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Structural Usage Monitoring and Flight Regime Recognition—Compliance Validation and Demonstration Using the Health and Usage Monitoring System Advisory Circular 29-2C MG 15

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Final Report

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16. Abstract

Monitoring actual aircraft structural usage could increase rotorcraft safety enhancements provided by Health and Usage Monitoring Systems (HUMS) and could potentially reduce operating costs via usage-based maintenance (UBM) credits. While flight regime recognition (RR) algorithms have been demonstrated, none have been fully validated; additionally, obtaining UBM credit approval remains elusive and presents complex certification issues. The FAA funded this research and development effort to establish and demonstrate a viable approach for validating and certifying HUMS RR-enabled UBM credits. An end-to-end UBM process was defined that fulfills the objectives of Advisory Circular (AC) 29-2C, is technically sound, and works with available HUMS. The Sikorsky Aircraft Corporation (SAC) S-92® aircraft was used as a representative platform to demonstrate elements of the process.

The existing S-92 HUMS RR algorithms were evaluated using extensive fleet data. The onboard RR results cannot be used directly because of inconsistencies found with the established SAC fatigue substantiation procedures. However, the onboard algorithms produced sufficiently accurate results to be used for UBM with appropriately defined offboard data mining processing by the rotorcraft original equipment manufacturer. T his would allow UBM credit validation and AC compliance without changing the current HUMS installation, onboard RR algorithms, or fatigue substantiation methods. A new postprocessing technique, known as a regime-clustering algorithm, was developed that would be key to successfully mapping HUMS onboard system RR sequence output into selected damaging composite worst-case (CWC) usage spectrum regimes, which can be used in the existing retirement time analytical process. A key feature of the procedure is the automatic calculation of reliability factors that account for uncertainties in the clustering algorithm to maintain the baseline reliability of the original retirement time analytical process. Clustering algorithms were applied to a significant amount of fleet data for a subfleet of ten aircraft. Retirement time adjustments for the S-92 main rotor stationary swash plate were estimated by serial number for individual aircraft and by part number for the subfleet. For an individual component, improvements over the conservative retirement times were approximately 30%-40% based on an assumption of original CWC usage for all future operations. For a fleetwide adjustment, an improvement of more than 100% was shown to be feasible by using an updated CWC usage spectrum throughout the entire component lifetime based on availability of a statistically significant amount of fleet data and implementation of an additional usage monitor reliability factor.

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LIST OF ACRONYMS

AC	Advisory Circular
ADAPS	Advanced Data Acquisition and Processing System
ADC	Air data computer
ADS	Aeronautical Design Standard
AHRS	Altitude Heading Reference System
AMM	Aircraft maintenance manual
AoB	Angle of bank
APU	Auxiliary power unit
AWL	Airworthiness limitation
BIT	Built-in test
BMU	Bearing monitoring unit
CBM	Condition-based maintenance
CCRF	Cluster count reliability factor
CDAR	CWC Damage Accumulation Rate
CDRF	Cluster duration reliability factor
CFR	Code of Federal Regulations
CIS	Controlled introduction to service
CISP	Controlled Introduction to Service Plan
CG	Center of gravity
COTS	Commercial off-the-shelf
CP	Copilot
CRC	Cyclic redundancy check
CRT	Calculated retirement time
CVP	Credit validation plan
CWC	Composite worst case
D	Damage
DAQ	Data acquisition
DSP	Droop stop pounding
DTU	Data Transfer Unit
E&R	Entry and recovery
EFH	Effective flight hours
ETFHR	Estimate of total flight hours at retirement
FAA	Federal Aviation Administration
FADEC	Fully Automated Digital Engine Control
FAR	Federal Aviation Regulation
FHA	Functional hazard assessment
FLE	Fatigue life expended
FLS	Flight loads survey
FMECA	Failure modes, effects, and criticality analysis
FMOC	Fleet Management Operations Center
fps	Feet per second
FTP	File transfer protocol
Fwd	Forward
g	Load Factor

GAG	Ground-Air-Ground
GBS	Ground-based system
GS	Ground station
GSS	Ground station software
GW	Gross weight
GWE	Gross weight expansion
GUI	Graphical user interface
HOMP	Helicopter Operations Monitoring Program
HQ	Handling qualities
HUMS	Health and Usage Monitoring System
IBIT	Initiated built-in test
IBTF	Integrated Bench Test Facility
i.i.d.	Independent and identically distributed
ICA	Instructions for Continued Airworthiness
IFR	Instrument Flight Rating
IPT	Integrated Product Team
IGE	In-ground effect
IMD	Integrated mechanical diagnostics
I/O	Input/output
kt	Knots
LLP	Life-limited part
LPP	Loading for peak-to-peak
LSS	Loading for steady state
LT	Left
LTR	Loading for transient
MDC	Maintenance data computer
MG	Miscellaneous Guidance
Mod	Moderate
MMEL	Maintenance minimum equipment list
MMIS	Maintenance Management Information System
MPU	Main processing unit
MR	Main rotor
MUD	Memory unit download
NR	Design rotor speed
OBS	Onboard system
ODA	Organization Designation Authorization
OGE	Out-of-ground effect
OEI	One engine inoperative
OEM	Original equipment manufacturer
PC	Personal computer
PCMCIA	Personal Computer Memory Card Interface Adaptor
PDAR	Peak-damage accumulation rate
PPD	Partial power descent
PRCP	Preretirement checkpoint
QA	Quality assurance

RDF	Raw data file
RFH	Remaining Flight Hours
RR	Regime recognition
RRC	Regime recognition clustering
rpm	Revolutions per minute
RT	Right
RUL	Remaining useful life
S-N	Stress-life
S/W	Software
SAC	Sikorsky Aircraft Corporation
SAR	Search and rescue
Sev	Severe
SUM	Structural usage monitoring
Sym	Symmetric
T	Time duration
TR	Tail rotor
UBM	Usage-based maintenance
UMRF	Usage monitor reliability factor
V&V	Verification and validation
VBROC	Velocity at best rate of climb
Vma	Velocity for autorotation
Vne	Velocity not to exceed
WCS	Web coverage service
WOW	Weight on wheels
WPB	West Palm Beach

EXECUTIVE SUMMARY

Current Health and Usage Monitoring Systems (HUMS) typically perform vibration monitoring, exceedance monitoring, and rotor track and balance to detect mechanical faults and to avoid mechanical failures in rotorcraft. Further improvements could be achieved by fully exploiting the capability of structural usage monitoring (SUM) algorithms (e.g., regime recognition (RR)) that are also included in many existing HUMS. Knowledge of actual aircraft structural usage would ensure safe usage profiles and potentially reduce operating costs via usage-based maintenance (UBM) credits. While advanced SUM algorithms have been demonstrated, an end-to-end UBM process has (as of this writing) not been validated as being compliant with Advisory Circular (AC) 29-2C Miscellaneous Guidance (MG) 15, which provides high-level guidance for obtaining airworthiness approval of HUMS-based credits. SUM and UBM credits in particular have remained elusive, presenting complex certification issues for both the airborne- and ground-based parts of the system. As a result, the Federal Aviation Administration (FAA) funded this research to establish and demonstrate a viable approach to validate and certify techniques for SUM and UBM credits.

The Sikorsky Aircraft Corporation (SAC) used the S-92® aircraft as a representative platform to develop, validate, and demonstrate elements of an end-to-end UBM process that (1) fulfills the objectives of the AC, (2) is technically sound, and (3) can be used without significant changes to existing HUMS hardware, SUM software, and data management processes. The S-92 has a state-of-the-art HUMS that is fully integrated with the avionics suite and installed as part of its baseline configuration. The HUMS airworthy hardware and procedures for HUMS onboard data acquisition and offboard data management processes were certified in compliance with the AC. Over time, the state-of-the-art SUM regime recognition (RR) algorithms deployed in the S-92 HUMS have proven to provide reasonable results and significant insight into how an aircraft and the fleet, in general, are being used.

The objective of the current program is to establish a UBM end-to-end process that can maintain aircraft reliability and airworthiness risks that are at least as good as the baseline reliability and risks associated with current FAA-approved design and fatigue life management methods. This results in the following two goals:

- Verification that SUM algorithms measure the actual aircraft usage spectrum within an acceptable level of accuracy.

- Substantiation that the reliability of the component retirement process under the proposed UBM approach is consistent with current practice.

Under the current program, the existing S-92 HUMS RR algorithms were evaluated using extensive flight test and fleet data. It was concluded that the onboard RR results cannot be used directly because of some inconsistencies found with the established SAC fatigue substantiation procedures. However, the inconsistencies were addressed by offboard processing by the rotorcraft original equipment manufacturer (OEM), allowing FAA credit validation and compliance with AC criteria without changing the current HUMS installation, algorithms, or fatigue substantiation methods. A new postprocessing technique, known as regime-clustering algorithm was developed that would be key to successfully mapping HUMS RR sequence output

into selected damaging composite worst-case (CWC) usage spectrum regimes used in the existing retirement time analytical process.

A dedicated, scripted flight test was conducted to validate and demonstrate the installed HUMS RR algorithm performance for high-bank angle turns and pullouts, which are the most damaging regimes for the main rotor (MR) swash plate that was selected as a representative component for demonstrating the credit validation procedure. The flight test results indicated that the current onboard HUMS RR algorithms correctly detected a pullout at some point in the maneuver for 100% of the test points flown. For high-bank turns from level flight, the correct roll angle was detected in at least 89% of the test runs. However, for more complex turns, such as those in dives or aggressive left-right combinations, the correct bank angle turn was detected in only 25% of the maneuvers flown.

The clustering algorithm eliminates the need for perfect onboard RR performance. Using the existing RR onboard output, the clustering algorithm produced monitored turn and pullout maneuver counts and durations, along with data-driven reliability statistics, to provide a substantially improved level of accuracy that is acceptable for retirement time adjustments. Cluster definitions were determined using a verification data set consisting of both scripted flight test and in-service operational data. Process integrity is maintained by an OEM engineering expert who substantiates the accuracy of the verification data sets and UBM credit calculations to ensure that the clustering definitions are compatible with related data, such as known physics of flight and aircraft performance characteristics. Initial transition and certification of the proposed UBM credit would involve a controlled introduction to service in which all offboard processing and UBM adjustments would take place at the OEM, where procedures, analysis techniques, and computing systems consistent with those used in the original retirement time determination would be applied.

Clustering algorithms were applied to a significant amount of fleet data for a subfleet of ten S-92 aircraft. Retirement time adjustments for the MR stationary swash plate were estimated for an individual component (serial number-based) and for a fleetwide (part number-based) application. For an individual component, improvements over the conservative retirement times were approximately 30%-40% based on an assumption that all future usage was CWC and on the imposition of reliability factors. For a fleetwide adjustment with application of the updated spectrum throughout the entire component lifetime, the retirement time could be more than doubled based on the availability of a statistically significant amount of fleet data and the implementation of an additional usage monitor reliability factor.

The research described in this report is a substantial step toward the realization of HUMS-enabled structural UBM credits for dynamic components. It requires (1) only a reasonably accurate set of onboard SUM or RR algorithms certified to a s oftware criticality level commensurate with the criticality of the UBM credit, (2) a data management system that ensures data integrity as it is transferred to the rotorcraft OEM, and (3) an approach to address any deficiencies in the onboard RR or SUM algorithms through offboard data mining (e.g., regime clustering) to map into existing FAA-approved OEM design and fatigue substantiation processes. Key elements of ensuring data and process integrity throughout the end-to-end UBM process are provided. The next step is to develop a proof-of-principle UBM credit application for a specific credit and secure FAA concurrence with the approach.

1. INTRODUCTION.

Current Health and Usage Monitoring System (HUMS) applications typically perform engine and drive train vibration monitoring, exceedance monitoring, and rotor track and balance 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 (SUM). The HUMS installation typically consists of a variety of onboard sensors, algorithms, and data acquisition systems. The acquired data may be processed onboard the rotorcraft, on a ground station (GS), or both, providing the means to measure against defined criteria and to generate instructions for the maintainers and flight crew for intervention. To meet these needs, a variety of HUMS were developed and put into service. Initially, these systems were installed to demonstrate the feasibility of gathering meaningful data to modify required maintenance and operational actions. The degree of qualification required for this type of installation is relatively low.

A comprehensive knowledge of actual aircraft structural usage would ensure safe operational procedures and usage profiles and could potentially reduce operating costs via usage-based maintenance (UBM) credits. Ultimately, the rotorcraft industry's goal is to safely transition from time-based to usage-based and condition-based maintenance (UBM/CBM) methods. SUM via regime recognition (RR) supports this goal.

The established structural design methodology has relied on conservative inputs for fatigue substantiation of rotorcraft dynamic components, as shown for a typical approach in figure 1. The baseline fatigue substantiation process is described in this report. The 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 the rotorcraft original equipment manufacturer (OEM) historical knowledge of rotorcraft usage. The CWC usage spectrum is a conservative estimate of the most severe operations expected in service, typically reflecting the 90th percentile of total population of the anticipated usage.

Loads for these regimes are initially determined early in the design process through fatigue flight loads analysis, including analytical flight modeling and simulation or appropriate scaling of historical test data. This is followed by flight loads survey (FLS) tests 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, including severity, for example, a 2.5-g symmetric pullout at 150 knots. Data are typically recorded starting from a steady-state condition and ending once the aircraft has recovered from the transient portion of the maneuver. While variations exist between different OEM fatigue substantiation methods, typically, a 95th-percentile value of the recorded vibratory flight loads is conservatively used for analysis of steady maneuvers. For transient maneuvers in which significant load variability is expected, top-of-scatter load data intended to reflect the 99th percentile of the total population of the anticipated load and cycle-counting methods are used to obtain a conservative distribution of loads for each regime.

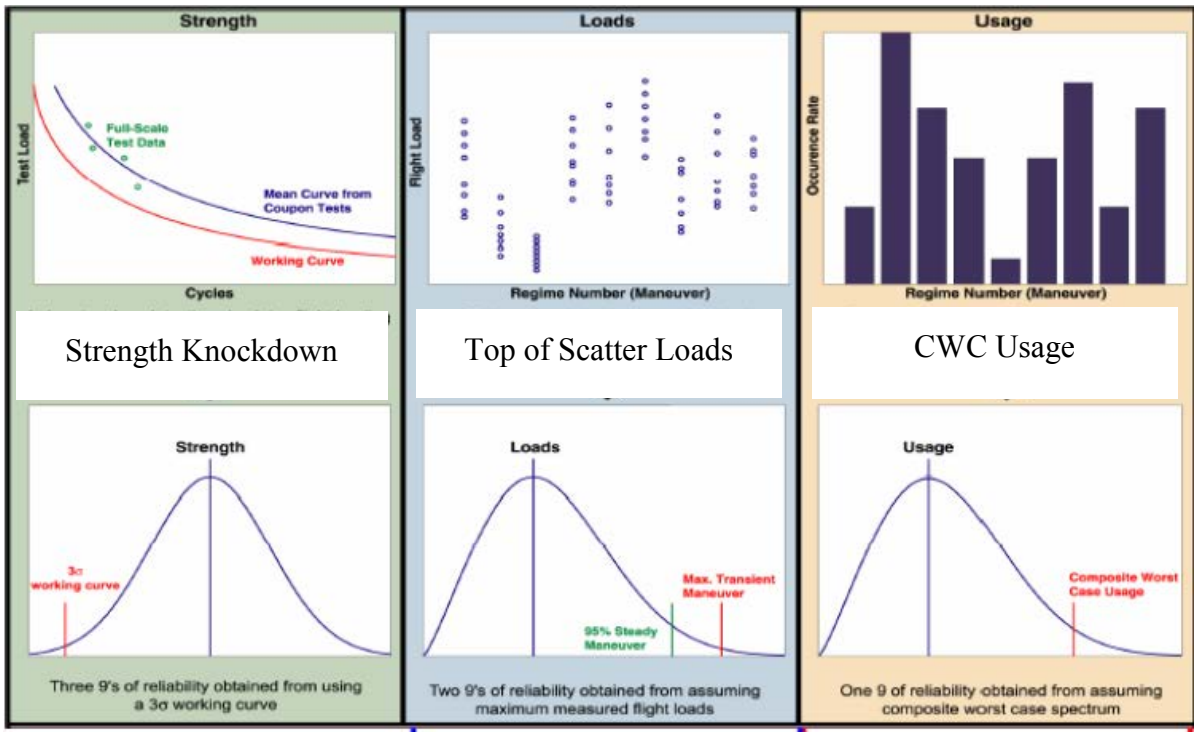


Figure 1. Inputs for Current Dynamic Component CRT Calculation

The data were then processed by the OEM engineering group responsible for fatigue life substantiation who determine a calculated retirement time (CRT) for a component using assumed CWC usage data, conservative loads, and full-scale component fatigue design working curve (e.g., stress-life (S-N) curves containing established knockdowns, typically 3 sigma) defined to reflect typically the 99.9th percentile of total population of components. Although typically equivalent to the published retirement time in the airworthiness limitations (AWL) document, the CRT value may be rounded, adjusted to match maintenance interval, or reduced as part of safe-life methodology conservatism. In this report, the term AWL CRT is assumed to be the same as the published retirement time reflecting current maintenance practiced by the aircraft operator. Along with regular inspection intervals, each OEM-specific variation of the general approach is considered safe and reliable and has been approved by the Federal Aviation Administration (FAA) for fatigue design and part life management. In general, the accepted baseline risk associated with aircraft design is less than one part in a population of one million parts will fail, providing "six-nines" or 99.9999% of baseline reliability.

One potential benefit of HUMS with embedded RR algorithms is the ability to monitor each aircraft in the fleet. The OEM can compare the actual usage spectrum for an individual aircraft or any portion of the fleet to the CWC design usage spectrum to adjust when components must be inspected, maintained, and/or retired. Such a UBM credit approach would still assume the same conservative component loads used in the current design process for each regime. Since, by definition, the CWC is supposed to represent a top-of-scatter usage among the entire fleet, substituting monitored usage would most often result in a retirement time adjustment beyond the AWL CRT. However, in the event an operator is unknowingly using the aircraft more severely than the CWC design assumptions, the same approach could be used to retire the part earlier to

maintain baseline risk standards for airworthiness. The impact of a usage monitor on the baseline six-nines process reliability has been investigated in related Sikorsky Aircraft Corporation (SAC) studies [1] and is leveraged in the development of a UBM credit.

FAA Advisory Circular (AC) 29-2C Miscellaneous Guidance (MG)-15 [2] (hereafter referred to as "the AC") provides guidance for achieving approval for HUMS and airworthiness credits. A HUMS credit (e.g., UBM or CBM) can be defined as the approval of a HUMS application that adds to, replaces, or intervenes in previously approved maintenance practices or fight operations for non-HUMS equipped systems. An airworthiness credit can be defined as the sustainment or reduction in baseline risk in allowance for a HUMS UBM/CBM credit based on the use of a validated and approved UBM/CBM system. Definitions are provided in appendix A for key terms used throughout the report. The definitions were adopted from two sources, the AC and Aeronautical Design Standard (ADS)-79B [3].

The AC establishes an acceptable, but not the only, means of certifying a rotorcraft HUMS and a process for UBM credits. The application of HUMS SUM and RR technology to obtain approved UBM credits remains an elusive goal, presenting complex certification issues related to HUMS hardware and software, for both the airborne- and ground-based parts of the system. As a result, the FAA funded the program documented herein to establish and demonstrate a viable approach for validating and certifying HUMS-based UBM credits. The AC guidelines and inferred requirements related to certification of UBM credits are discussed in section 2.

1.1 OBJECTIVE.

While advanced usage-monitoring and flight 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 the AC [2].

The objective of this research was to address both of these needs by using 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. The primary objectives of this effort were to

- develop an end-to-end UBM process that can be used to adjust a component maintenance interval (e.g., CRT) while assuring safety and reliability, and address the issues of HUMS installation, credit validation, and continued airworthiness in accordance with the AC.

- demonstrate a combination of on-aircraft and off-aircraft, usage-monitoring RR algorithms that can be used for UBM credit application.

1.2 APPROACH.

This program used the following approach to fulfill the objectives of defining and demonstrating a viable end-to-end UBM process. The S-92® aircraft was designed and produced by SAC and was used as a representative aircraft platform for defining and demonstrating the end-to-end UBM process. The S-92 aircraft has a state-of-the-art HUMS that is fully integrated into the baseline avionics suite of this digitally bussed aircraft. The S-92 HUMS airborne installation has

partially validated embedded RR algorithms. Furthermore, the S-92 HUMS is fully supported by SAC as the OEM, which has over 150,000 flight hours of fleet data. Assessments of the reliability of the onboard RR algorithms indicate that they are sufficient for initial UBM credit applications. Thus, existing onboard RR algorithms were used in this program along with newly developed offboard data-mining, regime-clustering techniques. S-92 dynamic components were used to establish representative credits to demonstrate the end-to-end UBM process. Finally, S-92 aircraft flight test and fleet data were used to validate selected damaging regimes most critical to the representative UBM credit and to estimate the potential magnitude of retirement adjustments for an operator's fleet of S-92 aircraft components (part number-based) and for individual components (serial number-based).

This report documents a proposed end-to-end UBM credit process and demonstrates compliance with the AC, using SAC processes and the S-92 aircraft as representative examples for a general methodology. Table 1 summarizes the general steps in the end-to-end UBM credit process at a high level and compares it to existing design and fatigue life management methods, using the S-92 aircraft as an example. The existing approved fatigue substantiation processes for material strength and component loads are unchanged and the component retirement time reliability is maintained for the monitored usage.

Table 1. End-to-End Comparison of Current Life Management vs UBM Credit

Item	Current Method (FAA-Approved Process)	HUMS-Based UBM Credit
HUMS installation	HUMS approved to Level B standards: DO-160 and DO-178.	No change. Less than Level B software may be sufficient for lower-criticality UBM credits.
Usage spectrum	Design usage spectrum based on CWC usage derived from all defined missions, using pilot surveys and engineering judgment (indirect evidence).	Actual usage calculated by onboard HUMS RR algorithms qualified per DO-178 standards combined with ground-based, clustering algorithm to conservatively map HUMS regimes into CWC regimes (algorithm performance validated by direct evidence from scripted flight test and operational data).
Fatigue strength	Fatigue testing to failure of critical components for multiple full-scale specimens to generate stress-life curves.	No change

Table 1. End-to-End Comparison of Current Life Management vs UBM Credit (Continued)

Item	Current Method (FAA-Approved Process)	HUMS-Based UBM Credit
Flight loads	Obtained during flight loads survey of instrumented aircraft performing representative maneuvers in design usage spectrum.	No change
Fatigue damage summation	Miner's cumulative damage	No change
Fatigue life—individual component (serial number-based)	Fatigue damage accumulation for each CWC regime based on percent time or number of occurrences.	To maintain baseline risk standards for airworthiness credit, additional reliability factors are applied to CWC regime duration and counts in previous usage. Future usage assumes original CWC spectrum.
Fatigue life—fleetwide (part number-based)	Same as for individual component.	Same reliability factors for individual component are applied plus an additional usage monitor reliability factor to account for fleet variability. Past and future usage assumes new updated CWC spectrum.

Initial transition and certification of the proposed UBM credit would involve a controlled introduction to service (CIS) in which all offboard processing and usage/retirement time adjustments would take place at the rotorcraft OEM where the same consistent procedures, analysis techniques, and computing systems as used in the original retirement time determination would be applied. After CIS, the UBM credit procedure could continue to be performed offboard by the OEM, and eventually the clustering algorithm and retirement time calculations could be moved to the onboard HUMS. It is not deemed prudent to require HUMS data processing and credit calculations by the operator, who do not have sufficient expertise to ensure process integrity using commercial off-the-shelf (COTS) hardware and software. The requirement of data processing by the operator would result in stringent certification requirements for COTS GS hardware and software that may not be practical.

The proposed method uses COTS hardware and software for downloading and transmitting HUMS data files to the OEM, but does not depend on any data processing to be conducted by the operator. COTS hardware and software are also assumed to be used by the OEM to mine the RR data, perform clustering analysis, and calculate retirement time adjustments using controlled processes similar to those used in design and fatigue substantiation.

A key feature of the clustering algorithm approach is the automatic calculation of reliability factors and confidence levels that account for uncertainties in the computational results to maintain the same or better levels of reliability as the current baseline method for the monitored component critical regimes.

2. ADVISORY CIRCULAR 29-2C HUMS GUIDANCE.

The AC [2] provides guidance for achieving airworthiness approval for HUMS installation and HUMS-based maintenance credits for a full range of HUMS applications, including HUMS-based credits that intervene with standard OEM-defined maintenance requirements for rotorcraft flight critical components. According to the AC, the following key, high-level, interdependent requirements must be addressed in a HUMS credit application, as shown in figure 2.

- Credit and end-to-end system definition
- Installation
- Credit validation
- Continued airworthiness

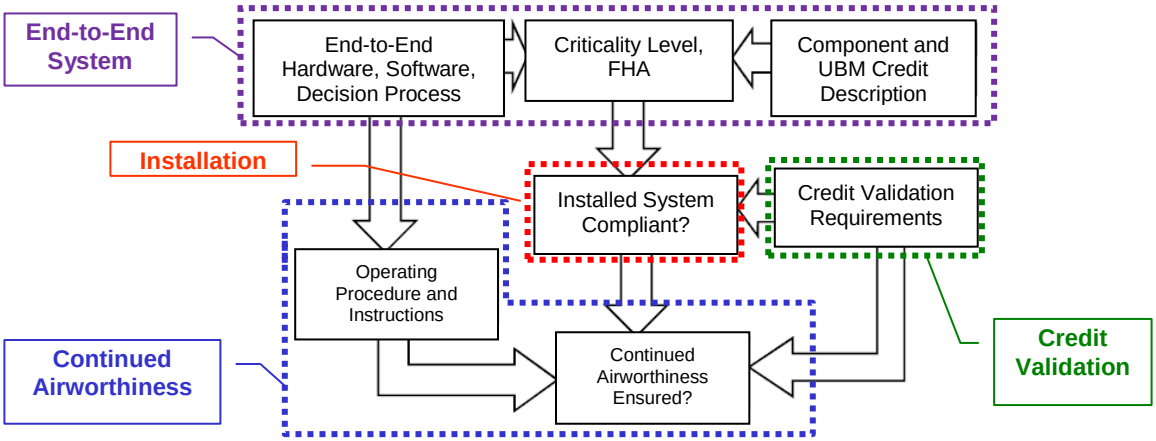


Figure 2. The HUMS UBM Airworthiness Approval

Key high-level aspects of each element are discussed below. D etailed discussion of the application of each element in the proposed end-to-end process is provided in throughout this report.

The first step toward AC compliance is to adequately define the HUMS credit, end-to-end system/process required to achieve the credit, and credit criticality. This straightforward definition establishes the framework for demonstrating compliance. In particular, credit criticality establishes the acceptable compliance methods.

The term end-to-end, as used by the AC, 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. T his starts from airborne data acquisition until a meaningful result is found relating 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 validation and qualification of the end-to-end process.

For UBM credits involving SUM and RR technology, the credit typically being sought relates to CRT extensions for one or more components. If all aspects of adjusted CRT calculations are deployed in embedded software with the HUMS, the endpoint of the system would be the data transfer mechanism from the aircraft to relevant ground-based systems used to display the results. Alternatively, if the regimes are calculated onboard, but adjusted CRTs are calculated by the OEM, then the system endpoint would reside within the OEM engineering community. Different scenarios will be discussed in section 4.4.1.

The AC definitions of system/credit criticality levels range from minor to hazardous/severe-major and are consistent with the levels and definitions given in reference 4. At the time of this writing, the AC precludes credits having the highest criticality level (Catastrophic). The airworthiness qualification requirements, which are dependent on the level of criticality, must be commensurate to the criticality of the most severe adverse effect of a failure of the end-to-end system, which results in an inappropriate maintenance action or intervention.

Standard OEM functional hazard assessment (FHA) and failure modes, effects, and criticality analysis (FMECA) processes are typically conducted to determine HUMS credit and end-to-end system criticality. Typically, an FHA is a top-down approach to identifying significant hazards to aircraft functionality and, thus, safety. For example, loss of main rotor (MR) control could result in a catastrophic failure. The FMECA is a bottom-up analysis of credible failure modes that are relevant to significant FHA-identified hazards, including analysis of cascading effects, end-item impact, and resultant criticality of the failure mode before and after taking into account mitigating actions. Credible failure modes have a reasonable probability of occurring, which may cause a system or component to go beyond a limit state, causing a loss of function and/or secondary damage. FHA and FMECA processes use engineering and pilot judgment, probabilistic risk analysis, engineering tests, and/or actual occurrences of field failures to establish credible hazards and failure modes that are likely to occur.

In aircraft product design, operational procedures and maintenance system requirements are defined to mitigate these failure modes to achieve acceptable baseline risk and reliability targets. For HUMS-based maintenance credits, risk mitigation is used to retain baseline risk and reliability despite maintenance intervention defined by the credit. In theory, risk-mitigating actions can be used to reduce the defined criticality level, but in practice, are more likely to affect qualification requirements. The FMECA traces the cascading effects to determine the worst end effect of each credible failure mode. The worst effect of all credible failure modes associated with the HUMS credit establishes the credit criticality level.

The structured FMECA process naturally results in identification of the process' weakest links allowing directed attention toward the process points of failure and the development of appropriate mitigation strategies. The unique aspects of criticality assessment for UBM credits involving RR algorithms depend on the component selected, as discussed in section 4.3.

Installation compliance requires demonstration that the reliability of the end-to-end system required to achieve the credit is commensurate with the criticality level associated with the credit being sought. Thus, installation compliance addresses all airborne- and ground-based hardware, software, and decision processes, including all elements associated with acquiring, storing, processing, and displaying the HUMS application data. Further details for RR-based UBM credits are discussed in sections 5.1 through 5.4.

Credit validation addresses the requirement to provide evidence of performance effectiveness of the end-to-end system, such as data processing algorithms, acceptance limits, and their associated validation/demonstration methods. The AC acknowledges that some evidence can, and should, be developed prior to system deployment, while other evidence must be developed under a CIS plan after system deployment. The objective of the credit validation plan (CVP) is to define the evidence required to validate that the end-to-end system provides the same, or better than, baseline system risk and reliability. The AC credit validation guidelines emphasize the importance of (1) basing the CVP and risk-mitigating actions on a solid understanding of the end-to-end system failure modes and physics of failure of cascading effects and (2) the use of reliability factors to deal with various sources of uncertainty. With respect to RR-based UBM credits, a thorough understanding of the component failure modes and loading conditions provides the basis for selecting the regimes required for credit validation for the components and credits selected. The credit validation technique developed in this research is discussed in detail in section 6.5 for RR-based UBM credits.

Finally, a plan is needed to ensure continued airworthiness of the systems and components that are affected by the HUMS-based credit. For the system to remain in service, Instructions for Continued Airworthiness (ICA) documents are required to define operating procedures and instructions for the operator. In addition, the AC guidance states that arrangements should be made to validate the performance of an approved credit throughout its service use. To complete the credit validation, additional relevant data from the field are gathered during service and combined with other engineering data, analysis, and evidence for a total synthesis of the credit. If necessary, modifications to the HUMS application or the component and equipment being monitored are re-evaluated.

The AC provides detailed guidance on many aspects, which must be addressed to obtain FAA approval for HUMS-based credits. SAC has analyzed and translated the guidance of the AC into a high-level flow chart (figure 3) that can be used to guide the development of a HUMS credit application. The detailed guidance underlying figure 3 can be found in the AC and is not discussed in this report. However, the flow chart and underlying principles will be applied and discussed to demonstrate how an SUM and RR-based credit and process can be defined to comply with the AC.

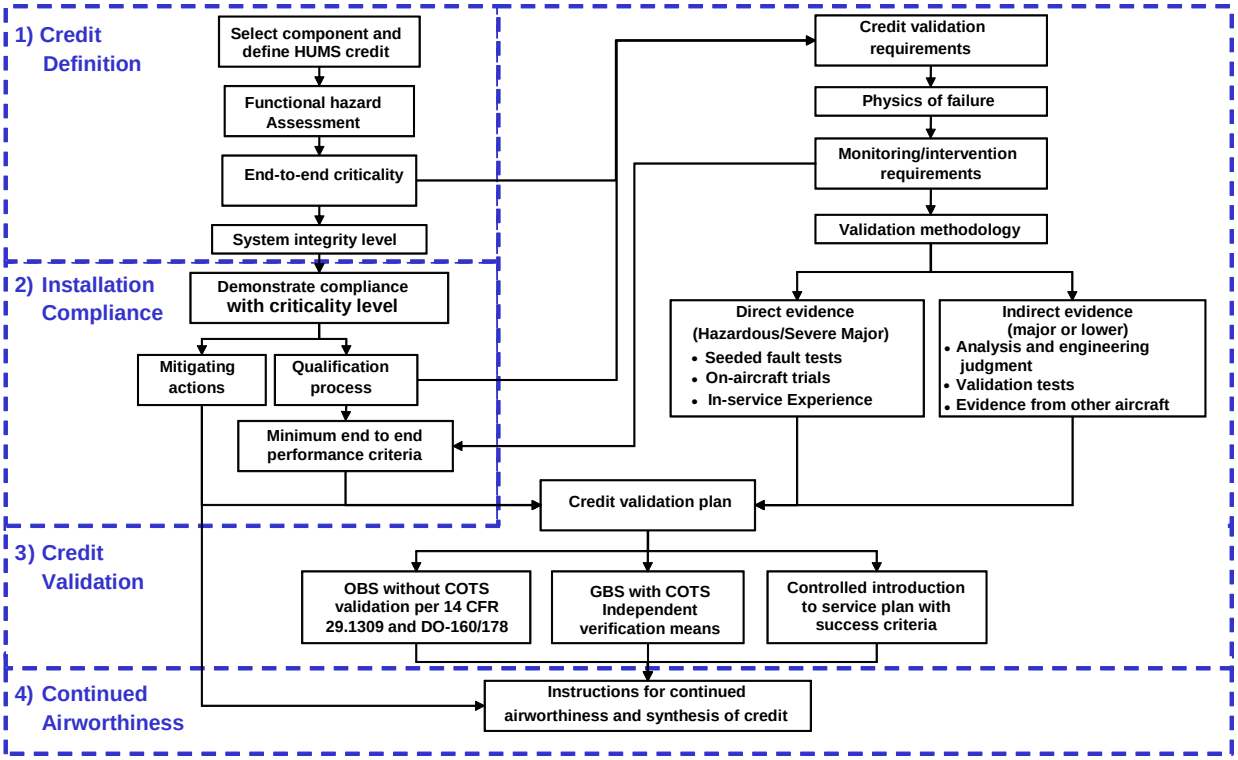


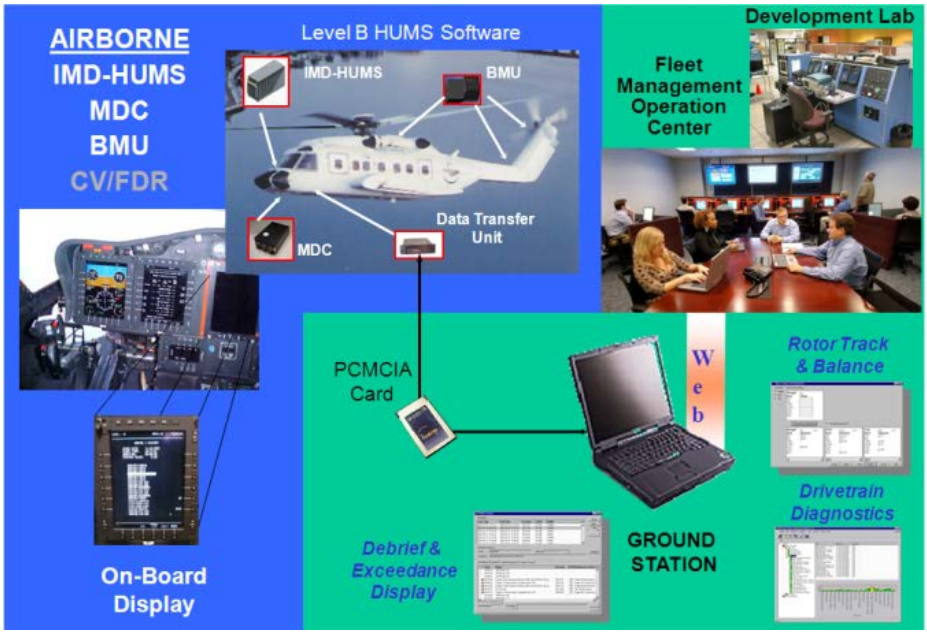
Figure 3. Detailed AC 29-2C MG 15 End-to-End Process Validation Requirements

3. THE S-92 AIRCRAFT HUMS DESCRIPTION.

The end-to-end system for a general HUMS-based credit likely will include the airborne HUMS, a ground-based data management and analysis software environment located at the operator's facility, and a data management and analysis software environment located at the OEM. A brief description of the S-92 HUMS and data management processes is contained herein and is representative of other OEM systems. Elements most relevant to SUM installations, RR algorithms, and UBM credits are emphasized, and typical differences with other OEM systems are noted. More detailed descriptions of the S-92 HUMS can be found in reference 5. Further details specific to RR-based credits are provided in section 4 that define example credits and demonstrate AC compliance.

The S-92 aircraft has a certified state-of-the-art airborne HUMS that is fully integrated within the baseline aircraft design (see figure 4) and interfaces with all aircraft subsystems through the aircraft digital bus (see figure 5). The S-92 airborne HUMS onboard system (OBS) installation collects, processes, and records data from a large array of dedicated sensors (e.g., accelerometers and rotor position sensors) and independent aircraft systems on a per-flight basis, which is made available to maintenance personnel on the ground. This data is then analyzed using a GS, which can be used to identify conditions that require maintenance. The S-92 HUMS data without further processing is also automatically transmitted via the Internet on a daily basis to SAC's Fleet Management Operations Center (FMOC). The FMOC processes data from the field and

provides a means for proactive customer support. Routine FMOC activities include data handling, storage, and distribution within SAC, data analysis, and forecasting spare parts requirements.



PCMCIA = Personal Computer Memory Card Interface Adaptor
FDR = Flight data recorder
IMD = Integrated mechanical diagnostics
MDC = Maintenance data computer
CV = Cockpit voice recorder

Figure 4. The S-92 Aircraft HUMS

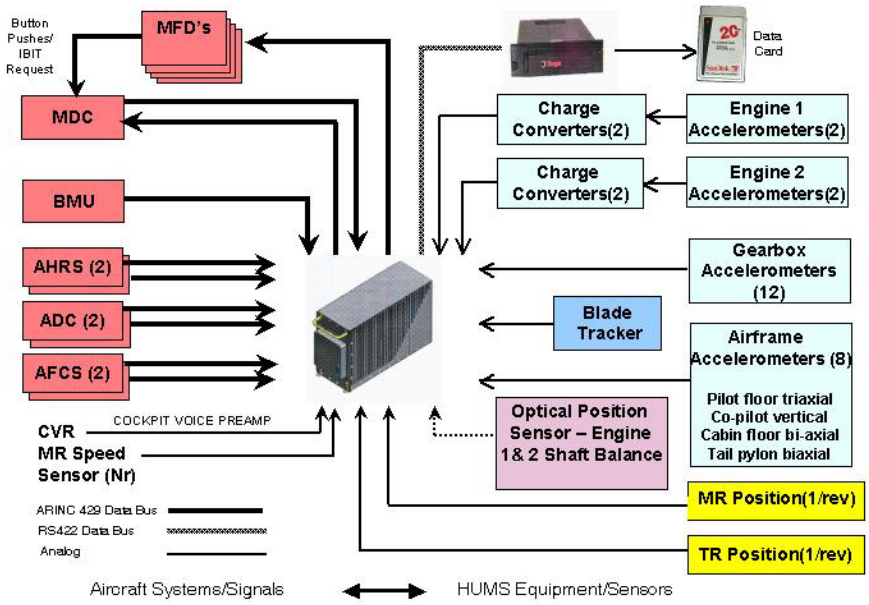


Figure 5. Airborne System Block Diagram

The S-92 airborne HUMS installation is comprised of three primary subsystems (listed below) that perform specific aircraft health monitoring tasks.

