HUMS Condition Based Maintenance Credit Validation

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Abstract
There is an increasing desire to use rotorcraft Health and Usage Monitoring Systems (HUMS) to facilitate Condition Based Maintenance (CBM) approaches to achieve operating cost reductions and other benefits. This type of application must be supported by the certification process, as it is an example of a “maintenance credit”. Guidance material on the process of obtaining a credit is presented in Advisory Circular AC 29-2C MG-15.

Current HUMS have achieved very few credits, and the material in the AC is largely untested. However HUMS in-service experience shows that the potential for future credits does exist. This paper presents work performed by Smiths Aerospace and Sikorsky Aircraft Corporation (SAC) on an FAA research program, with the primary goal being to research the end-to-end process for approving an example HUMS CBM credit in accordance with the requirements of the AC. The primary target CBM credit selected for the work is to extend or eliminate a current 2,500 hour TBO on the oil cooler of the S-92 helicopter.

A key element of the work is to demonstrate and validate the ability of HUMS algorithms and methodologies to detect incipient mechanical faults and facilitate timely maintenance intervention. The work will assess the CBM credit potential of both the current mechanical diagnostic algorithms and methodologies in in-service HUM systems, and the additional capabilities gained through the application of emerging advanced HUMS analysis methodologies.

The results of the FAA program will go into the public domain, and should be of value in helping to test and refine the guidance material in AC 29-2C MG-15, and to realise the maintenance credit potential of HUMS.

INTRODUCTION
First generation rotorcraft Health and Usage Monitoring Systems (HUMS) were primarily fitted to provide a safety benefit through early detection of mechanical faults, and were not intended to fundamentally modify the maintenance schedule or lifting of components. The degree of qualification required for this type of installation was relatively low since the HUMS was certified on a non-interference basis.

As HUMS has matured, there is an increasing desire to use the system as an enabler for a change from a traditional scheduled aircraft maintenance policy towards Condition Based Maintenance (CBM). This type of application requires a higher degree of qualification, commensurate with the criticality of the most severe effect of the intervention action(s) on the rotorcraft. Furthermore, the adoption of CBM must be supported by the certification process, as this is an example of a maintenance credit, defined as: “To give approval to a HUMS application that adds to, replaces, or intervenes in industry accepted maintenance practices or flight operations”.

Guidance material on the process of obtaining a credit is presented in Advisory Circular AC 29-2C MG-15 (Reference [1]). The FAA recognized the need for validating the AC and demonstrating how representative credits could be achieved. Therefore it initiated multiple HUMS research programs. On one of these programs Smiths Aerospace and Sikorsky Aircraft Corporation (SAC) are researching the end-to-end process for approving and implementing an example credit in accordance with the AC. Previous work has primarily focussed on ‘usage’ rather than ‘health’ credits as these are more straightforward to define. This work focuses on a CBM credit based on HUMS mechanical diagnostics, and primarily on Vibration Health Monitoring (VHM) functions. This paper summarizes the results of the first year of a five year effort, with the primary objective being to establish the focus and scope of the remainder of the program.

The credit approval process involves the demonstration and validation of HUMS algorithms and methodologies to detect incipient mechanical faults and facilitate timely maintenance intervention. The work will assess the ability of both current
standard HUMS algorithms and methodologies, and also advanced methodologies that are in development, to facilitate CBM credits.

ASSESSMENT OF HUMS CBM CREDIT POTENTIAL

A review of the current credit status of in-service HUMS systems highlighted the fact that very limited credit has been awarded to current HUMS mechanical diagnostics functions. The only credits that have been awarded are those in which HUMS replaces an item of ground test equipment, where it is possible to show directly from experience that HUMS provides the same results as an independent measuring system. However, in-service experience does indicate the future credit potential of HUMS mechanical diagnostics.

HUMS in-Service Experience

The following are three examples of HUMS in-service experience which, although in no case has any formal credit been awarded, illustrate a potential for credit.

