ABSTRACT
Driven by increasing demands for increased safety and reduced operational costs, advanced Health and Usage Monitoring System (HUMS) technologies and applications are emerging/maturing that can be used to introduce structural Usage Based Maintenance (UBM) credits. FAA Advisory Circular AC-29-2C, Section MG 15 addresses airworthiness approval of rotorcraft HUMS and HUMS-based maintenance credits. The AC provides general guidance for achieving airworthiness approval for installation, credit validation, and instructions for continued airworthiness.

This paper describes an FAA funded R&D effort to assess and validate existing regime recognition algorithms and establish a viable end-to-end UBM process that would be compliant with the FAA AC and therefore certifiable. This is accomplished by two sets of tasks. First, a proposed end-to-end UBM process is shown to exploit the capability of currently available HUMS, while mitigating any deficiencies, to enable near-term benefit of regime recognition technology. Second, existing HUMS regime recognition algorithms are evaluated against both flight test and HUMS fleet data. A new technique is presented to post-process available HUMS output to make it compatible with the established dynamic component life assessment process and credit validation guidelines. The UBM process is demonstrated to be compliant to the FAA AC as one but not the only means of complying.

INTRODUCTION
Current HUMS typically perform engine and drive train vibration monitoring, exceedance monitoring, and rotor track and balance in order to detect mechanical faults and avoid mechanical failures. This level of functionality has led to increased safety that could be further improved by adding the capability of structural usage monitoring. HUMS typically consists of a variety of onboard sensors, algorithms, and data acquisition systems. The acquired data may be processed onboard the rotorcraft or on a ground station (or a combination of both) providing the means to measure against defined criteria and generate instructions for the maintenance staff and/or flight crew for intervention. To meet these needs, a variety of HUMS have been developed and put into service. Initially, these systems were installed to demonstrate the feasibility of gathering meaningful data to modify required maintenance and/or operational actions. The degree of qualification required for this type of installation is relatively low.

A comprehensive knowledge of actual aircraft usage would help assure safe operational procedures and usage profiles and could potentially reduce operating costs via usage based maintenance (UBM) credits. Ultimately, the goal is to transition from time-based to condition-based maintenance methods. Usage monitoring via regime recognition is a means to accomplish this. The degree of qualification for UBM is high.

The established structural design methodology has relied upon conservative inputs for fatigue substantiation of rotorcraft dynamic components, as shown in Figure 1. Definition of design usage has traditionally relied on developing a Composite Worst Case (CWC) usage spectrum derived from the customer’s detail specifications, legacy specifications, pilot surveys and Sikorsky historical knowledge of rotorcraft usage. The usage spectrum is a conservative estimate of the most severe operations expected in service.
Loads for these regimes are initially determined through fatigue flight loads analysis, either using analytical flight simulation or by scaling appropriate test data. This is followed up by flight loads survey testing on prototype aircraft, where in-flight loads data for each maneuver are recorded from the instrumented components. During these flight test programs, the pilots are given a flight card that describes the specifics of a maneuver, for example a 2.5g symmetric pull-up at 150 knots. Data is typically recorded starting from a steady state condition and then ended once the aircraft has recovered from the transient portion of the maneuver. A 95th percentile value of the recorded vibratory flight loads is conservatively used for analysis of steady maneuvers. For transient maneuvers where significant load variability is expected, cycle counting methods are used to obtain a distribution of loads.

These data are then processed by ground test engineers, who, with the use of full scale component strength S-N curves with established strength knockdowns, and determine calculated retirement times (CRT) for the assumed usage. Along with regular inspection intervals, this is considered a reliable and safe approach for fatigue design and part life management and has been approved by the FAA for S-92 operations.

One potential benefit of HUMS is that it can monitor and record the regimes that are flown on each aircraft in fleet. The Original Equipment Manufacturer (OEM) can then compare the actual usage spectrum for an individual aircraft or fleet to the CWC design usage spectrum to see when components must be inspected or retired. Component loads would still be assumed for each regime based on existing flight test data. This method is called “usage based component retirement” whereby UBM credits could be given to delay the time until parts are retired.