- Integrated mechanical diagnostics (IMD)-HUMS
- Maintenance data computer (MDC)
- Bearing monitor unit (BMU)

The IMD-HUMS performs vibration monitoring, rotor track and balance, operational usage monitoring (flight time, takeoffs and landings, engine cycles, engine run time, rotor turn time, rotor brake applications, and auxiliary power unit cycles/run time), exceedance monitoring, and onboard RR algorithms. The MDC determines the health, status, and faults for major avionic systems, subsystems, and line replaceable units, including accelerometers. The MDC collects and processes subsystem built-in test (BIT) data and analog/discrete data. The MDC also uses initiate BIT (IBIT) for individual subsystems. The BMU monitors the vibration and temperature of flight critical aircraft bearings, which include the swash plate, oil cooler, and tail rotor driveshaft hanger bearings.

The IMD-HUMS also collects HUMS related data from all other aircraft monitoring systems and writes the data to one Personal Computer Memory Card Interface Adaptor (PCMCIA) data card via the data transfer unit (DTU) located in the cockpit. These other monitoring systems include the Altitude Heading Reference System (AHRS), air data computer (ADC), automatic flight control system, BMU, MDC, and cockpit voice recorder. Aircraft system and subsystem status and fault data are displayed on the aircraft multifunction displays through a "HEALTH" menu. Health data is also downloaded to the GS via the PCMCIA card.

Per SAC requirements, the S-92 IMD-HUMS software was developed and certified to be in compliance with the stringent DO-178B requirements [4] commensurate with Level B criticality applications. The intent was to preserve and ensure the integrity of all source and processed data written to the PCMCIA card for future potential use in support of HUMS-based maintenance credits, including parametric data required for both onboard RR algorithms and offboard RR calculations. Note that the source of all parametric data required for RR are avionics systems designed and certified to Level A. HUMS on most other aircraft are currently certified to Level D or lower.

The S-92 HUMS GS is a COTS personal computer (PC) with Goodrich GS software (GSS) installed. The GSS can be used by the operator to display and analyze HUMS data for maintenance decision support, but passes HUMS data without further processing to SAC. The difficulties and cost of developing, certifying, and sustaining Level D or higher certification levels for GSS are well known. There is no known GSS developed and certified to criticality Level D or above. Certification issues arise if an end-to-end HUMS process is dependent on GSS data processing by the operator, which is beyond the scope of the subject effort. Certification issues that are related to the use of the GS to transfer HUMS data to the rotorcraft OEM without intermediate data processing are addressed in detail in section 4.4.1 for issues.

HUMS RR algorithms are used to identify and categorize how the aircraft has been flown. They comprise a key element to short-term SUM approaches being pursued by various OEMs and Department of Defense Services to obtain approved UBM credits. All S-92 RR inputs originate from avionics units that have the highest levels of reliability for hardware and associated software and are essential for flight control and pilot decision making. Figure 6 shows standard input and output data types for the S-92 RR data flow. The S-92 RR input data can be grouped into the following categories.

- Basic aircraft and system data, which include directly measured parameters and parameters that typically depend on some level of pilot input
- Derived air data parameters
- Aircraft attitude parameters
- Stick position
- Aircraft discrete parameters
- Aircraft rigid-body accelerations

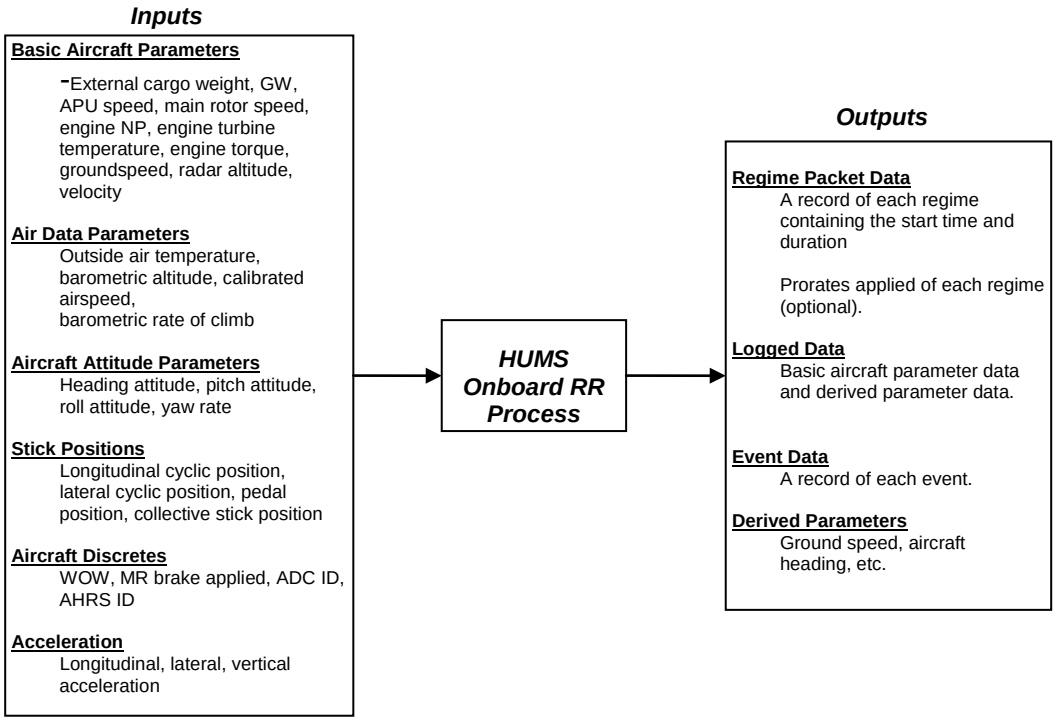


Figure 6. The S-92 HUMS RR Algorithm Data Processing

While the details of RR algorithms vary, the types of required input data are typical for most OEM rotorcraft platforms. The S-92 RR output includes all raw parametric data, derived parameters, regime records, and event records. For RR algorithms that identify broader maneuver categories rather than detailed regimes, fewer input parameters may be required.

Most mature RR algorithms are based on hierarchal Boolean logic that compares input parameters against a set of predefined ranges to determine the general aircraft flight conditions and maneuvers, such as steady level, turn, climb, or pullout. This result is refined with other parameters (e.g., airspeed, load factor, angle of bank, and rate of climb/descent) that indicate maneuver severity. Further detailed regime definition is possible with knowledge of aircraft configuration, such as gross weight (GW), center of gravity (CG), external load, and external stores. This allows allocation of the most accurate component loads to these finer regime categories rather than using the same peak loads for all instances of a general maneuver. This prorating is frequently used for military rotorcraft regime definitions, but less so for commercial rotorcraft, which typically use only the maneuver severity to form prorated regimes.

During the development of the S-92 aircraft RR algorithms, SAC mapped the RR process into a series of logic diagrams for five distinctly different types of maneuvers, as shown in figure 7.

- Ground operation
- Takeoff/landing
- Hover
- Low-speed flight
- High-speed flight

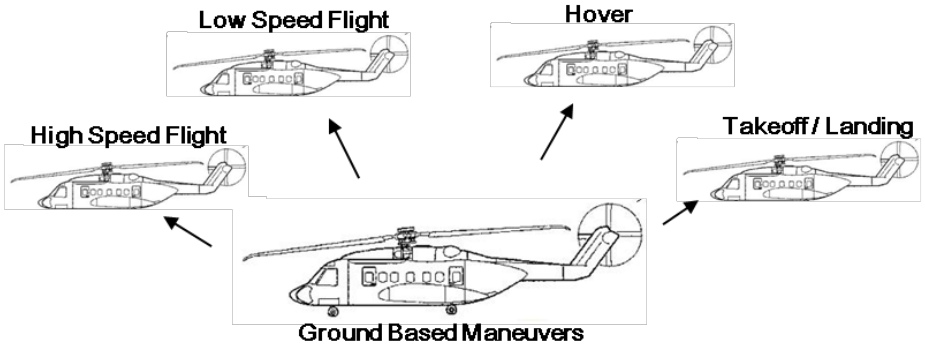
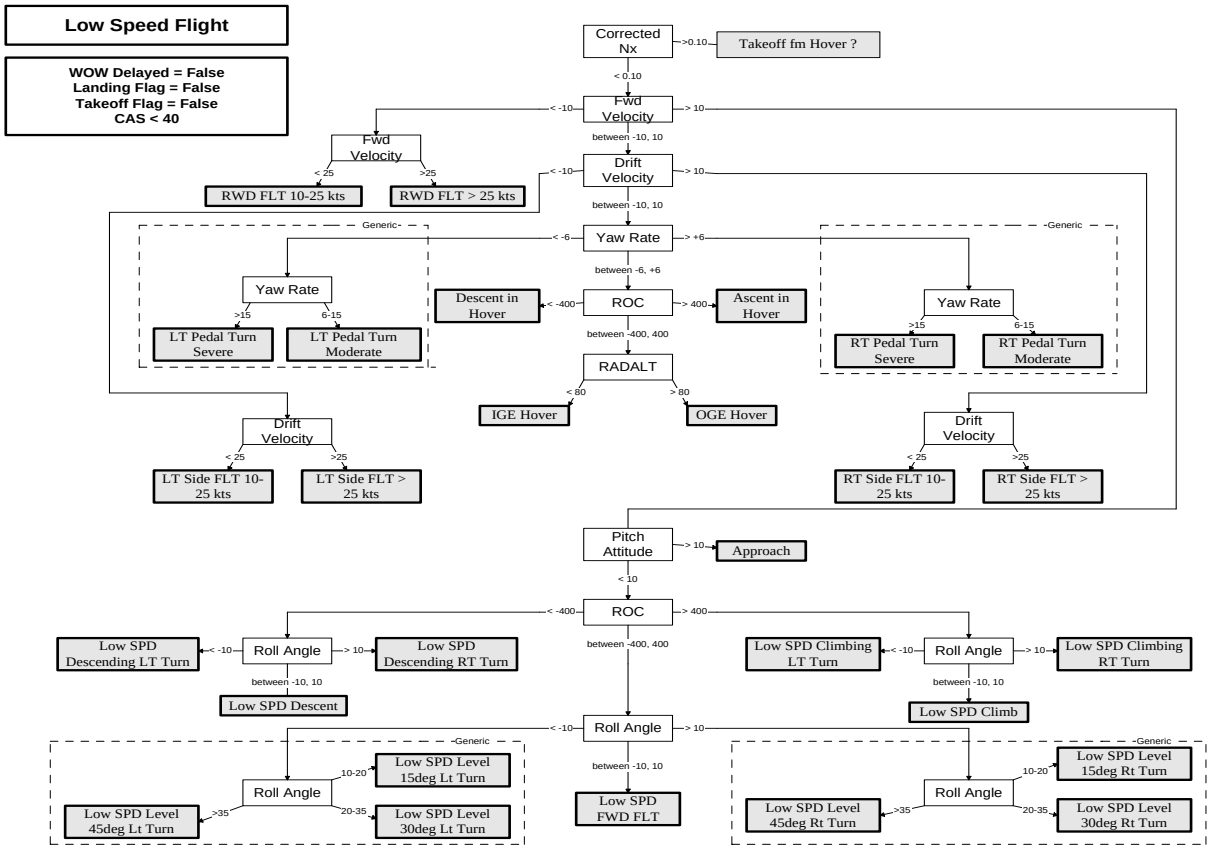


Figure 7. Overall Flight Regime Breakdown

These broad categories are distinguish based on a handful of measured (e.g., weight-on-wheels (WOW) or airspeed) or derived discrete parameters (e.g., landing and takeoff "flags"). For example, entry to low-speed flight occurs when the WOW, landing, and takeoff flags are false and airspeed is below 40 knots. The specific low-speed regime is determined by stepping through the associated logic tree, as shown in figure 8, for low-speed flight. The regimes are similarly determined for high-speed flight, above 40 knots. This approach ensures that each regime is unique and mutually exclusive from the rest.



Nx = Longitudinal acceleration	RT = Right	FLT = Flight
Radalt = Radar altitude	LT = Left	OGE = Out of ground effect
ROC = Rate of climb	SPD = Speed	IGE = In-ground effect

Figure 8. Regime Definitions

On the S-92, RR processing occurs continuously and, in the background, recording updated HUMS regime packet data every second whenever the MPU is powered. Note that the S-92 HUMS provides both onboard RR results and parametric data that can be used for further offboard RR processing if, in the future, it is desired to develop new RR algorithms or modify regime definitions. The S-92 regime identification logic described above is accomplished by using configurable regime definition tables. Each table consists of a set of expressions that, when combined using Boolean compound “AND” logic, completely defines a specific regime. If all expressions are true for a particular definition, then the aircraft is determined to be in the defined regime.

Regimes were defined in a manner that allowed an efficient search and a smooth transition between regimes while eliminating gaps. The first step was to test data validity. If a parameter used for a definition was invalid for all defined regimes, the regime was marked with an “Undetermined” classification. If all the parameters were valid for one or more defined regime, but no definitions were found to match, then it was declared an “Unrecognized” regime.

4. THE UBM CREDIT DEFINITION.

A UBM credit is an approval of any change to the maintenance for a specific end item or component, such as an extension or reduction in inspection intervals or CRT established for the baseline system prior to incorporation of UBM as the approved approach. UBM credits are based on selected aspects of actual service usage history of specific monitored equipment versus the assumed usage of general equipment population. This section discusses the three elements of defining a general RR-based UBM credit. This entails monitoring of actual structural usage of fatigue sensitive, life-limited components using RR and the calculation of an adjusted retirement time, while maintaining baseline risk and reliability. The end-to-end process is similar for most credits and is discussed in section 4.1. An example RR-based UBM credit is then defined by the selection of a specific representative component, as discussed in section 4.2. The criticality of the example credit is defined in section 4.3. While the focus of the example UBM credit defined herein anticipates more benign actual usage for a retirement time extension beyond the published AWL CRT (or other usage-driven, flight hour-based, dynamic component maintenance actions), the process is general and can also produce a retirement time reduction if more severe actual usage is discovered.

4.1 THE UBM END-TO-END PROCESS.

Calculation of an RR-based UBM credit focused on CRT adjustment is predicated on the ability to conservatively estimate accrued fatigue damage from monitored actual part structural usage using RR technology. This process is notionally shown in figure 9, where the assumed damage accumulation rate from a CWC-based conservative damage model is compared to a typical damage accumulation curve based on actual structural usage. Note that, at times, actual fatigue damage accumulation rates can briefly exceed the conservative damage accumulation model but, on average, is assumed to be much lower than the highly conservative CWC-based damage accumulation rate. Thus, the CRT adjustment is most often expected to take the form of a life extension; however, the adjustment could take the form of a life reduction if operator usage is found to be more severe than the CWC for a finite period of time. An important element of the process is to conservatively estimate actual damage to account for known uncertainties or accuracies in the RR algorithms. Additional safety margins or reliability factors can also be imposed based on other elements of the end-to-end process to ensure that baseline risk and reliability are maintained or improved.

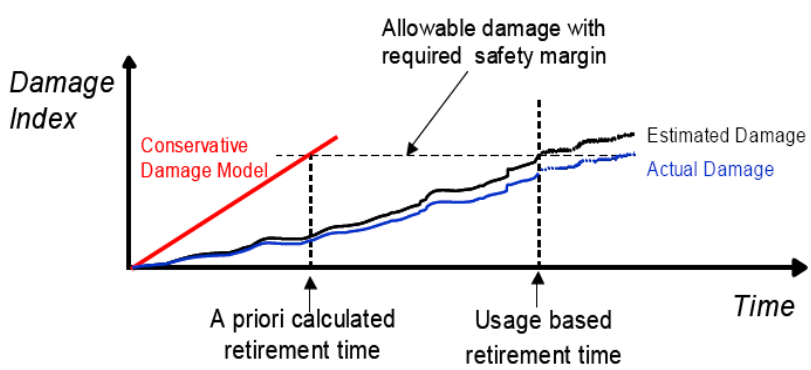


Figure 9. Notional RR-Based UBM Process

Details of an RR-based CRT adjustment process and certain elements of the end-to-end system can vary based on various approaches or scenarios with respect to data management, data processing, and decision support. Certification issues associate with various scenarios are discussed in section 4.1.1.

4.1.1 Scenarios for Implementing UBM Credits.

Table 2 shows several possible scenarios based on combinations of three types of UBM credit application and three locations and methods of adjustment calculation. For example, the credit procedure can be set up to calculate and apply CRT adjustments at discrete decision points (e.g., after a c ertain number of flight hours that correspond to a predefined fatigue damage accumulation threshold) allowing for engineer-in-the-loop calculations. Alternatively, adjusted CRTs could be calculated continuously as flight data is recorded and effective flight hours are automatically transmitted to the Maintenance Management Information System (MMIS) at the conclusion of each flight. Different combinations of these options present various opportunities for UBM technology insertion and for application growth and expansion as the emerging technologies mature.

Table 2. Combinations of Technology Options for UBM

		Frequency of Intervention		
		Single Adjustment	Multiple Adjustments	Continuous Adjustments
Location/Method of Adjustment	Offboard semi- to full automation (OEM)	Focus of this Effort	Focus of this Effort	
	Offboard full automation (Operator)			
	Onboard full automation (Operator)			

The red fields in table 2 show combinations that pose additional technical or business risks, which would likely result in significant additional cost to mitigate these risks and achieve and maintain end-to-end system certification. For example, semi- or fully automated tools in the GS would raise a variety of issues related to oversight, ownership, quality assurance (QA), and data integrity. The rotorcraft OEM would be held responsible for efficacy of the process, but would have much less process control.

The yellow fields show possible, but not attractive, scenarios as either the costs will most likely outweigh the benefits or the option does not take full advantage of the potential benefits of the technology. For example, near-continuous adjustments when the process is only semiautomated will likely be too costly to be practical. On the other hand, using advanced onboard damage calculation software to apply only a single adjustment per credit ignores the full potential of such technologies for UBM.

The green fields are deemed the most practical and attractive options based on anticipated ease and reduced cost of risk mitigation and certification and/or potential benefit. While the long-term goal is to deploy all the algorithms within the onboard HUMS unit and calculate adjustments continuously to achieve maximum benefit, current SUM technologies are not ready, resulting in higher, short-term risk and cost. Thus, the UBM end-to-end process proposed herein was developed for an offboard adjustment calculation conducted by the rotorcraft OEM with multiple discrete adjustments allowed. This option has the following advantages:

- It is considered to be most accessible for current fielded HUMS RR technology to introduce UBM credits with the fewest changes to existing data management processes.

- It takes advantage of existing HUMS (minimizes installation compliance issues) and exploits existing HUMS onboard software and existing RR algorithms whether deployed onboard or offboard.

- It involves OEM and non-real-time implementation, which maximizes the opportunities for cost-effective risk mitigation and process enhancement based on lessons learned.

The following credit applications were considered. Each type would involve one credit application, regardless of whether only a single, one-time or multiple CRT adjustment(s) can be made under an approved credit application. An adjustment can be either positive or negative, depending on whether actual usage is less or more severe than CWC usage assumptions during the previous usage interval.

- Single adjustment: A single, one-time CRT adjustment is applied when a specified threshold, based on flight hours or CWC-based cumulative fatigue damage, is reached. The adjustment would calculate the effective flight hours from the threshold value by an amount that depends on the difference between the actual and CWC usage spectra. For example, if the threshold is set at 75% of the CWC-based original AWL CRT, the credit application may lower the effective flight hours to 50%, after which the component can be retired at 125% of the original retirement time, assuming CWC usage for all future operations after the adjustment.

- Multiple adjustments: Under this scenario, adjustments are applied each time a predefined threshold of estimated cumulative damage is reached. At each adjustment point, the threshold would be based on the previously adjusted flight hours or cumulative flight hours plus subsequent flight hours or CWC-based damage. Multiple adjustments under the credit application would be possible up to a fixed number of adjustments. Each time, the effective flight hours or consumed life from the threshold would be adjusted by an amount that is based on a comparison between actual usage and CWC usage spectra. For example, if the threshold is 75%, the first application of credit may adjust the effective flight hours to 50%. The second time the 75% threshold is reached (based on assumed CWC usage since the adjustment), the applied credit may lower the effective flight hours to 67%. This process would be repeated until the allowable number of adjustments is reached or no more credit is allowed (e.g., a cap on maximum retirement time adjustment).

- Continuous adjustments: Under this scenario, after each flight, a delta in effective flight hours is calculated. Furthermore, statistics about the rate of effective flight hour versus actual flight hour accumulations can be constantly updated for each component to predict the number of flight hours left before a maintenance action is triggered.

The location and methods for calculating the adjustment have very important implications for the certification process. The following locations and methods of adjusted CRT calculation are considered.

- Offboard semi- to full automation (OEM): This is the most likely option for an initial UBM credit. The calculations are done offboard by the OEM. This allows the frequent application of engineering know-how and judgment to complement software tools developed for regime-based data mining and calculation of credits. Although the processes will become more automated as the methods mature, the manufacturer continues to retain ownership of the software operations.

- Offboard full automation (Operator): As more experience is gained with the use of UBM technologies and processes, it is possible that fully automated software may be developed and maintained by the manufacturer but delivered to the fleet operator for processing in the GS. Although a theoretical possibility, there seems to be little benefit or justification for this scenario, given the additional cost of certification and risk mitigation required to ensure data and computational integrity when using an operator's GS, which typically are based on COTS hardware and operating system software.

- Onboard full automation (Operator): Enhancement and simplification of UBM software would ultimately allow onboard implementation. Under this scenario, the GS would act as a "thin client," providing different views of the results already computed in HUMS, but not process the data as part of the end-to-end UBM process.

As more experience is gained with the use of UBM technologies and processes, a UBM credit scenario in which fully automated software is deployed onboard to continuously calculate maintenance adjustments becomes practical and cost-effective.

4.1.2 Definition of the End-to-End Process.

The proposed end-to-end process for a RR-based UBM credit adjustment is shown in figure 10. Annotated mapping is provided to show how the process corresponds to the four essential certification elements that must be addressed per the AC, and the organizational structure of this document is also provided. The corresponding report sections also are identified in figure 10, where further discussion and details are provided on AC compliance using the S-92 aircraft and a specific UBM credit as a representative example.

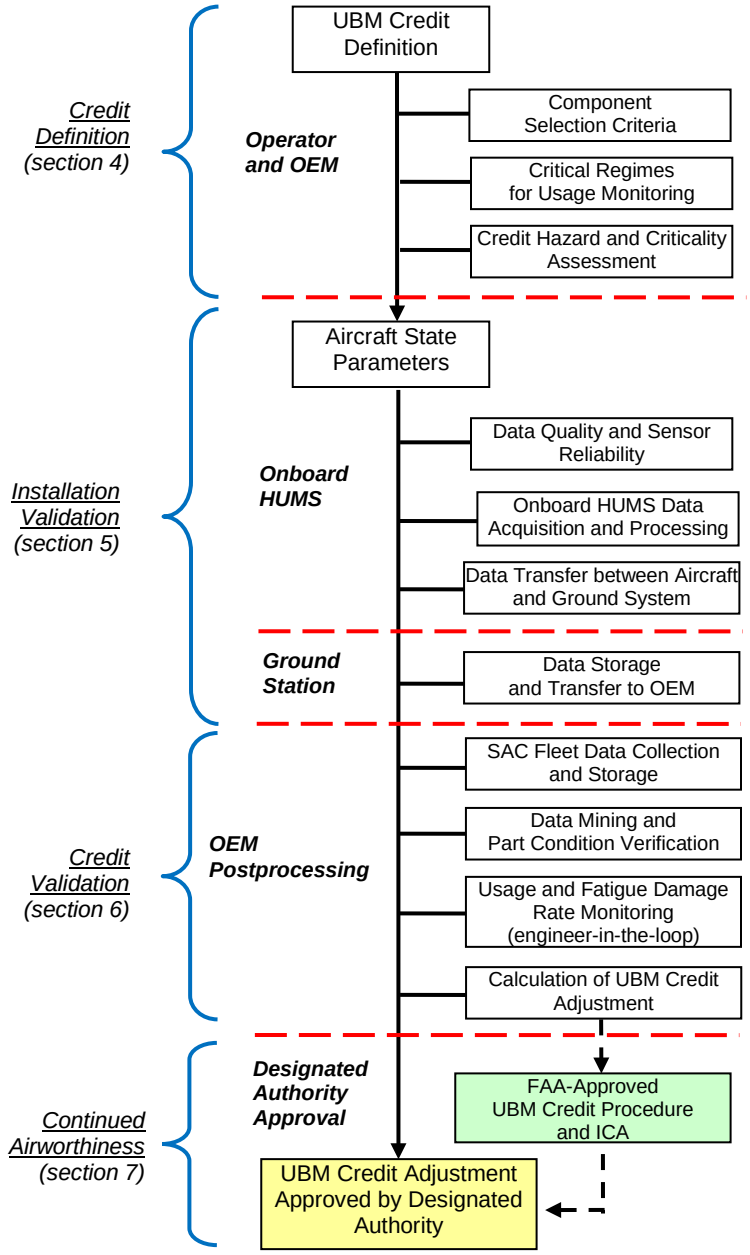
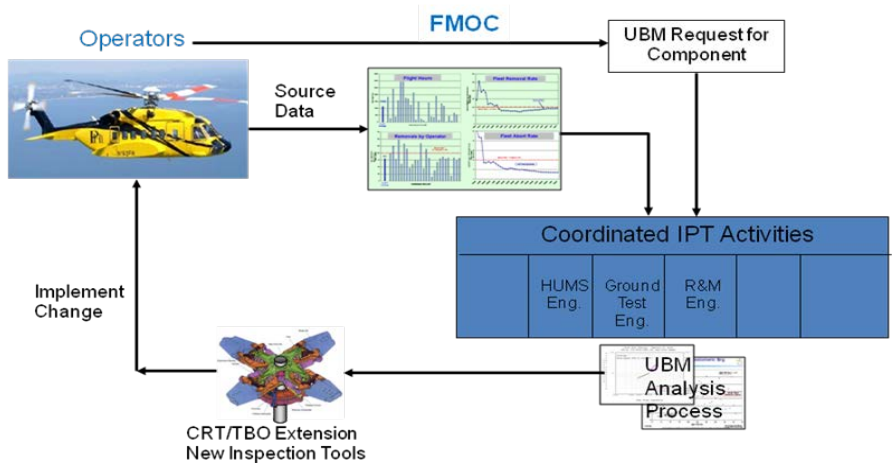


Figure 10. Proposed UBM End-to-End Process

The end-to-end system is comprised of all hardware and software elements required to execute the UBM process elements beginning with acquisition of required RR input state parameters and ending with designated authority approval.

Figure 11 shows how the discrete UBM credit process would be triggered by the aircraft operator and implemented by SAC. Every production S-92 is equipped with HUMS, and the data are transferred on a daily basis to SAC in an FAA-approved process. The proposed UBM end-to-end process requires no changes to the existing onboard equipment or procedures for transferring

and storing data. To obtain an approved UBM credit, the operator applies with substantiating documentation showing that processes are in place to satisfy credit requirements (e.g., data management protocols and OEM processes, as shown in figure 10). Once the UBM credit is FAA-certified, the operator can request an adjustment when the subject component reaches a threshold, for example 75% of the AWL CRT based on accumulated flight hours. Note that to maintain safety in the event of more severe usage, it is recommended that the OEM perform usage checks starting as early as 25% of the AWL CRT. In a postprocessing mode using procedures that ensure data integrity, SAC mines the operator aircraft or fleet database to validate HUMS data and inspect maintenance records for the component. SAC then coordinates among the relevant Integrated Product Team (IPT) and determines a CRT adjustment for the component with an engineer-in-the-loop to provide expert judgment and risk mitigating actions to calculate and validate the adjustment. Upon approval of the adjustment by a designated authority, SAC notifies and supplies instructions to the operator regarding disposition of the credit request. The operator or maintainer makes the appropriate adjustment to the component's effective flight hours based on the approved UBM credit and records it in the MMIS and on the component log card.



R&M = Reliability and maintainability

Figure 11. Discrete UBM Credit Process for S-92 Example

4.2 THE UBM COMPONENT SELECTION.

To meet credit validation compliance criteria in the AC, the components 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 or logistical impact of early retirement or replacement of the component) and ease or validity of applying the UBM credit process on the component. A selection approach is presented that determines the most appropriate component to use for development and demonstration of a UMB credit methodology. The selection approach consists of the following steps:

- Establish the criteria for component evaluation.
- Review the fatigue analyses of components.
- Evaluate the candidate components using a selection matrix.

4.2.1 Selection Criteria.

The following is a preliminary set of criteria. These are intended to be further discussed, refined, and amended prior to the final component selection.

- Replacement cost or logistical impact is relatively significant: To show relevance to the end user, the component should show promise for significant cost avoidance or benefit to aircraft availability.

- CRT analysis indicates part is life-limited: The component life should be limited to demonstrate a UBM credit. Parts that are not life-limited can also be considered if the time between overhaul is low.

- Damage is highly dependent on RR: The CWC is a conservative spectrum, and the ability to more accurately monitor regimes will be significant for the UBM credit. Damage dependence on several regimes also shows a certain degree of complexity that stands apart from other more simplistic investigations that have been done.

- Damage is driven by manageable number of regimes: The extent of RR algorithm validation increases with the number of critical regimes that must be monitored.

4.2.2 Selected Component and Critical Regimes.

Figure 12 shows the S-92 aircraft components considered as representative examples for UBM credit examination. The MR hub was evaluated in a prior internal study where it was shown that the dominant source of damage is from centrifugal force ground-air-ground (GAG) cycles based on rotor revolutions per minute (rpm). A simple UBM credit process was developed and submitted to the FAA for approval based on monitoring of only MR rpm where RR was not required [6]. FAA approval remains pending as of this writing.

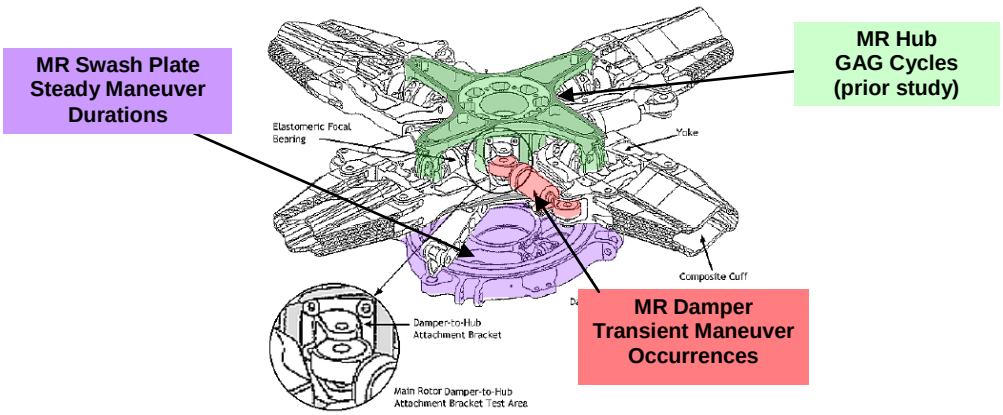


Figure 12. Dynamic Component Candidates for UBM Study

Under this study, S-92 dynamic component fatigue substantiation reports [7] were examined to identify components that could potentially benefit from the monitoring of a manageable number of regimes. Rather than trying to rigorously validate RR algorithm performance for all HUMS regimes, the developed approach focuses only on the key regimes that are found to be damaging to selected components that are considered good candidates for UBM. Based on this evaluation, the MR stationary swash plate and MR damper were deemed to be good sample candidates. The fatigue substantiation reports revealed that the most damaging CWC regimes for these components are high-bank angle steady turns and symmetric-pullout transient maneuvers. Other maneuvers with comparable load severity include dives and symmetric pushovers. 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 stationary swash plate was selected as the component for this research because the primary damaging regimes can be modeled using the existing HUMS RR output, and there is a relatively minimal amount of damage from regimes that HUMS cannot currently recognize. The installation is shown in figures 13 and 14. The replacement cost and impact on aircraft availability is expected to be relatively significant because the entire rotor head has to be removed and several flight control servos have to be disconnected to replace the swash plate, which requires rigging checks and dedicated check flights following replacement. Finally, the critical regimes and load sources for failure modes are well defined, documented, and understood.

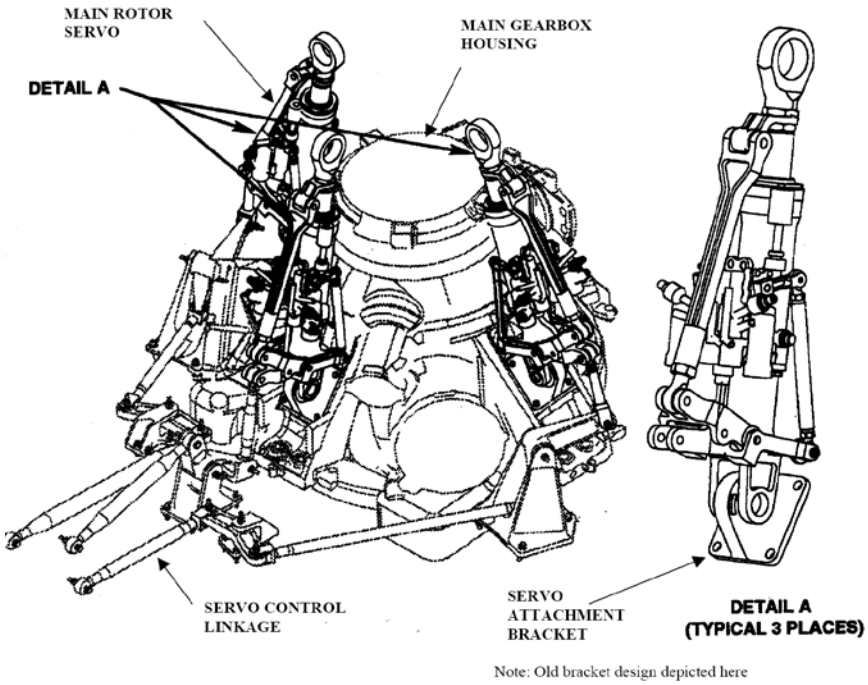


Figure 13. The MR Swash Plate Servos

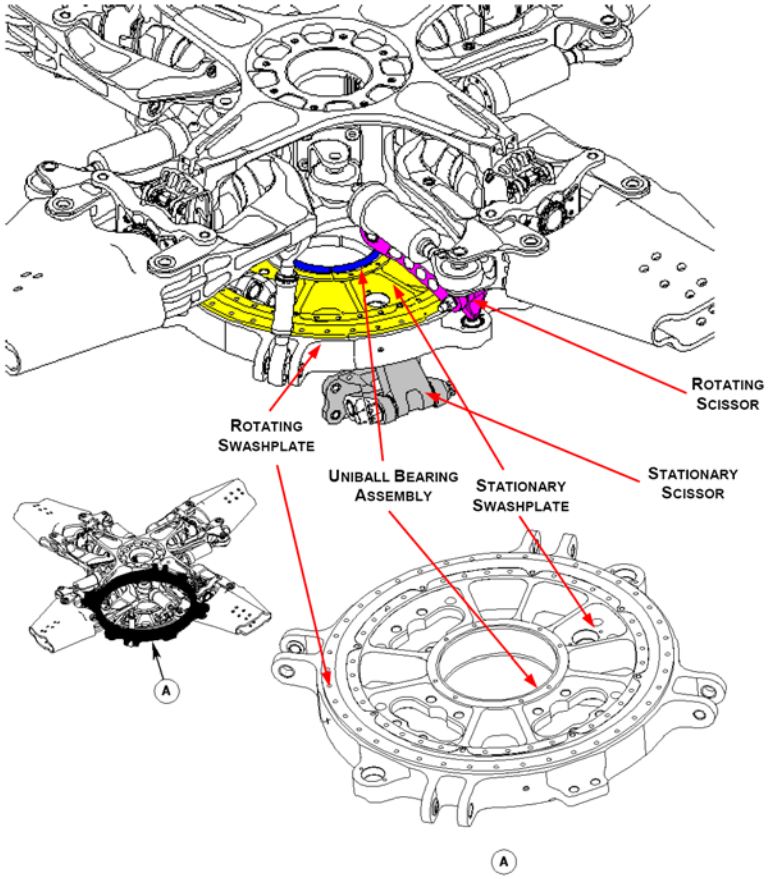


Figure 14. The MR Swash Plate Installation

4.3 CREDIT HAZARD AND CRITICALITY ASSESSMENT.

The objective of the sample UBM credit application investigated in this research was to adjust the maintenance practice for a flight-critical, life-limited dynamic component that could result in a catastrophic loss of the aircraft if loss of functionality occurred. Such parts are designed and maintained with the safe-life methodology to ensure the probability of failure (i.e., baseline risk) is an improbable event, with process reliability on the order of six-nines, as discussed in section 1. Therefore, a key premise of the UBM process is that any adjustment of the maintenance procedures for these types of components must be shown to maintain the same levels of baseline risk and reliability, i.e., airworthiness credit. The S-92 MR stationary swash plate was deemed to be a good representative component because it is a nonredundant, flight-critical, life-limited component, which presents interesting, but manageable certification challenges. If the swash plate fails, the pilot could lose control of the aircraft, potentially resulting in a catastrophic loss of aircraft and crew. Thus, at first glance, focusing on a UBM credit for such a component may not appear to be prudent because the AC excludes discussion of the highest level of criticality (Catastrophic). A justification must be made for considering a UBM credit for such a component and for using elements in the end-to-end process that have a lower than Level A software criticality level. The discussion and proposed approach (discussed in sections 4.3.1-4.3.8) for the MR swash plate will provide what is accepted as a prudent and

viable approach that complies with the AC for defining and certifying UBM credits for such flight-critical components. SAC recommends that, to assess UBM credit criticality, the following steps be taken that affect flight-critical components.

1. Conduct aircraft system/component FHA

2. Identify relation between UBM credit and system/component FHA

3. Identify credible critical failure modes for UBM end-to-end system/process

4. Perform FMECA of end-to-end UBM credit system

5. Establish credit criticality and integrity level for end-to-end UBM credit system/process

6. Determine if end-to-end integrity level meets or exceeds criticality requirements

7. Refine UBM credit system and process changes, if necessary, to meet criticality requirements

8. Define mitigating actions to maintain baseline risk or better

Figure 15 shows a proposed flow chart for applying these credit criticality assessment steps, indicated by number. The process is an expansion on the simpler credit definition process required by the AC, as shown in figure 3. As shown, final credit definition may need to be an iterative process to arrive at credit and end-to-end system/process definitions that can provide the necessary integrity level commensurate with credit criticality requirements.

The depiction of mitigating factors and the determination of compliance within the expanded credit definition and criticality flow chart shown in figure 15 may appear to overlap with the continuous mitigating actions in the installation compliance portion of figure 3. However, in figure 15, mitigating actions are considered an element of the one-time, iterative, up-front process that may be employed to converge on a viable credit definition and end-to-end system/process to maintain baseline risk.

Each step in figure 15 is discussed in sections 4.3.1 through 4.3.8, including what steps can be safely eliminated for lower-criticality credits. Each section includes both a generic discussion of the key criteria that should be addressed within each step and a more specific discussion related to the example swash plate credit.