Example 1: HUMS Detection of Accessory Gearbox Defects—On the AS332L2 there have been a number of repeat occurrences of a particular defect type within an accessory gearbox, resulting in gearbox rejections before the Time Between Overhaul (TBO) limit is reached. Through in-service experience, it has been possible to demonstrate that the HUMS mechanical diagnostics function can reliably detect changing vibration characteristics associated with the defect, therefore the HUMS information has been used to determine when gearboxes should be rejected. The gearboxes could be considered to have been operating ‘on-condition’ for this particular defect mode.

Example 2: Use of HUMS to Perform a Fleet-Wide Health Check—Soon after the introduction of HUMS on a military CH-47D fleet, an aircraft with a newly fitted HUMS suffered the break-up of a combiner transmission bearing (Reference [2]). The bearing failure was detected by a chip detector as no mechanical diagnostics thresholds had yet been set in the HUMS. However, the system was recording raw transmission vibration data. The raw HUMS data from that aircraft was evaluated and a failure characteristic was identified. This characteristic was then used to perform a fleet-wide health check, and all of the other HUMS embodied aircraft were screened within 12 hours. The screening established that no other transmissions displayed similar failure characteristics, thus allowing the aircraft to remain available for operations. If HUMS had not been installed on the aircraft with the failed transmission it would not have been possible to identify the failure vibration characteristic. Therefore, to ensure airworthiness, the only option available would have been to ground the fleet and remove, inspect and replace all combiner transmissions. Again, for a single failure mode that could be shown to be detectable on an in-service aircraft, it was possible to award the HUMS a ‘one-off credit’ – in this case preventing a fleet grounding for gearbox removal and inspection for a particular bearing failure mode.

Example 3: HUMS-Based Tail Drive Shaft Bearing Servicing—HUMS operators have experienced cases of rising trends in the vibration energy level indicators on the tail drive shaft bearings of AS332L2 aircraft. As the accelerometers are located close to the bearings, they are sensitive to both the condition of the bearings and the state of the grease lubrication. On the first occurrence an inspection of the affected bearings was performed and no visible defects were found. Greasing was then carried out and the energy levels of the indicators returned to normal. Repeating greasing cycles created a ‘saw tooth’ trend, with progressive increases in vibration followed by step decreases. The rising HUMS vibration trends have been used to indicate when bearing re-greasing is required.

Summary—The above examples from HUMS in-service experience illustrate that HUMS mechanical diagnostics do have the potential to provide CBM credits. They also suggest that the realization of this potential can be most straightforwardly achieved in cases where:

- Only a limited number of specific defect modes are involved.
- There is direct evidence from in-service experience of the ability of the HUMS mechanical diagnostics to reliably detect these defect modes in a timely and unambiguous manner.

Candidate CBM Credits for HUMS Mechanical Diagnostics

Using the above information together with an engineering analysis of the requirements for different types of HUMS CBM credit, it is possible to define in generic terms the most promising candidates for a credit.

Elimination or Extension of Gearbox and Other Component TBOs—If HUMS mechanical diagnostics can provide reliable and timely detection of all the failure modes which are currently controlled by the routine overhaul procedure, gearboxes could be run on-condition. Because of their internal complexity, this is likely to be impractical for a main gearbox on the basis of HUMS alone, but may be feasible for an intermediate or tail gearbox.

There is an established procedure for extending gearbox TBOs based on in-service reliability information. In theory, if a TBO extension is limited by a small number of defect modes, and some can be reliably detected with HUMS, whilst others can be designed out, then the HUMS could be awarded credit to allow the TBO extension to be introduced (possibly in combination with the introduction of some component modifications). In another scenario, new defect modes may be encountered over the life of an aircraft which are not reliably detectable by traditional monitoring processes. Without HUMS, a decision has to be taken as to whether to implement a modification so that the problem is eliminated, or to operate the aircraft over the remainder of its life with a limited TBO on the gearbox. However, if it can be shown that the problem defect mode can be reliably
detected by HUMS, then the gearboxes could continue to operate ‘on-condition’ for that particular defect, with the remainder of the defect modes still being covered by the unlimited TBO.

