufficient budget for procuring replacement parts.

**User/Operator**

*Monitor*

The users/operators of fielded aircraft are not interested in monitoring activities that do not have the direct benefit in reducing maintenance workload or improving aircraft availability. The act of monitoring itself takes time and has an adverse impact on maintenance and availability.

*Predict and Remediate*

The users/operators of fielded aircraft are extremity supportive of any opportunity to reduce maintenance requirements and delay the removal and replacement of dynamic components. Predicting maintenance requirements and RUL, and improving the structural integrity, of critical dynamic components offer the potential for reducing user/operator workload and improving aircraft availability.

**Project Management Office (PMO)**

PMO support varies greatly from platform PMO to platform PMO. In general, CBM interest and support increases when there is the potential for grounding aircraft. This condition is driven by:

- Budget: Funding is insufficient to procure replacement components.
- Schedule: Lead-time to procure replacement components results in grounding aircraft.

**Original Equipment Manufacturer (OEM)**

*Monitor*

Some OEMs have implemented usage monitoring on their civil helicopters to ensure that the owner/operator is not exceeding warranty limits. This has led to limited involvement and support of HUMS systems in military helicopters. However, in general, OEMs have little interest in using HUMS information to monitor damage accumulation, and material condition. There appears to be little OEM interest in these monitoring functions, and, because of a "not invented here" (NIH) attitude, the OEMs generally do not provide support for third party efforts to monitor the results of operational usage.

*Predict and Remediate*

In general, OEMs do not appear to be interested in supporting efforts that have the potential for extending the operational usage of critical components. There are two possible reasons for lack of support: 1) any extension of operational usage is perceived to introduce an element of risk, and 2) component usage extension would adversely impact the OEMs sales of spare components.

## Summary

Frontline combat helicopters are typically aging fleets that will remain in service for years. Many of these aircraft are experiencing escalated operational tempos in extremely harsh environments. HUMS data are available to monitor helicopter operational usage and critical component fatigue damage accumulation. Technologies are also available to monitor component loads, monitor and trend the condition of component material, and remediate component structural integrity to improve maintenance intervals and RUL. The first step in achieving these potential benefits is to collect and analyze the HUMS data that is required to support dynamic component CBM. Success is dependent upon obtaining the acceptance and support of multiple organizations, which is not a linear, coherent process. Regardless of these challenges, any approach to achieving the potential benefits of HUMS and CBM must focus on the users/operators to enable them to more effectively perform their mission.