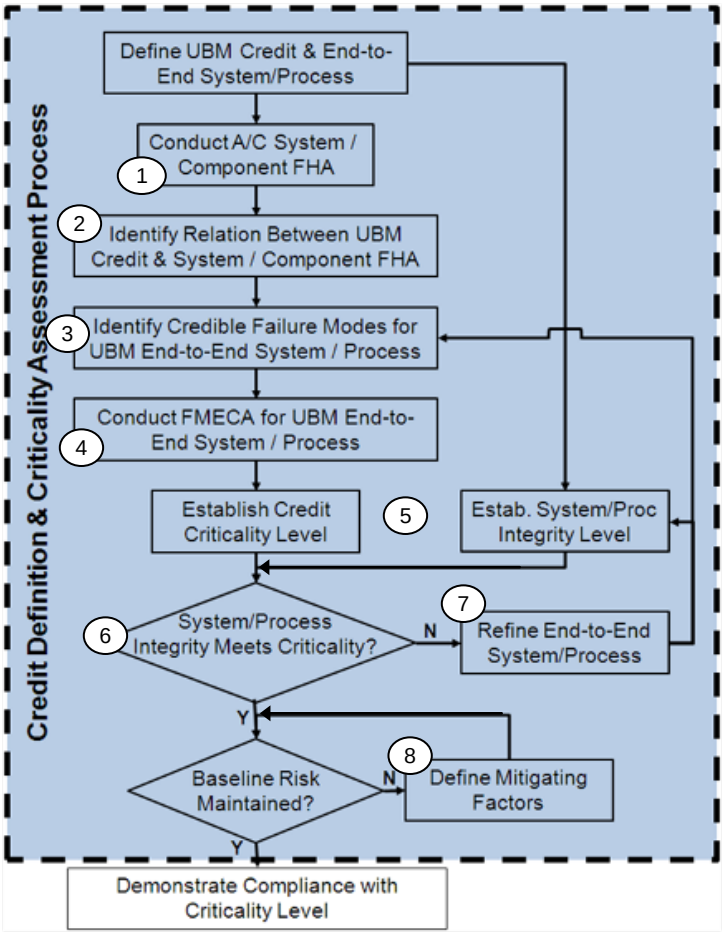


Figure 15. The UBM Credit Hazard and Criticality Assessment Flow Chart

4.3.1 Step 1: Aircraft System/Component FHA.

An FHA is a structured, top-down, function-based approach to identifying significant hazards to aircraft functionality and, thus, safety. Function classification considers the loss of and/or degradation of the function (e.g., erroneous and misleading data) in terms of the possible impact or hazard to the rotorcraft, its occupants, and flight crew. The hazards are classified using the five failure condition categories defined in the AC: no-effect, minor, major, hazardous/severe-major, and catastrophic. The product of the FHA is a determination of the failure/malfunction condition category for each system. Controls in place to limit the likelihood or severity of identified hazards are described. The FHA also identifies the need for further analyses required for safety verification and aircraft certification. The aircraft-level FHA focuses on the functions performed by the rotorcraft, independent of the systems that perform the functions. By identifying the critical aircraft functions, the interactions of various systems are considered. For example, the S-92 FHA [8] indentified 12 functions for which loss or degradation of the function could result in a catastrophic effect and 17 functions that could have a hazardous/severe-major effect. These results flow down to the generation of subsystem FHAs, including rotor design and a drive design assessments. Each OEM has its own FHA process, which may include a combination of qualitative and qualitative analyses based on inputs from pilots, flight safety

analysts, and engineers, depending on the complexity of the system and similarity to previously fielded systems.

The example swash plate credit considered herein is related to a function in which failure could lead to catastrophic effects, namely, the ability to maintain the desired flight path. Loss of this function could cause a catastrophic crash. The S-92 aircraft FHA continued to identify six functions whose failure could result in the loss of ability to maintain the desired flight path. Only one functional hazard (i.e., the loss of mechanic/hydraulic flight control) was relevant to the example stationary swash plate credit. Loss of flight control could lead to a catastrophic effect. The relationship to the example credit will be examined in the discussion of step 2.

4.3.2 Step 2: Relation Between UBM Credit and System/Component FHA.

The example UBM credit is defined as the CRT adjustment of the MR stationary swash plate. Conceivably, inappropriate extension of the swash plate retirement time could lead to fatigue failure at one or more locations on the swash plate (e.g., cracking at the connection with one of the servos). If such a fatigue crack were to proceed undetected until total fracture occurred, the end effect would be loss of control of the MR and loss of ability to maintain the desired flight path. If the analysis stopped at this point, the swash plate credit could be characterized as having catastrophic criticality, requiring the highest level of end-to-end system/process integrity, including a requirement for Level A software for all data processing.

If the credit criticality based on this high-level assessment was such that a practical end-to-end system could be defined to provide the commensurate system/process integrity and maintain baseline risk, then no further analysis would be required. However, this cannot be the case because no HUMS has been developed based on Level A software. Furthermore, the HUMS community has deemed the cost of developing and maintaining HUMS with Level A software to be excessive, impractical, and lacking sufficient business case to warrant its development. Therefore, a more sophisticated criticality assessment is warranted, as discussed in the next few steps.

4.3.3 Step 3: Credible Failure Modes for End-To-End System/Process.

Identification of all credible failure modes that could lead to the most significant hazards established in step 2 is crucial to conducting a more sophisticated criticality assessment in step 4. The objective of Title 14 Code of Federal Regulations (CFR) 29.1309 [9] is to ensure an acceptable safety level for equipment and systems as installed on the rotorcraft. Corresponding AC guidance states that a logical and acceptable inverse relationship must exist between the average probability per flight hour and the severity of failure condition effects. Additional guidance comes from ADS-79B [3], stating that the focus should be on a credible failure mode, which is defined as a believable manner in which a system or component may go beyond a limit state and cause a loss of function and/or secondary damage, as supported by: engineering tests, probabilistic risk analysis, and/or actual occurrences of failures.

Full-scale fatigue tests and CRT analysis revealed that the stationary swash plate component life is limited by the MR servo trunnion attachment holes. A trunnion serves as the connection point for each of three MR fixed-system control servos (see figure 16). It consists of an integral clevis

and a mounting plate that is fastened to the swash plate with four bolts. The trunnion and servo pin are not life-limited and the attachment bolts are subject to periodic inspections. Thus, the only credible failure mode that is relevant to the swash plate example UBM credit is a fatigue crack in one of the four trunnion attachment holes. Although there are three separate trunnions for the front, left, and right servos, it is noted that a combined worst-on-worst servo load spectrum is used conservatively for the CRT analysis. The severity class for this failure is deemed hazardous/severe-major because the effect of the fatigue crack failure mode is a degraded ability to support the trunnion with potentially increased localized deflections if more than one hole experiences cracking. This results in a degraded ability to control the tilt of the swash plate, followed by degraded rotor performance, handling qualities (HQ), or vibration, which are readily observed by the crew, who would still have sufficient control of the aircraft to perform an emergency landing.

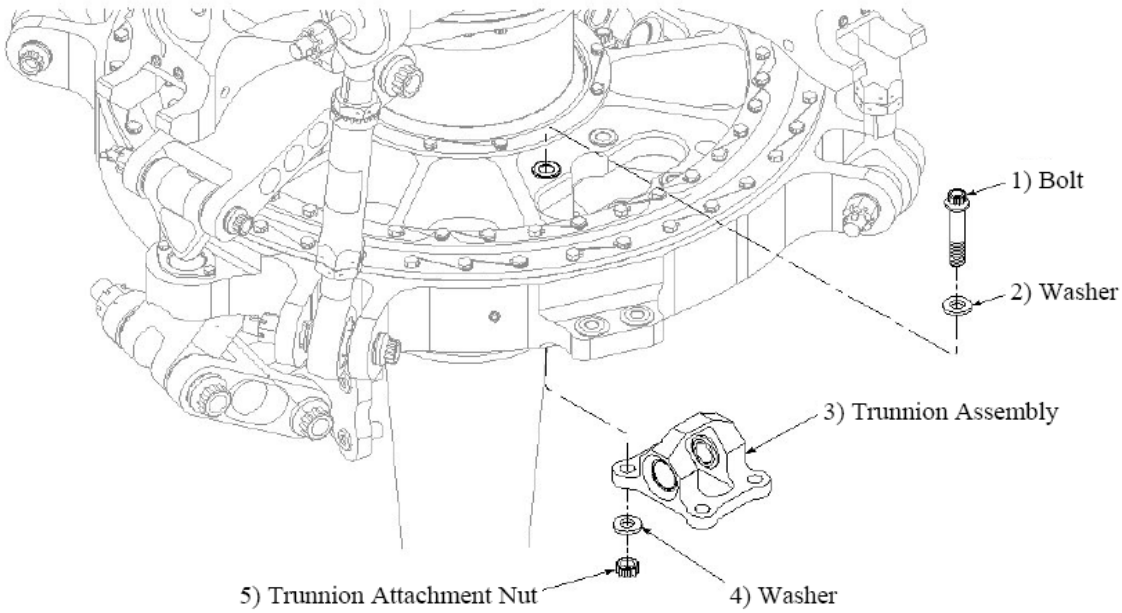


Figure 16. Trunnion Attachment Life-Limiting Failure Mode for Stationary Swash Plate

There are two extremely unlikely and potentially catastrophic end effects that are not considered credible failure modes. The first is related to a possible locked servo connection because of loss of alignment between the pin and the trunnion. The associated end effect would be increased coupling between various pilot inputs, resulting in degraded HQ, and possibly significant reduction in MR control if control limits are exceeded. S uch an end effect would only be possible with significant loss of trunnion retention, which would only be plausible with complete loss of functionality of two or more retention bolts. The second is a complete loss of an individual trunnion connection, resulting in degradation or total loss of control, depending on the configuration of the servo attachments and which attachment fails. This would only be possible with complete loss of functionality of all four retention bolts. The complete loss of functionality of the trunnion connection, due to degradation in HQ or increased vibration, is considered implausible and not a credible end effect. This assessment leads to the conclusion that a fatigue crack is a credible failure mode, but complete loss of rotor control due to stationary swash plate

trunnion attachment hole cracking is deemed to be a noncredible mode when assessing the UBM credit criticality.

Other component failure modes that are not directly related to the credit must be analyzed to determine if changes in maintenance could result in higher risk of occurrence. For example, in addition to the trunnion attachment holes the stationary swash plate has other potential failure modes described in the rotor systems design report [10]. These include fatigue cracking of the inner ring, outer ring section, and bearing degradation. The fatigue lives of the stationary swash plate inner and outer ring sections are infinite. The S-92 swash plate bearing also has an infinite life. Therefore, extension of the swash plate retirement time would not increase the risk of failure due to fatigue effects on these components. However, it would be prudent to re-evaluate CRTs at the same time the credit CRT adjustment is calculated. Other causes of bearing degradation are not a direct function of time in flight and will continue to be managed by existing maintenance practices, including monitoring by a BMU.

Credible failure modes of the UBM end-to-end system/process must be established. Referring to section 4.1.1, there are a number of different end-to-end systems/processes that could be used to implement a stationary swash plate retirement adjustment credit. Each scenario or variant thereof would have specific failure modes. The following is a list of conceived failure modes that would likely be relevant to most practical end-to-end systems for the example credit as well as most other UBM credits that use RR to monitor actual structural usage.

- Sensor failures or degraded sensors
- Insufficient sampling rate or corrupted data acquisition
- Inaccurate regime algorithms
- Data loss/corruption
- Data tampering
- Inaccurate usage calculation
- Inaccurate credit calculation
- Application of the credit to the wrong part
- Erroneous application of the credit to the right part

All the failure modes result in effects on the end-to-end process that ultimately could lead to the next failure mode in the chain, causing an inappropriate extension of swash plate retirement time. An inappropriate retirement time adjustment can, in turn, lead to swash plate fatigue cracks in single or multiple attachment holes. Without adequate UBM system/process design and integrity, the risk of this end effect becomes more likely and is considered a credible cascading set of failure modes. The FMECA is summarized in the next section for the above credible UBM system/process failure modes.

4.3.4 Step 4: FMECA of End-to-End UBM Credit System.

The FMECA is a bottom-up analysis of credible failure modes that are relevant to significant and credible FHA-identified hazards, including analysis of cascading effects, end item impact, and resultant criticality of the failure mode before and after accounting for mitigating actions. The typical FMECA process uses engineering and pilot judgment, probabilistic risk analysis,

engineering tests, and/or actual occurrences of field failures to establish credible failure modes and credible resultant hazards. The results of a s ample FMECA conducted for the example swash plate credit is shown in table 3.

The table captures the credible failure modes for the stationary swash plate subsystem function to maintain tilt c ontrol. Because of compensating provisions in the design (e.g., design redundancy) and maintenance (e.g., periodic inspections) of this component, the credible end effects are degraded control and HQ, but not complete loss of function. The assessed failure classification is deemed to be Category II, hazardous/severe-major, because of increased crew workload due to reduced aircraft performance and HQ.

The FMECA results for credible UBM system/process failure modes are also shown in table 3. As discussed above, all the failure modes result in effects on the next failure mode in the end-to-end process, which ultimately could lead to an inappropriate CRT extension.

Table 3. Sample FMECA Results for Example Swash Plate UBM Credit

Subsystem	Function	Failure Mode(s)	Interim/End Effects	Candidate Detection Methods	Candidate Compensating Provisions or Mitigating Actions	Failure Class
Swash plate	Swash plate Attitude Control	Fatigue Crack	Reduced swash plate control Degraded HQ	Standard visual inspections Pilot observations	Redundant retention for each attachment/control point Limited servo redundancy Antifretting coating applied	II—Hazardous/ Severe-Major
UBM	Sensor Measurement	Sensor failure Degraded sensor	Inaccurate RR, usage, and credit	Pilot cockpit data observation Data QA	Level A data sources Pilot debrief Data QA checks	II—Hazardous/ Severe-Major
UBM	DAQ	Insufficient sample rate Corrupted DAQ	Inaccurate RR, usage, and credit	Data QA checks	S/W design and V&V Data QA checks	II—Hazardous/ Severe-Major
UBM	Regime Recognition	Inaccurate regime algorithms	Inaccurate usage and credit	Data QA checks	S/W design and V&V Data QA checks	II—Hazardous/ Severe-Major
UBM	Data Transmittal	Data loss/corruption Data tampering	Inaccurate RR, usage, and credit	Data integrity and QA checks	Limited access to GSS and databases	II—Hazardous/ Severe-Major
UBM	Actual Usage Calculation	Inaccurate usage	Inaccurate credit	Data QA checks	S/W design and V&V Data integrity and QA checks Data processing QA checks	II—Hazardous/ Severe-Major
UBM	Credit Calculation	Inaccurate credit	Fatigue crack Reduced blade/swash plate control	Data QA check	S/W design and V&V Data processing QA checks	II—Hazardous/ Severe-Major
UBM	Credit Application	Apply to wrong part Apply wrong credit	Fatigue crack Reduced blade/swash plate control	Data QA checks	MMIS QA checks	II—Hazardous/ Severe-Major

V&V = Verification and validation
DAQ = Data acquisition

4.3.5 Step 5: Criticality and Integrity Level for End-to-End System/Process.

The FMECA conducted in step 5 traces the cascading effects to determine the worst end effect of each credible failure mode. The worst effect of all credible failure modes associated with the HUMS credit establishes the overall credit criticality level. The FMECA results in table 3 classify each sample UBM system/process failure mode as Class II, Hazardous/Severe-Major. The rationale is that the failure mode could lead to fatigue cracks and reduced swash plate control as the most severe credible end-effect hazard. The resultant failure conditions (which are

consistent with the Class II criticality definition) reduce the capability of the rotorcraft or the ability of the crew to cope with adverse operating conditions to the extent that there would be

- a large reduction in safety margins or functional capabilities.
- physical distress or excessive workload such that the flight crew's ability is impaired to where they could not be relied on to perform their tasks accurately or completely.

Note that according to the AC guidance, Hazardous/Severe-Major failure conditions can include events that are manageable by the crew's use of proper procedures, which if not implemented correctly or in a timely manner, may result in a Catastrophic Event. This is indeed the case for the example failure mode of reduced swash plate control described above.

Thus, the criticality level for the sample swash plate UBM credit is deemed to be Class II, Hazardous/Severe-Major. The fundamental principle is that a logical and acceptable relationship must exist between the criticality level and the system integrity expressed as an average probability per flight hour (i.e., system reliability). For a Hazardous/Severe-Major severity level, failure conditions must be no more frequent than extremely remote. Extremely remote events are not expected to occur during the total operational life of a random single rotorcraft of a particular type, but may occur a few times during the total operational life of all rotorcraft of a particular type, using the language and definition found in Section 1309 of reference 2. The associated system integrity level requirements are commensurately high, including the requirement of Level B software for onboard data processing and decision processes that are time critical and cannot be validated offboard.

In the authors' opinions, offboard data and process integrity can be maintained without Level B software being required as long as data and process integrity can be ensured by engineering subject matter experts. It is also the authors' opinions, that less than Level B OBS software can be used if the UBM process again ensures data and process integrity by engineering subject matter expert oversight. The rationale is that, in the case of the example credit (which is representative of most, if not all, regime-based UBM credit), the data gathering and decisions that are made during the end-to-end process to update the component retirement time occur over the course of years, yielding ample time for mitigating actions, such as data and RR process QA checks performed by engineering subject matter experts. However, the authors believe that Level B software would have to be used for onboard parametric data logging and processing to ensure the integrity of the data that engineering experts have available. Thus, the software integrity level is highly dependent on where data is processed, the ability to conduct data and process QA checks, and the ability to perform mitigating actions. Less than Level B software may be acceptable for lower-criticality credits.

4.3.6 Step 6: End-To-End Integrity Level vs Criticality Requirements.

The FMECA performed in step 4 provides the data required to establish criticality and integrity requirements for the end-to-end UBM system performed in step 5. In step 6, each end-to-end process element must be analyzed to determine if the criticality and integrity requirements are met. In the iterative credit definition process shown in figure 15, a quick qualitative assessment of compliance is conducted to determine the need for refinement of the UBM system/process in

step 7. A more rigorous assessment of compliance is performed in the credit validation process depicted in figure 3. The details of this assessment and demonstration of installation compliance are discussed in section 5. Here, only some qualitative examples are discussed to demonstrate the high-level process using the following scenarios (in section 4.1.1).

- Fully automated onboard usage and CRT adjustment implemented by the operator without OEM involvement

- Fully automated offboard usage and CRT adjustment implemented by the operator without OEM involvement

- Semiautomated offboard usage and CRT adjustment by the rotorcraft OEM

4.3.6.1 Fully Automated Onboard CRT Adjustment.

In this scenario, the operator would download a usage and/or maintenance adjustment calculated onboard. Without the ability to ensure data processing integrity through offboard QA checks by OEM subject matter experts, Level B onboard software would be required despite the lack of any real-time, time-critical, decision-making processes. If the onboard HUMS software is only certified to Level C, the system would not meet the UBM credit criticality and integrity requirements. A UBM system/process change would be required, which is discussed in step 7.

4.3.6.2 Fully Automated Offboard CRT Adjustment Implemented by the Operator.

In this scenario, the operator calculates usage and credits using GSS. Current ground-based systems used by the operator for HUMS data analysis are typically based on COTS hardware and operating system software. Without the ability to ensure data processing integrity through offboard QA checks by OEM subject matter experts, Level B onboard and GSS would be required despite the lack of any real-time, time-critical, decision-making processes. It is the authors' opinions that typical operators lack the expertise to perform their own QA checks. If the onboard HUMS software is Level B, but the GSS is only certified to Level D, the system would not meet the UBM credit criticality and integrity requirements. A UBM system/process change would be required, which is discussed in step 7.

4.3.6.3 Semiautomated Offboard CRT Adjustment by the Rotorcraft OEM.

In this UBM credit scenario, parametric and onboard regime data is transmitted to the OEM for calculation of aircraft structural usage. With the appropriate offboard processes to ensure the integrity of data transfer, storage, retrieval, and processing, OEM custom software can be executed on COTS computer hardware and operating software in the same environment used for design CWC usage spectrum and fatigue life calculations. Even in this scenario, onboard data acquisition software would need to be Level B, because offboard processes cannot mitigate possible corruption of the original data source. Likewise, regime processing performed onboard would need to be performed by Level B software unless data are available for use by the OEM to periodically validate the onboard calculations. This is the scenario used in sections 6 and beyond to discuss installation and credit validation.

4.3.7 Step 7: System/Process Changes to Meet Criticality Requirements.

In section 4.3.6, two scenarios were discussed to explain the need to refine the UBM system/process to ensure compliance with criticality and integrity requirements. The following options could bring the refined UBM system/process into compliance.

4.3.7.1 Fully Automated Onboard Usage/CRT Adjustment.

For the scenario in which the HUMS onboard software is certified only to Level C, the UBM system/process would need to be changed, which could involve either recertification of portions of the HUMS to Level B or provision of offboard data QA checks by OEM subject matter experts. Again, onboard parametric data collection software would have to be certified to Level B at a minimum.

4.3.7.2 Fully Automated Offboard Usage/CRT Adjustment Implemented by the Operator.

For the scenario in which the onboard HUMS software is Level B, but the GSS is only certified to Level D, the UBM system/process would need to be changed. The UBM system/process change could be used to develop non-COTS GSS and to certify it to Level B. An alternative would be to augment the end-to-end UBM system/process to include OEM data processing QA checks.

4.3.8 Step 8: Mitigating Actions to Maintain Baseline Risk or Better.

In aircraft product design, operational procedures and maintenance system requirements are defined to mitigate the critical failure modes to achieve acceptable baseline risk and reliability targets. For HUMS-based maintenance credits, risk mitigation is used to retain baseline risk and reliability despite maintenance intervention defined by the credit. In theory, risk mitigating actions can be used to reduce the defined criticality level, but in practice, are more likely to affect qualification requirements. Candidate mitigating actions are shown in table 3 for each UBM system/process failure mode. Specific examples of the use of mitigating actions to achieve baseline risk are given in section 5.

5. INSTALLATION VALIDATION.

The term end-to-end, as used in the AC, is intended to address the boundaries of the HUMS application and the effect on the rotorcraft (see figure 10). For the selected swash plate component and critical regimes to be monitored (high-bank angle turns, symmetric pullouts, and dives), the boundaries are the starting point that correspond with all the hardware, software, and processes involved in the data flow from airborne data acquisition and processing to the time of a meaningful result relating to the defined credit without further significant processing.

The HUMS OBS is standard S-92 aircraft equipment, along with a GS that stores raw data and provides visibility to high-level summary HUMS data. Collectively, these are considered part of the installation, since the operators and maintainers manipulate this equipment in the field.

The use of the current installation in the UBM end-to-end process is discussed in sections 5.1 through 5.4. The FHA or FMECA of the end-to-end process requires identification and assessment of credible faults at all points within the process. Once identified, compensating provisions can be used in the design of the process to reduce the likelihood of occurrence or criticality of the end effect. Finally, mitigation strategies are devised to eliminate or reduce the rate of faults to an acceptable level or limit and control their impact on critical functions of the process. The following sections provide an assessment of each portion of the process identified in figure 10. Each section includes a description of the functions provided by the process portion, possible faults and compensating provisions for each portion, and potential mitigation strategies. The existing installation and proposed procedures would be compliant with the AC.

5.1 ONBOARD DATA QUALITY AND SENSOR RELIABILITY.

Sensing refers to the measurement of electromechanical and hydraulic signals throughout the rotorcraft, as well as any possible analog or digital processing of the measured signals required to generate the parametric and discrete data acquired by HUMS for use in RR algorithms. For the S-92 aircraft, all parametric and discrete data are pulled from the digital bus, which does not affect the integrity of originating sensor data or intervening processing. On the other hand, tapping into sensor circuits on an analog aircraft is a known risk to sensor data quality.

5.1.1 Possible Failures.

Various faults can affect the sensing functions. They include various sensor faults such as noise, drift, out of calibration, saturation (when out-of-bound signals are received), and vibration-induced errors. On an analog aircraft, tapping into sensor circuits can increase the risk of these degraded sensor readings that may be a function of uncontrolled variables, such as local temperature. Some parameters required by HUMS for RR algorithms may require processing to calculate derived parameters. Thus, incorrect RR output due to degradations or failures in other avionic systems is a failure mode to be considered. On the S-92 aircraft, all data acquired by the onboard RR software are used in the flight control system, that is certified to Level A standards and requires sensor hardware reliability that exceeds the example credit requirements. Further, the data are taken directly from the digital bus, and HUMS data extraction has been demonstrated to have no effect on data integrity. Finally, the avionic systems that serve as the source of this data have BIT functionality to identify degraded functionality, including sensor functionality. All compensating provisions in the S-92 aircraft serve to significantly reduce the likelihood of occurrence of degraded sensor or processed data acquired by HUMS for RR.

5.1.2 Mitigation Strategies.

The S-92 aircraft end-to-end process for the example credit requires no further mitigation strategies for the reasons stated above. Regardless, the onboard RR software has logic to identify parametric data that is out of bounds or nonsensical, resulting in an “Undetermined” regime classification. These are extremely rare in the current historical fleet database of 150,000 flight hours. An aircraft exhibiting a large number of Undetermined regimes indicates bad sensor data that can be flagged, fixed, and mitigated through the use of CWC usage during periods of degraded sensing. More burdensome, or more sophisticated, data QA algorithms and processes may be required for analog aircraft. Candidate mitigating actions may include the

requirement for periodic validation of the parametric data by the operator. More sophisticated algorithms also could be used to perform univariate statistical assessment of sensor data for individual aircraft compared to the fleet and multivariate consistency logic.

5.2 ONBOARD HUMS DATA ACQUISITION AND PROCESSING.

During aircraft operations, the HUMS OBS acquires parametric data, processes the data to calculate regimes and usage, and records the data to the DTU. Continuous BIT logic is also performed by the HUMS OBS to identify internal failure modes. On the S-92 aircraft, acquisition for RR-based UBM credits is confined to extracting parametric and discrete data from the bus at the required sampling rate. Data processing consists of the execution of RR algorithms. Finally, all data, including raw parametric and discrete data and regime sequences, are written to a memory unit download (MUD) file by the DTU. The primary difference for an analog aircraft is the analog to digital conversion of data from various analog circuits before digital data can be processed within the HUMS.

5.2.1 Possible Failures.

For a HUMS OBS that acquires data from a digital bus, as is the case with the S-92 aircraft, the primary failure modes for the example credit are hardware or software failures that affect digital processing. The compensating provision on the S-92 is the development of a Level B system that significantly reduces the risk of such failure after validation and certification are completed.

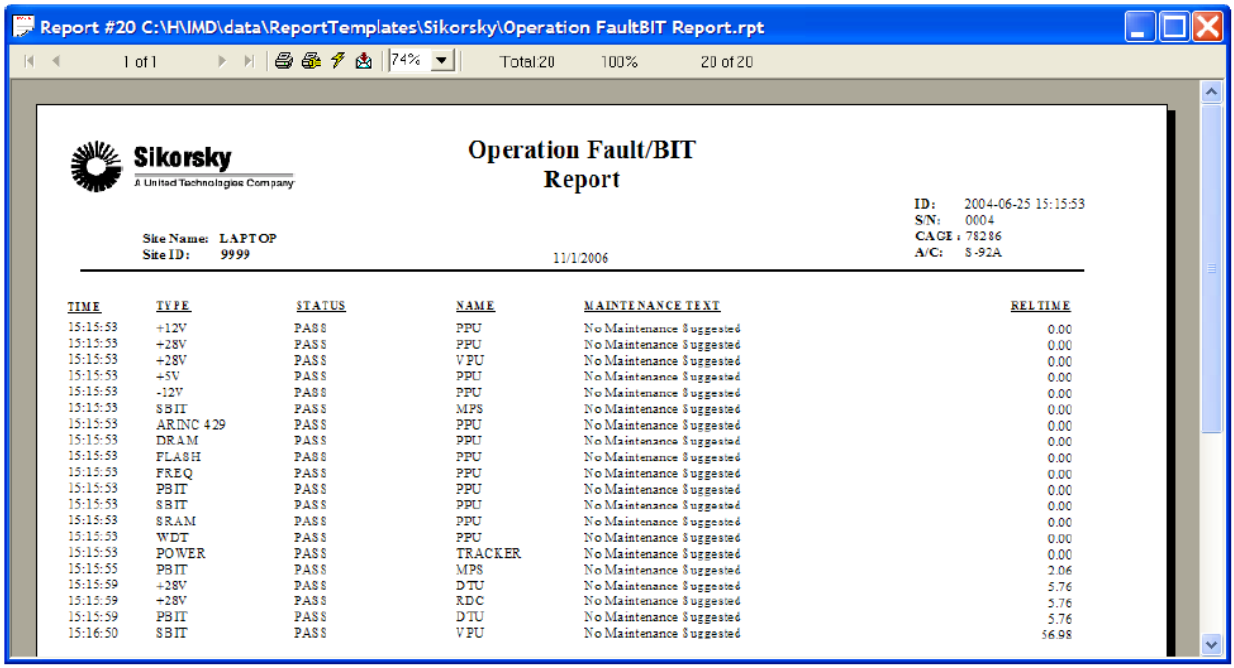
Because HUMS functionality and applicability is continually improving, software upgrades are expected periodically. If field loadable software is allowed, the risk of noncertified software or corrupted software uploads must be addressed.

5.2.2 Mitigation Strategies.

The S-92 HUMS OBS contains BIT features to identify failures that can affect digital processing. The GSS provides a report for operational faults, as shown in figure 17. Based on the report, operators can quickly take action to identify and correct any associated system hardware and software installation deficiencies. These BIT codes are also available to SAC to identify data that may have been corrupted during the calculation of a CRT adjustment. Although not required for Level B systems, a good mitigating strategy is to develop automated QA algorithms that can be used to assess RR and usage sequences and statistics for individual aircraft to compare to fleet statistics. Abnormalities can be flagged for investigation by engineering experts, including offline application of RR software to validate abnormal onboard usage patterns. The HUMS user's guide [5] contains procedures for initialization of the DTU card to ensure that the proper information has been transferred before the card is removed from the GSS. Any data that is corrupted can be replaced with CWC usage data. The user's guide permits flight for up to ten calendar days with a faulty or missing HUMS. This translates to about 25-50 flight hours for medium- to heavy-use operators. Any such gaps in the data are filled with CWC usage.

SAC carefully controls software upgrades, changing the hardware part number whenever software is modified. The Goodrich HUMS supplier makes changes to the S-92 HUMS software

based on SAC requests and specifications only. Revised software undergoes thorough certification tests prior to fielding. Retrofit of upgraded HUMS software is also carefully controlled. Until recently, operators were required to return the HUMS box for uploading of new software and changing the part number. Recently, SAC developed and certified a field loading procedure to ensure the integrity of uploads. For any HUMS OBS software upgrade, approval must be granted to perform field loading of the OBS software. Initially, customers are notified of the availability of the OBS upgrade. A backpack, consisting of a laptop computer with upgrade software and a cable, is shipped to each customer. This is used to upgrade the OBS software in a completely automated and consistent fashion. This adheres to the FAA-certified field loading procedure, which requires that the work be performed under the operator's local repair station certificate in compliance with Title 14 CFR Part 145 requirements [11].



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Sikorsky
A United Technologies Company

Operation Fault/BIT Report

ID: 2004-06-25 15:15:53
S/N: 0004
CAGE: 78286
A/C: S-92A

Site Name: LAPTOP
Site ID: 9999

11/1/2006

TIME	TYPE	STATUS	NAME	MAINTENANCE TEXT	REL TIME
15:15:53	+12V	PASS	PPU	No Maintenance Suggested	0.00
15:15:53	+28V	PASS	PPU	No Maintenance Suggested	0.00
15:15:53	+28V	PASS	VPU	No Maintenance Suggested	0.00
15:15:53	+5V	PASS	PPU	No Maintenance Suggested	0.00
15:15:53	-12V	PASS	PPU	No Maintenance Suggested	0.00
15:15:53	SBIT	PASS	MPS	No Maintenance Suggested	0.00
15:15:53	ARINC 429	PASS	PPU	No Maintenance Suggested	0.00
15:15:53	DRAM	PASS	PPU	No Maintenance Suggested	0.00
15:15:53	FLASH	PASS	PPU	No Maintenance Suggested	0.00
15:15:53	FREQ	PASS	PPU	No Maintenance Suggested	0.00
15:15:53	PBIT	PASS	PPU	No Maintenance Suggested	0.00
15:15:53	SBIT	PASS	PPU	No Maintenance Suggested	0.00
15:15:53	SRAM	PASS	PPU	No Maintenance Suggested	0.00
15:15:53	WDT	PASS	PPU	No Maintenance Suggested	0.00
15:15:53	POWER	PASS	TRACKER	No Maintenance Suggested	0.00
15:15:55	PBIT	PASS	MPS	No Maintenance Suggested	2.06
15:15:59	+28V	PASS	DTU	No Maintenance Suggested	5.76
15:15:59	+28V	PASS	RDC	No Maintenance Suggested	5.76
15:15:59	PBIT	PASS	DTU	No Maintenance Suggested	5.76
15:16:50	SBIT	PASS	VPU	No Maintenance Suggested	56.98

Figure 17. A Screen Capture of HUMS Installation BIT Report Available on the GS

The validity of RR output is a key driver of uncertainty in damage calculations. Improvement in the accuracy of OBS RR algorithms will, to some extent, mitigate this risk. This is assessed in sections 6.5.1 through 6.5.3 in terms of HUMS predictions versus actual usage conditions for critical maneuvers. However, no matter what RR algorithms are used, their uncertainty must be quantified and considered when calculating maintenance adjustments. The process developed in this project accomplishes this by postprocessing the existing HUMS RR output so enough conservatism is built into the predictions to ensure safety and reliability. This is detailed further as part of the credit validation methodology in section 6.5.4.

5.3 DATA TRANSFER BETWEEN AIRCRAFT AND GROUND SYSTEM.

Possible methods of transfer involve any combination of automated, semiautomated, or manual processes for data transfer from the OBS to the GS for subsequent higher-level processing,

storage, and transmittal to the rotorcraft OEM. Ensuring against corruption and loss of data during transfer to the GS is an important element of data integrity assessment. Data transfer for the S-92 aircraft is a manual process that involves taking the DTU card from the unit in the cockpit and physically inserting it into the GS.

5.3.1 Possible Failures.

The primary risk during this transfer is the loss or corruption of data. For example, the DTU card could be lost or filled prior to transfer to the GS. Note that the S-92 aircraft HUMS OBS will not overwrite the card if it becomes full and issues a "check HUMS" warning in the cockpit upon activation of WOW following a flight.

5.3.2 Mitigation Strategies.

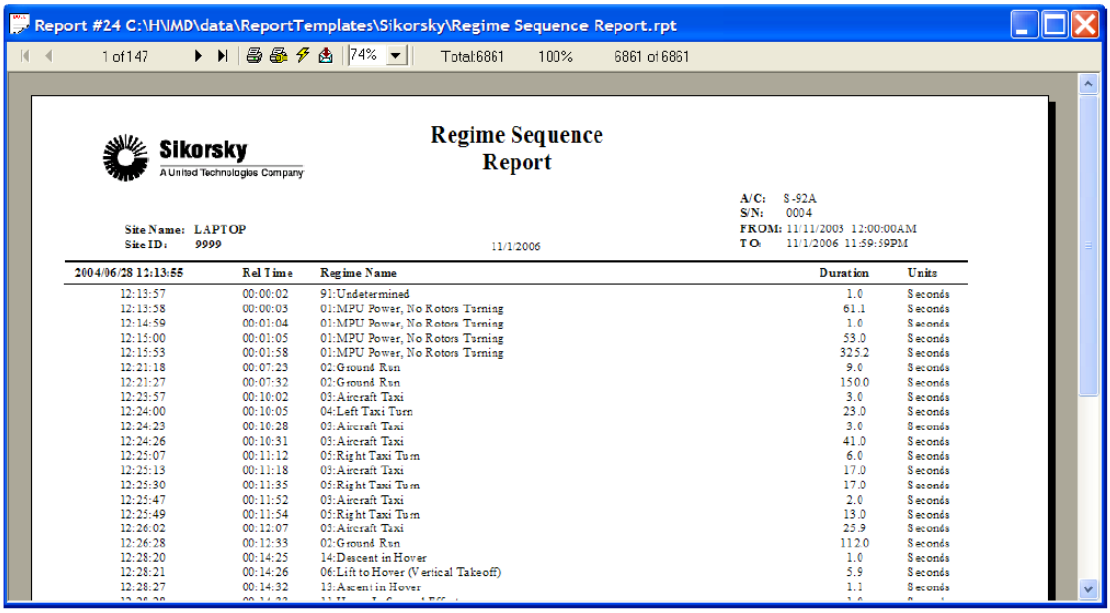
Data corruption may be detected using several techniques. This may be partly addressed through checksum error detection and correction, and partly by automating the transfer process. The idea of checksum is to compute a hash function of the data, include the result in the transmission, and ensure that the checksum relations hold at the receiving end through application of standard algorithms. Note that checksums only ensure against accidental data corruption and not corruption caused by malicious attacks. Risk of malicious attacks can be mitigated by operator processes used to control access to the data card and GS. It can be further mitigated through the application of data quality checks. It should be noted that the malicious corruption of data that could withstand such checks, even if data card and GS access is not controlled, is not plausible because of the highly proprietary and binary data structure used to write the data file in the OBS. The detection of such attacks on data integrity is discussed further in section 5.4.

A number of mitigating actions can be conceived to identify loss of data or data gaps. A simple mitigating action is to require the pilot debrief feature on the GS to be included in the operator postflight procedures. The GS provides a selection of standard reports that can be viewed or printed. These standard reports include data commonly used to support maintenance activities. When loading the DTU card onto the GS, the aircraft and maintenance crews can review the data immediately to ensure that data has not been corrupted or lost. The GS pilot debrief feature specifically includes the ability to acknowledge or correct HUMS-reported flight hours, exceedances, and data anomalies.

In addition, automated loss of data algorithms can be readily developed. One simple approach to detect data loss is to independently verify the total flight hours for an aircraft within a period and compare them to the total length of data received. Such a process would need to account for the potential differences in the independent source of flight hours. For example, one operator may record flight hours from the time the crew enters the cockpit to the time the crew departs. Another operator may record the time between rotor turn and rotor stop. It is well known that pilots tend to round up logbook flight hours. Any missing block of data may then be replaced conservatively, e.g., by using CWC spectrum.

Figure 18 shows that the regime sequence report provides a tabulated time history of HUMS RR output. This is the single primary source of HUMS data used in the UBM credit process. The report is available to the pilots and ground crews for immediate review after each flight to

determine if there was any faulty data collection. To assist in the assessment, the RR output is summarized graphically using the regime spectrum graph feature on the GS, as shown in figure 19. This collects all durations and occurrences of HUMS regimes and provides them to the reviewer in a succinct format that can be assessed for compatibility with the mission flown and also compared to graphs from previous operations to ensure similarity. This capability could be used for either CIS or periodic validation of the onboard regime and usage calculations. Such an ongoing mitigating action would be more crucial to the credits that did not involve the rotorcraft OEM in the calculation of CRT adjustments.