In general, the elimination or extension of a TBO on a simpler assembly such as an oil cooler fan (e.g. for bearing replacement), represents an easier target CBM credit for HUMS mechanical diagnostics. There are fewer potential defect modes to be detected, and the hazard level associated with a failure can be lower than that associated with a failure in the main drivetrain. In summary, it is possible to identify some potential for the extension or elimination of existing TBOs, and this could provide worthwhile benefits.

Elimination of Component Inspections, or Extension of Inspection Periods—For external components such as tail drive shafts and swashplates, periodic visual inspections are required to ensure continued airworthiness. If a HUMS mechanical diagnostic function can reliably monitor the defect modes that an inspection is targeted at, then it may be possible to eliminate the inspection, or extend the inspection period. However, a number of items can be checked on an inspection, for example checking the condition of dynamic components such as shafts and bearings, and also checking static components such as pipes or cables for signs of chafing. In this case, HUMS mechanical diagnostics are unlikely to be able to monitor all the potential defect modes that are being checked for, and therefore the potential for eliminating the inspection is limited. For more targeted inspections, such as for a swashplate bearing, there is greater scope for achieving a HUMS credit.

Condition Based Component Servicing—Experience has shown that there is scope for using HUMS data to determine when component servicing is required, for example the greasing of tail drive shaft bearings.

Modification of Responses to Traditional Indicators (e.g. Chip Detector)—Whilst traditional health indicators such as chip detectors mounted in the oil system have proved to be effective detectors of damage to oil washed components, their output may be limited to a binary state. This creates difficulties for the definition of responses to indications such as the detection of metallic debris. The result can be significant disruption both to operations and to maintenance schedules. In theory, where HUMS vibration-based mechanical diagnostics provide an additional monitoring capability, consideration could be given to modifying the required response to an indication from a chip detector. However, in practice there are a number of significant difficulties with this idea. It is unlikely that the source of any metallic debris can be identified without a detailed metallurgical analysis, therefore it would be difficult to seek confirming health information from vibration data. In addition, oil debris monitoring and vibration monitoring are generally considered to be complementary functions, in that the defect modes that they can most effectively detect are different.

SELECTION OF A ROTORCRAFT COMPONENT AND CBM CREDIT FOR THE RESEARCH PROGRAM

SAC performed an analysis to select a representative aircraft, drivetrain component, and CBM credit for the FAA research program. This analysis utilized detailed drivetrain documentation such as design, structural substantiation, and failure modes and effects analysis (FMEA) reports; plus Overhaul & Repair and Reliability & Maintainability databases. The S-92 (Figure 1) was selected as an ideal vehicle for the program, because it is based on state-of-the-art structural design practices, incorporates a comprehensive HUMS in the baseline aircraft configuration, and has considerable CBM potential due to Sikorsky’s ultimate goal to put key drivetrain elements on-condition. Further, as part of the S-92 controlled introduction to service plan, an S-92 Lead-the-Fleet (LTF) program is being conducted to support the validation of current TBOs and on-condition maintenance criteria for key drivetrain components. S-92 HUMS data will be continuously gathered for all aircraft in the fleet, including the LTF aircraft, therefore this provides a unique opportunity to cost effectively gather both HUMS and tear-down and inspection data to compare HUMS condition indices with component condition.

Figure 1: S-92 Helicopter

The selection of a component and CBM credit needed to be consistent with the scope of the research program and the objective to address the end-to-end credit approval process, including the collection of sample supporting evidence. It was also desirable to define a credit that was not overly complex, and was sufficiently beneficial to encourage an operator to work with an OEM to take the next steps toward actually implementing the credit validation plan and achieving the credit. A number of criteria were defined as the basis for the component and credit selection, including:

- Component history and CBM credit benefit
- CBM credit complexity and criticality
- Component fault inspectability, detectability, and testability
A semi-quantitative ranking matrix was used to guide component selection. The S-92’s oil cooler was selected as the representative drivetrain component based on this analysis and consideration of the program objectives (Figure 2). The detailed drivetrain subsystem FMEA was then used to ascertain what faults must be considered in the assessment of the criticality of any potential CBM credits for the oil cooler. The primary credit selected for examination in the program was the extension and ultimate elimination of the 2,500 hour oil cooler TBO, which translates to an extension of the 2,500 hour replacement time of the oil cooler bearings. The ultimate desire is to go “on-condition”. Additional credit options of modifying or eliminating the 50 hour and 250 hour inspections will also be explored.