The application of HUMS for UBM credits presents challenging certification issues related to HUMS hardware and software certification, for both the airborne and ground based parts of the system. FAA Advisory Circular AC-29-2C, Section MG 15 (Ref. 1), addresses airworthiness approval of HUMS. The AC provides guidance for achieving airworthiness approval for installation, credit validation, and continued airworthiness instructions for a full range of HUMS application. Installation includes all the equipment needed for the end-to-end application that is associated with acquiring, storing, processing, and displaying the HUMS application data, including airborne and ground-based equipment. Credit validation includes evidence of effectiveness for the developed algorithms, acceptance limits, trend setting data, tests, etc., and the demonstration methods employed. A plan is needed to ensure continued airworthiness of those parts that could change with time or usage and includes the methods used to ensure continued airworthiness. The AC establishes an acceptable means, but not the only means of certifying a rotorcraft HUMS and HUMS-based maintenance credits.

OBJECTIVE

While advanced usage monitoring and flight regime recognition (RR) algorithms have been demonstrated, none have been fully validated and certified for UBM credit application. Further, an end-to-end UBM process also needs to be developed and validated in compliance with Ref. 1.

The objective of the program described in this paper is to address both of these needs by utilizing flight test and fleet data to support the validation and demonstration of HUMS operation requirements, technologies, and processes and to collect and substantiate structural usage data. Existing usage monitoring and flight RR technologies for structures are used in this program. The primary sub-objectives of this effort are to:

1) develop an end-to-end UBM process that addresses the issues of HUMS installation, credit validation, and continued airworthiness in accordance with AC-29-2C Section MG 15
2) demonstrate a combination of on-aircraft and off-aircraft usage monitoring RR algorithms that can be used for UBM credit application
APPROACH

The high level objective of UBM credit application is to adjust a component maintenance interval (e.g., retirement time) while assuring safety and reliability. The approach undertaken in this project to fulfill this objective is summarized as follows.

- Establish a UBM end-to-end process in compliance with the AC considering both the current state of S-92 HUMS technology and level of manufacturer involvement
- Select S-92 UBM candidate dynamic components and identify the associated damaging regimes
- Using S-92 flight test and fleet data, validate selected damaging regimes and develop technology to mitigate risk in the end-to-end process for UBM credit

UBM END-TO-END PROCESS

Calculation of a UBM credit, or usage based retirement time, is predicated on the ability to conservatively estimate accrued damage from monitored part usage as notionally shown in Figure 2. This process compares the CWC conservative damage model to that for measured usage. Safety is first maintained by estimating damage to be more severe than the actual damage accrual. Additional safety margins may also be imposed based on all of the elements in the end-to-end process.

![Figure 2 Notional UBM Process](image)

Actual measured usage may be applied to update the time for dynamic component maintenance action or retirement. This is expected most often to take the form of a credit, although retirement time could be debited if operator usage is found to be more severe than the CWC. The UBM adjustment could be applied at discrete decision points, e.g. after a certain number of flight hours that correspond to a predefined life threshold or even in a continuous mode as flight data is recorded. In addition, various life calculation options may be envisioned ranging from semi-automated offboard software and processes run by the OEM, to fully automated software in the ground station or onboard in the HUMS. Combinations of these options present various opportunities for insertion of UBM technologies in current practices and to grow and expand application of UBM credit as the technology matures.

The UBM end-to-end process outlined here is developed accordingly for an offboard credit evaluation process and one-time life adjustment. In the future, as more experience is gained with the use of UBM technologies, one may envision a scenario where fully automated software is developed and maintained by the manufacturer but delivered to the fleet operator for processing in the ground station. Ultimately, UBM software could be implemented in a fully onboard fashion.

Ref. 1 provides guidance for achieving airworthiness approval for HUMS installation, credit validation, and instructions for continued airworthiness (ICA), in particular for any process or application that intervenes with maintenance of rotorcraft flight critical components. As Figure 3 shows, installation, credit validation, and ICA are not completely independent.

Installation requirements show that the system as installed, including all the hardware, software, and decision processes, complies with the criticality level associated with the component for which a credit is sought.