2004/06/28 12:13:55	Rel Time	Regime Name	Duration	Units
12:13:57	00:00:02	91:Undetermined	1.0	Seconds
12:13:58	00:00:03	01:MPU Power, No Rotors Turning	61.1	Seconds
12:14:59	00:01:04	01:MPU Power, No Rotors Turning	1.0	Seconds
12:15:00	00:01:05	01:MPU Power, No Rotors Turning	53.0	Seconds
12:15:53	00:01:58	01:MPU Power, No Rotors Turning	325.2	Seconds
12:21:18	00:07:23	02:Ground Run	9.0	Seconds
12:21:27	00:07:32	02:Ground Run	150.0	Seconds
12:23:57	00:10:02	03:Aircraft Taxi	3.0	Seconds
12:24:00	00:10:05	04:Left Taxi Turn	23.0	Seconds
12:24:23	00:10:28	03:Aircraft Taxi	3.0	Seconds
12:24:26	00:10:31	03:Aircraft Taxi	41.0	Seconds
12:25:07	00:11:12	05:Right Taxi Turn	6.0	Seconds
12:25:13	00:11:18	03:Aircraft Taxi	17.0	Seconds
12:25:30	00:11:35	05:Right Taxi Turn	17.0	Seconds
12:25:47	00:11:52	03:Aircraft Taxi	2.0	Seconds
12:25:49	00:11:54	05:Right Taxi Turn	13.0	Seconds
12:26:02	00:12:07	03:Aircraft Taxi	25.9	Seconds
12:26:28	00:12:33	02:Ground Run	112.0	Seconds
12:28:20	00:14:25	14:Descent in Hover	1.0	Seconds
12:28:21	00:14:26	06:Lift to Hover (Vertical Takeoff)	5.9	Seconds
12:28:27	00:14:32	13:Ascent in Hover	1.1	Seconds

Figure 18. A Screen Capture of HUMS Regime Sequence Report

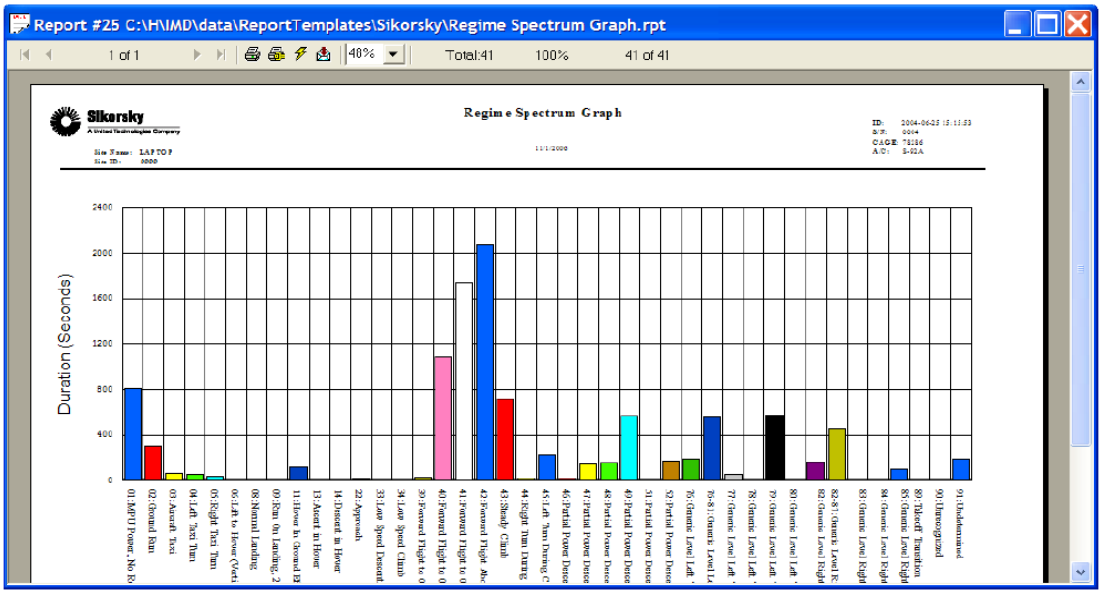


Figure 19. A Sample HUMS Regime Spectrum Graph

The HUMS OBS has, as of this writing, produced more than 150,000 flight hours of fleet usage information that is examined on a regular basis by SAC engineers. When followed properly, the existing processes for data transfer to the GS have been shown to be highly reliable with extremely minimal loss of data. The present S-92 aircraft HUMS data transfer procedures outlined in the user's guide [5] are, therefore, considered to be compliant with the UBM end-to-end process with minimal risk. Any lost data can be replaced with the conservative CWC usage assumptions, or possibly, a more severe appropriate spectrum, if peak damage accrual rate temporarily exceeds the CWC assumption.

5.4 GROUND STATION DATA STORAGE AND TRANSFER TO OEM.

The GSS is a system of integrated software applications, primarily the Goodrich GS application, that was designed to be consistent with DO-178B, Level D, but was never formally certified by the FAA. An operator may also have one or more MMIS applications used for activities, such as parts tracking or maintenance actions. The GSS facilitates the reduction of maintenance workload and increased access to aircraft flight health, usage, and maintenance recorded data. The S-92 aircraft HUMS GSS software applications operate on Windows® 2000/XP® or Windows Server 2003 operating system and use an underlying Oracle® relational database management system (9i or 10G RDBMS). The GSS downloads the recorded MUD files from the DTU and condenses them into a more efficient raw data file (RDF) format. No significant data processing occurs on the GSS; it is for display purposes only. Every packet in a MUD or RDF is wrapped in a 32-bit cyclic redundancy check (CRC) word. When the GS reads those packets, it verifies the CRC to ensure the data matches what was written by the OBS. The CRC data is in both the MUD and RDF file formats for use in verifying data integrity at any point along the data management chain. The binary format makes it very difficult to intentionally modify that data. Both inadvertent and malicious corruption of data would be detected, and the effected packet data would be rejected upon download or reprocessing by the OEM. The detection of the corrupted data would be sent via messages in the download log file.

Most S-92 aircraft operators have their GSS configured to automatically send a copy of the RDF to an outgoing folder for SAC to retrieve via file transfer protocol (FTP). Some smaller operator or their field service representatives manually copy the RDF file to a predetermined outgoing folder for SAC retrieval via FTP.

SAC hosts servers that have scheduled batch files that access the operator's FTP site, traverse to the correct outgoing folder, invoke the FTP file transfer command that brings the file into the SAC server system, and then, automatically deletes the operator's RDF files from the outgoing folder. These batch files are scheduled to run usually after operators transfer their daily RDF files to the outgoing folder. The customer's time zone is taken into account in the scheduling of the batch files.

To exploit a near-term transition of UBM technology using existing HUMS RR algorithms, all data processing is performed offboard by the OEM at a centralized facility, such as the FMOC. Under this scenario, the GSS acts only as a conduit, employing existing capabilities, such as storing data and tracking parts, with no changes to processes that are already well-accepted by the operators and FAA.

5.4.1 Possible Failures.

COTS is equipment hardware and software that is not qualified to aircraft standards (e.g., a PC and its operational software). If data processing in the COTS software on the GSS is required as part of the end-to-end UBM process, an independent means of verifying the GSS processing must be devised as part of an overall mitigation strategy.

5.4.2 Mitigation Strategies.

Verification of the integrated OBS and GS requires that the GS successfully parses and displays information contained in files generated by the OBS. For S-92 aircraft, GS laptop computers are imaged by a subcontractor and then delivered to SAC, where a review of the GS functionality is conducted using HUMS RDF files produced during flight tests. Flight hanger acceptance test procedures are run prior to initial aircraft ground runs and flights to ensure that the system and all components are operating properly.

Prior to any analysis, a final mitigating action ensuring automated data integrity and quality checks are performed to flag suspect data for OEM engineering expert assessment. Similar mitigating actions, as discussed in section 5.3 (e.g., checksum), would be appropriate for the OEM to use as well.

Experience has found extremely minimal loss or corruption in the very large volume of fleet data collected for the S-92 aircraft. The present GSS data storage and transfer procedures are, therefore, considered to be compliant with the UBM end-to-end process with appropriate levels of minimal risks associated with credit evaluation. Any data that might be lost or corrupted is replaced with the conservative CWC usage assumptions.

6. CREDIT VALIDATION COMPLIANCE.

Demonstrating compliance with the credit validation requirements is one of the essential elements for obtaining UBM credit approval. While specific details will vary for each individual HUMS application, the focus for this research was to develop an acceptable means of certifying a UBM credit for life-limited parts (LLP).

The validation of a HUMS-based UBM credit requires execution of a CVP. The CVP should address five primary elements: (1) define the credit, (2) demonstrate installation compliance with the AC, (3) demonstrate credit compliance with the AC of the recurring end-to-end process elements, (4) establish processes for maintaining airworthiness, and (5) establish CIS. The first two were already discussed in detail in sections 4 and 5. The last two are discussed in detail in sections 7 and 8. Thus, sections 6.1 through 6.4 focus on the credit validation requirements for the recurring steps of end-to-end process performed by the OEM, as shown in figure 10 and discussed in table 2; and the nonrecurring process of RR algorithm validation are discussed in section 6.5 in accordance with the CVP.

6.1 FLEET DATA COLLECTION AND STORAGE.

HUMS and maintenance data must be collected to calculate the actual usage and CRT adjustment for an aircraft or the updated CWC for an aircraft fleet. This requires the collection and storage of large quantities of HUMS data over a period of years at a location accessible to the organization having responsibility for the calculation of actual usage and CRT adjustments. In the preferred scenario, discussed in section 4.1.1 (table 2), the OEM has this responsibility. Thus, the data must be collected and stored at the OEM's location after transfer from the operators. To maintain the required system integrity level, an engineer-in-the-loop approach is proposed in which data integrity is ensured once it is received from the operators and archived for future calculation of UBM credit adjustments.

The present SAC S-92 aircraft data management system and FMOC already have advanced data integrity methods that can be applied to the UBM end-to-end process. Automated data integrity checks are implemented as data is received from each operator each day. Further, trained specialists process and review data that have been downloaded from each aircraft. This data is archived and is available for later viewing and use in postprocessing activities. In summary, automated data integrity checks are performed each time the data is extracted, transferred, and archived.

6.1.1 Possible Failures.

The primary concern is data loss or corruption during the storage process.

6.1.2 Mitigation Strategies.

Figure 20 shows the process currently used for the S-92 aircraft fleet. Any daily customer flight data received by SAC is collected and held for processing in a folder on a dedicated server. Before any processing is done to the files, a copy is made and placed in an archive folder. Each month, these files are moved from the archive folder to an external hard drive, again, checking data integrity as the data is transferred. Using external hard drives as a backup for the server accomplishes two purposes: (1) if the server crashes, the external hard drives will not be affected; and (2) the external hard drives offer quick access to the archived files. SAC also archives the RDF data files, and Oracle export files of the GSS to a read-only archive array. Oracle backups are done at the end of each month. Thus, there are multiple sources for restoring data in case data is lost in one or more databases.

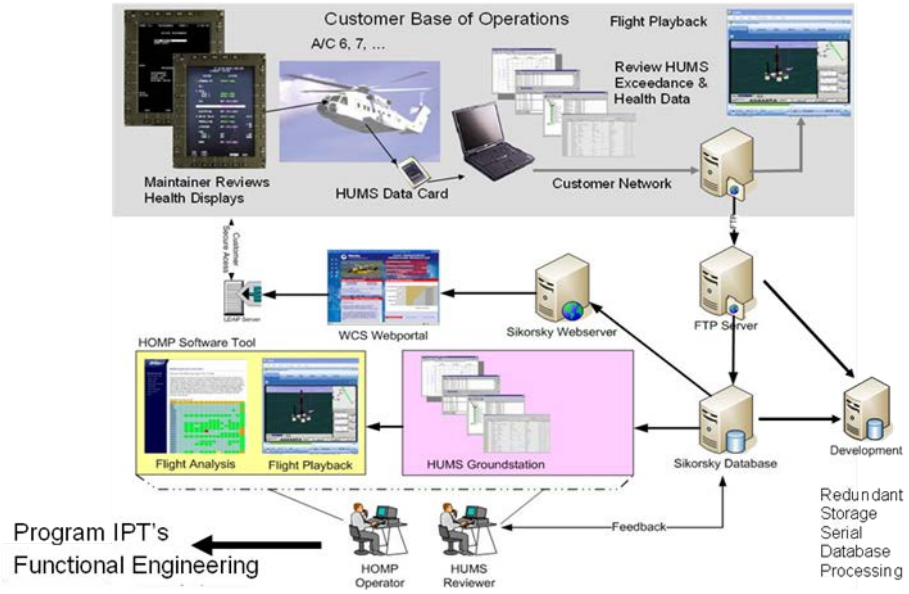


Figure 20. Fleet Data Collection and Storage

The existing procedure enables the review of information by multiple stakeholders and provides the appropriate levels of redundancy and backup to prevent loss of fleet data at the OEM. This is an acceptable UBM credit procedure that requires no changes.

6.2 DATA MINING AND PART CONDITION VERIFICATION.

Data mining is required to extract from HUMS binary RDF files only the information that is relevant to the objectives of a particular credit application and preprocessing (e.g., data checks and assembling formatted database) to prepare for usage and credit adjustment analysis. Large quantities of HUMS data must be mined and merged with maintenance data to calculate actual usage and CRT or CWC adjustments. For a serial number-based credit, the usage and CRT adjustment must be calculated for an individual component serial number that may have been installed on more than aircraft during its service history. Thus, the first step in data mining is determining the service history through maintenance data, including any repairs or other maintenance actions that may invalidate eligibility for a credit adjustment or may require specialized analysis. The service history also must be mapped to the specific HUMS RDF files that must be extracted, mined, and analyzed. For a part number-based credit that entails adjusting the CWC usage spectrum, large quantities of fleet data must be mined, processed and analyzed with efforts made to ensure that a statistically significant and representative subset of fleet data is used. For both types of credit, the mined data will likely cover several years.

Data mining typically results in a standard file or database that will be used for credit adjustment analysis. One reason for storing the results is because the extraction, processing, and analysis steps are time-consuming. Further, data analysis may be iterative in the event that downstream data quality checks result in invalidation of subsets of data. Storing these results makes it easy to quickly retrieve, validate, and display them, thereby reducing the number data mining steps.

Once extracted data are been mined and the results are stored, the final step is to present the results to users in a format that makes the results easy to understand and makes missing, corrupt, and anomalous data readily apparent.

6.2.1 Possible Failures.

The primary concern is data loss or corruption during mining and preprocessing. Because such large amounts of data are required for the calculation of UBM credit adjustments, automated data mining tools are required, which poses the risk of extraction errors, such as incorrect data (e.g., wrong tail number) or overlooking sets of relevant data. The use of a COTS hardware and software computing environment for automated data mining tools poses risks associated with changes in the COTS environment (e.g., a new operating system or computer upgrade).

6.2.2 Mitigation Strategies.

Automated data integrity checks are performed when the data is extracted from the RDFs. Data validity is established and statistics are generated for the data extracted from each RDF at the time of extraction. Extracted data is tagged with a validity code and identifying information that can be traced back to the originating RDF file, including date, time, tail number, and operational usage statistics (e.g., flight hours, engine cycles, and takeoffs and landings) that are cross-correlated with maintenance data and operational log files, which further validates data integrity and identifies missing or corrupted data. Structural usage statistics are calculated from onboard RR sequences at the time of extraction and stored with extracted data for use in downstream data quality checks via crosschecking results from offboard data processing. Automated analysis of data and usage statistics is performed to validate self-consistency of data throughout the entire sequence of RDFs (e.g., check ending and beginning cumulative flight hours for adjacent RDFs in sequence). Results are presented in a format that is easy to understand and can readily be compared to maintenance data, and anomalous data can be readily identified for further investigation. Independent tools are developed to allow crosschecking of results during CIS and during periodic process audits. Finally, an engineer ensures that all information regarding fleet data integrity and part condition is accurate and commensurate to the high level of critically for the life-limited dynamic rotorcraft components being assessed.

6.3 USAGE AND FATIGUE DAMAGE MONITORING.

Once relevant parametric, operational usage, and RR sequence data are mined, they must be further analyzed to develop trends in usage (i.e., CWC regime occurrences per 100 flight hours and average durations) and fatigue damage rate (i.e., damage per flight hour). These are necessary parameters for a CRT adjustment; and periodic monitoring is an effective means to trigger an intervening action if an operator is exceeding CWC assumptions, requiring a possible earlier retirement of LLPs. These trends are examined at each 25% interval of the published AWL CRT for the subject UBM component, which this research considers appropriate.

6.3.1 Usage Trending.

Clustering is a way to solve the current problems with using existing HUMS RR output to obtain more accurate measurements of usage for CWC regimes, where a CWC regime is defined as a

standard maneuver used to develop a CWC usage spectrum and to establish CRTs for LLPs. The clustering algorithm works by developing a CWC map that is used to filter, smooth, aggregate, and map the onboard RR algorithm output into usable standard CWC regime data (i.e., counts and durations). The benefit of such an offboard approach is the ability to achieve UBM credits without the need to develop sophisticated complex onboard algorithms. As shown in figure 21, the CWC mapping process is designed to minimize the uncertainty in the mapped regimes versus a set of truth data. The clustering methodology is a key aspect of the credit validation technical approach involving the onboard RR algorithms and offboard processing. Sections 6.5.1 through 6.5.3 provide a detailed description of the evaluation of current S-92 RR algorithms and how the clustering algorithm maps the RR output into CWC regime events (section 6.5.4). The clustering process has been embodied in a semiautomated RR clustering (RRC) software tool that enables process control by an engineering expert (section 6.5.5).

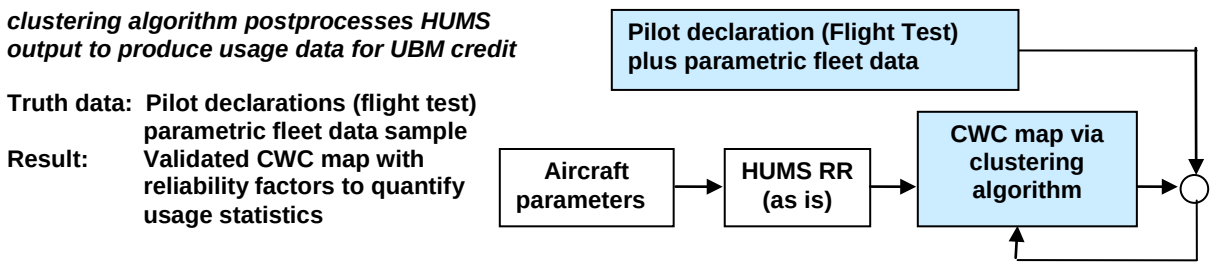


Figure 21. Clustering Algorithm Concept

The clustering algorithm also automatically calculates reliability factors that provide quantitative data that can be used to show that the monitored usage results are compatible with the baseline system integrity level of the FAA-approved SAC process that established the published AWL CRT. Since the calculation of reliability factors is such a significant issue for UBM credits, it is covered in significant detail in appendix B.

For this study, actual usage was calculated by applying the clustering algorithm to 12 individual S-92 aircraft for the most critical stationary swash plate CWC maneuvers consisting of 45° turns, entry and recovery (E&R) for 30° and 45° turns, and pullouts. Two aircraft were selected from the entire fleet to represent the individual best aircraft (i.e., most benign usage) and worst aircraft (i.e., most severe usage) from the perspective of potential UBM benefit. The ranking system was based on nine factors relative to GAG cycle rates and the percentage of time spent in known high-time spectrum regimes and overall aircraft-damaging regimes. Results for these two aircraft represent the two extremes for a spectrum that is critical to multiple dynamic component and airframe parts. The spectrum was not critical for just the swash plate and, therefore, does not correspond to the usage extremes for the swash plate. Results for those aircraft are provided for reference only.

The remaining ten aircraft comprise a sample of an operator subfleet selected to mimic the scenario where an operator would apply for a maintenance adjustment to apply to his entire fleet of aircraft. S-92 aircraft HUMS operational data for this subfleet was collected for 12 months of operations in a format that allows queries of usage statistics, including existing RR, GW, CG, and associated aircraft operational parameters. To compute representative statistics for the

operator's fleet operations, the clustering algorithm was individually applied to the ten tail numbers to determine a distribution of usage severities. This distribution was used to determine a reliability factor for fleet usage monitoring [1].

Twelve months of operations were collected for each individual aircraft. Basic statistics are shown in table 4. The number of RDFs represents the approximate number of flights. Table 5 shows the results of the clustering algorithm for the critical regimes for each individual aircraft. The results are expressed as a ratio of the cluster duration and count to the CWC per 100 flight hours. It is clear that the usage in these damaging regimes is much less than the CWC.

Table 4. Statistics for Aircraft Used in UBM Credit Evaluation

Individual Tail Identifier	March 1, 2010 Total Time (hr)	Flight Time for Files Monitored (hr)	RDF Files Processed
1	8290.48	1558.1	1467
2	5139.47	1678	1118
3	2480.2	1521.5	1197
4	2184.9	1815.4	1309
5	2463	1810.2	1369
6	2452	1880.1	1389
7	2320	1078.3	1322
8	3255.3	1860.2	1079
9	1050.6	948.9	990
10	904.56	934.45	759
Worst	5518.9	2014.7	1329
Best	3791.5	1229	529

Table 5. Clustering Results on Individual Usage for Critical Regimes

Individual Tail Identifier	45° Turn (duration) Ratio to CWC	E&R Turns (counts) Ratio to CWC	Pullouts (counts) Ratio to CWC
1	0.04	0.40	0.03
2	0.04	0.34	0.03
3	0.06	0.52	0.27
4	0.04	0.51	0.06
5	0.04	0.53	0.08
6	0.04	0.53	0.05
7	0.10	0.85	0.14
8	0.03	0.32	0.10
9	0.02	0.22	0.09
10	0.03	0.34	0.05
Worst	0.03	0.37	0.07
Best	0.03	0.34	0.12

The clustering results include reliability factors associated with the clustering algorithm. The cluster duration reliability factor (CDRF) is applied to steady regime durations that are easily translated into spectrum percent time. The cluster count reliability factor (CCRF) is applied to transient regime occurrences. The reliability factors are presented in table 6. Details of these calculations are documented in section B.7.

Table 6. Clustering Reliability Factors

Maneuver	Regression Multiple	CDRF	CCRF	UMRF
Pullout	1	1.8	1.5	2.2
30° right turn (M30RT)	0.83	1.06	1.9	1.7
45° right turn (M45RT)	0.83	1.06	1.9	4.3

An additional usage monitor reliability factor (UMRF) is calculated based on subfleet statistics to apply a fleetwide UBM credit at the part number level. SAC engineers from the ground test and structural methods organizations previously developed an approach that is applicable to a fleetwide UBM credit validation [1]. This approach prescribes the UMRF as the ratio of two suitable percentiles (e.g., 90th to 50th) of a probability distribution fitted to the sampled data points in table 5 for each regime. Table 7 shows the results for these regimes with the UMRF applied as a ratio to the original CWC.

Table 7. Fleet Usage Clustering Results for Critical Regimes

	45° Turn (duration) Ratio to CWC	E&R Turns (counts) Ratio to CWC	Pullouts (counts) Ratio to CWC
Subfleet Usage	0.08	0.66	0.17

6.3.2 Fatigue Damage Rate Trends.

Once the clustering output and structural usage statistics are calculated, they must be checked for quality and validated. After this validation, the actual usage statistics are used to calculate an estimate of accumulated fatigue damage to compare against the expected damage rates for the CWC spectrum. The SAC safe-life fatigue evaluation methodology for S-92 aircraft principal structural elements is detailed in reference 12 and summarized below.

The safe-life scope for the defined UBM credit is limited to the application of Miner's rule that uses S-N material strength to determine CRTs for metallic structures. This excludes sample crack growth predictions in metals or composite materials [12]. These situations require life assessment models that depend not only on the measured spectrum content, but also the order of measured regimes, as shown in figure 22, which is outside the scope of this effort.

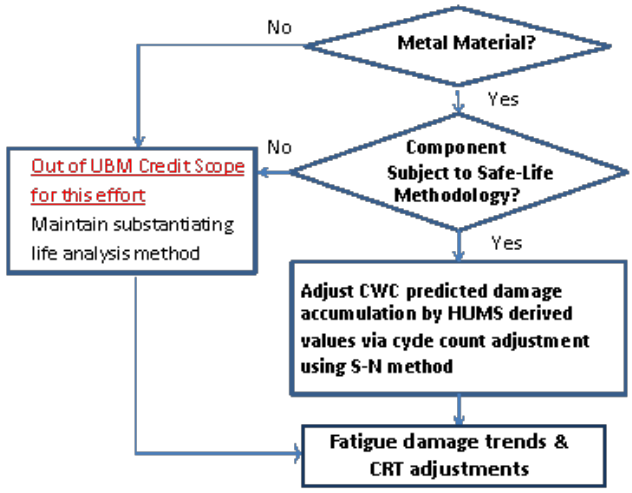


Figure 22. The UBM Methodology Scope for Safe-Life Parts

The steps involved in damage calculations for components that use the S-N methodology are shown in figure 23. As this figure shows, damage is calculated as the sum of three terms, D_V, D_{GAG}, and D_{TR}.

- The total damage accumulation is calculated as the sum

$$D_{HUMS} = D_V + D_{GAG} + D_{TR}$$

- Steady-state vibratory damage: Observed HUMS regimes (r) during flight i combined with a HUMS to CWC map, in effect assigns a time duration (T) to every combination of load (L), and number of cycles per unit time (c). Using S-N curves, component damage is accumulated via

$$D_V = \sum_i \sum_r T_{r,i} \frac{C_{r,i}}{SN^{\mathrm{INV}}\left(L_{r,i}\right)}$$

where SN^{INV} $(L_{r,i})$ is the number of allowable cycles corresponding to the CWC regime load, L_r, during flight i, as read from the S-N working curve.

- Low-cycle GAG damage and high-frequency transients: From observed HUMS regimes (r) and HUMS to CWC maps, compute during each flight i

  - GAG peak-to-peak loads (LPP)
  - GAG steady loads (LSS)
  - Number of times (ν) transient regime j with maximum load LTR occurs

Low-cycle GAG damage (D_{GAG}) and transient damage (D_{TR}) are then accumulated via

$$D_{GAG} = \sum_i \left[\frac{1}{SN^{\mathrm{INV}}(LPP_i)} + \frac{1}{SN^{\mathrm{INV}}(LSS_i)} \right]$$

$$D_{TR} = \sum_i \sum_j \frac{V_{i,j}}{SN^{\mathrm{INV}}(LTR_{i,j})}$$

Damage rate is simply the expression of fatigue damage as a function of time. CWC damage rates are usually expressed in terms of 100-flight hour blocks. The accumulated damage rate for actual usage is obtained by normalizing the total damage (figure 23) to the same unit of time. The notional UBM process (shown in figure 9) can be used to show this concept graphically. The assumed conservative CWC damage accumulation rate (CDAR) is a linear function shown by the red line in figure 9. However, the actual accumulated damage is not a linear function, therefore, the slope varies over time (as does the estimated damage rate, which is conservatively made higher via incorporation of reliability factors described above).

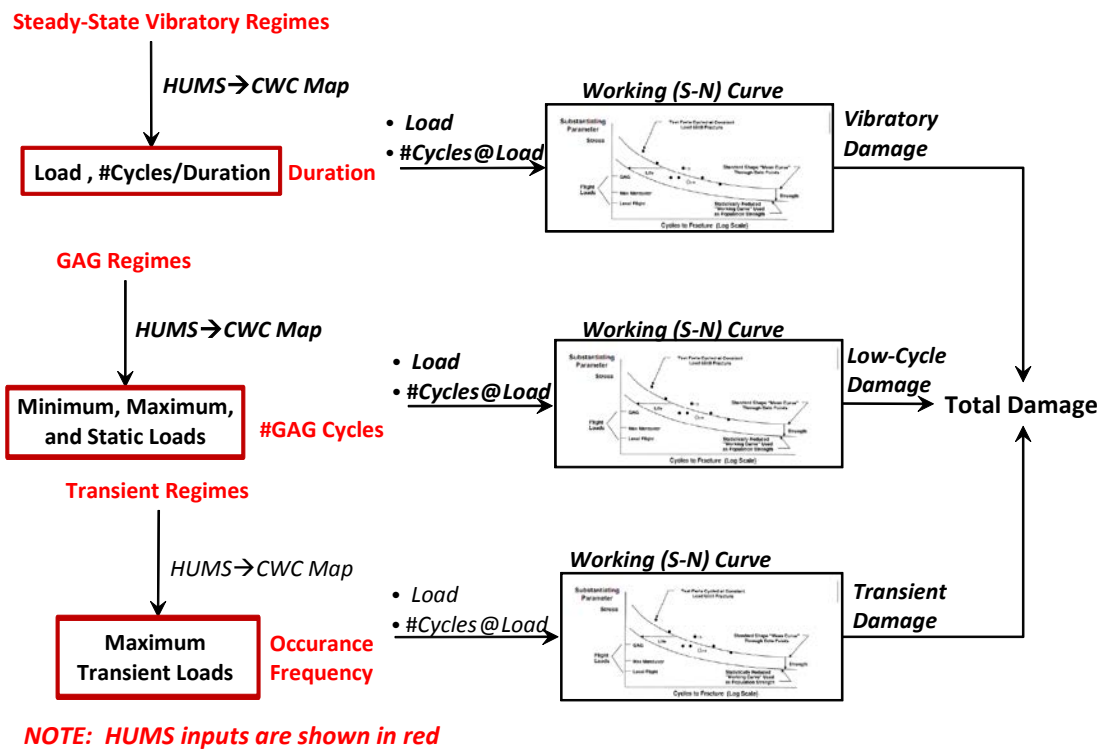


Figure 23. Calculation of Accumulated Damage for Actual Usage

As a result, the actual damage rate statistics are relevant. The average rate is determined by considering all flight hours up to the point in time when the trends are monitored. If the average rate exceeds the CDAR, then the rotorcraft is operating more severely, which would prompt a notification from the OEM to the operator.

In addition, a peak-damage accumulation rate (PDAR) is computed by examining, for example, 100-flight hour blocks, or some other useful time interval to capture peak-usage periods and defining PDAR as a reasonable value of the distribution; for example, 95th percentile. The

PDAR determines whether to use CWC usage to mitigate missing or corrupted data. If PDAR exceeds CDAR, then the operator has experienced more severe usage than the design assumption and, therefore, would be the appropriate parameter for gap filling.

6.3.2.1 Possible Failures.

Calculation of actual usage and fatigue damage accumulation using this method with a HUMS-derived spectrum is obviously subject to uncertainties that must be addressed. 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 has the largest influence on any error in calculated damage accumulation. This is quantified by several reliability factors built in to the clustering algorithm process and the development of an RRC tool to establish consistent, repeatable processes.

6.3.2.2 Mitigation Strategies.

New mitigating strategies, which are addressed in section 6.5, are required to account for potential errors in RR. Trending of usage and computation of accumulated fatigue damage are appropriate mitigating actions to trigger in-depth analysis of usage, assessment of overall compliance with CWC conservative assumptions, and appropriate data gap filling. For example, gap filling is used with an appropriate level of conservative usage that is the greater of the assumed CWC or observed peak-usage periods. Furthermore, if the actual damage rates, either average or PDAR, are above a critical value, the operator would be alerted.

6.4 CALCULATION OF UBM CREDIT ADJUSTMENT.

Once actual structural usage statistics are developed and validated, the credit adjustment must be calculated, taking the form of either a CRT adjustment (manifested via an adjustment in effective flight hours) or a CWC spectrum update. The sample credit adjustments are calculated below for the selected swash plate component to demonstrate the proposed process and to determine the potential level of benefit. Potential CRT adjustments were estimated for both individual aircraft and components and a fleetwide population with the former accounting only for past usage history for individual aircraft components (and the latter based on an updated CWC spectrum used for both past and future usage). Note that both types of UBM credit build upon processes already used by OEMs to occasionally update CWC spectra through traditional methods, such as pilot/operator surveys.

6.4.1 Serial Number-Based Individual Component CRT Adjustment.

The appropriate intervention action for the UBM credit is determined to be a notification to the operator via formal documentation describing a modification to maintenance practices (i.e., approved CRT adjustment). A sufficient history of HUMS data is necessary. A value of 75% of the published AWL CRT is proposed herein, unless determined by fatigue damage trending to be sooner. The CRT adjustment for an individual component is shown in figure 24 as example where trending has indicated that the aircraft is operating less severely than the design CWC usage (based on comparison of damage accumulation rates described in section 6.3.2).

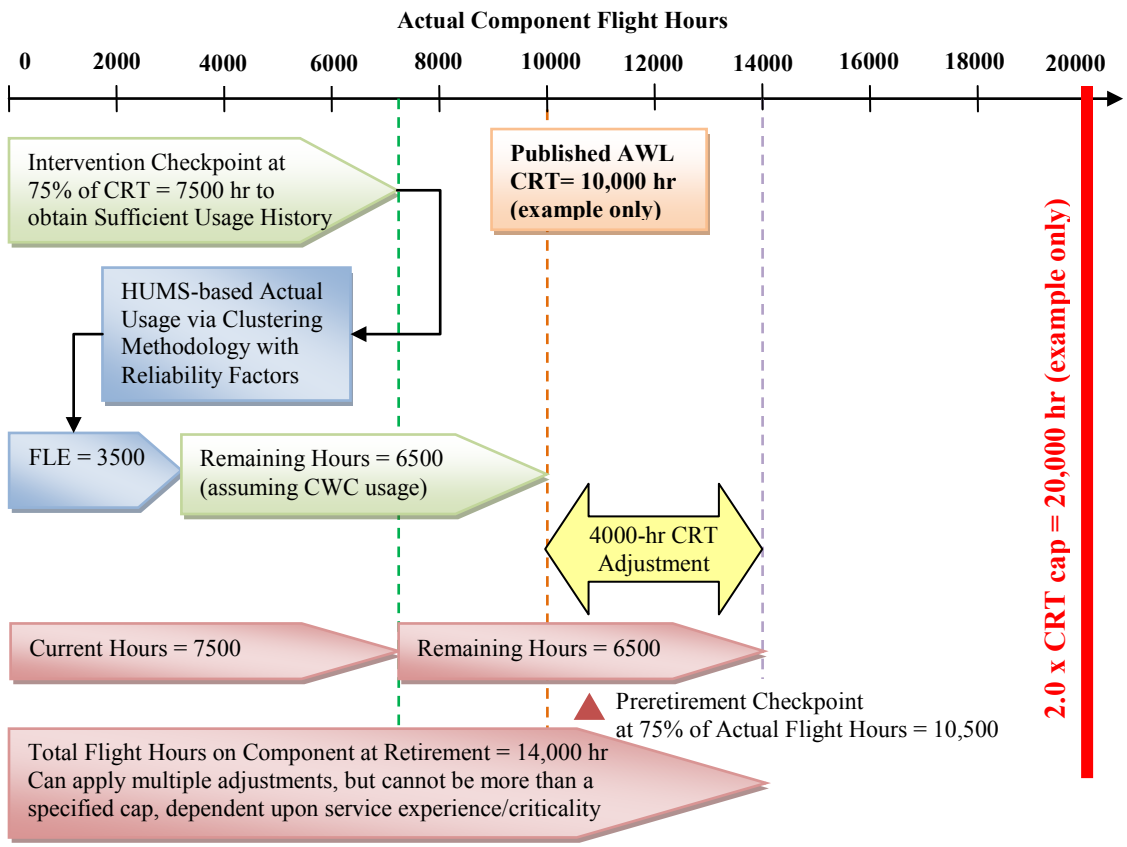


Figure 24. Individual Component UBM Credit and CRT Adjustment Calculation

The fatigue life expended (FLE) in flight hours is easily computed by inverting the total damage resulting from the actual usage (see figure 23). The assumed CWC FLE is equivalent to the current flight hours on the component. FLE is used as the basis for determining the CRT adjustment and is a measure of the effective flight hours on the part. FLE can be lower (less severe usage than CWC) or higher (more severe usage than CWC) than the current flight hours. When the clock time, or effective flight hours (EFH) on the part is rolled back according to the FLE, the CRT adjustment can be quantified as follows:

$$
\begin{aligned}
\text{EFH} &= \text{FLE} \\
\text{Remaining flight hours (RFH)} &= (\text{AWL CRT} - \text{EFH}) \\
\text{Estimate of total flight hours at retirement (ETFHR)} &= (\text{Current hours} + \text{RFH}) \\
\text{CRT adjustment} &= (\text{ETFHR} - \text{AWL CRT}) \\
&= (\text{Current hours} - \text{FLE})
\end{aligned}
$$

Note that the FLE can result in CRT adjustment that can either be positive (a later part retirement) or negative (an earlier part retirement). Figure 24 shows the terminology and graphically shows the effect of the CRT adjustment on ETFHR. The figure and the subsequent discussion focus on the adjustment calculation process, not the implementation, which is addressed under ICA in section 7.1.

When calculating the CRT adjustment for individual components, future usage is assumed to be the more conservative either of the original CWC spectrum or peak-period usage determined by the PDAR. Table 8 shows what the new ETFHR would be as a ratio of AWL CRT for the swash plate, assuming future usage as CWC. Results are presented as a percentage of AWL CRT. The measured usage that includes the reliability factors was applied to estimate the accrued actual part damage based on recorded HUMS data. Any missing data in the HUMS records were filled with the original design CWC usage. This UBM scenario is for a one-time adjustment, so the ETFHR is simply the adjustment plus the AWL CRT. However, if multiple applications are made, the effects would be compounded.

Table 8. The CRT Adjustment Estimates for Individual Components

Individual Tail Identifier	Current Flight Hours on Aircraft (% of AWL CRT)	CRT Adjustment (% of AWL CRT)	Actual Time at Retirement (% of AWL CRT)
1	60	43	143
2	37	27	127
3	18	12	112
4	16	11	111
5	18	12	112
6	18	10	110
7	17	17	117
8	23	06	106
9	8	05	105
10	7	05	105
Worst	40	29	129
Best	27	20	120

As part of a risk mitigation strategy, a cap on the total actual component time is recommended. Figure 24 shows a cap of 2.0 times the AWL CRT as an example. The cap should be component-specific; dependent on the component criticality, UBM system/process uncertainty, and next tier constraints (e.g., other fatigue-sensitive features or components affected by CRT adjustments or other failure modes); proportional to the magnitude of the AWL CRT; and established by the level of service experience associated with the UBM credit. The initial cap should start out as a smaller, more conservative value and increase as part of the CIS strategy.

Note that the highest amount of all aircraft flight time analyzed is only 60% of the CRT for the swash plate. The example in figure 24 shows an intervention action for a one-time UBM credit adjustment occurring at a 75% checkpoint as a guideline to take the most advantage of the actual usage history. As the individual aircraft results indicate, the lower amount of flight time on the aircraft, the less CRT adjustment is needed. The operator continues to accrue hours as normal after the adjustment and usage trends continue to be monitored at prescribed intervals. The operator informs the OEM when the component effective flight hours reaches a preretirement checkpoint (PRCP) (e.g., 75% of ETFHR) and provides a similar data package to the OEM to ensure that the usage assumptions since the adjustment remain valid.

Alternatively, this process is easily adaptable to performing multiple adjustments if desired (see table 2). For multiple adjustments, the operator accumulates additional hours after the first CRT adjustment, requesting another extension when the effective flight hours reach 75% of the published AWL CRT. To ensure safety in the event of more severe usage, it is recommended that the OEM monitor usage, perform fatigue damage rate checks periodically (e.g., intervals of 25% of the published AWL CRT), and notify the operator if more extreme CWC usage is discovered in the damaging regimes.

6.4.2 Part Number-Based Fleetwide Part CRT Revision.

Table 7 showed the adjusted fleet usage for the monitored critical swash plate regimes based on a representative subfleet sample size of ten aircraft and associated reliability adjustment by the UMRF. The difference in time between the monitored critical maneuver data and the original assumed CWC data must be conservatively assigned to other damaging maneuvers. Therefore, any difference in the monitored critical regimes versus their original CWC usage was redistributed to other regimes critical to the swash plate component (because not all critical regimes can be recognized by HUMS or processed by the clustering algorithm). The same CWC ratios of these regimes were maintained by inflating their durations and counts by the same percentage. Table 9 shows the resulting updated CWC spectrum for the swash plate critical regimes only. Note that all of the other CWC regime data is unchanged.

Table 9. Updated CWC Spectrum for Revised Fleet CRT

Swash Plate Component Damaging Regimes	UBM Updated CWC Usage (ratio of original CWC time)
Left-turn 45 Vne	0.08
Right-turn 45 Vne	0.08
Dive 1.1 Vne	1.46
E&R dive 1.1 Vne	1.46
E&R left-turn 30 and 45 Vne	0.66
E&R right-turn 30 and 45 Vne	0.66
Symmetric pullout moderate Vne	0.17
Symmetric pullout severe Vne	1.46
Symmetric pullout moderate 0.8 Vne	1.46
Symmetric pullout severe 0.8 Vne	1.46
Symmetric pushover Vne	1.46
Symmetric pushover 0.8 Vne	1.46
Longitudinal reversal level flight Vne	1.46
Collective Rev LF Vne	1.46
External load collective reversal level flight 0.8 Vne	1.46
External load E&R partial power decent	1.46

Vne = Velocity not to exceed

The resulting revised fleet CRT is 2.52 times the published AWL CRT for the associated swash plate failure mode. All other modes on the part must also be checked to determine if the new usage has caused another crack location to become critical. Any approved CRT adjustment would be subject to a conservative cap, as described in section 6.4.1, which could be extended as part of a CIS plan. For example, with a cap of 2.0, the revised fleet CRT would be changed by a factor of 2. The revised fleet CRT increase is much larger than for any individual aircraft, as shown in the previous section, because the updated CWC is used for both past and future usage, whereas the original CWC is assumed for future usage for individual parts.