APPLICATION OF HUMS ALGORITHMS AND METHODOLOGIES

There are three elements to the HUMS data analysis to be performed in support of the oil cooler CBM credit validation research. The first is a statistical analysis of the outputs from the current S-92 HUMS mechanical diagnostic algorithms and methodologies from the in-service S-92 fleet, together with any additional aircraft test data. The analysis will correlate the HUMS data with component condition and maintenance information, and also establish data variability across the operational fleet. This will provide direct evidence for credit validation (Reference [1]). HUMS data from other aircraft types may also be used to provide additional indirect evidence.

The second element will be the application of Smiths Aerospace’s gear, shaft and bearing VHM techniques to vibration data acquired from oil cooler seeded fault testing. These techniques have been validated through both seeded fault testing and extensive in-service HUMS operational experience. Because of the nature of the desired CBM credit, the primary focus will be on bearing VHM. Although there are detailed differences in the algorithms and methodologies implemented by different HUMS suppliers, all the current major suppliers have adopted the similar approaches. Therefore it should be possible to read across between the results of analysis of the seeded fault data and in-service HUMS data.

The third element of the HUMS data analysis will be the application of some of Smiths’ advanced HUMS data analysis methodologies to the oil cooler data. The primary goal of applying such methodologies is to determine the impact they may have on the ability to achieve HUMS CBM credits in accordance with the requirements of the AC.

As a result of a desire to further improve the fault detection performance of HUMS, in 2004 the UK CAA commissioned Smiths, in partnership with Bristow Helicopters, to undertake a research project to establish the practicality and effectiveness of applying unsupervised machine learning (i.e. anomaly detection) to the analysis of HUMS VHM data in an in-service environment. The objective of anomaly detection is to identify abnormal behavior that might be indicative of some fault. Anomaly detection can be difficult, but HUMS VHM data present significant additional challenges. For example, due to instrumentation issues, the effect of various maintenance actions, and the lack of feedback from gearbox overhauls, the condition of any training data set is unknown.

A novel data modelling process was developed to overcome the unique challenges of HUMS VHM data (Reference [3]). The modelling process suppresses the effects of anomalous data always found in any training set comprising data from in-service aircraft. As a result, models constructed using training data that contain some anomalies are still capable of highlighting similar anomalies. The anomaly detection processing simplifies a complex data picture through an effective fusion of multiple HUMS condition indicators. This fusion emphasizes abnormal combined indicator trends and suppresses trends that are within normal ranges. The process was implemented in a web-based HUMS data warehouse and anomaly detection system (Figure 3). The system operates as a secure web server, located at Smiths in Southampton UK, and has been successfully trialled by Bristow Helicopters in Aberdeen on data downloaded from their North Sea AS332L helicopter fleet.
Work is continuing on the development of an automated reasoning capability for the post-processing of anomaly model outputs. The across-model fusion of anomaly information can be handled by a probabilistic network inference engine. The anomaly model has a direct formal mapping into a probabilistic (Bayesian) network. It is therefore possible to represent anomaly models within a probabilistic reasoning system. This ability means that the outputs from multiple models can be fused, and other data/information can be fused with anomaly model outputs. This higher level fusion for reasoning further enhances the diagnostic and prognostic information that can be extracted from the HUMS data. Figure 4 shows a graphical representation of the fusion of four anomaly models in a probabilistic diagnostic network within Smiths’ reasoning tool.