Credit validation requires that (1) accrued and accumulated damage must be founded on physics of fatigue analysis and material reliability and (2) reliability factors must be built to deal with various sources of uncertainty in damage calculations. Additionally empirical evidence must be produced to demonstrate the validity of the methodology. Credit validation requirements are particularly important to demonstrate compliance of the installed system and its continued airworthiness.

In order for the system to remain in service, instructions for continued airworthiness (ICA) are required to demonstrate that operating procedures and instructions are available to the operator.

The term "end-to-end" as used by AC-29 MG 15 is intended to address the boundaries of the HUMS application and the effect on the aircraft. The boundaries are the starting point that corresponds
with all the hardware, software, and processes involved in the data flow from airborne data acquisition to the result that is meaningful in relation to the defined credit without further significant processing. Therefore the integrity and accuracy of data (as measured, sampled, stored, transferred, or quantized) and the validity of all algorithms used in the process drive the validity and qualification of the end-to-end process. The proposed end-to-end process for credit calculation and evaluation is shown in Figure 4.

Every production Sikorsky S-92 aircraft comes equipped with HUMS and data is transferred on a daily basis to the OEM in an FAA approved process. In the proposed UBM process, there are no changes to the existing on-board equipment or procedures for transferring and storing data. To obtain a UBM credit, the operator would request a retirement time adjustment when the subject component reaches a threshold, for example 75% of the original CRT. In a post-processing mode, Sikorsky would mine the fleet database to validate HUMS data and inspect maintenance records for the component. Sikorsky would then calculate a life adjustment for the component with a human in the loop to provide expert judgment, and recommend a UBM credit adjustment via an FAA approved UBM procedure for the component. Upon approval of the retirement time adjustment by a designated authority, the OEM notifies and supplies instructions to the operator. The operator or maintainer will make the appropriate adjustment to the component hours based upon the approved UBM credit.

HUMS INSTALLATION AND ICA COMPLIANCE
The installed S-92 HUMS is manufactured by Goodrich and consists of data acquisition and processing hardware and software. The airborne system interfaces with sensors and sub-system data buses. The data is written to a memory card for data transfer to the ground station, a commercial off the shelf personal computer with HUMS data processing software.

HUMS RR algorithms are used to identify and categorize how the aircraft has been flown. All HUMS RR inputs are essential for flight and originate from avionics units that have the highest levels of reliability for hardware and associated software. The RR processing routine collects basic aircraft data from available sensors on the aircraft and then checks these parameters against a set of predefined conditions to determine the
aircraft flight regime. The actual identification of a regime is accomplished by using configurable definition tables. A definition that is used for the identification of a regime consists of a set of expressions that are combined using Boolean Compound “AND” logic. If all expressions are true for a particular definition, then the aircraft is determined to be in the defined regime. The regime recognition data flow is illustrated in Figure 5 showing standard input and output data types.

Input data includes basic aircraft and system data, external atmosphere derived data, aircraft attitude, stick position, and accelerations. The key performance parameters are classified into bands such as Gross Weight, Airspeed, Altitude Density, Engine Torque, Load Factor and Rotor speed. The output includes derived parameters, Regime record, Event record, and Log record. Additional outputs include derived parameter calculations such as heading, ground velocity, weight on wheels flag, etc. HUMS regime packet data output is updated every second.

During the development of the S-92 RR algorithms, Sikorsky mapped the process of regime determination into a series of logic diagrams based on the available HUMS parameters. Flight maneuvers were separated into low and high speed flight regimes, while ground based regimes were split into Ground Operations, Takeoffs, and Landings. Entry to low speed flight occurs when Weight-On-Wheels, landing, and Takeoff “Flags” are false and airspeed is below 40 knots. The specific low speed regime is determined by stepping through the logic tree. Similarly, the regimes are determined for High Speed, above 40 knots. This approach ensures that each regime is unique and mutually exclusive from the rest.

All HUMS software algorithms were evaluated in the Sikorsky HUMS Development Laboratory prior to installation on airborne equipment. Once installed, regime processing occurs continuously and in the background, when the main processing unit is powered. Regimes are defined in a manner that allows efficient search and a smooth transition between regimes while eliminating gaps. The data validity for each parameter used in an expression is also checked. If a parameter used for a definition is invalid, the regime is marked as “Undetermined.” If all of the parameters are valid and none of the definitions are found to match, then the regime is declared as “Unrecognized”.