6.4.2.1 Possible Failures.

While the proposed process for calculating the credit adjustment is straightforward and uses traditional methods and software, errors can arise from improper data handling. Procedures must be followed to ensure data quality during the CRT adjustment calculation. Another potential failure is improper implementation of the CRT adjustment for example on the wrong part serial number. Processes must be established to formally track and document all data flowing between the operator and the OEM. These are presented in section 7.

6.4.2.2 Mitigation Strategies.

Continuing actions, such as implementing checkpoints, provide appropriate times to reassess the data to ensure that proper procedures were followed and any usage assumptions can be verified. The implementation of the described UBM credits should begin with a CIS plan (section 8) to validate and identify any new mitigating actions if necessary.

6.5 CREDIT VALIDATION TECHNIQUE DETAILS.

This section examines concepts that are fundamental to the proposed credit validation, providing details necessary to demonstrate compliance; however, the details were not sufficient enough to include in the descriptions of the recurring end-to-end process steps presented in sections 6.1 through 6.4. The details support the AC requirements to understand the physics involved in the proposed process for UBM credit. The proposed technique is to maintain the FAA-approved safe-life analysis process described in figure 1, adjusting only the usage via recorded HUMS RR output (figure 18). Usage adjustment requires a mapping of HUMS RR output into usable CWC regime information (i.e., counts and durations) via the new clustering algorithm developed in this research. Because the mapping is intended to maintain UBM process integrity commensurate with a hazardous/severe-major criticality level, a great deal of effort was put into the investigation of the current onboard RR algorithm software validation and performance and the development of the clustering algorithm methodology to complement the OBS.

6.5.1 The RR Software Verification and Validation Techniques.

RR technology has been developed and used on various fixed- and rotary-wing aircraft. Although RR algorithms for various rotorcraft platforms have been tested to OEM standards and have been thoroughly exercised in fleet and flight test operations, none have been validated to

more rigid standards required for UBM applications. One objective of this program is to appropriately demonstrate a process for validating RR technology to a level of confidence that will reliably allow their use in UBM processes.

The current practice for validation relies heavily on nonautomated procedures that can often be tedious and time-consuming. The traditional methodology includes the high-level steps shown in figure 25 and described in the subsequent text.

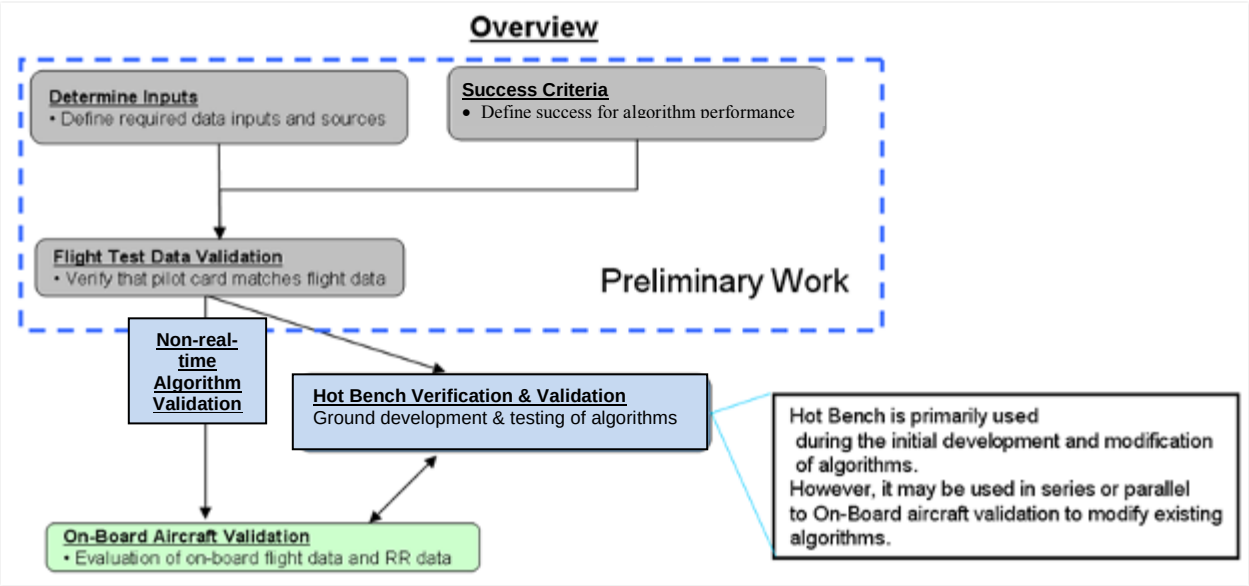


Figure 25. Current Practice for RR Validation and Verification Methodology

- Input Definition: The validation process begins with the determination of requirements and inputs, including a list of regimes to validate associated regime algorithms, data parameters, sampling rates, aircraft configurations, tolerances, and various aircraft data sets. This is simply a list of items needed to perform the validation and verification process.

- Success Criteria: Validation is highly dependent on how success is defined. Success is often based on previous RR validation and flight test experience. The S-92 aircraft HUMS currently supports 94 recognized regimes and 1 provision for undetermined and 1 provision for unrecognized regimes. While it is agreed that these have been validated to the traditional success criteria, more stringent and quantifiable criteria are needed to substantiate UBM credits. These criteria must maintain the same high levels of reliability as the original analysis using the CWC spectrum. However, the stringent requirements only need to be applied to key regimes that are relevant to credits of interest. For example, it is not important to accurately classify dozens of nondamaging regimes as long as the system can accurately distinguish between damaging and nondamaging regimes and accurately classify the few damaging regimes of relevance to specific

component credit. The pervasive notion within the industry that RR algorithm validation must include all CWC regimes has been inhibitive because of the cost of such an endeavor.

- Flight Test or Operational Data Validation: The quality of recorded flight test data must ensure integrity and accuracy is used in the validation process. A key issue is the accuracy of written pilot cards or run logs, which can be assessed by comparing them to recorded time history flight data using engineering judgment of parameter interactions and accepted flight test tolerances. Subsequently, the RR performance can be compared to this quantified set of flight data. SAC developed tools to allow the vast amount of fleet data to be leveraged to create additional truth or pseudo flight test data. These tools are based on e ngineering validation and categorization of fleet data into agreed upon instances of various regimes. This tool leverages processes previously used by SAC to acquire operational data to update CWC spectra.

- RR AlgorithmValidation (non-real-time environment): This step uses both flight test and fleet operations data. Sufficient flight or validated fleet data should be collected to enable the determination of RR performance sensitivity relative to variations in aircraft configuration and piloting skill level (e.g., ability to conduct certain maneuvers within accepted constraints) and technique. The latter is important because of the level of loads associated with a regime can vary significantly with small changes in technique and the identification. Similarly, it is suspected that the identification, filtering, clustering, and mapping of regimes to CWC regimes is also sensitive to these changes in technique. Regime performance must be valid for all normal flight operations, environments, and crew operating techniques. New methods for validating OBS RR algorithm performance and new methods for postprocessing to provide better performance without the need to change OBS algorithms are discussed in detail in the following sections.

- Integrated Bench Test Facility (IBTF) for RR OBS Software Verification and Validation (V&V): Initial software development traditionally uses an IBTF and test procedures to incrementally verify that each module of the software has been coded correctly and to ultimately validate software performance. The IBTF simulates the data stream in and out of the actual HUMS installation to match the S-92 aircraft ARINC 429 data bus. This enables a thorough check of the onboard software and interfaces to other aircraft systems prior to placing them on an aircraft. RR algorithms are programmed into the HUMS and various sensor input signals are applied to perform V&V of assess hardware and software performance, including data acquisition and RR algorithm performance. Modifications are made as required based on the results. All HUMS software algorithms were evaluated on the SAC S-92 HUMS IBTF prior to installation on airborne equipment.

- Onboard RR Software Validation: The final step for new software development is to conduct a flight test to validate RR software performance using many of the same techniques used for initial RR algorithm performance in a non-real-time environment. The S-92 HUMS OBS already has embedded RR algorithms that have matured over a number of years. Thus, the RR algorithm validations below are applicable to both.

The installed S-92 aircraft HUMS hardware and software satisfy FAA certification requirements per the documented certification plans and analyses [6 and 12-15]. Although the installed HUMS equipment and software satisfied Level B airworthiness requirements, the RR algorithms were not verified for compliance with credit validation requirements. These requirements depend on the component for which a credit is being sought and must be rigorously tested to quantify their actual performance for comparison to a reliability standard. The certification focused on the installation of the HUMS as a data recorder for usage and regime information, but did not qualify the system for the purpose of UBM credit. This was intended to be done at a later time after the S-92 aircraft was fielded and there was a sufficient amount of fleet information to investigate the certification process for UBM credit validation.

Verification of the installed RR algorithms was conducted by comparing HUMS output to recorded flight parameters and run logs were gathered in several flight tests. A similar approach was taken to verify the RR algorithms for the UH-60M Black Hawk [16]. Based on S-92 aircraft flight test data, a qualitative assessment was performed by SAC ground test engineers to verify that the RR algorithms were performing as intended. The installed HUMS RR algorithms were functioning reliably and consistently in the field and provided usage information for every S-92 aircraft in the fleet, gathering over 150,000 flight hours of fleet operation.

6.5.2 Direct Evidence From Flight Test and Operational Usage.

The AC [2] guidance states that for HUMS applications classified as hazardous/severe-major, direct evidence must be gathered as part of the credit validation methodology. Recommended direct evidence sources include actual service experience (i.e., fleet RR output) and on-aircraft trials (i.e., scripted flight tests) of HUMS-equipped aircraft to establish that the HUMS application provides appropriate response sensitivity and accuracy necessary for the UBM credit.

There are two primary data sources of direct evidence for RR algorithm verification. HUMS data for both flight test and fleet data is obtained from the RDFs produced after each flight and transferred to SAC. The second source is unique to the SAC flight test and consists of S-92 aircraft flight test data available on the Advanced Data Acquisition and Processing System (ADAPS). Processing of HUMS and ADAPS output for monitoring of critical regimes takes place as shown in figure 26. Extraction of the ADAPS data follows standard SAC West Palm Beach (WPB) Flight Development Center procedures and utilities, as shown in figure 26. HUMS data mining for UBM credit is currently a custom process that involves an engineer-in-the-loop. The final data consists of recorded HUMS parametric time histories, HUMS regime sequence reports, and ADAPS flight test time histories for aircraft state parameters and component loads. The ADAPS files adhere to their unique formatting and data structure, but the HUMS data format can be customized depending on the use of the data.

It is important to check all available direct evidence data for quality and integrity. While flight and ground crews go to great length to ensure the accuracy of test data, issues of data quality, omission, or misclassification can occur.

The flight test procedure consists of writing pilot cards to specify the aircraft configuration and a set of maneuvers to be flown. Run logs are stored in the ADAPS and represent formal versions

of the pilot card (which may have been adjusted during the test) and document data for configuration and maneuvers. A run log is shown in figure 27. ADAPS also stores all the recorded data from the flight test that can be plotted as a time history, as shown in figure 28.

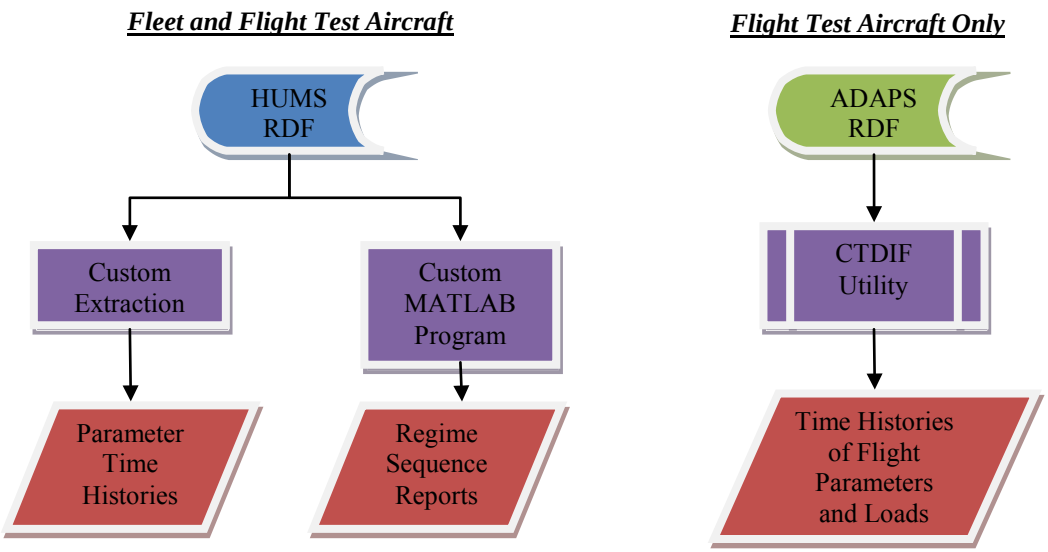


Figure 26. The RR Algorithm Verification Data Sources

Run Log

Date	2009-01-21		**Facility**	DFC WPB FL		**Aircraft**	003
Model	S92A		**Test Type**	FLIGHT		**Testno**	1087

TestPlan	920252	**Flight**	880	**Plan**	K	**Cond**	16

FltSeq	1	**TO Time**	14:35:00	**FltHrs**	1.4	**GndHrs**	0.2
NomGw	27700	**ESGW**	28484	**TOFuel**	5150	**HP**	-200
NomCg	360.5	**ESCG**	360.9	**LDFuel**	3300	**OAT**	13
NomLatCG		**ESLatCG**		**VhDay**		**Wind**	300/8
NomHd		**Pilot**	BECKER	**CoPil**	KNAUST	**Obs**	
Config	Crit. Alt. 7000 ft density -- Heavy GW/Aft CG						

Run	Maneuver	MnvrCode	MKey1	MKey2	Trans	FltNo
1	AMBIENT					1
5	AMBIENT					1
6	HOVER IGE	83	HOV		0	1
7	CLMB SS MCP/105 TRIM	167	CLMB	SS	0	1
8	CLMB L SS MCP/105 10DEG	167.1	CLMB	SS	0	1
9	CLMB L SS MCP/105 20DEG	167.2	CLMB	SS	0	1
10	CLMB R SS MCP/105 10DEG	168.1	CLMB	SS	0	1
11	CLMB R SS MCP/105 20DEG	168.2	CLMB	SS	0	1
12	AUTO 120KTS/110%NR	205.85	AUTO		0	1
13	AUTO REC 120KTS 110%NR	204	AUTO		1	1
14	AUTO 120KTS/95%NR	205.65	AUTO		0	1
15	AUTO REC 120KTS 95%NR	204	AUTO		1	1
16	SYM P O 120KT/105% 1.5G	251.15	LF	PLOT	1	1
17	SYM P O 120KT/105% 1.75G	251.18	LF	PLOT	1	1

Figure 27. A Sample ADAPS Run Log

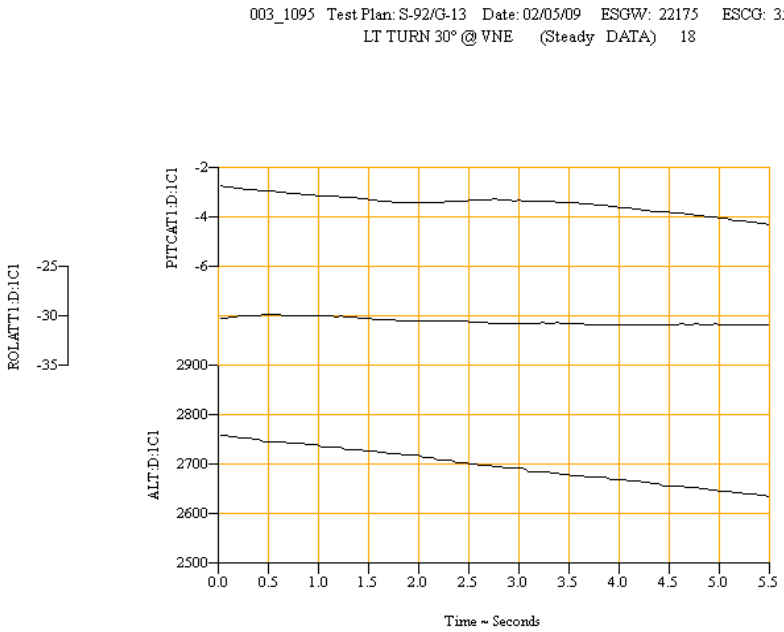


Figure 28. A Sample ADAPS Time History

The HUMS also stores regime sequence and time history data. The HUMS operation regime sequence report (shown in figure 18) provides information that is similar to the ADAPS run log. A HUMS time history plot is shown in figure 29. Both of these products are generated via the GSS applications.

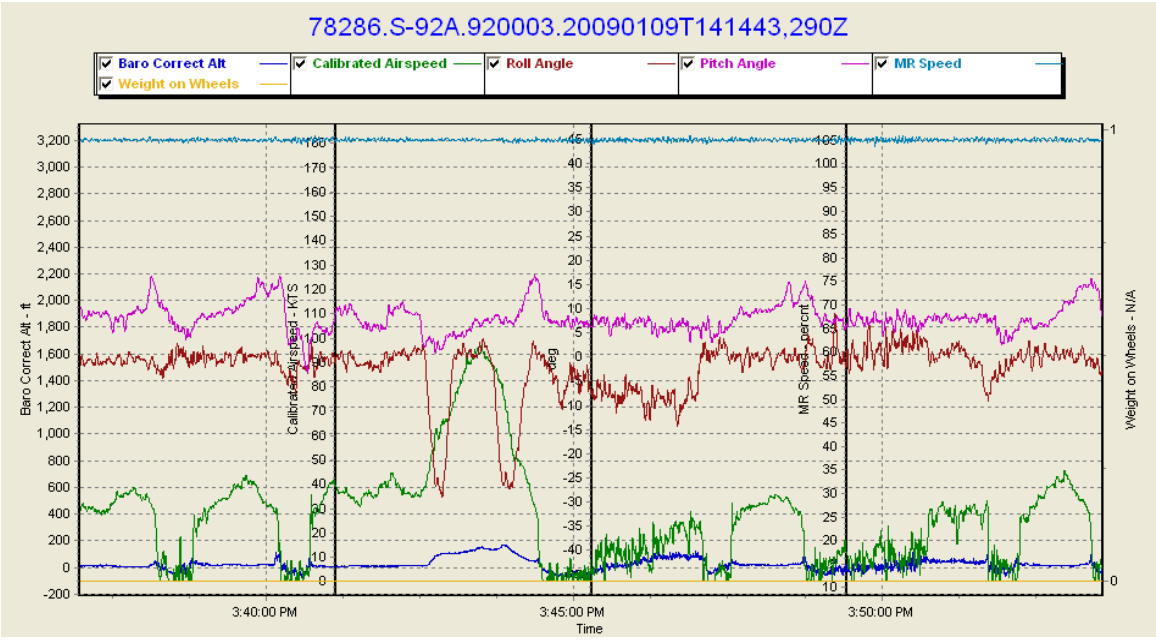


Figure 29. A HUMS Time History

Data is manipulated and stored in several steps using various in-house software applications implemented in a COTS software environment. Data loss and corruption are possible due to customized processing required to use the data for a specific application. Therefore, evaluation includes screening the incoming data for detection and correction of any detected anomalies. All data mining tools for UBM credits should be standardized, automated, and verified before being used for data mining to ensure consistency and quality of the data. Tools intended for one-time use should be verified by engineering peer review of the tool and sample results.

For UBM credit consideration in this research, certain critical damaging maneuvers were selected as high priority for RR validation using available fleet and flight test data. The following general process was followed by an expert engineer-in-the-loop to ensure the integrity of the data sets.

- ADAPS database mining: The database was mined to extract data for each required configuration and regime.

- Data integrity check: The run logs were verified by visually comparing them to the time history data of basic parameters, such as roll angle and airspeed. If a run log entry did not match the time history, the run was marked as questionable and further investigated for disposition.

- Data quality assessment: For each run, the data quality was examined and marked as bad, low, or good. Bad indicates data that is spiky, incomplete, or outside of tolerances/ranges for the indicated regime. Low indicates data that is complete and the maneuver was flown correctly and within tolerances, but the maneuver may not have been flown precisely. For example, a 30° angle-of-bank (AoB) left turn may have been flown at 25° with nonsteady altitude or control inputs. Good indicates all parameters are available and have a high-quality signal, the maneuver was flown correctly, within tolerance, and precisely.

Figure 30 shows a plot for a left-level 30° AoB turn from the ADAPS database. However, HUMS indicates that a descending turn was flown. Examination of the time history trace for altitude shows that, in fact, the aircraft was descending during the turn. This shows the importance of checking the maneuver data sets to ensure that flight test tolerances were observed for key parameters during the maneuver. WPB does not have an automated tolerance process and adherence is left to the judgment of the pilots and engineers. This example shows how HUMS data can assist in that process to determine whether to eliminate the data set entirely or simply reclassify the ADAPS maneuver by changing the label.

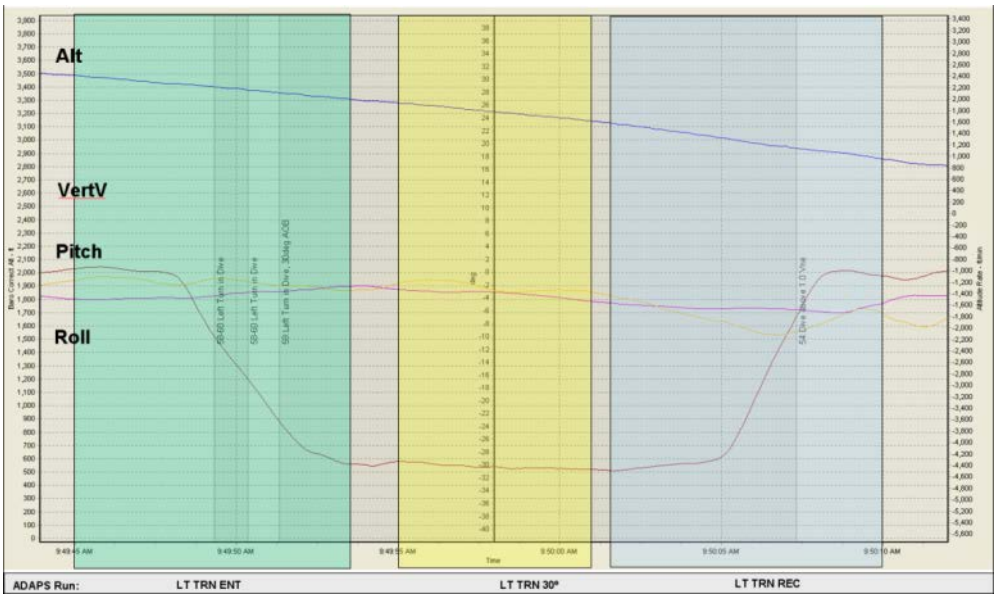


Figure 30. Maneuver Verification Example

To mitigate risk and demonstrate the methodology, direct evidence was further established by performing scripted flight tests to provide truth data and establish a comprehensive database for validation of selected HUMS regimes and their associated clustering algorithms. This research used flight test data from a HUMS-equipped S-92 aircraft that was fully outfitted with load-measuring instrumentation. The record provided by the HUMS was compared to the record of each flight, as provided by the pilot's flight card and the onboard instrumentation system. Direct-measured loads were also available for many flight tests as an additional parameter for comparing the RR performance. Detailed flight test data is contained in appendix C and is summarized here to describe how the data supports the clustering algorithm approach.

Data were collected during three phases of flight tests using aircraft serial number S920003 (referred to as A/C 392) as the test asset. Using the same aircraft ensured consistency and continuity of data. Phase 1 data was gathered on a previously planned FLS flights on a noninterference basis. The FLS test aircraft was instrumented with strain gages on numerous dynamic components, including the swash plate. Similarly, Phase 2 data were gathered on a noninterference basis for subsequent flight tests conducted for a variety of other purposes, including performance and HQ. These tests include maneuvers that are considered to be closer to fleet flight operations than the carefully performed regimes flown in an FLS. In addition, A/C 392 retained and recorded much of the load instrumentation from the FLS. Phase 3 data was gathered as part of a dedicated flight test to evaluate the HUMS RR software performance under a variety of maneuver conditions.

Table 10 provides an overall summary of flight test data used for the study. The first four columns list the flight test number, date, objective, and importance to the RR study. The remaining columns list the state parameter and loads information determined to be important for investigating the regimes critical to the swash plate.

Table 10. Flight Test Data Summary

	Flight #	Date	Objective	Importance	AOB (deg)	Nz (g's)	Alt (ft)	Climb (ft/min)	Total Damper Load (lbs)	Total MR Shaft Bending (in-lb)	Vibratory Damper Load (lbs)	Vibratory MR Shaft Bending Load (lbs)	Vibratory Swashplate Moment (in-lb)
PHASE 1 - FLIGHT TESTS	1083	1/9/09	Hvy Aft FLS	CWC Maneuvers	X	X	X	X	X	X	X	X	X
	1084	1/13/09	Hvy Aft FLS	CWC Maneuvers	X	X	X	X	X	X	X	X	X
	1085	1/16/09	Hvy Aft FLS	CWC Maneuvers	X	X	X	X	X	X	X	X	X
	1086	1/21/09	Hvy Aft FLS 7K alt	CWC Maneuvers	X	X	X	X	X	X	X	X	X
	1087	1/21/09	Hvy Aft FLS 7K alt	CWC Maneuvers	X	X	X	X	X	X	X	X	X
	1088	1/22/09	Hvy Aft FLS	CWC Maneuvers	X	X	X	X	X	X	X	X	X
	1089	1/27/09	Hvy Fwd FLS	CWC Maneuvers	X	X	X	X	X	X	X	X	X
	1090	1/28/09	Hvy Fwd FLS	CWC Maneuvers	X	X	X	X	X	X	X	X	X
	1091	1/28/09	Hvy Fwd FLS 7K alt	CWC Maneuvers	X	X	X	X	X	X	X	X	X
	1092	1/28/09	Hvy Fwd FLS 7K alt	CWC Maneuvers	X	X	X	X	X	X	X	X	X
	1093	1/29/09	Hvy Fwd FLS	CWC Maneuvers	X	X	X	X	X	X	X	X	X
	1094	2/3/09	Hvy Fwd FLS	CWC Maneuvers	X	X	X	X	X	X	X	X	X
	1095	2/5/09	Light Aft FLS	CWC Maneuvers	X	X	X	X	X	X	X	X	X
	1097	2/10/09	Light Fwd FLS	CWC Maneuvers	X	X	X	X	X	X	X	X	X
PHASE 2 - FLIGHT TESTS	1098	2/12/09	RIG APPROACH DEVELOPMENT	Simulated Operational Flight Profile	X	X			X	X			
	1107	3/3/09	RIG APPROACH DEVELOPMENT	Simulated Operational Flight Profile		X			X	X			
	1150	8/4/09	RIG APPROACH DEMONSTRATION	Simulated Operational Flight Profile	X	X							
	1165	9/24/09	FAA certification of AMS and SAR.	Simulated Operational Flight Profile	no data	no data	no data	no data	no data	no data	no data	no data	no data
	1168	10/19/09	FADEC Checkouts, 2 Piece Filter Bowl FLS	CWC Maneuvers	X	X	X	X	X	X	X	X	X
	1169	10/20/09	Loads Survey. Exp GWE FLS TR Re-fly	CWC Maneuvers	X	X	X	X	X	X	X	X	X
	1170	10/20/09	Loads Survey. Hvy GWE FLS TR Re-fly	CWC Maneuvers	X	X	X	X	X	X	X	X	X
	1187	1/12/10	Hvy GWE HQ Flights - 10.5K Altitude	Simulated Operational Flight Profile	X	X	X	X					
	1190	1/18/10	Hvy GWE IFR HQ & Engine Cuts	Simulated engine cuts, studied longitudinal static stability	X	X	X	X	X	X	X	X	X
	1193	2/2/10	Hvy Aft High Altitude AFCS hard overs	Simulated aggressive flight maneuvers	X	X	X	X			X	X	X
	1206	3/16/10	Hvy GWE Engine Vibes	Many 45deg turns at 120kt	X	X	X	X	X	X	X	X	
	1215	4/1/10	Hvy GWE HQ @ Aft/Right Lateral CG	Simulated Operational Flight Profile	X	X	X	X	X	X	X	X	X
PHASE 3 - FLIGHT TESTS	1243	6/28/10	HUMS Regime Recognition	Critical CWC Maneuvers for UBM Credit with Intentional Variations	X	X							

SAR = Search and rescue
Hvy = Heavy
FADEC = Full Authority Digital Engine Control

The Phase 1 data set consists of 14 flights flown at several GW, CG, and altitude combinations. A full set of instrumentation was active that provided a very robust set of loads data.

The Phase 2 data set consists of 12 flights that were picked from a set of over 100 available tests using aircraft 392 flown over the course of a year. The data sets provide additional FLS data plus some simulated operational flight profile data. Different sets of instrumentation were active at different times, as shown in table 10.

The Phase 3 data set is comprised of a single, dedicated flight that flew hundreds of data points focused on the swash plate critical regimes. Variations were performed to quantify HUMS performance for turns with different roll rates during entry/recovery, symmetric pullouts, dives, diving turns, and compound turn maneuvers. Many maneuvers were repeated by the copilot to determine the effect of pilot variability. Because this test was flown after the FLS flights were completed, very few loads measurements were still active, and none were available pertaining to the MR stationary swash plate.

The total data set provides a very comprehensive database for RR performance assessment and development of regime clusters. All the direct-measured information combined with engineering knowledge serves to demonstrate the necessary degree of reliability to calculate a CRT adjustment for the UBM credit. Fusion of data and knowledge is enabled by a semiautomated UBM RR Clustering (RRC) tool described in section 6.5.5.

6.5.3 The RR Performance Evaluation.

The fundamental issue that must be addressed before using this data is to determine how reliable the RR output is for critical maneuvers. The UBM credit validation evaluation only considers items related to usage monitoring via HUMS RR algorithms. This evaluation of HUMS regimes requires a set of validation data or truth data. Traditionally, the primary set of truth data has been pilot declarations from scripted flight tests, coupled with the associated, directly measured aircraft state parameters.

Flight tests of a fully instrumented S-92 aircraft at the WPB facility provided an opportunity to gather HUMS information in a controlled environment that is comprised of focused maneuver execution and rigorous measurements, thereby providing a valuable set of truth data for evaluating the installed HUMS RR algorithms. HUMS and ADAPS traces were compared for data integrity and accuracy. Table 11 shows a side-by-side comparison for a typical CWC maneuver sequence: 30° right-turn entry, steady turn, and recovery. As shown, there is no one-to-one correspondence between HUMS and the CWC maneuvers. Instead, HUMS typically identifies numerous regimes.

Table 11. Current HUMS RR Comparison to Flight Test

ADAPS Run Log	Log Time (seconds)	HUMS RR Output	HUMS Time (seconds)
Right-turn 30 entry	10	Forward flight	5
		Generic level right turn	2
		Generic level right turn 30°	3
Right-turn 30	13	Generic level right turn 30° (continued)	3
		Partial power descent right turn	5
		Generic level right turn 30°	5
Right-turn 30 recovery	15	Generic level right turn 30° (continued)	2
		Right turn in climb	4
		Steady climb	1
		Steady climb	1
		Forward flight	5
		Partial power descent	2

From 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 recognized a generic right turn. When the aircraft settled into a 30° bank, HUMS correctly detected the condition. During the ADAPS steady turn, the HUMS regime carried over from the entry and did not break at the same time as the run log. Next, a partial power descent (PPD) was 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 when the rate of climb fluctuated, showing that HUMS is sensitive to changes in that parameter and toggles back and forth to the generic 30° 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 other instances with back-to-back repeats of the same HUMS regime (i.e., steady climb).

The installed HUMS RR algorithms tend to identify numerous short duration regimes rather than the entire intended maneuver having a longer duration. 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 31 notionally 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, wherein HUMS identifies a climbing regime. If the rate of climb reduces past a certain level, HUMS may 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° turn after the roll angle has crossed over a bound

parameter, 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 processing HUMS output for UBM credits, namely underestimating the duration of occurrences and overcounting occurrences of the intended target maneuver. However, because the regime parameter definitions are static and the physics of aircraft flight are predictable, it is hypothesized that a finite set of regimes are expected to be recognized by HUMS every time the aircraft executes a turn maneuver.

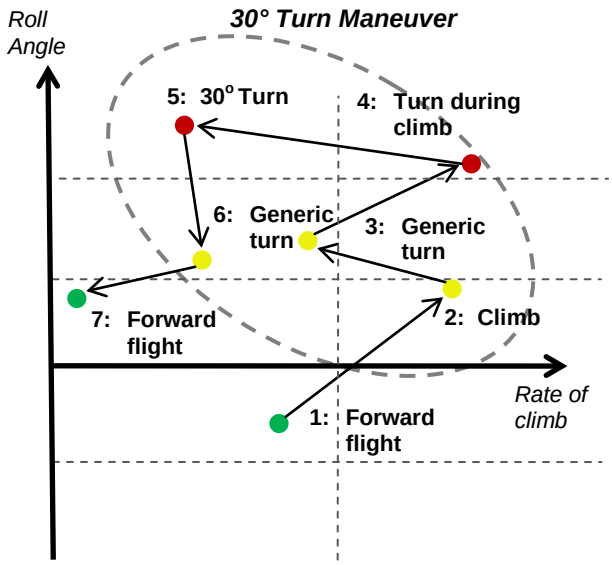


Figure 31. The HUMS Toggling Behavior Root Cause

Note that if usage statistics could be treated entirely as percent time, the two aforementioned errors tend to cancel out. It may be feasible to develop a validated and AC-compliant UBM process that takes the approach of calculating usage statistics entirely in terms of percent time rather than using occurrences for transient maneuvers. However, this is such a radical departure from traditional SAC fatigue damage and lifing methods, that it was not pursued in the subject effort. Rather, it was decided to develop an approach for postprocessing regime sequences calculated by existing OBS RR algorithms and mapping these sequences more effectively into traditional CWC regime definitions.

HUMS sensitivity 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 do not fluctuate much 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 E&R 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 and ultraconservative count of transient maneuver occurrences, which tend to be critical, damaging regimes.

The success criteria developed for the this research were to

- develop a postprocessing approach that maps the RR sequences calculated by existing OBS algorithms that map well and conservatively into traditional CWC regime definitions.

- develop reliability factors that can be used to add additional quantifiable conservatism that results in maintenance of baseline risk.

The focus should be on the critical damaging regimes for the target component and intended credit.

6.5.4 Clustering Algorithm Description.

Based on the observed algorithm performance and success criteria noted in section 6.5.3, a new method was developed to effectively postprocess the HUMS regime sequence data. To map the HUMS output to the CWC maneuvers, a clustering algorithm was developed for aggregating HUMS regime sequence segments around an intended maneuver of interest from the CWC spectrum. Clustering solves the current problems associated with HUMS RR toggling and provides the ability to achieve UBM credits without the need to develop sophisticated complex onboard algorithms.

The development of the clustering algorithm has led to an evolving lexicon. To help the reader, the following definitions are provided below for foundational terms and concepts.

- Cluster: A grouping of neighboring HUMS regimes that represent a single CWC regime occurrence. This may be subject to a minimum length requirement corresponding to flight characteristics to minimize false detection.

- Cluster regime: A HUMS regime often found in close proximity to a target regime in a HUMS regime sequence report.

- Cluster set: The set of cluster regimes selected as part of the defining cluster parameters.

- Crossover: Time padded to the beginning and end of the cluster to accommodate possible errors due to HUMS RR resolution or update rate (typically 1 sec per current S-92 aircraft HUMS RR algorithm refresh rate).

- CWC regime: Standard maneuver used to develop CWC usage spectrum and to establish CRTs for life-limited components.

- CWC mapping: The general process being developed to take HUMS RR output and transform it into CWC maneuvers for the purpose of calculating CRT adjustments using existing life calculation methodology. The mapping can be accomplished by postprocessing the HUMS output with the clustering algorithm.

- HUMS regime: A regime determined by the onboard HUMS RR algorithms.

- Persistence: The maximum time in seconds to allow inclusion of a HUMS regime as part of a cluster versus considering it as a legitimate separate entity.

- Target regime: A HUMS regime that is physically close to the CWC regime of interest, usually a principal damaging regime, which must be identified by HUMS RR in order to form a cluster. This may be subject to a minimum length requirement corresponding to flight characteristics to minimize false detection.

- Target set: The set of target regimes selected as part of the defining cluster parameters, if more than one target regime is used to identify with the CWC regime of interest.

- Validation matrix: A table that contains data to quantify RR and clustering methodology accuracy for a set of CWC maneuvers of interest.

Figure 32 shows the outcome of the clustering algorithm, which is further detailed in appendix B. The process aggregates HUMS regimes that are not explicitly mapped to the intended CWC regime based on the following criteria:

- The regime segment is likely to be picked by HUMS during an intended CWC regime. Because there is no one-to-one correspondence between HUMS and CWC regimes, the target CWC maneuver must be described as a set of RR labels that most closely resemble it, i.e., the target set. Other regimes around the target are known as cluster regimes and are determined via analysis of flight test data and engineering judgment.

- 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 conceptually to the flight characteristics of the aircraft.

- 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.

- Any clusters that do not meet an expected minimum length determined by engineering judgment (e.g., target maneuver or total cluster duration) would be eliminated from the results to minimize the chance of falsely detecting a regime.

- A crossover time is padded to the beginning and end of the cluster to accommodate possible errors due to HUMS RR resolution or update rate.

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

11:14:51	40:Forward Flight to 0.8 Vne	15
11:15:06	82-87:Generic Level Right Turn	3
11:15:09	83:Generic Level Right Turn, 30deg AOB, 0.8 Vne	10
11:15:19	44:Right Turn During Climb	3
11:15:27	83:Generic Level Right Turn, 30deg AOB, 0.8 Vne	29
11:15:56	44:Right Turn During Climb	2
11:15:58	43:Steady Climb	4

2. The algorithm constructs a single maneuver from HUMS RR sequence files, producing a cluster whose duration and count is relevant to the CRT analysis.

11:14:51	40:Forward Flight to 0.8 Vne	15
11:15:06	82-87:Generic Level Right Turn	3
11:15:09	83:Generic Level Right Turn, 30deg AOB, 0.8 Vne	10
11:15:19	44:Right Turn During Climb	3
11:15:27	83:Generic Level Right Turn, 30deg AOB, 0.8 Vne	29
11:15:56	44:Right Turn During Climb	2
11:15:58	43:Steady Climb	4

3. The algorithm parameters calibrated using fleet data and other sources and validated/fine tuned based on expert screening. Time is padded at beginning and end based on RR refresh rate. Cluster durations may be increased based on calculated reliability factors.

11:14:51	40:Forward Flight to 0.8 Vne	15
11:15:06	82-87:Generic Level Right Turn	3
11:15:09	83:Generic Level Right Turn, 30deg AOB, 0.8 Vne	10
11:15:19	44:Right Turn During Climb	3
11:15:27	83:Generic Level Right Turn, 30deg AOB, 0.8 Vne	29
11:15:56	44:Right Turn During Climb	2
11:15:58	43:Steady Climb	4

Figure 32. Clustering of HUMS Regime Sequences

The cluster definitions (target set and cluster regimes) must be established and an initial persistence parameter chosen using flight test 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. Last, the model is checked against all available truth from flight test and the fleet to determine its validity and quantify its reliability.

A calibration of the persistence parameters is performed on a representative sample of fleet data. Histogram matching, as shown in figure 33, is one method used to do this. 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 to provide a measure of true maneuvers. The clustering algorithm is run with various persistence parameters, and the cluster durations are plotted on histograms to compare against the roll angle based on true maneuver duration. As shown in the

example, a persistence of 9 seconds best fits the data and is reasonable to expect from aircraft performance characteristics. A single persistence parameter can be used in this manner, or different values can be tailored to specific cluster regimes.