**END-TO-END CBM CREDIT APPROVAL PROCESS**

**Review of AC-29-2C MG-15**

AC 29-2C MG-15 states that: “The certification of HUMS must address the complete process, from the source of data to the intervention action. There are three basic aspects for certification of HUMS applications: Installation, Credit Validation, and Instructions for Continued Airworthiness (ICA).” These three aspects of HUMS certification are not totally independent and do have varying interactions with each other. Whilst noting relevant installation and ICA aspects, this research on the approval of a CBM credit is primarily targeted at credit validation. The AC states: “HUMS applications for which credits are sought must be validated. For each application, evidence shall be provided that the physics involved is understood and therefore that the monitoring technique/algorithm/parameter, rejection criteria,
and associated intervention actions are well chosen. The validation process would generally need to include the following:

- Description of application and associated credit.
- Understanding of the physics involved.
- Validation methodology.
- Introduction to service.
- Continued airworthiness (synthesis)."

Figure 5 below converts the text in AC 29-2C MG-15 specifying the key certification requirements that must be addressed in the awarding of a HUMS credit into a flow chart. This is intended to serve two purposes: (i) To define the generic end-to-end certification process for a HUMS CBM credit; and (ii) To identify relationships and interactions between the different elements of the certification process that are contained in the three separate sections of the AC (i.e installation, credit validation, and Instructions for Continued Airworthiness).

Figure 5 : Certification Process for a HUMS CBM Credit
AC 29-2C MG-15 provides useful guidance material, and contains well-founded requirements. Whilst these are defined in generic terms, they are considered to be appropriate for a document of this type. Potential issues to be addressed in applying the AC to the end-to-end process of achieving a particular CBM credit may include:

1. Understanding the interactions between requirements in different sections of the document, primarily between the sections on installation and credit validation.

2. Converting the generic guidance into specific plans for a defined HUMS application providing a CBM credit that is deemed to be acceptable to a certifying authority.

3. Determining the cost effectiveness and appropriate timing of any CBM credit application. For example, conducting a series of seeded fault tests to provide direct evidence to validate a credit can be expensive. However, after a number of years of HUMS operations on a reasonably sized helicopter fleet, much of the required direct evidence may have been accumulated from the in-service experience at little cost. This indicates the importance of having an effective HUMS maturity plan that ensures that data and evidence from in-service experience is properly documented and reviewed.

Application of AC-29-2C MG-15 to the Primary Target CBM Credit – Extension or Elimination of 2,500 Hour Oil Cooler TBO

Physics of Failure—Only oil cooler system failure modes related to the bearings need to be considered for the target CBM credit. None of the other failure modes are addressed by the 2,500-hour oil cooler TBO and bearing replacement time, nor will they be affected by the extension or elimination of the bearing replacement time.

The FMEA identifies four oil cooler bearing failure modes: (i) wear of bearing balls and races, (ii) ball sliding, (iii) ball spall, and (iv) bearing cage fracture. Complete oil cooler bearing failure can result in possible loss of blower shaft position, bearing seizure, contact between blower fan impeller and stator, wear of fan blades, impeller failure, loss of cooling air, increased oil temperature, and excessive vibration. It is important to note that complete oil cooler bearing failure, including possible bearing seizure, does not result in tail drive shaft failure as evidenced by extensive H-60 experience.

Credit Criticality—Extension or elimination of the 2,500-hour oil cooler TBO and bearing replacement times could increase the possibility of oil cooler bearing faults. The primary failure mode that drives the criticality for this target credit is bearing failure. The following is a generic summary of two bearing fault progressions which must be considered. Either may result from a number of initial causes such as loss of grease, contamination, shaft misalignment, etc.

1. bearing wear, sliding, pitting, spalling, and/or cracking ⇒ increased vibration ⇒ increased wear rate ⇒ excessive vibration

2. bearing cage failure ⇒ bearing failure ⇒ possible loss of shaft position or bearing seizure ⇒ excessive vibration ⇒ possible impeller/stator impact ⇒ possible impeller failure ⇒ loss of oil cooling

The first progression is classified as Class IV, Minor effect (Reference [1]), because the primary end-effect is excessive oil cooler vibration, which would not reduce the functionality of the aircraft. The second progression is currently classified as Class III, Major effect, because the compensating provisions result in end effects (e.g., noise, vibration, and oil temperature increases) that are minimized and are detectable long before conditions become hazardous. The target credit seeks to eliminate one of the compensating factors (i.e., 2,500 hour bearing replacement), but keeps in place all of the other compensating provisions.