The installed S-92 HUMS hardware and software satisfy FAA certification requirements and have demonstrated continued airworthiness for over 150,000 of fleet flight hours of operation. In addition, the methods for data transfer to the ground station and subsequent data transfer and storage at the OEM have demonstrated compliance by employing established data management and data integrity methods for use in mechanical diagnostics applications. Likewise, RR algorithms have been functioning consistently and provided usage information for every aircraft in the fleet. However, the RR algorithms have not been verified for compliance with credit validation requirements.

**HUMS RR CREDIT VALIDATION EVALUATION**

In order to meet credit validation compliance criteria of Ref. 1, the component(s) for which UBM credit is sought must be selected. Definition of these components is based on a variety of considerations such as business objectives (e.g. cost of early retirement or replacement of the
component) and ease or validity of applying the UBM credit process on the component.

To select components for this effort, all life-limited S-92 components were investigated. In a previous Sikorsky research and development effort, the S-92 hub was the subject of a credit evaluation based primarily on direct measurement of centrifugal Ground-Air-Ground (GAG) cycles which are the major contributor to fatigue damage for that component. In order to build upon that experience, the components selected for this program targeted a critical steady state maneuver whose damage is proportional to the total time spent in the regime. The swashplate was selected because it showed the most damage from steady regimes. Further examination of the UBM credit validation process is achieved by measuring transient maneuvers whose damage is dependent upon the number of occurrences. The Main Rotor (MR) damper was selected because it had the largest contribution of damage from transient regimes. Also, the other MR damper damaging maneuvers are similar to the swashplate, so that the verification of regimes for that component will be directly applicable. Figure 6 illustrates the S-92 components selected for UBM credit examination.

The swashplate and MR damper fatigue substantiation documents show that high bank angle steady right turns, which have higher loads than the corresponding left turns, and symmetric pullout transient maneuvers are the most damaging regimes for these components. Rather than try to rigorously evaluate all HUMS regimes, the developed approach focuses on key regimes that are found to be damaging to selected components that are considered good candidates for UBM. The RR analysis was therefore narrowed to these types of maneuvers for evaluation of credit validation compliance in the end-to-end UBM process.

The damage calculation process for UBM credits remains unchanged, adhering to existing FAA approved fatigue substantiation methodology for ensuring aircraft flight safety and airworthiness. Material strength and loads shown in Figure 1 are not adjusted, and so the UBM credit validation evaluation will consider only items related to usage monitoring via HUMS RR algorithms.

Evaluation of HUMS regimes requires a set of validation, or ‘truth’ data. The primary set of truth data is considered to be the pilot declarations from scripted flight tests. This project utilized flight loads survey data from a HUMS equipped S-92 aircraft that was fully outfitted with load measuring instrumentation. In addition, a representative 1,600 flight hour sample of existing S-92 fleet data was used to further validate algorithm performance as compared to the conservative CWC design usage spectrum.

An S-92 flight loads survey provided an opportunity to gather HUMS information in a controlled environment that is comprised of precise maneuver execution and rigorous measurements, thereby providing a valuable set of truth data for RR algorithm verification. A significant portion of the evaluation process involves referencing HUMS data to S-92 flight test data available on the Sikorsky Advanced Data Acquisition & Processing System (ADAPS). Run Logs are stored in ADAPS and represent formal versions of the pilot card which may have been modified during the test, and document data for configuration and maneuvers. ADAPS also stores all of the recorded data from the flight test that can be plotted as a time history.

HUMS and ADAPS traces can be compared for data integrity and accuracy. Table 1 shows a side by side comparison for a typical CWC maneuver sequence: 30 degree right turn entry, steady turn, and recovery. As shown, there is not a one-to-one correspondence between HUMS and the CWC maneuvers. Instead, HUMS typically identifies numerous regimes.
Starting at the beginning of this flight test run, HUMS correctly recognized a forward flight steady condition where the ADAPS data recording began. During the turn entry, HUMS recognizes a generic right turn. When the aircraft settles into a 30 degree bank, HUMS correctly detects the condition. During the ADAPS steady turn, the HUMS regime carries over from the entry and does not break at the same time as the run log. Next, a partial power decent is recognized in the middle of the steady turn. After examination of the time history data and flight parameters, it was found that the aircraft was within flight test tolerances for a level turn, but there were brief periods where the rate of climb fluctuated, showing that HUMS is sensitive to changes in that parameter and ‘toggles’ back and forth to the generic 30 degree level right turn. During the ADAPS turn recovery, HUMS identified several regimes, including back-to-back occurrences of a steady climb and a return to forward flight. Overall HUMS identified seven different regimes and ten total regime counts with some instances of toggling back and forth and others back-to-back.