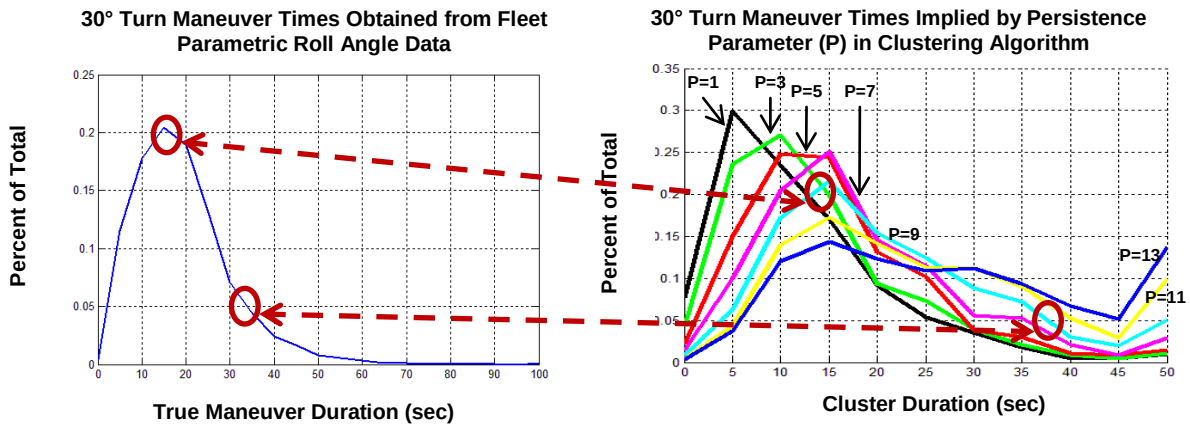


Figure 33. Calibration of Persistence Parameter

Figure 34 shows the details of a 30° 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, and the nonshaded regimes are members of the cluster set. The HUMS sequence identifies two occurrences of a generic 30° turn, in essence, double counting the maneuver. Furthermore, the total duration according to the targets is only 39 seconds versus the 56-second cluster duration. Note that the persistence parameter for the 30° cluster definition is tailored for different cluster regimes. The steady portion of the turn is shown to be 41 seconds.

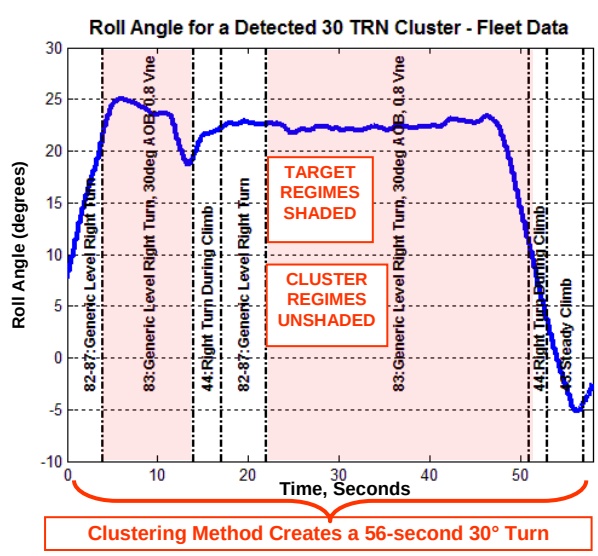


Figure 34. Cluster for 30° Turn Maneuver From Fleet Data

Figure 35 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) by the existing RR algorithm. However, the duration is only 3 seconds versus the 10-second cluster duration. If the pullout duration is considered to be from a 1.0-g loading condition, the actual duration is about 7.5 seconds. However, to increase reliability, the clustering algorithm conservatively adds one second of crossover time to each end of the cluster since the HUMS regime updates occur at a 1-Hz rate.

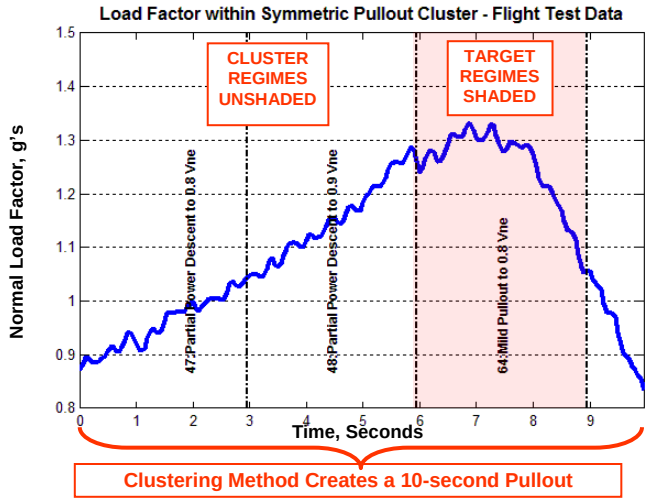


Figure 35. Cluster for Symmetric Pullout Maneuver From Flight Test Data

6.5.4.1 Possible Failures.

Some onboard HUMS RR algorithms are narrowly defined and do not converge until several parametric constraints are met. Consequently, they may not capture the entire duration of a maneuver very well. For example, if turns are known to be damaging to a critical component of the aircraft, usage calculated only from observed durations in the existing HUMS turn regimes may underestimate the actual time spent in critical maneuvers since a change in a parameter-like rate of climb may cause the RR output to temporarily exit a turn regime before re-entry a few seconds later. Although the clustering algorithm addresses this toggling phenomenon, a potential downside of connecting the regimes into a larger maneuver cluster is a reduction in the observed maneuver count, which may lead to a lower damage estimate for transient maneuvers (see figure 23).

Conversely, some broadly defined HUMS regimes, such as turns in power descent or climb, are triggered when the actual AoB exceeds 10° but do not capture the maximum AoB experienced during the turn. If only a subset of such broadly defined regimes are damaging, e.g., turn in power descent when the AoB is 35° or larger, then inclusion of the entire regime in the monitored usage will lead to overly conservative damage calculations, since only a fraction of such turns are expected to occur at higher roll angles. Ignoring these regimes altogether is not advisable either, because the damage would be underestimated.

This raises the issue of undetected damaging maneuvers and the inherent tradeoff in definition of the target set around what clusters are formed. Expansion of the target set to include broadly defined regimes, such as turn in power descent, will lead to more conservative results (i.e., more clusters including AoB below a nondamaging level will be formed around the additional target regimes).

One factor in the tradeoff of target regime selection relates to the probability of loads exceeding a set threshold when the aircraft operates in a given regime as obtained from the analysis of flight test data. The other factor is the frequency of occurrences. While HUMS RR allows direct observation of regime occurrences, bundling key subregimes into broadly defined regimes mask their occurrences unless additional parametric data (e.g., roll angle) is used to separate them from the larger set. For example, if a PPD turn is included in the target set, roll angle may be used to separate occurrence of the subsets that are at an AoB of 35° or larger.

The previous examples show that the clustering algorithm represents the intended CWC maneuvers very well and can rectify the current HUMS toggling phenomenon. However, although the clustering results are much more compatible for UBM than current HUMS performance, residual errors exist that must be mitigated. Thus, reliability factors were developed to deal with these sources of uncertainty to maintain the same levels of reliability inherent to original AWL CRT analysis based on the CWC. Intuitively, there are three scenarios that could result from inaccuracies in the clustering methodology.

- Overclustering—the choice of algorithm parameters may lead to extended cluster lengths, as shown in figure 36. While large clusters typically imply more conservative damage estimation based on duration for steady-state maneuvers, maneuver counts will be low, which may be nonconservative for transient maneuvers.

- Underclustering—the choice of algorithm parameters, e.g., small persistence, may lead to fragmented clusters, as shown in figure 37. This may lead to larger number of counts but smaller cluster durations, which would be conservative for transient maneuvers.

- Missed instances—even if the RR algorithm performs as designed, there may be instances where the intended CWC regime is not detected.

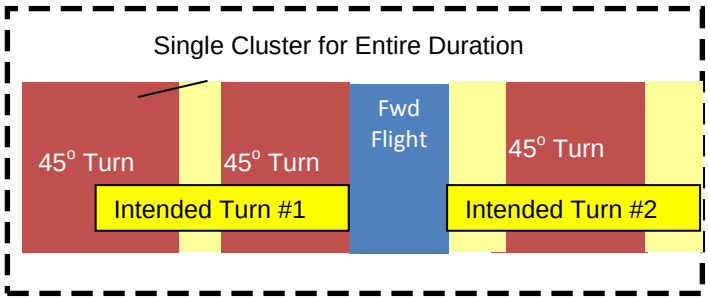


Figure 36. Overclustering Example

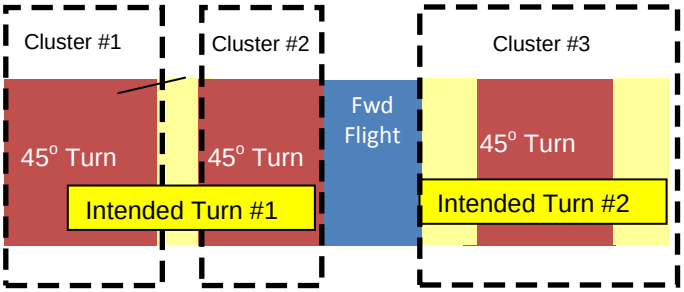


Figure 37. Underclustering Example

6.5.4.2 Mitigation Strategies.

Once these potential inaccuracies are investigated and quantified, appropriate revisions must be made and reliability factors must be developed to deal with residual errors. Appendix B details the methodology developed to determine these factors. The concept and application are discussed in this section.

Quantifying the 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. Scripted flight test is the best source of data but, by itself, would result in enormous and expensive flight test programs. Consequently, the focus of this project is to provide 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

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

Figure 38 shows the overall process for the clustering algorithm validation and reliability assessment. To ensure the highest levels of integrity commensurate with safety-of-flight dynamic components, a engineer-in-the-loop is required throughout all steps of the iterative procedure. Expert judgment and interpretation of results is provided for various engineering disciplines with knowledge of HUMS RR algorithms, flight characteristics, performance, HQ, flight test procedures, component fatigue testing, and fatigue substantiation analysis.

For each critical damaging CWC maneuver, an initial definition of a cluster is established by examining corresponding flight test data and a small validation training set of fleet data. Since the flight test data is crucial to the clustering algorithm, examination and filtering of such data prior to use is essential. The cluster definition is determined by ranking the nearest neighboring regime around a target regime, or regimes, that best resembles the CWC maneuver.

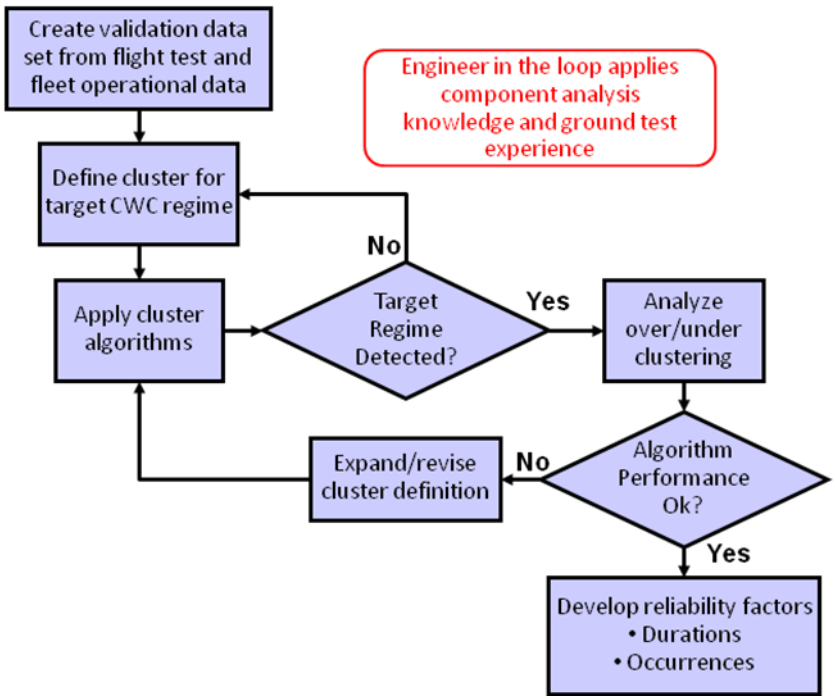


Figure 38. Clustering Algorithm Optimization and Reliability Assessment

After the cluster is defined, it is tested to determine how it detects all occurrences of true maneuvers in the validation data sets. Indications of overclustering and underclustering are noted and the persistence parameter tailored, as necessary. If there are missed instances, these are further investigated by examining available loads and state parameters to see if they are damage-causing CWC regimes. If so, the possibility of modifying the cluster definition is examined; for example, expanding the target set definitions to capture the damaging regime. If implemented, the adjusted clustering algorithm is checked again with the validation data. If the existing cluster definitions cannot 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 the missed conditions that are not detected, similar statistics are generated and used to determine appropriate reliability factors.

A detailed description of the reliability factor methodologies for maneuver duration and counts is provided in appendix B. At a top level, the methodology addresses the impact of overclustering and underclustering on the estimated duration and count of damaging maneuvers. The approach consists of the following steps.

1. Build a regression equation to relate the cluster maneuver lengths to the true maneuver lengths obtained by mining a training set of fleet data for occurrences of parametric conditions that conservatively reflect high-load occurrences.

2. Extract intended CWC maneuvers from fleet parametric data analysis to build truth data for development of regression equations to relate cluster durations to actual maneuver durations.

3. Use the goodness of the regression fit to compute confidence intervals for maneuver length predictions as a function of the observed cluster lengths.

4. Compare the automated predictions of the regression equation against expert judgment on some selected maneuvers to ensure adequacy of the predictions.

5. Build probability distributions describing maneuver count reliability.

Once the cluster definition for a CWC maneuver has undergone this process using the training set of fleet and flight test data, no m ore improvement can be gained from the clustering algorithm capabilities, and the associated reliability factors are finalized. They are then applied to the entire usage history to calculate CRT adjustments for the UBM credit.

6.5.5 Semiautomated RR Clustering Tool.

To address the large amount of data necessary for defining regime clusters, semiautomated tools are necessary for an engineer-in-the-loop to efficiently run necessary checks for data integrity and clustering algorithm reliability. A comprehensive software tool was developed that accommodates the large set of time history and regime sequence data. This UBM RRC tool provides several methods for risk mitigation to detect lost or corrupt data. The tool also incorporates several modules developed by SAC for developing cluster definitions that map HUMS RR output to CWC maneuvers. The tool can also be used to develop and validate new regime definitions for future HUMS software upgrades. The RRC tool was designed with the following objectives and potential applications in mind.

- Replicate existing OBS RR algorithm using parametric data as inputs to verify data integrity and as an independent means of verification of OBS algorithms

- Develop existing HUMS RR algorithm error characteristics and statistics of neighboring regimes around a target maneuver

- Define regime clusters to reconstruct more accurate past usage data (regime sequences/spectra)

- Optimize or redesign new RR algorithms for future release to the OBS

- Exploit fleet data to allow an OEM expert to efficiently identify a set of fleet usage events (analogous to flight test maneuver event) that are categorized for future use in RR algorithm validation

The modular functionality was grouped into five components from a main control panel, which are accessible at any time by the user. Each module has a specific graphical user interface (GUI) to assist the user.

- ADAPS Time Synchronization (i.e., truth data definition)
- ADAPS Plot Configuration (i.e., HUMS RR evaluation)
- HUMS Maneuver Tuning (i.e., cluster definition optimization)

- HUMS Validation (i.e., CWC map validation)
- Usage Statistics (i.e., cluster application to fleet data)

6.5.5.1 The ADAPS Time Synchronization.

The GUI, shown in figure 39, supports interactive time synchronization of the HUMS with direct-measured ADAPS parametric data that is considered to be the source for truth data. Because the HUMS clock is independent from the ADAPS instrumentation clock, the signals must be aligned for a valid comparison. Without it, HUMS RR algorithm validation using scripted flight test data is not possible. Typically, the clocks differ by several minutes. In previous HUMS RR verification efforts, the alignment required very tedious manual methods. The RRC tool automates this process for an easy evaluation of a large amount of flight test data. For a selected flight test number, the user can select any run number or search for a specific run either by maneuver code or maneuver description. The user can then select the signals to be aligned. The alignment is accomplished by either clicking on Auto Align, manually keying in a number, or via manual slider controls. Once complete, the user can save the information so the data are aligned and ready for use in all other modules.

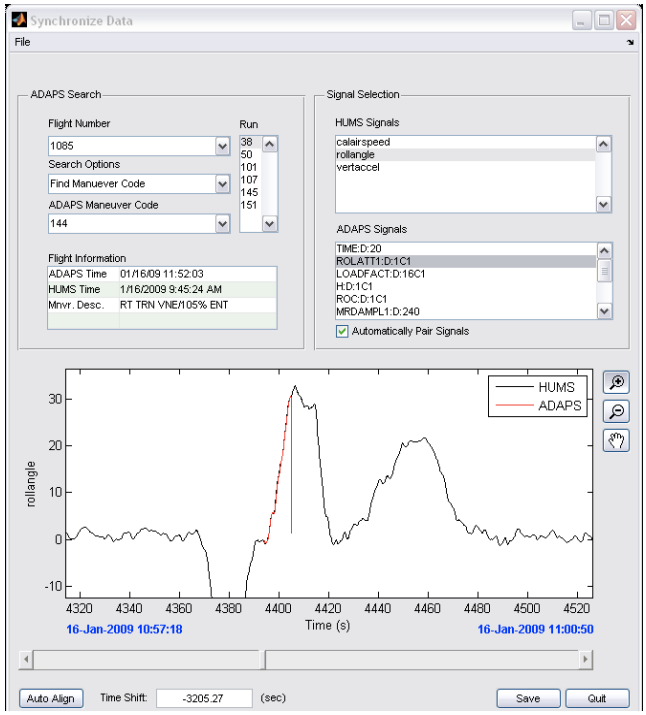


Figure 39. The HUMS and ADAPS Signal Time Synchronization

6.5.5.2 The ADAPS Plot Configuration.

Flight test FLS maneuvers are flown in a controlled fashion and the data are recorded per standard WBP procedures. Figure 40 depicts a representative 45° turn time history plotted from the HUMS GS, showing the HUMS RR output along with a few key flight parameters, including the aircraft roll angle. The corresponding FLS pilot declaration from the ADAPS database is

overlaid showing the recorded portions of the data. Several things are to be noted for a typical flight test record. To capture all the data, the pilot starts recording the measurements prior to entering the maneuver. Similarly, the data are recorded for a short time after recovery. These periods of setup and exit must be identified in the time history to correlate HUMS performance during the actual maneuver time period, as shown in the figure. There is a roll angle threshold of about 8° before HUMS recognizes a turn maneuver, so this was chosen to define when the maneuver starts and ends. The total time for the ADAPS record is approximately 40 seconds, but when the setup and exit are trimmed away, the actual maneuver duration is 28 seconds.

The HUMS refresh rate is 1 Hz, so every regime has a minimum duration of one second. During the actual period of the turn maneuver, HUMS does not explicitly recognize the transient E&R periods, but instead, frequently picks generic turns or level turns at a lower bank angle than the 45° target. During entry, HUMS labels a 45° regime whenever the bank angle is greater than 35°, illustrating the built-in tolerance to the RR algorithms to provide conservative classification. During the target maneuver, HUMS detects regimes in the target set and other regimes as well, including diving and PPD turns.

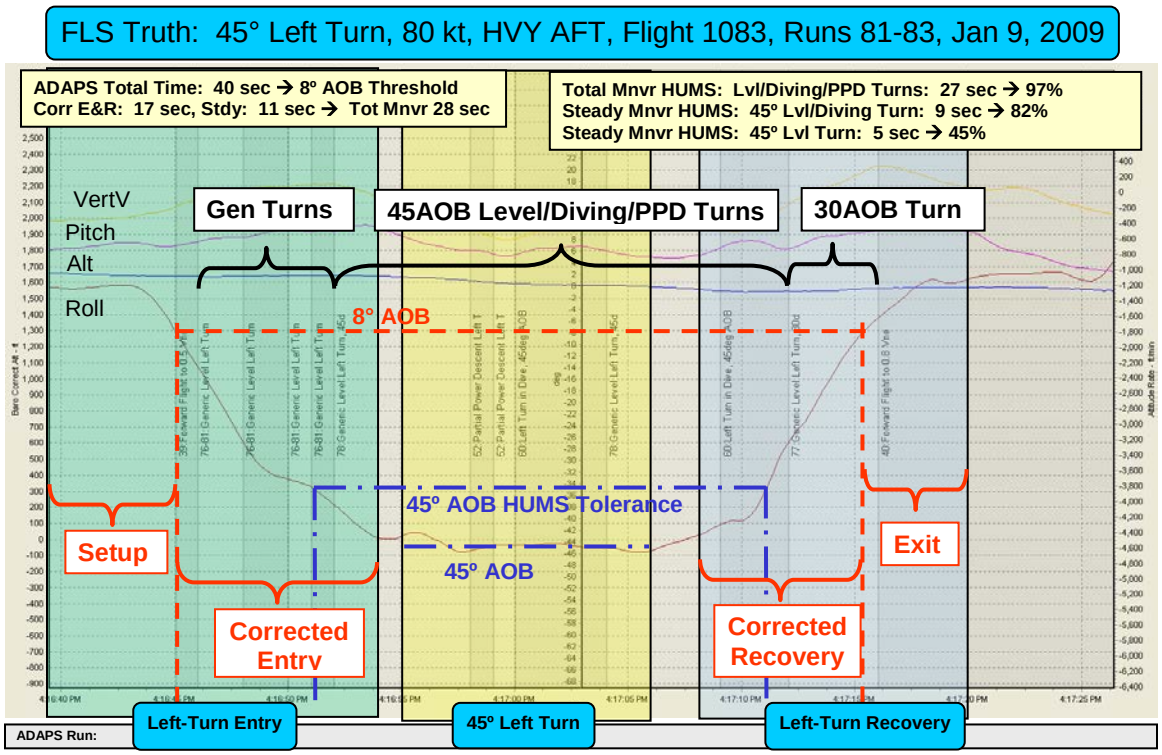


Figure 40. The HUMS RR During a 45° Turn Maneuver

There are several ways to look at the statistics. If the entire turn, including the steady portion plus E&R, is considered and all HUMS generic, level, diving, and PPD turns are valid, the RR accuracy is 97% for this example. If only the steady portion of the turn is considered, and HUMS regimes for level and diving turns are valid, the accuracy is 82%. If only HUMS level turns are defined as valid, the accuracy is 45% for the steady turn. This shows that reliable

calculation of times in target maneuvers requires further postprocessing of HUMS output. This was part of the motivation for developing a clustering algorithm.

The next GUI developed, shown in figure 41, automates this process and allows the user to easily find specific ADAPS or HUMS data and customize a chart to display the data. Regime sequence data from the HUMS RR output data are displayed in figure 40, and parametric time history is shown in figure 41. A semitransparent, user-manipulated highlighting window (shown in light green over the displayed HUMS regime sequence) is used to eliminate flight test setup and exit portions of the maneuver that are not applicable for RR verification. The data in the highlighting window are used in the calculation of all statistics (e.g., counts and percentage of time). Comparative HUMS statistics are shown in table 12 and can be written to a file.

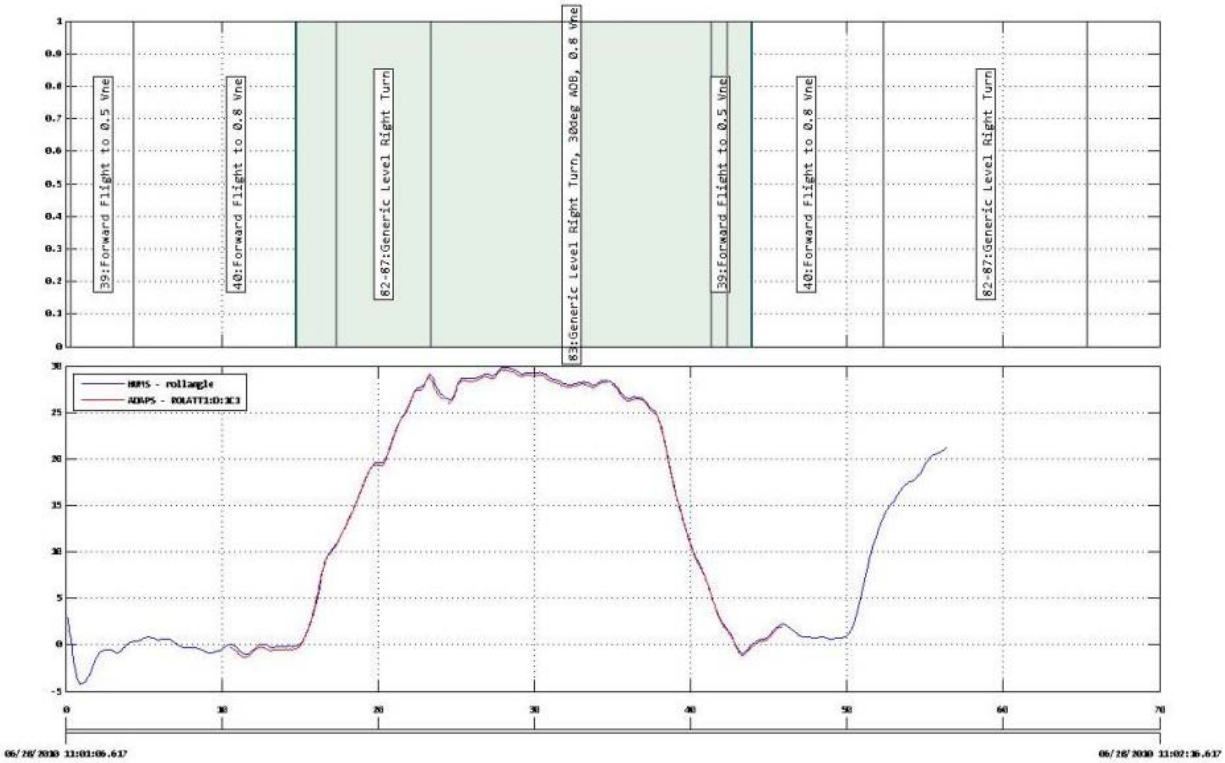


Figure 41. Manipulation Window for ADAPS Maneuver Data

Table 12. The HUMS RR Statistics for ADAPS Maneuver

CWC Regime: 0.8 Vne, Level Right 30° AoB, Normal	Counts	Time (%)	Time (sec)
39: Forward flight to 0.5 Vne	1	3.43	1
40: Forward Flight to 0.8 Vne	2	14.252	4.16
82-87: Generic level right turn	1	20.579	6
83: Generic level right-turn, 30° AoB, 0.8 Vne	1	61.738	18

Vne = Velocity not to exceed

6.5.5.3 The HUMS Maneuver Tuning.

The HUMS Maneuver Tuning GUI provides a development environment for the SAC maneuver clustering algorithm. Designing HUMS maneuver clusters is an iterative process that involves both HUMS regime sequence data and HUMS (or ADAPS) parametric data, as shown in figure 38. Through this interface, the user can build candidate cluster definitions using target sets, cluster regimes, and persistence parameters.

A representative sample of existing S-92 aircraft fleet data is used to validate the cluster definition by comparing it to the CWC maneuver. A sample size of 1600 flight hours was used in this study, consisting of both fleet and flight test data. The user selected a set of target HUMS regimes based on their close physical match to the CWC maneuver. After an initial target regime set was defined, the RRC tool examined the data for nearest neighbor regimes and used the findings to automatically provide an initial recommendation of candidate cluster regimes.

Next, the user defined conditions on t he parametric data that corresponded to the CWC maneuver. These conditions are processed on the sample set to find all instances. The result of processing these user-defined clusters and the CWC maneuver definitions was conveniently presented in a time-synchronized fashion to facilitate the iterative tuning (optimization) of the maneuver, shown in figure 42. The cluster is represented in the upper graph by the target regimes (shown in red) and the neighboring cluster regimes (shown in yellow).

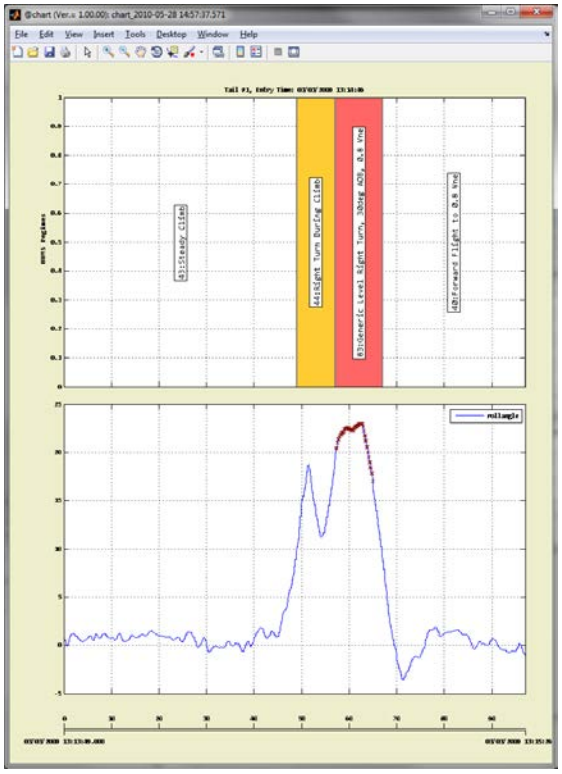


Figure 42. Cluster Comparison to CWC Maneuver Parameters

The objective of the tuning process was to minimize the difference between the two results. The RRC tool provides a regression analysis and histograms to assist the user in the optimization process, shown in figure 43. The tool easily assimilates all instances of the cluster and associated CWC parameters produce regression plots and corresponding statistics. Regressions can be done for both cluster durations and cluster counts. The user can examine each individual point in detail using the plot format shown in figure 42. This is extremely useful for investigating outliers to ensure that the fleet parametric and regime sequence data are correct and not erroneously skewing the correlation.

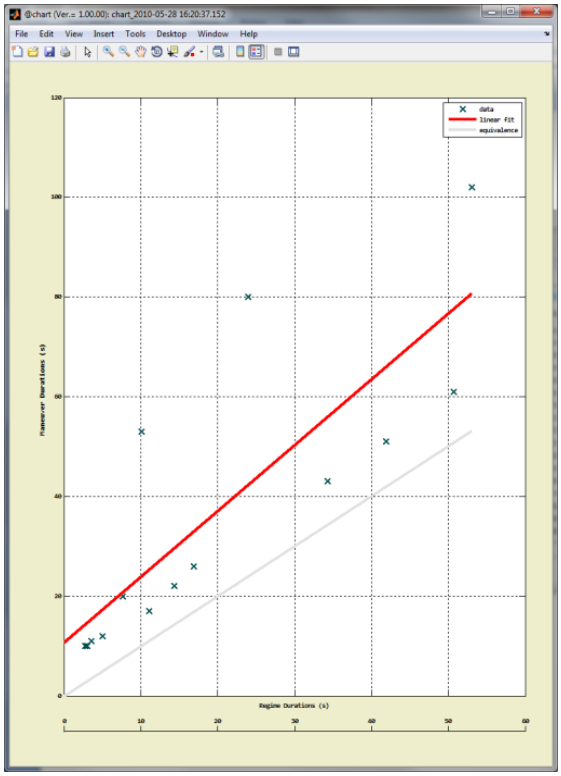


Figure 43. Regression Plot of Cluster vs CWC Maneuver

6.5.5.4 The HUMS Validation.

The HUMS validation GUI, shown in figure 44, provides an interface to validate the fleet HUMS parametric and regime sequence data and to validate the existing HUMS regime definitions that generate the sequence data. This general purpose interface also facilitates additional analysis of user-defined maneuver clusters and regimes to further build confidence that these definitions capture the important characteristics of their corresponding CWC maneuver. The objective of the design process was to ensure that the duration and number of these identified maneuvers accurately captured the actual statistical properties of a corresponding maneuver in the CWC spectrum. To build such confidence in a cluster definition, this module finds all instances of a defined CWC maneuver (based on parametric definitions) and a defined cluster (based on regime labels) for a robust comparison.

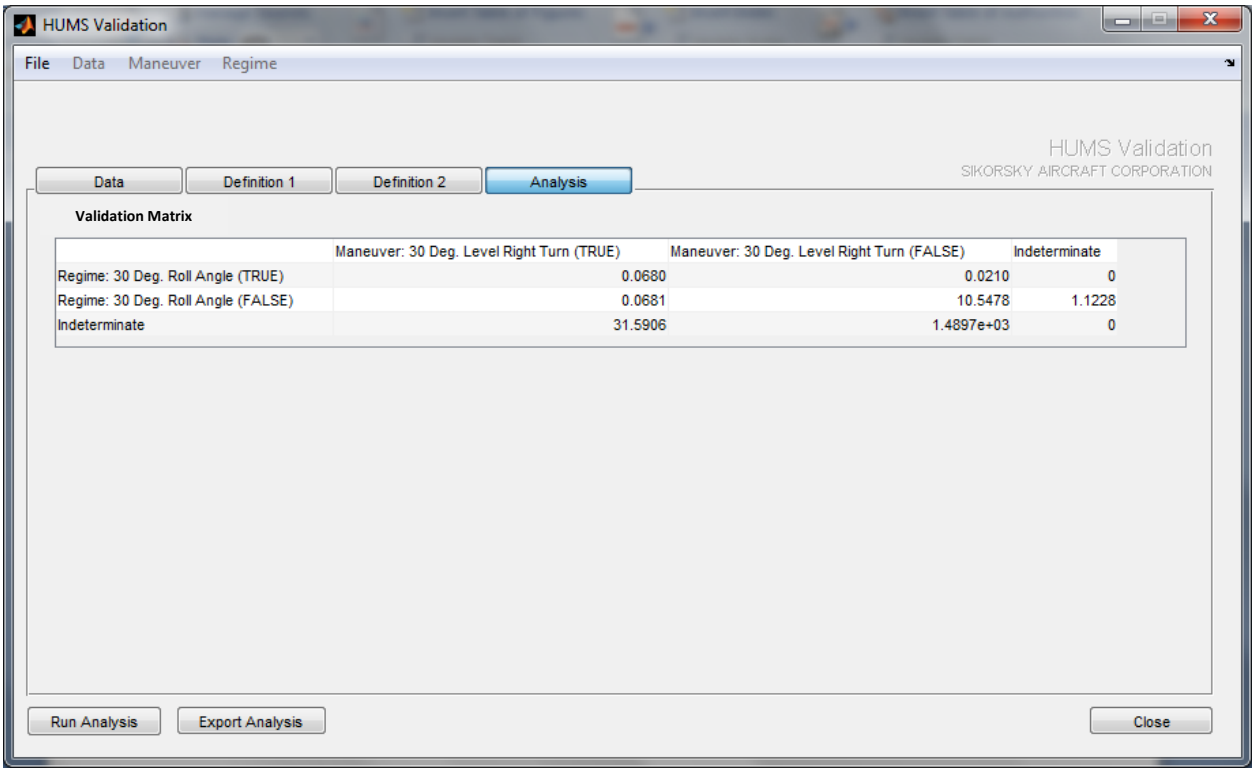


Figure 44. The HUMS Validation—Sample Analysis Results

As figure 44 s hows, the comparison is presented in a three-row by three-column validation matrix. The row and column added to the traditional validation matrix are included to account for the absence of either HUMS regime data or HUMS parametric data. The elements that comprise the upper two-row by two-column validation matrix provide the actual comparison of the two definitions on overlapping data. Here, the diagonal elements give the number of hours in the data for which both definitions are simultaneously true and the number of hours for which both definitions are simultaneously false. The values in the off-diagonal elements show the number of hours the two definitions do not match (i.e., when one is true and the other is false).

The analysis can be run by clicking on run analysis at the bottom left corner of the GUI window. Sample analysis results are shown in figure 44. To interpret the matrix, initially examine the indeterminate results in row 3 and column 3. Recall that a 1600-flight hour training set was used to prototype a cluster definition for a 30° level right turn in this case. While regime sequence data was available for all 1600 flight hours, HUMS parametric time histories were extracted for a separate data set that mostly overlapped the 1600 flight hours during the prototyping phase of the RRC tool. When either regime sequence or parametric data is missing in the side-by-side comparison, the matrix labels it indeterminate and places it in the appropriate row and column. From the matrix results, there were approximately 31.6 hours of data for which a 30° level right-turn maneuver was found, but there was not corresponding parametric data available. There were approximately 1489.7 hours for which this definition was false, but there was also no corresponding parametric data to process the regime definition. Similarly, there were 1.1228 hours of regime data for which the 30° roll angle regime definition was false and there was no corresponding regime sequence data to process the maneuver definition. While it is expected

that corresponding parametric and HUMS sequence data exist when developing and optimizing clusters, this is a convenient way to check the match between the two data sets for lost or corrupted data.

From figure 44, in the two-row by two-column portion of the validation matrix, the results show that for 0.068 hour both the maneuver definition and the regime definition were true. Similarly, there were 10.5478 hours for which both definitions were false. The off-diagonal elements of the two-row by two-column validation matrix highlight the difference in the two definitions. For 0.0681 hour, the regime definition was false, while the maneuver definition was true, and for 0.021 hour, the maneuver definition was true and the regime definition was false.

The outliers in the off-diagonal elements can be investigated on a case-by-case basis using the plot format of figure 42 to determine if there was some anomaly in the data, such as corruption, loss, or HUMS mislabeling. Any anomalies in the fleet data that are traced back to the HUMS installation can be purged from the data set and replaced with CWC usage.

Although the example compares a cluster to a CWC maneuver parametric definition, the validation module is versatile enough to be used to validate any two data sets. The interface is very similar to the maneuver-tuning GUI, with four panels to select data, define maneuvers and regimes, and review the analysis results. Each definition can be either a cluster that is applied to HUMS regime sequence data or a regime definition that is applied to HUMS parametric data. Thus, it is possible to compare the following data sets:

- a maneuver cluster with a CWC parametric definition, as shown in figure 44
- a maneuver cluster with a maneuver cluster
- a parameter (flight state or load) with a CWC parametric definition

Such versatility enables a histogram to be calculated over the regimes encountered during a flight and the result compared to a baseline histogram as another means of checking for errors and raising an exception if the discrepancy is beyond a set threshold. The calculated histogram over the regimes may not coincide exactly with the histogram over the observed HUMS regimes. This is because known RR errors should be accounted for when histograms overencountered regimes are developed. Blocks of data found to be anomalous, corrupt, or missing could be replaced using a conservative CWC spectrum.

6.5.5.5 Usage Statistics.

After the cluster definitions have been validated, they are applied to fleet HUMS regime sequence reports. The final module of the semiautomated UBM RRC tool accomplishes this for individual tail numbers.

7. CONTINUED AIRWORTHINESS.

When implementing any UBM credit process, airworthiness must be maintained with the application of processes that ensures that baseline risk is sustained. This necessitates ICA documents for new operator requirements. The methods and procedures proposed here would have to be approved by an FAA Aircraft Certification Office for the purpose of using HUMS

data for maintenance adjustments. In addition, the FAA Aircraft Evaluation Group must review, for their acceptance, the OEM aircraft HUMS users' guide [5], and the procedures described therein, as adequate for the purpose of collecting and transmitting HUMS data to the OEM from the operator.

A viable methodology was developed to apply component usage history, as measured for a specific aircraft component (serial number basis) or fleet of aircraft (part number basis), into a credit adjustment of safe retirement time for that specific component or fleet. The process consists of the following steps, which are compliant with the AC requirement.

- Develop a method for identifying and mitigating missing data, unrecognized regimes, and inoperative HUMS time.

- Statistically adjust measured rates of occurrence and loads upwards to provide a specific reliability margin, accounting for validated system error and variability, and to maintain baseline risk.

- Employ a retirement time cap (i.e., a maximum retirement time that cannot be exceeded in service regardless of the structural usage monitor result). This would be initially set to a more conservative factor on the CRT and could be increased as part of the CIS plan and/or throughout credit service history.