Fault Detection Requirements—The primary faults that must be detected in order to completely eliminate the 2,500-hour bearing replacement and 2,500-hour oil cooler TBO are the two failure modes that are classified as Class III, Major; bearing failure and cage failure. Detection of bearing failure must occur well before bearing damage and collateral fan damage can become hazardous. In fact, in order to provide overall benefit to the operator, fault detection must occur prior to expensive collateral damage and in sufficient time to allow the maintainer to proactively schedule maintenance as opposed to reactively pull an aircraft from service. Thus, it is desired that HUMS reliably detect the other failure modes (i.e., spall, sliding, and wear), which are leading indicators and result only in excessive oil cooler vibrations (Class IV, Minor). Ideally, a method that could detect loss of lube through vibration monitoring would be beneficial because it is an even longer lead indicator of a condition that can lead to bearing wear and fatigue damage.

Candidate Mitigating Actions—The candidate mitigating actions would be the 50, 250, 500 and 1250-hour inspections already required in the maintenance manuals. For the CBM credit of extending or eliminating the 2,500-hour bearing replacement, no other mitigating actions are required.

Validation Methodology—Since the criticality of the target CBM credit is deemed to be Class III, Major, the validation methodology can depend on indirect evidence (Reference [1]). The most cost effective approach would be to use direct evidence from similar aircraft types and similar oil cooler designs as indirect evidence to develop and validate the methods for the S-92 (H-60 data would be most relevant). Limited testing on the S-92 oil cooler and/or bearings would then be performed to provide direct evidence for final validation despite the fact that it is not required by the AC for Class III criticality credits.
CONCLUSIONS

There is a desire to increase the level of Operating and Support (O&S) benefits from HUMS by using the system as an enabler for a change from a traditional scheduled aircraft maintenance policy towards Condition Based Maintenance (CBM). This change requires the awarding of “credit” to HUMS, whereby assurance has been obtained that the HUMS can reliably detect any failure modes that are currently controlled through scheduled maintenance, and can initiate timely maintenance intervention to prevent any adverse impact on airworthiness. Guidance material on the process of obtaining a credit is presented in Advisory Circular AC 29-2C MG-15.

As part of a wider FAA effort to validate the AC and demonstrate how representative credits could be achieved, Smiths Aerospace and SAC are undertaking a five year program to research the end-to-end process for obtaining an example CBM credit. This paper has presented the results of the first year of effort, scoping out the remainder of the program.

A review of HUMS in-service experience showed that current systems have so far been awarded very limited credit, however a number of examples were identified that illustrate the future credit potential of HUMS. This could be most straightforwardly achieved in cases where a limited number of failure modes are involved, and where there is direct evidence from in-service experience of the ability of HUMS to reliably detect these failure modes. The credit potential of HUMS should therefore increase as in-service experience accumulates.

The target aircraft for the FAA-sponsored CBM credit research described in this paper is the Sikorsky S-92. This relatively new helicopter type is an ideal candidate for the program, being based on state-of-the-art structural design practices, and incorporating a comprehensive HUMS. On the basis of a multi-criteria scoring matrix, the S-92 oil cooler was selected as the best candidate component for the work. The primary target CBM credit is an extension of the current 2,500 hour TBO on the oil cooler, which in turn requires an extension of the 2,500 hour replacement interval for the oil cooler bearings. The highest level of criticality of this credit has been identified as “Major”. The potential for eliminating some oil cooler inspection requirements will also be explored.

The credit validation research will be based on both the current HUMS mechanical diagnostic algorithms and methodologies, and advanced anomaly detection and reasoning technologies that are being applied in a UK Civil Aviation Authority HUMS research program. There will be a primary focus on the application of bearing VHM techniques.

In addition to assessing the practical application of AC 29-2C MG-15, this work should enable an assessment of the cost effectiveness of obtaining CBM credits at different stages of the life cycle of a particular aircraft type and HUMS combination. The results of the FAA program will go into the public domain, and should be of value in helping to test and refine the guidance material in the AC, and to realise the maintenance credit potential of HUMS.

REFERENCES


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