The sensitivity of the HUMS and the associated toggling behavior creates disparities with the intended CWC maneuver. This must be reconciled before applying the measured usage to the established CRT analysis. Per the analysis, the middle portion of the turn is categorized as a steady maneuver because the loads are not fluctuating and the associated damage is directly proportional to its time duration. However, HUMS toggling does not permit an accurate measurement of the time spent in the steady turn. Also per the established CRT analysis process, the entry and recovery portions are categorized as transient maneuvers because the loads fluctuate significantly and are accordingly modeled on an occurrence basis. The HUMS toggling behavior results in an inaccurately large count of transient maneuver occurrences.

Although HUMS correctly identifies the intended CWC maneuver during some part of the flight test run, a methodology for UBM credits must address the observed toggling behavior due to the sensitivity of the currently implemented HUMS RR algorithms. The approach taken for this effort is to only post-process the HUMS sequence data in the ground based system to collect the separate HUMS regime classifications and aggregate them into a single set that represents the intended CWC maneuver. The intent of such an off-aircraft approach is to achieve benefit from existing HUMS RR algorithms to obtain UBM credits without the need to develop perfect onboard algorithms. However, in the future, RR algorithms could be modified to adjust their sensitivity so that toggling is avoided in the onboard system.

### REGIME POST-PROCESSING ALGORITHM

The installed HUMS RR algorithms tend to identify numerous short regimes in place of an intended longer duration whole maneuver. The root cause for this toggling behavior is that a HUMS regime is a categorical map that corresponds to narrowly defined regions in the continuous parametric space. For example, Figure 7 shows how several HUMS regimes can be recognized during a single maneuver. In the figure, the aircraft enters a turn from level flight at point number 1. While starting the turn, it may temporarily climb slightly in which HUMS identifies a climbing regime. If the rate of climb reduces past a certain level, HUMS might recognize a generic turn that has not reached a steady condition. If the rate of climb again fluctuates, HUMS may recognize a climbing turn as shown by point number 4 in the figure. Eventually, HUMS will recognize a 30 deg turn after the roll angle has crossed over a parameter bound, as shown by point number 5. The turn recovery may go through similar fluctuations among several regimes prior to returning to a level flight condition at point number 7. Perturbations around the value of one or more parameters alter the HUMS RR output. This phenomenon leads to difficulties with

<table>
<thead>
<tr>
<th>ADAPS Run Log</th>
<th>Log Time (sec)</th>
<th>HUMS RR Output</th>
<th>HUMS Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rt Turn 30 Entry</td>
<td>10</td>
<td>Fwd Flt</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Generic Level Rt Turn</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Generic Level Rt Turn 30 deg</td>
<td>3</td>
</tr>
<tr>
<td>Rt Turn 30</td>
<td>13</td>
<td>Generic Level Rt Turn 30 deg (cont’d)</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Partial Power Decent Rt Turn</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Generic Level Rt Turn 30 deg</td>
<td>5</td>
</tr>
<tr>
<td>Rt Turn 30 Recovery</td>
<td>15</td>
<td>Generic Level Rt Turn 30 deg (cont’d)</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Right Turn in Climb</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Steady Climb</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Steady Climb</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fwd Flt</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Partial Power Decent</td>
<td>2</td>
</tr>
</tbody>
</table>
processing HUMS output for UBM credits, namely underestimating total percent time and overcounting occurrences of the intended target maneuver. However because the regime parameter definitions are static and the physics of flight of the aircraft is predictable, it is hypothesized that a unique set of regimes are expected to be recognized every time the aircraft executes a turn maneuver.