7.1 INDIVIDUAL COMPONENT CRT ADJUSTMENT.

The individual component CRT adjustment approach considers issues specific to tracking usage for an individual component serial number. Most dynamic components stay on a single aircraft throughout their service life, which makes computing their usage history straightforward. However, maintenance practices permit swapping parts among aircraft. For LLPs, a paper or electronic log card is maintained for each serial number. The log card contains information regarding what aircraft the component was installed on, how much time was spent on each aircraft, time at overhauls, etc. Developing individual component UBM credit adjustments requires a data management infrastructure and processes for tracking component usage and repairs for a specific serial number, providing specific times spent on different aircraft tail numbers. All operators have either manual or electronic systems for tracking LLPs, and larger operators typically have a sophisticated MMIS, which provides the required infrastructure and processes. However, existing systems may need to be augmented to ensure tracking of cumulative UBM credit adjustments, traceability between specific times spent on different aircraft tail numbers, and associated HUMS data. This would enable mining of the HUMS data for the appropriate aircraft tail number for the time period in which the component was installed, as described in section 5. In this manner, the exact history for the individual component can be reconstructed to determine the usage and calculated credit adjustment, as described in sections 6.1 through 6.4.

The following process is similar to the recommended application of a UBM credit for the S-92 aircraft hub [6], which is based on the tracking of only one state parameter (MR speed). The overall process is also applicable for the sample swash plate UBM credit, which is based on

recorded HUMS RR sequence output and the clustering methodology described in section 6.5 and appendix B.

SAC and most rotorcraft OEMs are authorized by the FAA to act as a representative of the administrator for the purpose of performing design and airworthiness certification procedures under Title 14 CFR, Part 183, Subpart D, Organization Designation Authorization (ODA). The SAC ODA procedures manual [17] establishes the responsibilities and procedures to be followed when performing FAA-authorized functions, which include the approval to change life limits on LLPs by authorized ODA unit members.

The use of HUMS data and a known service history to determine a CRT adjustment for a component constitutes a major change to the S-92 aircraft maintenance process. If appropriate processes are not put in place, this change could affect the integrity of a basic load-bearing structure that is necessary for continued safe flight and landing or operation of the aircraft within approved limits, and could introduce new and unique operational considerations. Therefore, each UBM credit for a particular LLP and for an individual operator should require explicit FAA approval of UBM credit to certify the credit processes and operator procedures. Once the credit is certified, each CRT adjustment can be approved by an SAC ODA unit member. As UBM credit experience is gained, the FAA could decide to delegate the UBM credit approval itself to OEM ODAs.

Due to the change in the maintenance paradigm, as a result of UBM credits and the resultant importance of the associated airworthiness credit, the roles and responsibilities of the OEM and the operator must be explicitly defined. Proposed roles and responsibilities for a component CRT adjustment process are shown in table 13, which requires a slight modification of the existing roles and responsibilities for ensuring aircraft airworthiness. The roles shown assume the preferred UBM credit scenario from table 2 is invoked (i.e., the OEM is responsible for credit adjustment).

Table 13. Roles and Responsibilities for Individual Component CRT Adjustment

Responsible Entity	Actions
OEM FMOC	Collects, examines, and validates HUMS data at 25% intervals of the published AWL CRT. Monitors trends in usage damage accumulation rates. Notifies the operator if, in the unlikely event, actual damage rates are higher than CWC, which would pose a potential safety risk.
Operator	Requests CRT adjustment when component reaches checkpoint at approximately 75% of published AWL CRT, unless notified by SAC earlier (in the event of discovered severe usage). Assembles substantiation data package, including documentation of component service and repair history, maintenance records, and identification of associated HUMS data.
OEM FMOC	Upon operator request for adjustment, conducts the following: • Assigns LLP CRT adjustment request number for tracking purposes • Reviews operator request and substantiation package and requests clarification and/or missing information/data • Mines HUMS data, identifies data gaps, and assembles database required for calculating CRT adjustment, including a data quality log of missing data and data quality issues

Table 13. Roles and Responsibilities for Individual Component CRT Adjustment (Continued)

Responsible Entity	Actions
OEM Engineering	Upon operator request for adjustment, conducts the following: • Reviews operator request and substantiation package • Evaluates HUMS data quality and assesses compliance with credit requirements • Calculates CWC versus actual PDAR to determine appropriate usage for gap filling (see section 6.3.2). • Approves/rejects request based on criteria established in section 6, including limits on missing/corrupt data based on PDAR, and a cap on maximum CRT adjustment • Calculates CRT adjustment and translates to adjustment in effective flight hours for specific serial number and uses PDAR to establish PRCP. • Substantiates CRT adjustment results (see section 6.4) in a configuration controlled document, UBM CRT adjustment substantiation package, for the credit request tracking number. The UBM CASP should include a new standard form to capture high-level substantiation of the credit adjustment approval/rejection and results for subsequent transmittal to the customer after ODA approval/rejection. • Conducts independent peer review of UBM CASP. • Submits UBM CASP to ODA unit, along with CASP customer summary form.
OEM ODA Unit	ODA unit member reviews UBM CASP, approves or rejects CRT adjustment, and signs the UBM CASP and summary form.
OEM PM	Notifies operator of the approval or rejection of LLP CRT adjustment request. If approved, creates a Customer Service Notice containing CASP summary form and part-marking instructions.
Operator/ Maintainer	Performs the following: • Modifies log card and/or MMIS to record adjusted effective flight hours for the component for which adjustment was requested, records CRT adjustment tracking number, approved adjustment, new cumulative adjustment, and PRCP. • Re-identifies a particular component by adding an appropriate suffix (e.g., UBMCA) to the part number to indicate a UBM CRT adjustment has been applied. • Retains UBM CASP summary form in maintenance records. • Accumulates additional hours after life adjustment normally. Operator can request another extension at 75% of AWL CRT per effective time tracked on the log card. If no further requests are made, informs OEM when effective flight hours reaches PRCP and provides similar data package to OEM. • Retires components when log card times reach published AWL CRT in full accordance with SA S92-AWL-000 [18].
OEM FMOC/ Engineering	Evaluates usage at PRCP and determines if component must be retired early.

The checks and balances apparent in table 13 and prescribed substantiation documents are sufficient for ensuring process integrity and continued airworthiness in compliance with the AC. More details are in sections 5 and 6, as noted in the table. The overall process is shown in figure 45. The recurring CRT adjustment steps are shown in the green boxes, which reflect the actions by the responsible entity, as summarized in table 13. The process shown in the blue boxes is nonrecurring for optimizing the clustering algorithm for the component-specific UBM credit. This would likely be done as part of the UBM credit submittal for FAA certification, or it may be done as part of the CIS. While envisioned to be a one-time process, it could be periodically updated during synthesis of the credit based on improvements in the onboard RR algorithms or offboard clustering algorithms.

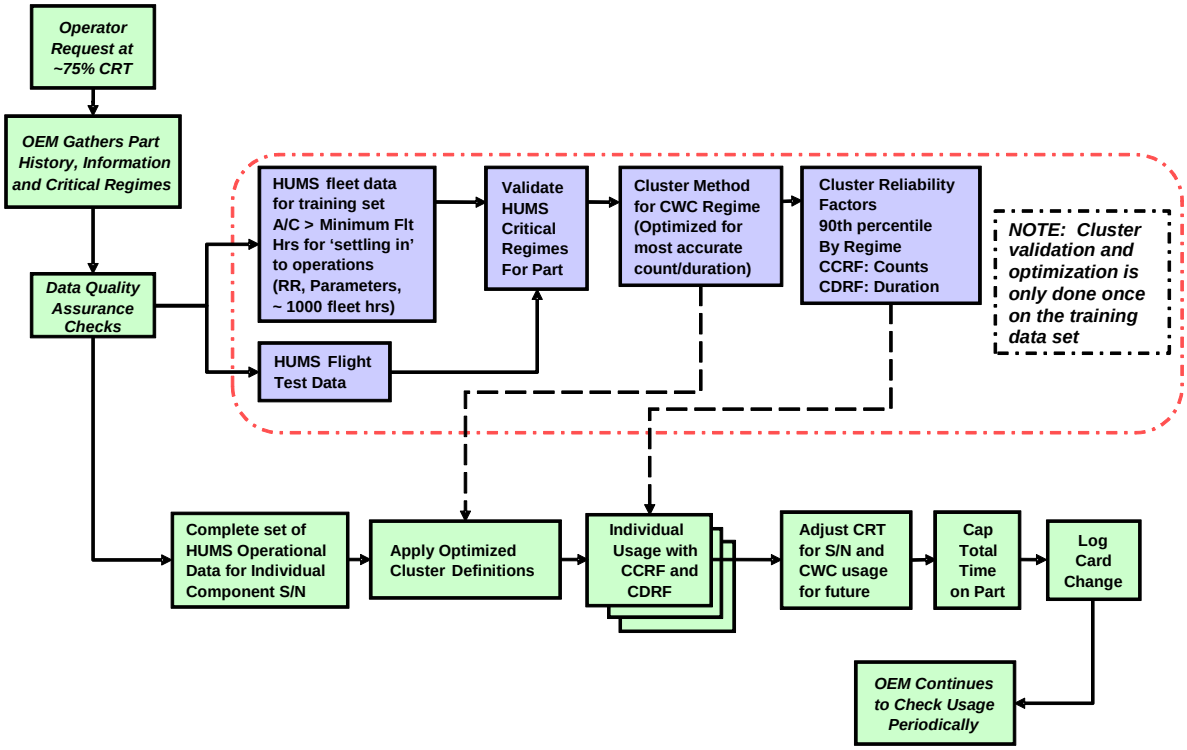


Figure 45. Individual Component Adjustment Methodology

Details of the CRT adjustment calculation and implementation are shown in figure 24. CRTs for all LLPs are published in Chapter 4 of reference 18. It is important to note that by adjusting the log card with a new effective flight hour value, the AWL CRT published in reference 17 remains unchanged. Therefore, the existing procedures specified in the manual are preserved, and a requirement for a tailored manual for each individual aircraft can be avoided. Instead, the formal OEM customer communication process (e.g., customer service notice) will provide the operator with an adjustment of the operator-recorded flight time for a particular component serial number.

All usage after the adjustment is assumed to be the original conservative CWC unless the calculated PDAR exceeds CWC assumptions. In such a case, the PDAR is used to establish the PRCP. The operator informs the OEM when effective flight hours reach the PRCP and provides a similar data package for OEM use in evaluating cumulative usage. This will indicate if the component should be retired even earlier than the published AWL CRT shown on the LLP log card.

The operator may request multiple credit adjustments with the frequency, maximum number of adjustments, and the cap on maximum CRT adjustment to be explicitly defined in the FAA-approved UBM credit. The frequency and maximum number of adjustments is, to some extent, an OEM business decision driven by the efficiency and costs required to evaluate a request and calculate the CRT adjustment. However, they should be part of the FAA-approved UBM credit to ensure process discipline is maintained.

7.2 FLEETWIDE CRT ADJUSTMENT.

Figure 46 shows the approach for a fleetwide CRT adjustment applicable to a specific fleet of helicopters calculated by updating the fleet usage spectrum. A comparison to figure 45 shows the major similarities and minor differences between the two implementations of UBM credit adjustment processes. The primary differences for the fleetwide adjustment process are:

- The fleetwide adjustment can be triggered by a single operator or by the OEM.
- Fleet usage is calculated, rather than individual component usage, requiring substantially more data mining and analysis, but also resulting in lower-criticality requirements for data integrity. Temporary loss of data on any given aircraft is much less important, as long as the data are available for a statistically significant representative fleet sample.
- In addition to individual component reliability factors, rates of critical regime occurrences are adjusted to provide a specific reliability margin and to account for system error and variability for the presence of a usage monitor. The process builds upon cluster algorithm statistics for critical CWC regimes, which may have been developed previously using a training data set. If so, then no further cluster definitions or optimization is required. If not, then new cluster definitions must be developed.
- For an operator's specific fleet of aircraft, the credit adjustment entails formal notification of the revised fleet CRT tailored for the set of operator tail numbers. The operator would also be required to notify the OEM if an aircraft leaves the subject fleet or enters from a different operator's fleet.
- If the OEM performs a credit adjustment for the entire fleet of all operators, this simply entails a change to the published fleetwide AWL CRT found in reference 18.

The roles and responsibilities are similar to those given in table 13.

An important consideration for this method is that it depends on several lead-the-fleet aircraft that comprise a significant representation of usage for the LLP. Depending on the fleet size, the number of lead-the-fleet aircraft selected has to be statistically significant to define the UMRF. The sampled points for each monitored CWC maneuver must sufficiently establish two percentiles (e.g., 90th and 50th) of a probability distribution for calculation of the UMRF.

Once an updated CWC spectrum is established from monitored fleet usage, a corresponding revised fleet CRT can be computed. This process assumes that the updated fleet usage is still applicable for future usage, and the resulting revised fleet CRT is still subject to a cap. For fleetwide application to all operators, the credit adjustment is published in an update to the AWL document [18]. For application to a specific operator's fleet, the credit adjustment would be implemented in a manner tailored to the subject set of operator aircraft. Furthermore, the OEM may be required to periodically check the actual usage to ensure that the updated fleet usage remains valid.

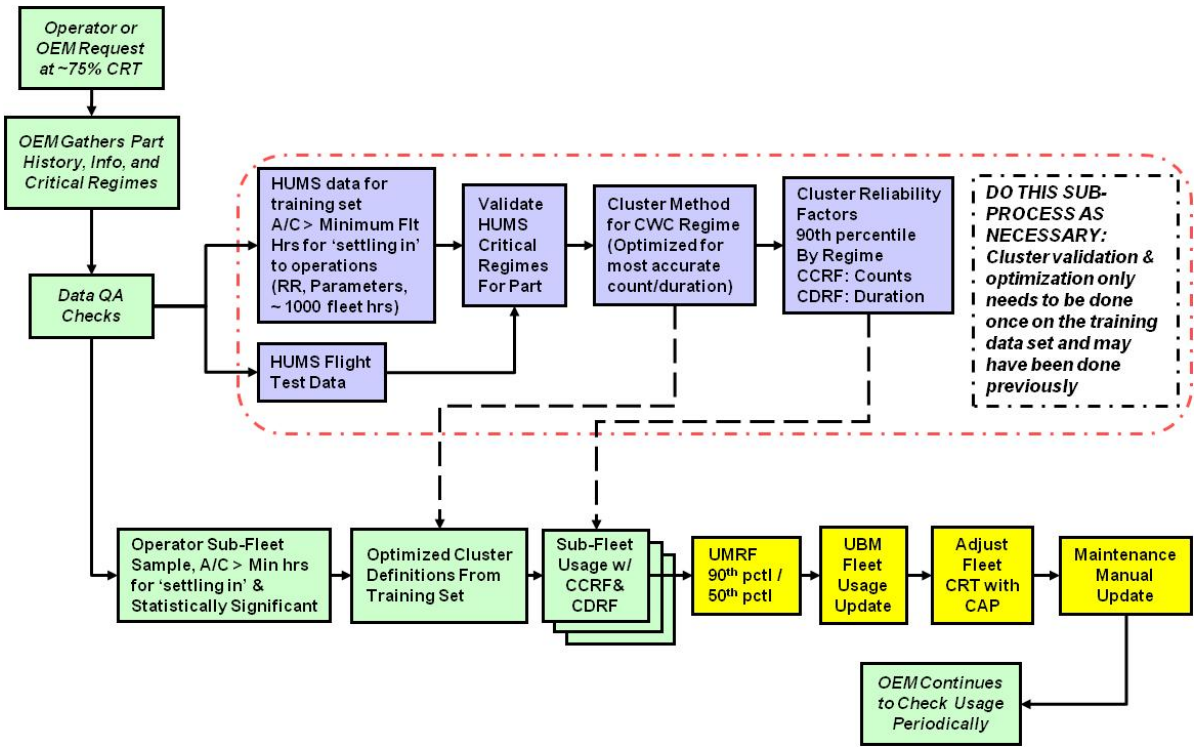


Figure 46. Fleetwide Component Adjustment Methodology

7.3 THE ICA.

An end-to-end process for implementing a HUMS credit has been described to enable transition from a time-based to a UBM program that applies measured usage rather than assumed usage. The credit application must include an ICA to demonstrate that adequate training, operating procedures, and instructions are available to ensure continued airworthiness of the aircraft. The ICA is operator-centric, providing directions for personnel in the field. In the preferred short-term UBM credit scenario proposed herein, the primary roles of field personnel are to gather and transmit HUMS usage data to the OEM while ensuring data integrity and to apply the credit adjustment through accurate modification of LLP component log cards and MMIS data systems.

All FAA-approved aircraft have a comprehensive aircraft maintenance manual (AMM) that includes procedures and instructions for ensuring aircraft airworthiness using baseline maintenance procedures. The S-92 aircraft HUMS is part of the baseline aircraft configuration and is on the aircraft maintenance minimum equipment list (MMEL). Further, HUMS-related procedures are fully integrated into the S-92 AMM [19], including a special chapter devoted to the HUMS users' guide [5] and explicit instructions throughout that specify maintenance actions to be taken as a result of HUMS indications. Thus, the S-92 AMM serves as an excellent foundation for providing additional HUMS airworthiness credit requirements for the operator to implement a UBM credit process.

The following key elements should be included in the ICA for a UBM credit, providing specific instructions related to the operator's roles and responsibilities listed in table 13.

- Operating instructions for each element of HUMS and a HUMS troubleshooting guide.

- Inclusion of HUMS on the MMEL with the maximum time that the aircraft can be operated without an operational HUMS. While an appropriate time limit would vary as a function of HUMS credit criticality and component AWL CRT, it is proposed that 10 calendar days or 50 flight hours would be an adequate limit for most UBM credits. This would represent only 5% of a very low 1000 flight hour CRT.

- Modification to the AWL document [18] and AMM [19] to annotate the published component CRT with the explanation that it is based on the original CWC design usage spectrum and that an adjustment may be possible after OEM aircraft review of HUMS data and maintenance records, provided that the operator uses the OEM-approved HUMS and FAA-approved UBM credit process.

- Instructions on the requirement for, and the use of, data verification procedures available within the GSS, including pilot debrief of relevant configuration parameters (e.g., GW and CG) and relevant operational usage parameters (e.g., flight hours, takeoffs and landing).

- Data acceptance or rejection criteria along with requirements for maintaining a data integrity log.

- Requirements for maintaining a maintenance log for LLPs that can be moved from aircraft to aircraft.

- Instructions for implementing specified mitigating actions.

- Instructions on requesting a CRT adjustment, including the data package required by the OEM to substantiate the adjustment and obtain FAA certification for the UBM credit, if not already done.

- Instructions on implementing an approved CRT adjustment, including required modifications to the component log card and MMIS data, and instructions on required part-marking procedures.

- Instructions to inform the OEM when the effective flight time has reached an OEM-prescribed PRCP, requiring another structural usage check.

In addition to the ICA, the OEM should provide a training program on the HUMS airborne and GS equipment and ICA requirements. The aforementioned additions to the standard aircraft ICA and AMM are operator centric. The OEM roles and responsibilities (listed in table 13) should be documented as detailed standard processes for use by responsible OEM functional groups. The input/output requirements and acceptance/rejection criteria should be provided for each portion of the process.

8. CONTROLLED INTRODUCTION TO SERVICE PLAN.

The Controlled Introduction to Service Plan (CISP) should define how to conduct a final in-service validation of the UBM credit process, carefully monitoring key process steps and mitigating actions for a finite period of time to ensure their efficacy and identify and implement process improvements, as necessary, to achieve defined CIS metrics for success. The CISP describes what specific additional data or direct evidence must be acquired to fully validate the end-to-end UBM credit process for individual component and fleetwide adjustments. Typically, a CISP for validation of certification of HUMS lasts 1 to 2 years. One year should be sufficient for validating UBM credit data management and data integrity-checking procedures. If further validation of RR algorithms is required using validated fleet data, 2 years may be more appropriate. It also may be deemed desirable by the OEM and FAA to extend the CISP to include the first credit adjustment. Note, however, that this could be 4 or more years for a credit related to CRT adjustment of a LLP with moderate service life (e.g., 5,000 to 10,000 flight hours, assuming 1,000 to 2,000 flight hours per year). If the OEM already has been collecting and ensuring the integrity of the parametric and/or regime sequence data for an extended period of time, it may be possible to reduce the duration of the CISP, including the time required to gather sufficient data for the first maintenance adjustment associated with the UBM credit. This is the case for the S-92 aircraft for which the HUMS has been a baseline system, and data have been collected since inception of the commercial fleet.

The overall strategy for a UBM credit CISP can be described in the following ways.

- Obtain initial conditional FAA approval of UBM credit process and CISP, including metrics for success
- Identify lead-the-fleet operators
- Obtain additional evidence, as required by the CISP
- Develop lessons learned and, if necessary, make UBM end-to-end process improvements
- Substantiate successful achievement of CIS metrics
- Obtain final FAA approval of UBM credit process and first maintenance adjustment

The proposed UBM credit approach is an offboard semi- to fully automated environment performed by the OEM, which will allow early introduction to service to achieve initial UBM credits without the need to modify onboard RR algorithms. This approach exploits the current installation of the HUMS and ensures reliability and safety through the application of conservative postprocessing algorithms and engineering expertise and judgment to complement software tools developed for calculation of CRT adjustments. Although the processes become more automated as the technology matures, the OEM continues to retain responsibility for the decision-making process and calculation of credit adjustments.

The defined clustering methodology is a significant aspect of the proposed approach because of the following features of the process.

- No changes are required to the existing HUMS installation and procedures (at least for the S-92 aircraft in which onboard HUMS RR algorithms perform sufficiently to be used by the clustering algorithm approach).
- A logical solution to RR behavior can be found in present-day HUMS technology.
- A large amount of all the fleet data gathered to date is used.
- Reliability can be quantified.

For the proposed scenario, the CISP would focus on va lidating the following three critical aspects of the UBM end-to-end process. (Note that all three are required regardless of the scenario used for table 2 and the use of the clustering algorithm.)

- The adequacy of the operator's processes and mitigating actions, which ensure data integrity is transmitted to the OEM
- The adequacy of the OEM's processes and mitigating actions, which ensure data integrity
- If necessary, the collection of sufficient additional fleet data to statistically validate the critical RR algorithms, UBM credit process reliability factors, and CRT adjustment calculation

UBM credit reliability factors will be developed to address sources of uncertainty and variability related to usage, as shown in figure 47. In this process, the existing HUMS installation will be used and the output postprocessed to appropriately map the HUMS regime sequence output into quantifiable CWC spectrum regimes. The source of the truth data for validation of the process can be either the pilot declarations from a scripted flight test or OEM expert transcription of operational fleet data segments. The CWC mapping process will be optimized to minimize the uncertainty in the mapped regimes versus the truth data to ensure conservative calculation of accumulated fatigue damage. The same approach can be used regardless of the approach used to map onboard RR sequences to CWC regimes.

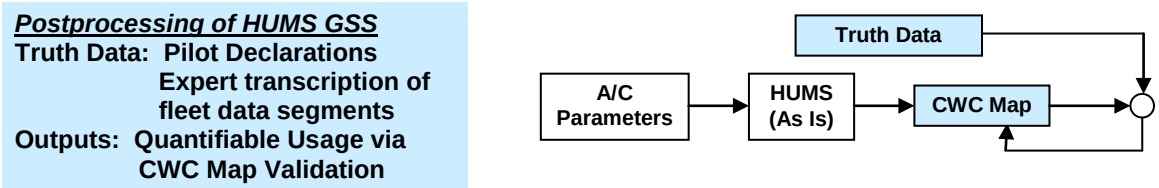


Figure 47. Credit Validation Scheme to Minimize Regime Uncertainty

Candidate elements of a generic UBM credit CISP are shown in figure 48. The process focuses on obtaining more supporting evidence, as necessary, to complete synthesis of the credit validation. The elements shown in red are not likely to be necessary. This represents two

elements: (1) an additional dedicated RR flight test, which, as discussed above, should not be necessary and (2) further fatigue tests, which should not be necessary unless the OEM or the FAA deem further substantiation of fatigue strength curves are required. The following sections discuss elements of each column in figure 48 in more detail, focusing on the OEM-centric approach proposed herein as the most easily transitioned into operations.

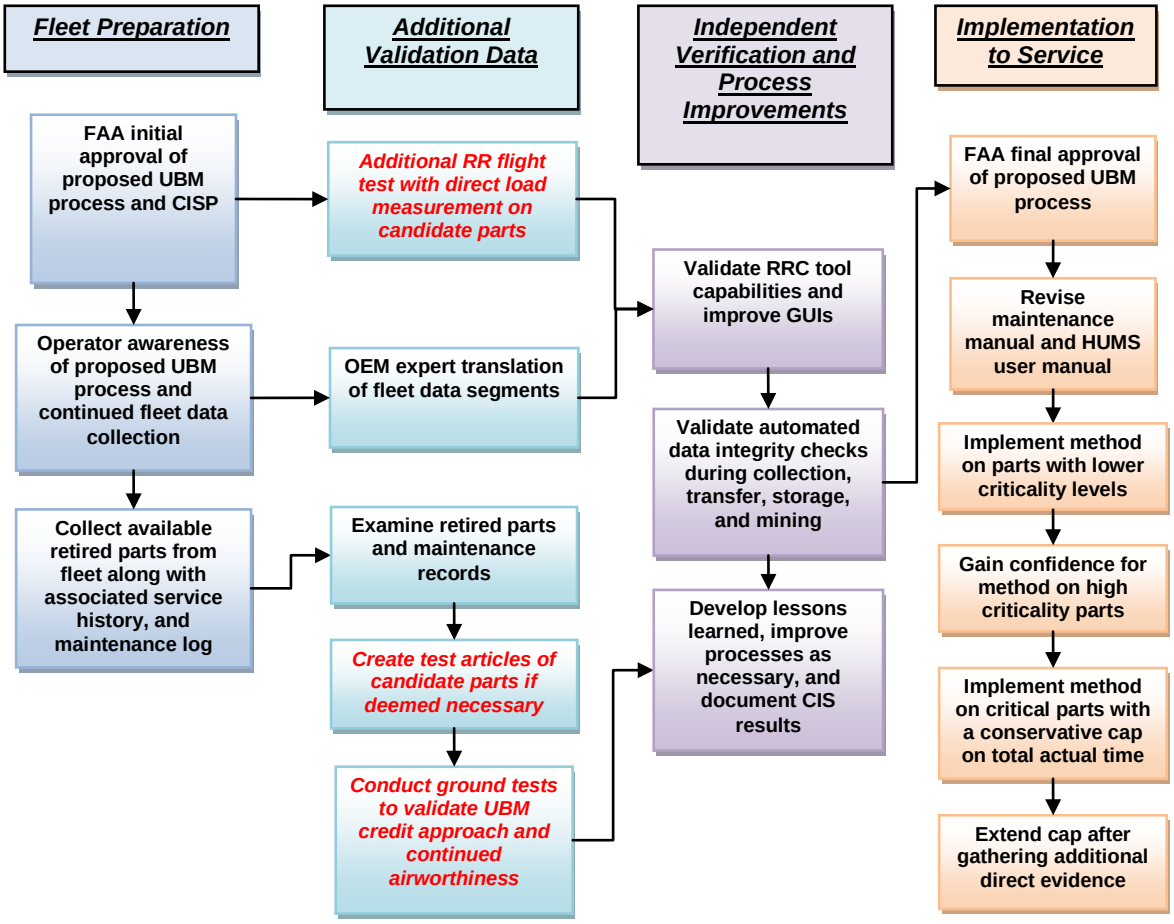


Figure 48. Candidate Elements of a General UBM Credit CIS Plan

8.1 FLEET PREPARATION.

The end-to-end UBM validation process, CISP, and ICA are formalized for a specific aircraft and component credit and submitted to the FAA for initial approval. Subsequent to the initial approval, operators need to be made aware of the UBM credit process that has been developed through various means of communication, such as written notices and workshops (e.g., annual S-92 aircraft user conferences). Lead-the-fleet operators are identified.

Provisions should be made to retain retired components along with maintenance records. The components and maintenance records should be examined to determine whether target LLPs would likely need to be overhauled, repaired, or scrapped for other failure modes if the CRT were extended. They also may be valuable as ground test articles to gather further direct

evidence to support UBM credit validation if additional fatigue data are deemed necessary, which generally should not be necessary.

8.2 ADDITIONAL CREDIT VALIDATION DATA.

Additional data may be needed to synthesize the credit in support of final credit verification. As shown in figure 48 (second column), this could entail four types of data: (1) dedicated RR validation flight tests, (2) translation of fleet data into truth data, (3) examination of service history, maintenance history, and part condition at retirement, and (4) additional fatigue tests of retired components.

The Phase 3 scripted flight test conducted under this research provided valuable experience for further verification of HUMS RR algorithms. While this test focused on high-bank angle turns and pull-up maneuvers, additional tests may be needed to obtain information for other critical maneuvers or other components. The flight tests should be conducted with instrumented components, if possible, to directly measure loads for comparison and correlation with the clustering methodology. In this manner, the CWC map can be expanded and refined for more maneuvers and components.

The RRC tool can be applied by an OEM expert to select fleet data segments and translate them into truth data for further validation of onboard RR algorithms or clustering algorithms. Once the onboard algorithms reach a level of maturity, this approach is considered as good as, or better than, test pilot declarations for two reasons. First, the same experts are used to translate fleet data into truth data, define regimes, test pilots plan the flight test maneuvers, and validate the adequacy of flight test data. Second, truth data is pulled from operational data to represent realistic maneuvers, which is the objective of free-flight tests conducted as RR algorithms reach maturity. By definition, success is achieved when the clustering algorithms consistently translate operational flight segments into the same or more conservative regimes than the experts that are responsible for defining the CWC regimes.

If additional fatigue tests are deemed necessary, test articles can come from new-part inventories as well as from available retired fleet parts. New parts can be tested with different fleetwide spectra models for their entire lives. Retired fleet parts can continue being loaded with the original CWC to accurately simulate an individual component UBM credit application. The ground test results provide an expanded database of fatigue lives for correlation to the UBM credit validation method and associated reliability levels. Note that it is expected that fatigue test results of retired LLPs, using current CWC-based CRTs, would be indistinguishable from new product results, given the variability typically present and the significant remaining useful life (RUL) that remains. This is because CRTs for LLPs are calculated using peak loads, but typically experience much lower loads that map into the flat end of the S-N curve. If deemed desirable to conduct further fatigue tests, a significant subpopulation should come from LLPs that were retired at the new cap on CRT adjustment.

8.3 INDEPENDENT VERIFICATION AND PROCESS IMPROVEMENT.

The only new element of offboard data processing within the end-to-end UBM process is the tool used to map onboard RR sequences into CWC regimes. During this research, the RRC tool was

developed to perform this function using the clustering approach. For other OEMs, it may be a comparable tool for performing this task, or the RR function may be executed entirely offboard using only parametric data collected onboard. Such a tool would need to be rigorously validated using a truth data set generated either from flight test data or expert translation of operational data, as discussed in the last section. Once validated, the software should undergo configuration control management and be revalidated with regressions tests for any software upgrades or porting to a new COTS computer environment. If the tool is to be used by nonexpert OEM engineers or on multiple COTS computer platforms, then the CISP should include independent verification by redundant processing using dissimilar computers with different COTS components, including desktop and laptop PCs versus workstations and perhaps different operating systems, depending on what variability in the application environment of different OEM users. Upon approval from the certifying authority, the RRC tool or equivalent can be deployed and applied without the independent verification. Other scenarios in which such tools are implemented within the GS at the operator's facility, having unknown COTS hardware and software computing components, the risk of incorrect results increases significantly, especially without expert engineers. Thus, much more rigorous independent verification tests should be conducted on multiple COTS computing configurations, which may not be practical. Further, such tests would have to be conducted whenever the operator modified the computing environment.

For example, the UBM RRC tool is an application that requires commercial MATLAB® programming software. MATLAB is available for multiple computers and operating systems. Independent verification can be performed by ensuring consistent results of data processing within each GUI using (1) different computers running the same version of MATLAB and (2) different software to process the data at various checkpoints within the GUI procedures.

The other key element that must be validated during CIS is the maintenance of data integrity throughout the data management supply chain, including the different mitigating actions used to ensure data integrity (e.g., those proposed in sections 5 and 6). Under the proposed OEM-centric UBM process, the only function of the GS is to download MUD files from the DTU card and convert to an RDF while checking data integrity. The efficacy of this process should be validated by downloading and checking the same data on several different GS variants, using different COTS components if the operators are permitted to use them. It is noted that the S-92 fleet all have the same COTS GS, which is imaged and tested by SAC engineers; so there is no need to test on different COTS hardware and operating systems, as long as they use a GS provided by SAC.

Security concerns are highest for the operator location and include access security, authentication and access control, intrusion detection, and information verification and accountability. First, only authorized users must be allowed to have access to the system. In addition to the use of passwords, undesired access to data or other security risks must be limited or eliminated using firewalls and encryption. Use of digital signatures should be considered part of the authentication process. Moreover, various users should be assigned different privileges, as determined by the system operational requirements. Attacks or other malicious activities, such as denial of service attacks, can be addressed using a variety of standard approaches, such as signature-based intrusion detection or host-based approaches [20]. System audit trails, including

the operating system, application programs, and user activities, should be available to ensure compliance with policies and procedures and to trace violations to individual users. A subset of the operational requirements is prudent to complement the routine information technology security measures already used at the OEM facility. There should be limited access to controlled, configured HUMS software and HUMS databases.

For the proposed OEM-centric process for UBM credit adjustment calculations, the primary mitigating actions would be conducted by the OEM. Figure 49 shows one process for detecting and correcting anomalies, regardless of origin, using automated data integrity checks and engineer-in-the-loop oversight. It starts with simple analyses that include checking audit trails of the data files received. File access and edit history information should be analyzed and exceptions raised if dates or frequency are outside the expected boundaries. The data must also be considered for validity of syntax, i.e., no unexpected symbol received. Additionally, all signals must be within their expected parametric bounds.

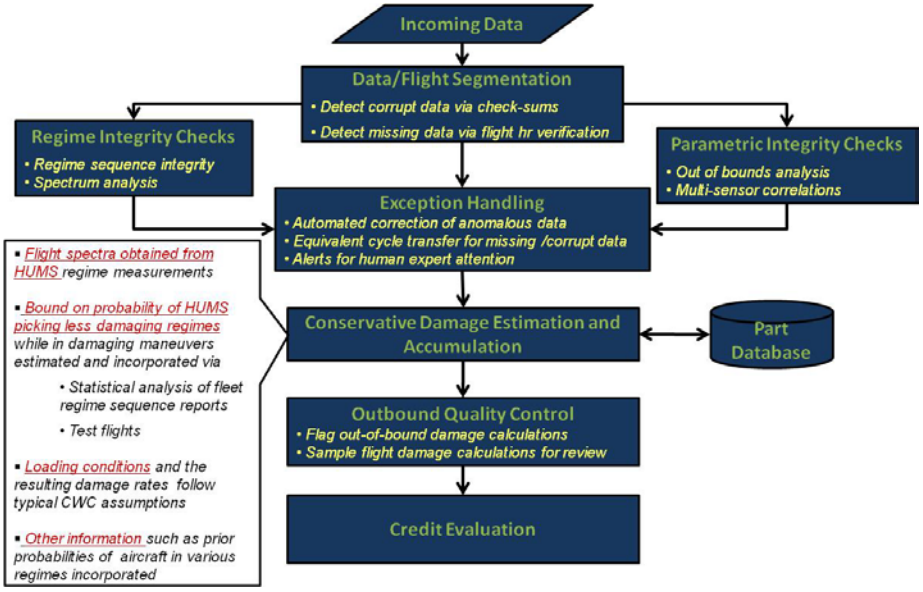


Figure 49. Detection and Correction of Data Anomalies in the End-to-End Process

Ensuring against corruption and data loss during a transfer to the OEM is an important element of the data integrity assessment. Data corruption may be detected using standard checksum techniques. The idea of checksum is to compute a hash function of the data, include the result in the transmission, and ensure that the checksum relations hold at the receiving end through application of standard algorithms. Note that checksums only ensure against accidental data corruption and not corruption caused by malicious attacks. Data loss is another important concern during the transfer of data. One simple approach to detect data loss is to independently verify total flight hours for an aircraft within a period and compare them to the total length of data received. Any missing block of data may then be replaced conservatively, e.g., by using CWC spectrum.

The next step in the process involves checking for discrepancies in the content of the data file. One method is to exploit expected relations and correlations among sensors. For example, a

subset of sensor signals may be expected to lie within an ellipsoid, which is estimated on the basis of historical data. The extent and frequency of violation from such rules may be used to raise exceptions. Another method is to look for parametric data values, drifts, and long-term trends of parametric data for known events (e.g., ground run with pedal at zero). There may be the desire or need to introduce a known event into the preflight check to enable more effective parametric data checks. For example, the preflight check may be modified to require the pilot to independently move his controls from stop to stop before initiating the release of the rotor brake and a rotor turn. Drift detection requires storage of databases for later referencing because long-term trends occur slowly and can only be detected through analysis and comparison of long data records. Exceptions should be raised depending on the parameters and thresholds of the detection algorithm.

Other data QA checks can be conducted by the OEM after parametric data and/or RR sequences are processed into usage spectra and accumulated fatigue damage. Trending both types of data for individual aircraft and fleet data can be used to flag anomalous data for expert examination.

The final element of the CIS validation and verification phase is to document lessons learned, process improvements made to address observed deficiencies, and validate results according to CISP requirements. The UBM credit substantiation document is then submitted for FAA approval.

8.4 IMPLEMENTATION TO SERVICE.

After sufficient data has been obtained, the FAA can grant final approval for implementation of the method into service, meaning that OEM ODA-approved maintenance adjustments are now allowed. If not accomplished earlier in the CIS, the HUMS users' guide and AMM should be revised to describe UBM credit processes and operator roles and responsibilities, as described in section 7. Initially, a conservative cap on cumulative credit adjustment is recommended, as discussed in section 6, so the total actual time on the part does not exceed a prescribed limit. The cap could be extended as more service experience is gained.

It may be desirable to limit initial applications LLPs that are not as critical (i.e., no failure mode is catastrophic or perhaps even hazardous/severe-major), but still rely on HUMS RR output. This encourages confidence in the methodology before proceeding to credits of higher criticality components. If further fatigue tests are required, a sample of these parts can be used for ground test articles by removing them at their original AWL CRT. Another sample can be used for testing after they have been retired for reaching their allowed cap on actual accumulated time. Provisions should also be made to conduct on-aircraft inspection of the components to look for damage at the original AWL CRT and periodically afterwards.

The next step is to extend application to flight-critical parts. The cap of 2.0 times the original AWL CRT can be retained for the safety-of-flight components based on demonstrated reliability levels. Remaining efforts would then focus on gathering additional evidence to extend or remove the cap.

9. TECHNOLOGY TRANSITION PLAN.

The UBM credit approach defined in this report requires few additional technological developments other than refining automation of newly developed elements of the end-to-end process, particularly, the RRC tool with data QA algorithms. Once the RRC tool is further automated, the end-to-end process would be ready for final validation under a formal CISP. However, additional technological development would improve the processes and provide a more significant potential benefit, and several options are shown in table 14. The options are shown in rough order of difficulty and cost with highest additional investment associated with changes to HUMS OBS software or sensor suite. As shown, the near-term objective pursued in this research was to find a means for enabling UBM credits using existing sensors, RR software, and data management processes. This was accomplished by relying on scripted HUMS RR flight tests to provide truth data used in the clustering algorithm technical approach. Outputs are CWC regimes built from HUMS regime sequence data with quantifiable, conservative durations and counts based on statistical reliability factors to maintain baseline risk for airworthiness credit. The clustering algorithm has the following inherent challenges and limitations, although it has been shown that these do not preclude the immediate implementation of the method to achieve near-term benefit.