In order to address this root cause, this project developed a method to effectively post-process the HUMS regime sequence data. As shown in Figure 8, the existing HUMS installation will be used and the output post-processed to quantify the monitored aircraft usage. This is accomplished by appropriately mapping the HUMS regime sequence output into quantifiable CWC spectrum regimes. The CWC mapping process is optimized to minimize the uncertainty in the mapped regimes vs. a set of truth data and to ensure conservative calculation of accumulated fatigue damage.

In order to map the HUMS output to the CWC maneuvers, a ‘clustering algorithm’ has been developed for aggregating HUMS regime sequence segments around an intended target maneuver of interest from the CWC spectrum. Clustering is a way to solve the current problem and enables HUMS output to be used to accurately measure occurrences and durations.

Figure 9 illustrates the outcome of the clustering algorithm. The process aggregates HUMS regimes that are not explicitly mapped to the intended target maneuver based on the following criteria:

1) The regime segment is likely to be picked by HUMS during an intended target CWC maneuver. (Because there is not a one-to-one correspondence between HUMS and CWC regimes, the target CWC maneuver must be described instead as a set of RR labels that most closely resemble it, i.e. the ‘target set’.) These regimes around the target are known as ‘cluster regimes’ and are determined via analysis of flight test data and engineering judgment.

2) The cluster regime does not exceed an expected duration that would indicate it is a correctly identified regime that stands alone from the target. The duration is known as the ‘persistence parameter’ and is tied empirically to the flight characteristics of the aircraft.

3) The cluster regimes that satisfy the persistence parameter must be in close proximity to the target maneuver in the HUMS sequence. A cluster is deemed valid only if it contains an element of the target set. Otherwise, it is considered an ‘empty cluster’.

The cluster definitions (target set and cluster regimes) must first be established and an initial persistence parameter chosen using flight test data and fleet data. Next the persistence parameters are calibrated based on a sample of truth data comprised mainly of fleet information from which occurrence and duration of intended maneuvers are estimated via analysis of parametric data.
Finally, the model is checked against all available truth from flight test and the fleet to determine its validity and quantify its reliability.

1. Damage estimation uses observed flight spectra as obtained from HUMS regime sequences which are further post processed via a clustering algorithm

<table>
<thead>
<tr>
<th>Time</th>
<th>Description</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>11:14:51</td>
<td>49: Forward Flight to 0.8 Vne</td>
<td>15</td>
</tr>
<tr>
<td>11:15:06</td>
<td>83: Generic Level Right Turn</td>
<td>3</td>
</tr>
<tr>
<td>11:15:09</td>
<td>83: Generic Level Right Turn, 30deg AOB, 0.8 Vne</td>
<td>10</td>
</tr>
<tr>
<td>11:15:19</td>
<td>44: Right Turn During Climb</td>
<td>3</td>
</tr>
<tr>
<td>11:15:27</td>
<td>83: Generic Level Right Turn, 30deg AOB, 0.8 Vne</td>
<td>29</td>
</tr>
<tr>
<td>11:15:56</td>
<td>44: Right Turn During Climb</td>
<td>2</td>
</tr>
<tr>
<td>11:15:58</td>
<td>48: Steady Climb</td>
<td>4</td>
</tr>
</tbody>
</table>

2. The algorithm reconstructs from low level sequences of HUMS regimes high level clusters of maneuvers whose durations and counts are relevant to the CRT analysis

<table>
<thead>
<tr>
<th>Time</th>
<th>Description</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>11:14:51</td>
<td>49: Forward Flight to 0.8 Vne</td>
<td>15</td>
</tr>
<tr>
<td>11:15:06</td>
<td>83: Generic Level Right Turn</td>
<td>3</td>
</tr>
<tr>
<td>11:15:09</td>
<td>83: Generic Level Right Turn, 30deg AOB, 0.8 Vne</td>
<td>10</td>
</tr>
<tr>
<td>11:15:19</td>
<td>44: Right Turn During Climb</td>
<td>3</td>
</tr>
<tr>
<td>11:15:27</td>
<td>83: Generic Level Right Turn, 30deg AOB, 0.8 Vne</td>
<td>29</td>
</tr>
<tr>
<td>11:15:56</td>
<td>44: Right Turn During Climb</td>
<td>2</td>
</tr>
<tr>
<td>11:15:58</td>
<td>48: Steady Climb</td>
<td>4</td>
</tr>
</tbody>
</table>

3. The algorithm parameters calibrated using fleet data and other sources and validated/fine tuned based on expert screening. Cluster durations may be increased based upon a calculated reliability factor

Figure 9 Clustering of HUMS Regime Sequences

A calibration of the persistence parameters is performed on a representative sample of fleet data. One method to do this is by histogram matching, as shown in Figure 10. A calibrating flight parameter is queried from the sample of fleet data that is closely tied to the CWC maneuver of interest. For example, roll angle is a reasonable parameter by which to measure turns. Turns are identified by excursions to and from a near zero roll angle. The turn durations from the fleet are quantified and plotted on a histogram. The clustering algorithm is run with various persistence parameters and the cluster durations are plotted on histograms to compare against the one based on roll angle. As shown in the example, a persistence of 9 seconds best fits the data and is reasonable to expect from aircraft performance characteristics. Either a single persistence parameter can be employed or different values tailored to specific cluster maneuvers.

Figure 11 shows the details of a 30 degree turn cluster identified in the fleet data. The roll angle parameter from the recorded flight data is overlaid along with the HUMS regime sequence labels. Shaded regimes are members of the target set while the non-shaded regimes are members of the cluster set. The HUMS sequence identifies two occurrences of a generic 30 degree turn, in essence ‘double counting’ the maneuver. Furthermore, the total duration according to the targets is only 39 seconds vs. the 56 second cluster duration. Note that the persistence parameter for the 30 degree cluster definition is tailored for different cluster regimes. The steady portion of the turn is shown to be 41 seconds.

Figure 12 shows a result from the application of a symmetric pullout maneuver clustering algorithm. After calibrating with fleet data, the algorithm was...
applied to flight test data. In this case, the HUMS sequence correctly recognizes a single occurrence of the pullout (note that this is not always the case and often multiple occurrences are recorded). However, the duration is only 3 seconds vs. the 10 second cluster duration. If the pullout duration is considered to be from a 1.0g loading condition, the actual duration is about 7.5 seconds. However to increase reliability, the clustering algorithm conservatively adds one second to each end of the cluster since the HUMS updates at a 1 Hz rate.

These examples show that the clustering algorithm represents the intended CWC maneuvers very well and can rectify the current HUMS toggling phenomenon. Even though the clustering results are much more compatible for UBM than current HUMS performance, reliability factors must be built to deal with various sources of uncertainty. Intuitively there are three scenarios that could result from inaccuracies in the clustering methodology.

Over-clustering: the choice of algorithm parameters may lead to extended cluster lengths where too many regimes are aggregated and individual instances of the target CWC maneuver are lost in a larger grouping. While large clusters typically imply more conservative damage estimation based on duration, maneuver counts will be low.

Under-clustering: the choice of algorithm parameters, e.g. small persistence, may lead to fragmented clusters that do not capture the entire intended CWC target. This may lead to larger number of counts but smaller cluster durations.

Misses: even if the RR algorithm performs as designed, there may be instances where the intended target maneuver is not detected.

Once these potential inaccuracies are investigated and quantified, appropriate revisions must be made and reliability factors must be developed to deal with residual errors.

**CLUSTERING ALGORITHM CREDIT VALIDATION COMPLIANCE**

Calculation of credits using this method with a HUMS derived spectrum is obviously subject to uncertainties which must be addressed during various steps of the proposed process in order to maintain the same accepted high levels of reliability in the CRT analysis based upon the CWC spectrum. Since usage-based damage calculations depend on the observed HUMS regime only through mapping to CWC, it is the error in the mapped CWC regimes that determines the error in calculated damage.

Quantifying error for this approach involves computing probability distributions for observed regimes given aircraft operations in any given maneuver. In practice developing such probability distributions is a highly complex problem requiring extensive amount of data. Flight test is the best source of data but by itself would result in enormous and expensive flight test programs. Consequently, this program focuses on providing meaningful data for the calculation of reliable UBM credits considering data available from flight test
and the operational fleet. Success for determining appropriate reliability factors is increased by

1) focusing on the damaging regimes for selected dynamic components,
2) combining experimental data with fleet data to improve the accuracy of HUMS error estimates, and
3) keeping an engineering expert in the loop to provide sound judgment based on knowledge of fatigue substantiating parameters and aircraft performance.

Figure 13 shows the overall process for the clustering algorithm reliability assessment. After the algorithm has been defined for the CWC maneuver of interest, it is tested to determine how it detects all occurrences of maneuvers in the validation data sets. Since the flight test data is crucial to the clustering algorithm, examination and filtering of such data prior to use is essential. Indications of overclustering and underclustering are noted and the persistence parameter tailored as necessary. If there are missed targets, these are further investigated by examining available loads and state parameters to see if they are damage causing events. If so, the possibility of modifying the cluster definition is examined, for example expanding the target set definitions to include the damaging event. If implemented, the adjusted clustering algorithm is checked again with the validation data. If the existing cluster definitions can’t be changed to include these regimes, another option is to create a new cluster definition for these maneuvers. These steps are repeated until the cluster definitions are optimized. Final statistics are determined to develop reliability factors for maneuver duration and counts. For those missed conditions that are not detected, similar statistics are generated and used to determine appropriate reliability factors.

Once the cluster definition for a CWC maneuver has undergone this process, no more improvement can be gained from the clustering algorithm capabilities, and the associated reliability can be determined through the analysis of errors for the three categories described earlier, i.e. over-clustering, under-clustering, and misses.

The reliability process described applies to the estimate of accrued actual part damage based on recorded HUMS data. Any missing data in the HUMS records are filled with the original design CWC usage. When calculated the UBM credit, future usage is assumed to be CWC.

The reliability model for credit validation compliance will also provide data to be considered for a controlled introduction to service strategy. Such a plan includes a gradual transition from the current time-based practice. During the time that maintenance decisions are being made via time-based methods, independent verification means may be employed to ensure correctness of HUMS based damage computations.

Finally it is noteworthy that the approach described in this paper addresses calculation of credits at both the serial number and part number levels. Tracking the usage on individual HUMS-equipped
aircraft tail numbers allows construction of the specific usage history for the component serial number. In contrast, UBM credit at the part number level involves examining data over the fleet to determine a usage-based updated CWC spectrum which is not as severe as the original design CWC but still encompasses all operational aircraft. Sikorsky ground test and structural methods engineers have previously developed an approach that is applicable to a fleet-wide UBM credit validation (Ref. 2). This approach prescribes a reliability factor as the ratio of two suitable percentiles (e.g. 90 to 50) of a probability distribution fitted to the sampled points. This reliability factor would be applied to all UBM damage calculations for a component.

CONCLUSIONS
An end-to-end process definition was presented for S-92 UBM credits that is believed to be compliant with AC 29-2C, technically sound, and works within the available HUMS process. Currently airworthy hardware and procedures for HUMS data collection are maintained that adhere to FAA standards. The installed HUMS RR algorithms, while appropriate for general monitoring of aircraft usage, were evaluated against credit validation requirements and found to be incompatible with Sikorsky fatigue substantiation procedures in their present implementation.

A new post-processing technique known as a ‘clustering algorithm’ was developed that would be a key ingredient to fulfill the FAA credit validation compliance criteria by successfully mapping HUMS RR sequence output into selected damaging CWC regimes that can be used in the existing retirement time analytical process. An important consideration in the development of the cluster definitions for damaging regimes is the integrity of flight test data. An engineer in the loop is necessary to substantiate the accuracy of the verification data sets and to ensure that the clustering algorithm parameters are compatible with known physics of flight and aircraft performance characteristics. A process to quantify errors from the clustering algorithm was defined to ensure the levels of reliability necessary for UBM credit determination. The research described in this paper is a substantial step forward toward the realization of HUMS-enabled UBM credits.

ACKNOWLEDGEMENTS
The authors wish to acknowledge Dr. Xiaogong Lee and Traci Stadtmueller of the FAA Rotorcraft Technical Center for their support of this work under Agreement No: DTFACT-06-C-00002.

REFERENCES