- Limited abilities because HUMS does not recognize certain critical regimes
- Based predominantly on regime labels rather than physical models
- Not as accurate as direct load estimates and measurements

These limitations can be reduced by an incremental approach in the technology roadmap to address areas requiring further improvement and reduce the impact of SUM and RR inaccuracies on UBM credits and structural reliability. While the proposed UBM process in this research focused on R R-based usage adjustment, it is recognized that regimes are simply a widely accepted means to classify loads in the baseline fatigue substantiation process presented in figure 1. Therefore, the long-term roadmap objective is to include loads monitoring directly into the SUM system and the calculation of RUL. Several interim approaches incrementally reduce loads uncertainty.

Table 14. Technology Roadmap for UBM Credits

Objective	HUMS Change?	Technical Approach	Truth Data	Sensor Inputs	Output
Find means for UBM credit with existing HUMS RR	No	Apply clustering algorithm (this research)	RR flight test or OEM expert translation of fleet data	Aircraft state parameters (no change)	Quantifiable RR to CWC mapping for CRT adjustment (this research)
Reduce load uncertainty with existing HUMS RR	No	Apply clustering algorithm with mapping to load bands	FLS and RR flight test with measured loads	Aircraft state parameters (no change)	RR to load mapping for CRT adjustment
Minimize OBS RR uncertainty	Yes	Update RR parameter bounds, hysteresis, etc.	RR flight test or OEM expert translation of fleet data	Aircraft state parameters, possibly augmented	Optimized HUMS output to CWC regimes

Table 14. Technology Roadmap for UBM Credits (Continued)

Objective	HUMS Change?	Technical Approach	Truth Data	Sensor Inputs	Output
Reduce load uncertainty with updated HUMS RR	Yes	Update HUMS RR parameter bounds, hysteresis values, etc.	Scripted HUMS flight test direct measured loads	Aircraft state parameters, possibly augmented	Optimized HUMS RR sequence file of estimated load cycles
Minimize uncertainty in GW and CG	Yes	Incorporate parametric- or physics-based W/CG models	GW and CG flight test	Possibly landing gear load sensors	Accurate GW and CG for prorating
Minimize uncertainty in loads with models	Yes	Incorporate parametric- or physics-based load models	FLS direct-measured loads	Aircraft state parameters, configuration information, possible sensors	Component load time histories for entire flight

Therefore, the second objective shown in the table is to reduce load uncertainty using existing HUMS RR algorithms and the application of the clustering algorithm methodology. To implement this technical approach, truth data would be based on direct-measured loads from required FLS tests and any additional scripted HUMS flight tests. There are no changes to the process inputs. However, the output is a mapping that produces a monitored load history that can be used in the CRT adjustment calculation. This mapping would produce duration and counts of component load bands that could eliminate the need for traditional CWC regime categorization and possibly significantly improve accuracy for certain components. The HUMS mapping would be optimized to minimize uncertainty in the mapped loads versus the measured loads for an individual component.

All the subsequent objectives involve changing the HUMS OBS SUM and RR software to reduce uncertainty in usage and loads monitoring, and require additional time and expense to validate and certify new OBS software. Of these, the nearer-term third objective is to minimize the uncertainty in the ability to recognize CWC regimes. This can be accomplished by following a technical approach that leverages the lessons learned in this research to create a better mapping to CWC regimes. Scripted flight test and flight simulations are used to determine the optimum set of state parameters and ways to subdivide the parameter space to produce HUMS RR output that is as compatible as possible with the CWC regime definitions.

The fourth objective involves a similar approach, but with a focus on loads instead of CWC regimes. In this scenario, the truth data source consists of direct-measured flight loads from dedicated, scripted HUMS flights. Parameter definitions and boundaries would be optimized so that the HUMS regime sequence output is mapped into quantifiable groups of estimated load cycles categorized into bands in which the cycles and magnitudes are the same as those typically assumed for fatigue substantiation, (i.e., 95th percentile loads for steady maneuvers and prescribed cycle counts for transient maneuvers).

The fifth objective is quite different in nature. It involves further maturation and transition of technology to accurately monitor aircraft GW and CG, either through the application of landing gear load sensors or the application of parametric models to accurately monitor GW and CG using a subset of parametric data already used for RR. The benefit of monitoring GW and CG is the ability to have regimes further prorated by GW and CG so more accurate load bands could be used, rather than the worst-case loads associated with the worst-case GW and CG configurations. Aircraft today typically rely on manually recorded estimates, which are known to have accuracy issues.

Finally, new SUM algorithms can eventually provide a path that more directly uses load histories in UBM credit calculation by direct measurement of loads or by accurate estimation of loads via parametric- or physics-based models. Load models are software applications that use existing HUMS parametric data to predict actual component load time histories after they have been calibrated to a set of measured FLS truth data, as shown in figure 50. This technology provides the possibility to estimate load histories without the need for direct load measurements. Loads monitoring could eventually replace traditional RR approaches found in present HUMS. If a loads-based system is adopted for UBM credit, the following criteria should be considered when selecting candidate components for application.

- Load sources for failure modes are well-defined, documented, and understood. The life-limiting failure mode and the associated load sources are important factors in the CRT analysis.

- Dominant loads are quantifiable in current fleet operations. An assumed high severity of loading creates much conservatism in the CRT analysis. If this can be quantified directly or indirectly in the fleet, this will have a significant impact on the UBM credit.

- Load monitoring is feasible. Either physical load monitoring is practical in a production aircraft environment via wireless, self-powered load sensors or accurate load models are feasible.

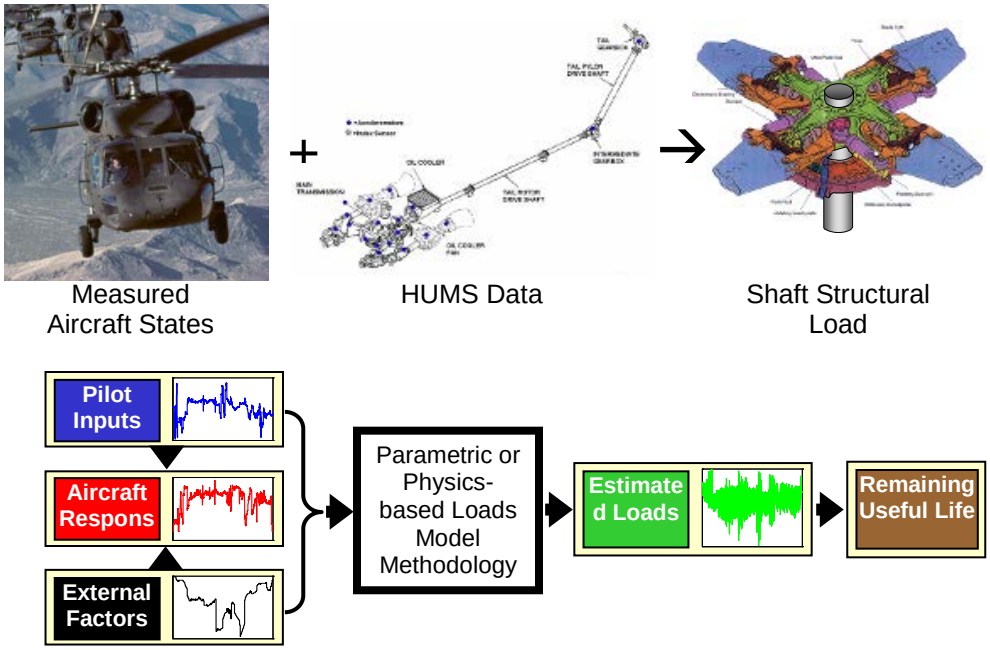


Figure 50. Loads Monitoring Concept Using Parametric- or Physics-Based Models

10. SUMMARY.

A viable approach for achieving UBM credits was developed and shown to be in compliance with the AC [2]. Significant progress was made in developing a promising new regime-clustering technique, which allows existing onboard HUMS RR software to be used without further refinement. This new technique can take advantage of the large volume of usage data recorded in the fleet and enable the adoption of UBM credits in the near future without a large investment in upgrading HUMS onboard software. Key accomplishments and findings are summarized for six project elements.

10.1 THE HUMS RR ALGORITHM EVALUATION.

Using data from the Phase 1 flight test, a tailored SAC validation methodology was outlined and a sample of maneuvers was investigated. Time synchronization is a necessary step to align HUMS and flight test data. A semiautomated software tool was developed to process large amounts of flight test data and to ensure the data integrity. Instrumentation problems can result in degraded data, and sometimes maneuvers are not performed with sufficient accuracy due to the difficulty of flying at the edge of the performance envelope. An engineer-in-the-loop is necessary to identify these types of issues. A few validated critical maneuvers were used to compare time history data from scripted flight test and HUMS to quantify RR performance. While the current onboard RR algorithms provided good qualitative usage results, several issues regarding quantitative accuracy were observed, including regime repeats and short-duration toggling among a set of regimes. These observations were further verified via evaluation of S-92 aircraft fleet regime statistics early in the project using the total available fleet database of 37,000 flight hours. At a high level, the onboard HUMS RR definitions were reasonable and could be mapped to CWC regimes, although they could not with a one-to-one mapping. While the

percentage of time spent in various regimes seemed reasonable, the occurrences of regimes were much higher than they should have been, and average durations were much shorter than they should have been. This was due to the aforementioned behavior of toggling between regimes. These issues were addressed by developing an RRC algorithm and tool.

10.2 END-TO-END UBM PROCESS DEFINITION.

Much work was done to fully understand AC requirements for UBM credits and to define an end-to-end UBM process for a representative S-92 aircraft, having a state-of-the-art HUMS with embedded RR algorithms installed in the baseline configuration. An example credit was investigated for a representative S-92 aircraft component (the stationary swash plate), which is a flight-critical, nonredundant LLP. A failure modes effects and criticality analysis showed the credit criticality to be Hazardous/Severe-Major rather than Catastrophic, which would be expected based on a high-level FHA. The proposed UBM process was in compliance with the AC, technically sound, viable within the available HUMS process, and compatible with SAC procedures to ensure a high level of reliability in the calculations of component life. Various UBM credit adjustment calculation options exist, including semiautomated offboard software and processes run by the rotorcraft OEM upon operator request, fully automated offboard software in the GS, and fully-automated software integrated within the airborne HUMS. From business and technical perspectives, the proposed OEM-centric approach poses the least risk and is most readily transitioned in the short term. The proposed process called for the UBM credit to be approved by the FAA, but for actual credit adjustments to be approved by delegation to an OEM Organization Designated Authority.

10.3 FLEET STATISTICS.

The latest fleet usage statistics were investigated to determine fleet variation per calendar year to identify changes in operational practices and any significant outlying aircraft, using the total fleet database of 135,000 flight hours available. Results showed that there was little variation in regime usage by year over the course of four years. It was concluded that S-92 operators have not changed the way in which they operate their aircraft. The outlying data is associated with low-time aircraft, i.e., with less than 500 total accumulated flight hours.

10.4 THE UBM ADJUSTMENT ESTIMATES.

Clustering algorithms were developed and applied to a significant amount of fleet data for a subfleet of ten S-92 aircraft. UBM credit adjustments for the S-92 MR stationary swash plate were estimated for an individual CRT adjustment (serial number-based) and also for a fleetwide (part number-based) application. For an individual component, improvements over the conservative retirement times using CWC usage were approximately 30% to 40% based on imposition of reliability factors and an assumption that all future usage is assumed to be the original CWC spectrum. For a fleetwide adjustment with application of an updated and revised CWC spectrum throughout the entire component lifetime, it was shown that the retirement time could be more than doubled, based on availability of a statistically significant amount of fleet data and implementation of an additional usage monitor reliability factor. It is recommended that the initial adjustments do not exceed a conservative cap (e.g., 1.5 to 2.0 times the original

published CRT airworthiness limitation) so the total actual time on the part does not exceed a prescribed limit. The cap could be extended as more service experience is gained.

10.5 CREDIT VALIDATION AND CONTINUED AIRWORTHINESS.

Detailed approaches for credit validation and continued airworthiness, including a CISP, were developed. Key aspects of the approach for validation were the concepts of (1) in-depth validation of only the critical damage regimes of relevance to the credit and (2) the use of OEM experts, using automated fleet analysis tools, to translate operational fleet data into truth data for final validation under the CISP. Detailed roles and responsibilities for the operator and the rotorcraft OEM were established for two types of credits: (1) individual component CRT adjustment and (2) fleet CWC spectrum adjustment.

Key elements of a viable UBM credit approach have been provided to take immediate advantage of fleet data to obtain an approved UBM credit. It requires (1) a reasonably accurate set of onboard RR algorithms certified to a software criticality level commensurate with the criticality of the UBM credit, (2) a data management system that ensures data integrity as it is transferred to the rotorcraft OEM, and (3) an approach to address any deficiencies in the onboard RR algorithms through offboard data mining (e.g., regime clustering) to map onboard RR sequences into existing FAA-approved OEM design and fatigue substantiation processes. The next step is to develop a proof-of-principle UBM credit application for a specific credit and secure FAA concurrence with the approach. The FAA plans to conduct such a follow-on effort with one or more rotorcraft OEMs. Future technology development includes moving towards a UBM credit based on loads monitoring to further improve the benefits achievable by the current RR-based approach.

11. LESSONS LEARNED AND RECOMMENDATIONS.

The recommendations in this section document the lessons learned in developing plans that satisfy the certification requirements defined in the AC [2] for UBM credits. Enhancements to the AC guidelines are recommended as appropriate. The AC provides suitable guidance for defining a viable UBM credit and validation processes. However, there are a few concepts that, if adopted and modified by the FAA for explicit inclusion in the AC, may reduce the ultraconservative interpretation of the AC that appears to remain a barrier to industry application.

11.1 HARDWARE AND SOFTWARE CERTIFICATION FLEXIBILITY.

The authors recommend the AC be updated so it explicitly provides for more flexibility in software certification requirements, depending on location of data processing (e.g., onboard versus offboard and operator versus rotorcraft OEM), that is commensurate with overall risk. Currently, the AC is very restrictive regarding ground-based software that is used by operators, because the typical operator would not have the expertise to independently validate the results of complex credit calculation algorithms executed on a COTS GS. Additionally, for practical reasons due to cost, such a GS is not likely to be certified to a higher than Level D. Thus, from a practical standpoint, UBM credits dependent on GS data processing will be restricted to lower-criticality credits unless the OEM is involved in data QA and risk mitigation. This investigation has shown that risk-mitigating processes should enable more flexibility with regard to offboard

software certification for ground-based UBM credit adjustments calculated and validated by the OEM. The assessment of whether the end-to-end process is AC-compliant should be based on an assessment of data integrity assurance and maintenance of the baseline risk rather than rigid application of DO-178B guidance to non-time-critical, decision-making processes. The OEM should be able to use a similar computational environment and processes for HUMS-based credits as that used for original CRT and substantiation.

11.2 ADDITION OF ADS-79 CONCEPTS.

It is recommended that two concepts highlighted in the U.S. Army ADS-79 document [3] be considered for adoption and/or modification for inclusion in the AC. The first is the requirement that UBM processes maintain the same or lower risk as the as-designed and as-maintained baseline product risk. This concept of baseline risk acknowledges that there are inherent, nonzero risks that are addressed by baseline design and maintenance processes. While aircraft are designed and maintenance processes are established to ensure the risk of failure of flight critical components is improbable (or remote, extremely remote, or extremely improbable using the definitions established in Section 1309 of the AC), the risk is not zero. The second is the concept of credible failure modes, which are defined in reference 3 as the believable manner in which a system or component may go beyond a limit state and cause a loss of function or secondary damage as supported by: engineering tests, probabilistic risk analysis, and actual occurrences of failures. According to reference 3, UBM processes must address the risks associated with credible risks as opposed to noncredible or improbable risks. The inclusion of similar concepts in the AC, providing guidance explicitly in the context of non-zero risk, may reduce the ultraconservative interpretation of the AC that appears to remain a barrier to industry application.

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APPENDIX A—KEY TERMINOLOGY

Aircraft Configuration: Definition of content and position of baseline aircraft and mission equipment that can affect aircraft gross weight, center of gravity, and flight loads; for example, the presence of external stores, position of landing gear, weight of external or internal cargo, and fuel quantity.

Airworthiness: A demonstrated capability of an aircraft or aircraft subsystem or component to function satisfactorily when used and maintained within prescribed limits.

Airworthiness Credit: The sustainment or reduction of baseline risk in allowance for a usage-based maintenance/condition-based maintenance (UBM/CBM) credit, based on the use of a validated and approved UBM/CBM system. The change can be specific to a component or part, aircraft tail number, or any group of items or aircraft defined in the respective credit application.

Airworthiness Limitation: A condition that defines a limit for maintaining airworthiness. This is a formally documented item, such as required maintenance, inspection, or replacement.

Application: A Health and Usage Monitoring System (HUMS) process implemented for a distinct purpose.

Baseline Risk: The acceptable risk in production, operations, and maintenance procedures reflected in frozen planning, the Operators' Manuals, and the Maintenance Manuals for that aircraft. Maintenance procedures include all required condition inspections with intervals, calculated retirement time (CRT), and time between overhauls.

Calculated Retirement Time: Conservative estimate of the component's useful life, based on CWC design usage spectrum, top-of-scatter loads, and fatigue design work curve to provide "six-nines" of reliability.

Clustering Algorithm: A method developed in this project to map HUMS regime sequence output into clusters corresponding to selected damaging composite worst-case (CWC) regimes that can be used to obtain a UBM credit for CRT adjustments while maintaining baseline risk.

Cluster: Pertaining to the clustering algorithm, a grouping of neighboring HUMS regimes that represent a single CWC regime occurrence.

Cluster Regime: Pertaining to the clustering algorithm, a HUMS regime often found in close proximity to a target regime in a HUMS regime sequence report.

Cluster Set: Pertaining to the clustering algorithm, the set of cluster regimes selected as part of the defining cluster parameters.

Composite Worst-Case Usage Spectrum: Spectrum or combination of regimes in terms of the number of occurrences and percent time per 100 flight hours that is defined by aircraft designers based on customer specification and historical fleet surveys with the intention to reflect the 90th percentile of the total population of the anticipated usage.

Credible Failure Mode: The believable manner in which a system or component may go beyond a limit state and cause a loss of function and secondary damage, as supported by engineering tests, probabilistic risk analysis, and actual occurrences of failures.

Credit: To give approval to a HUMS application that adds to, replaces, or intervenes in industry-accepted maintenance practices or flight operations.

Crossover: Pertaining to the clustering algorithm, time padded to the beginning and end of the cluster to accommodate possible errors due to HUMS RR update rate or resolution.

Criticality: This term describes the severity of the end result of a HUMS application failure or malfunction. Criticality is determined by an assessment that considers the safety effect that the HUMS application can have on the aircraft. Criticality categories range from catastrophic to no effect.

Critical Failure Mode: The mechanism that leads a system or component to go beyond a limit state and causes a loss of function and secondary damage. The criticality analysis determines the criticality level in relation to its impact on system or component operation and environment.

CRT Adjustment: An adjustment to the CRT published in the Airworthiness Limitations document. This defines the UBM credit for life-limited parts managed by safe-life methodology.

CWC Regime: Standard maneuver used to develop CWC usage spectrum and to establish CRTs for life-limited components.

CWC Mapping: The general process being developed to take HUMS regime recognition (RR) output and transform it into CWC maneuvers for the purpose of calculating CRT adjustments using existing life calculation methodology. The mapping can be accomplished by postprocessing the HUMS output with the clustering algorithm.

End-to-End: The boundaries of the HUMS application and the effect on the rotorcraft. The boundaries are the starting point that corresponds with the airborne data acquisition to the result that is meaningful in relation to the defined credit without further significant processing. In the case where credit is sought, the result must arise from the controlled HUMS process containing the three basic requirements for certification: (1) equipment installation/qualification (both airborne and ground), (2) credit validation activities, and (3) Instructions for Continued Airworthiness (ICA) activities.

Failure Modes, Effects, and Criticality Analysis (FMECA): The FMECA is a bottoms-up analysis of failure modes that are relevant to significant FHA-identified hazards, including analysis of cascading effects, end item impact, and resultant criticality of the failure mode before and after taking into account mitigating actions. The FMECA focuses on hardware failure modes, the effects of such failures, the means of detecting such failures, the severity class of such failures, and the compensating provisions within the design to lessen the likelihood or severity of such failures.

Fatigue Design Working Curve: Conservative model of material fatigue strength intended to reflect the 99.9th percentile of the total population of components.

Flight Conditions or Maneuvers: Combination of aircraft response parameters that define specific flight condition (e.g., steady level flight, turn, climb, and pullout), its severity (e.g., airspeed, load factor, angle of bank, and rate of climb/descent), and duration.

Functional Hazard Assessment (FHA): The FHA is a top-down analysis (which should involve pilots and flight analysts as well as engineers) that starts with the hazards to the rotorcraft and traces these hazards to the system, subsystem, and component level in the areas affected by HUMS. This type of analysis starts with the determination of what undesirable effects can occur as a direct or indirect result of using HUMS for maintenance or operational actions. The level of severity associated with this effect will result in assigning a criticality level that uses the definitions of criticality contained herein.

Ground-Air-Ground (GAG) Cycles: Relatively low-frequency, large-amplitude load cycles occurring during a given flight, but not present in any single flight condition. Examples include rotor start and stop cycles and load fluctuations between the various flight conditions encountered during performance of a mission.

Health Monitoring System: Equipment, techniques, and procedures by which selected incipient failure or degradation can be determined.

Health and Usage Monitoring System (HUMS): Equipment, techniques, and procedures that perform both health and usage monitoring.

HUMS Credit: Approval of HUMS application that adds to, replaces, or intervenes in previously approved maintenance practices or flight operations for non-HUMS-equipped systems.

HUMS Regime: A regime determined by the onboard HUMS RR algorithms.

Integrity: Attribute or reliability of a system or a component that can be relied on to function as required by the criticality determined by the FHA.

Loads Monitoring: Equipment, techniques, and procedures used to measure and calculate the loads (forces or moments) experienced by an aircraft component during operational flight.

Mitigating Action: An autonomous and continuing compensating factor that may modify the level of qualification associated with certification of a HUMS application. This action becomes a part of the certification requirements and, as such, is required to be performed, as long as that certification requirement is not changed by a subsequent re-certification.

Persistence: Pertaining to the clustering algorithm, the maximum time (in seconds) to allow inclusion of a HUMS regime as part of a cluster versus considering it as a legitimate separate entity.

Regime: Combinations of aircraft configuration (i.e., weight, altitude, and c.g.), maneuver, and maneuver severity that describe typical aircraft usage.

Regime Recognition (RR): Automatic detection of regimes.

Regime Recognition Clustering (RRC) Tool: A semiautomated software application developed in this project that incorporates the clustering algorithm procedures to efficiently manipulate large data files from fleet history and flight test sources.

Reliability: The probability that a functional unit will perform its required function for a specified interval under stated conditions.

Reliability Factor: Pertaining to the clustering algorithm, a statistically determined value based on an assigned probability and confidence interval that is used to magnify monitored usage results to compute CRT adjustments to maintain baseline risk.

Remaining Useful Life (RUL): An estimate of failure-free operation of the described component or system from point of assessment.

Safe-Life: The capability of as-manufactured structure, as shown by tests or analysis, based on tests not to initiate fatigue cracks during the service life of the rotorcraft or before an established replacement time.

Six-Nines of Reliability: Failure rate of less than one component in a population of one million components.

Structural Usage Monitoring (SUM): Monitoring of parameters, both measured and derived, that are required to calculate accumulated fatigue damage and life consumption (e.g., gross weight, center of gravity, regimes, usage spectrum, and loads).

Synthesis: The process of evaluating service history and any other relevant data with the objective of validating and, if necessary, refining the performance of an approved credit. Provisions should be made to allow for the synthesis of the service experience with other relevant engineering evidence from rejected components, development testing, seeded testing, etc.

Target Regime: Pertaining to the clustering algorithm, a HUMS regime that is physically close to the CWC regime of interest, usually a principal damaging regime, which must be identified by HUMS RR in order to form a cluster. This may be subject to a minimum-length requirement corresponding to flight characteristics to minimize false detection.

Target Set: Pertaining to the clustering algorithm, the set of target regimes selected as part of the defining cluster parameters, if more than one target regime is used to identify with a CWC regime.

Top of Scatter: Flight load records and summary data, which produce the highest fatigue damage for a given regime or load cycle when used in accordance with a given fatigue methodology.

UBM/CBM Credit: The approval of any change to the maintenance for a specific end item or component, such as an extension or reduction in inspection intervals or CRT established for the baseline system prior to incorporation of UBM/CBM as the approved maintenance approach.

UBM Credit: Credit awarded to equipment maintenance practices (i.e., inspections, overhaul, and life limit) based on selected aspects of actual service usage history of specific monitored equipment versus assumed usage of general equipment population.

Updated CWC Spectrum: A change to the conservative fleetwide spectrum intended to encompass operations of the individual aircraft that comprise the fleet.

Usage Monitoring System: Equipment, techniques, and procedures by which selected aspects of service (flight) history can be determined.

Usage Monitor Reliability Factor (UMRF): A reliability factor that is applied to fleetwide usage statistics for UBM credit to maintain the same baseline risk as the CWC usage spectrum. This can be based on a statistically significant sampling of subfleet usage.

Validation: The process of evaluating a system or software component during, or at the end of, the development process to determine whether it satisfies specified requirements.

Validation Matrix: Pertaining to the clustering algorithm, a table that contains data to quantify RR and clustering methodology accuracy for a set of CWC maneuvers of interest.

Verification: Confirms that a system element meets design-to or build-to specifications. Throughout the systems life cycle, design solutions at all levels of the physical architecture are verified through a cost-effective combination of analysis, examination, demonstration, and testing, all of which can be aided by modeling and simulation.

APPENDIX B—CLUSTERING ALGORITHM DETAILS AND APPLICATION

B.1 TERMS AND CONCEPTS.

The clustering algorithm is a method developed in this project to map existing Health and Usage Monitoring System (HUMS) regime recognition (RR) output into clusters corresponding to selected composite worst-case (CWC) spectrum regimes that can be used to obtain a usage-based maintenance (UBM) credit for calculated retirement time (CRT) adjustments. The intent of such an off-aircraft approach is to achieve UBM credits without the need to develop perfect onboard algorithms. The development of such an approach has led to an evolving lexicon. To help the reader, the following definitions are provided here for fundamental terms and concepts.

Cluster: A grouping of neighboring HUMS regimes that represent a single CWC regime occurrence. This may be subject to a minimum length requirement corresponding to flight characteristics to minimize false detection.

Cluster Regime: A HUMS regime often found in close proximity to a target regime in a HUMS regime sequence report.

Cluster Set: The set of cluster regimes selected as part of the defining cluster parameters.

Crossover: Time padded to the beginning and end of the cluster to accommodate possible errors due to HUMS RR resolution or update rate (typically 1 second and per current S-92 HUMS RR algorithm refresh rate).

CWC Regime: Standard maneuver used to develop CWC usage spectrum and to establish CRTs for life-limited components.

CWC Mapping: The general process being developed to take HUMS RR output and transform it into CWC maneuvers for the purpose of calculating CRT adjustments using existing life calculation methodology. The mapping can be accomplished by postprocessing the HUMS output with the clustering algorithm.

HUMS Regime: A regime determined by the onboard HUMS RR algorithms.

Persistence: The maximum time in seconds to allow inclusion of a HUMS regime as part of a cluster versus considering it as a legitimate separate entity.

Target Regime: A HUMS regime that is physically close to the CWC regime of interest, usually a principal damaging regime, which must be identified by HUMS RR to form a cluster. This may be subject to a minimum length requirement corresponding to flight characteristics to minimize false detection.

Target Set: The set of target regimes selected as part of the defining cluster parameters, if more than one target regime is used to identify with the CWC regime of interest.

Validation Matrix: A table that contains data to quantify RR and clustering methodology accuracy for a set of CWC maneuvers of interest.

Two specific damaging CWC regimes were considered for UBM credit consideration of the main rotor (MR) swash plate, namely 45° turns and symmetric pullouts (pull-ups). The Advanced Data Acquisition and Processing System (ADAPS) flight test database from the Phase 1 flight tests (see appendix C) were examined, and the maneuvers of interest were extracted. The flight test run logs were reviewed to check for applicability, completeness, and quality of the data. Table B-1 shows the data set used for the 45° angle-of-bank (AoB) turn and pullout maneuvers considered in the validation effort.

Table B-1. Flight Test Data Set for Algorithm Validation

CWC Regime	Flight Number	Number of Maneuvers	Total Duration in Maneuver (seconds)
45° Right Turn	A1083	1	40
	1085	4	93
	1086	2	98
	1088	2	63
	1095	1	24
	1097	1	14
Pullout	1085	17	234
	1086	2	28
	1087	5	82
	1091	9	153
	1095	2	37
	1097	2	37

The flight test data are used to develop statistical bounds on HUMS detection of damaging maneuvers as well as postprocessing algorithm for reliable estimation the amount of time in damaging maneuvers, as discussed in more detail below. The analysis and development of credit evaluation algorithms requires several key considerations.

B.2 THE HUMS REGIMES THAT CLUSTER WITHIN A CWC REGIME.

Because the legacy HUMS RR algorithm implementation did not consider UBM, several different HUMS target regimes can be associated with a single, damaging CWC regime. However, examination of actual HUMS sequence reports show that many other nonassociated cluster regimes that are in close proximity to, or cluster within and around, the CWC regime.

Figure B-1 shows a representative 45° AoB, left-turn time history plotted from the HUMS ground station, showing the HUMS RR output along with a few key flight parameters, including the aircraft roll angle. The corresponding pilot declaration from the ADAPS database is overlaid showing the portions of the CWC regime data. The HUMS refresh rate is 1 Hz, so every regime has a minimum duration of 1 second. During the actual period of the turn maneuver, HUMS does not explicitly recognize the transient CWC entry and recovery (E&R) regimes, but instead, frequently picks generic turns or level turns at a lower bank angle than 45°. During the 45° AoB left-turn CWC maneuver, HUMS detects several regimes, including level turns, diving turns, and partial power descent (PPD) turns.

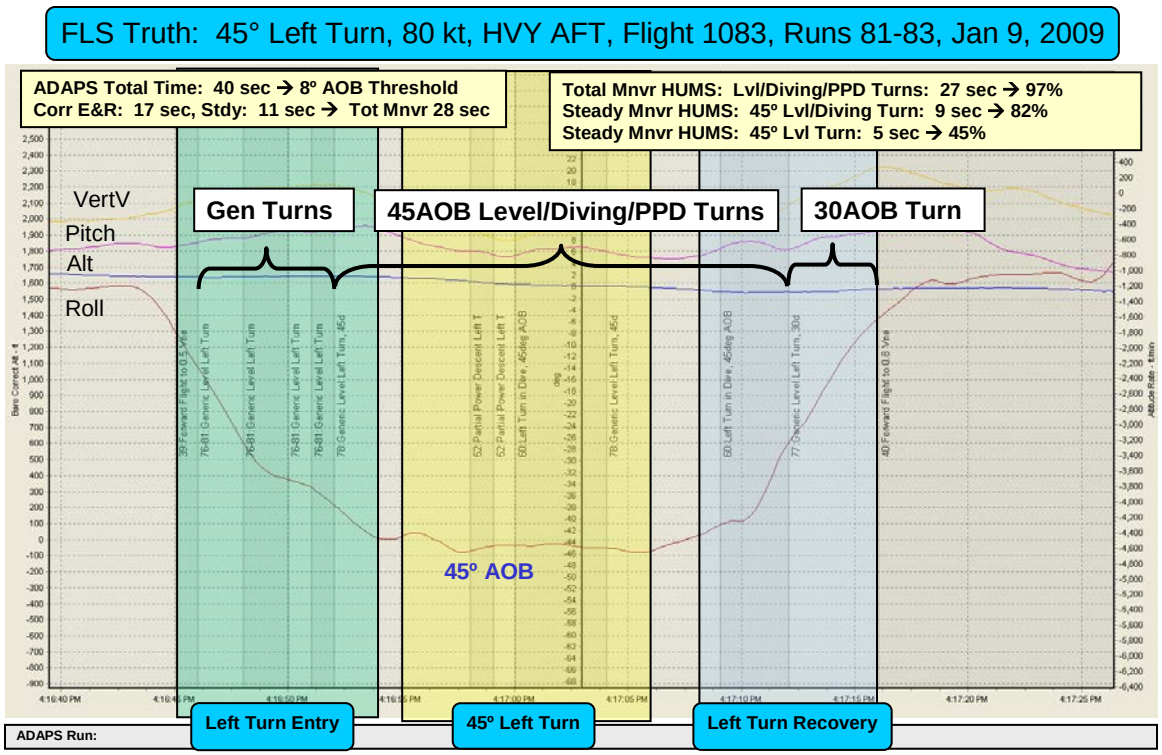


Figure B-1. The HUMS RR During a 45° Turn CWC Regime

Figure B-2 shows a representative transient pullout maneuver plotted from the ADAPS database. The HUMS RR labels from the output sequence file have been overlaid on the graph. Load factor is plotted on the top chart, with roll angle underneath. Two key loads are also plotted that display significant variability typical of a transient maneuver. The MR shaft bending load is on the bottom graph and the MR damper load above. The setup and exit portions of the ADAPS record are defined as the time spent before and after a 1.0-g level-flight crossing and are ignored in the comparison.

During the actual period of the pullout, HUMS detects other regimes that are not associated with the symmetric pullout CWC regime. After a 1.30-g load threshold is reached, a generic pullout HUMS regime is detected. After the peak 1.45-g level, a mild pullout HUMS regime is successfully identified. This results in two separate occurrences of a pullout in the regime sequence, when only one was flown in actuality. Numerous flight test data points for a pullout CWC regime were examined and the HUMS behavior was consistent, capturing only approximately 50% of the maneuver duration and overcounting the occurrences due to regime toggling.

These examples show that a simple mapping of multiple HUMS regimes is not sufficient to capture the accurate duration or count for a CWC regime event. This was part of the motivation to develop a clustering algorithm that would select the optimal definitions to map the HUMS output into individual CWC regimes.

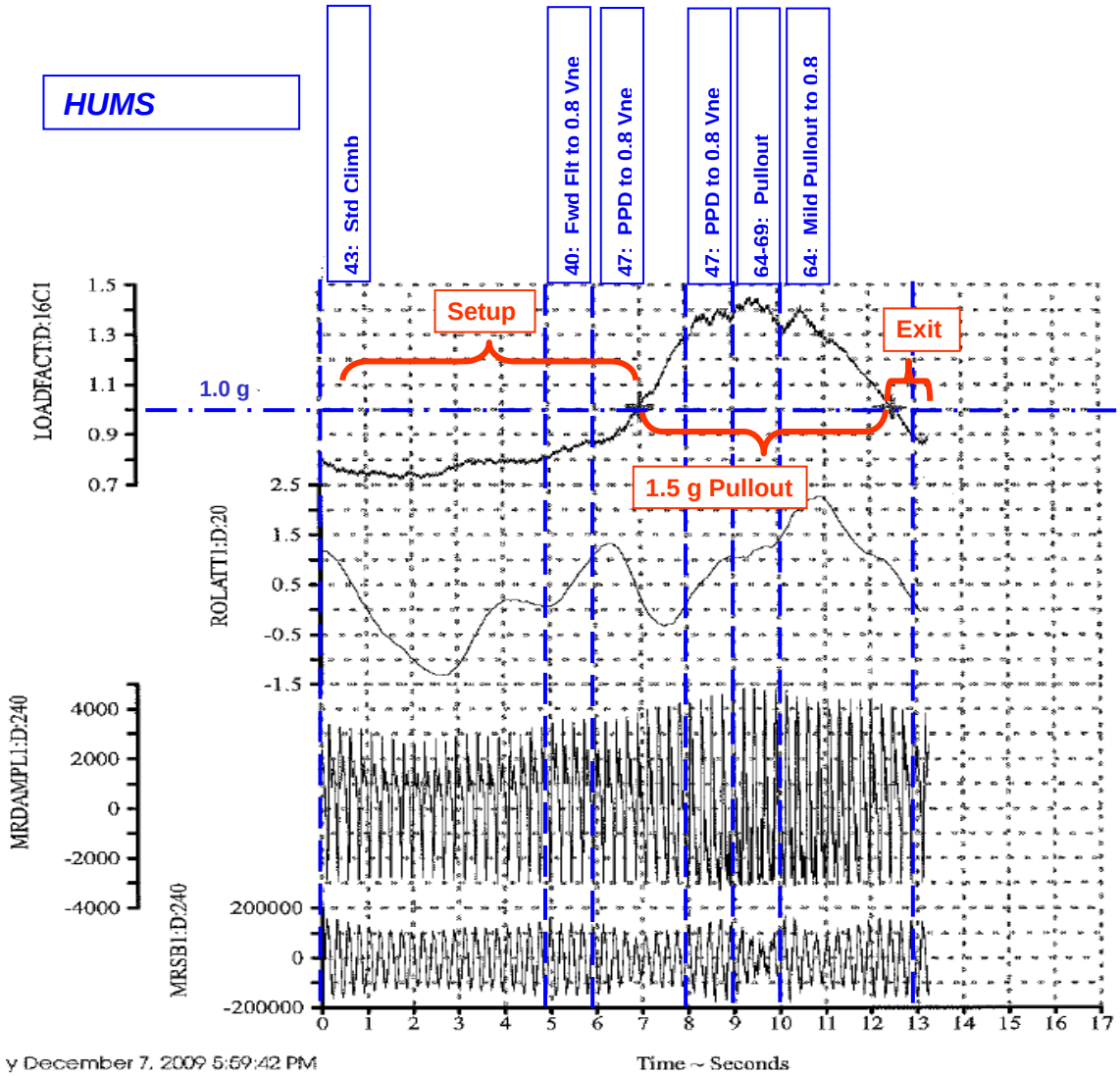


Figure B-2. The HUMS RR During a Symmetric Pullout CWC Regime

B.3 CLUSTERING ALGORITHM.

From the previous example for a single CWC regime event for a 45° AoB turn, it was shown that HUMS recognizes several regimes that are closely related, such as generic turns, turns in a dive, or PPD turns at different airspeeds as a percentage of the velocity not to exceed (Vne). These HUMS regimes are individually considered and determined whether to be legitimate target regime that could substitute for CWC regime. This process is based on engineering judgment, knowledge of physics of flight, and the ability of HUMS to consistently recognize them. Because there is typically not a one-to-one correspondence between a HUMS regime and a CWC regime, most often it requires more than one target regime to relate to a CWC regime. The resulting HUMS regimes are referred to as the target set for the CWC regime of interest.

- Target set for 45° AoB right-turn CWC Regime = {45° AoB right turn, generic turn; 45° AoB right-turn 0.8 Vne; 45° AoB right-turn 1.0 Vne HUMS regimes}

- Target set for symmetric pullout CWC Regime = {pullout, mild pullout to 0.8 V ne, moderate pullout to 0.8 Vne, Mild Pullout to 1.0 V ne, moderate pullout to 1.0 Vne HUMS regimes}

The clustering algorithm allows inclusion of a cluster regime, which is not in the target set but is likely to be detected by HUMS during the CWC regime. Cluster regimes are not explicitly mapped to the CWC regime, but cluster within or around it and are of insignificant duration (persistence) to be considered as a separate event. Such regimes are determined via analysis of flight test data, engineering judgment, or according to their likelihood of transitioning between members of the target set as estimated from fleet data analysis. As an example, analysis shows that the following regimes have a high degree of association with 45° AoB right turns and are therefore included in the cluster set for this CWC regime.

- Target set for 45° AoB right-turn CWC Regime

  - 83:Generic Level Right Turn, 30° AoB, 0.8 Vne
  - 82:Generic Level Right Turn, 15° AoB, 0.8 Vne
  - 86:Generic Level Right Turn, 30° AoB, 1.0 Vne
  - 85:Generic Level Right Turn, 15° AoB, 1.0 Vne
  - 39:Forward Flight to 0.5 Vne
  - 40:Forward Flight to 0.8 Vne
  - 41:Forward Flight to 0.9 Vne
  - 42:Forward Flight Above 0.9 Vne
  - 51:Partial Power Descent Right Turn
  - 46:Partial Power Descent to 0.5 Vne
  - 47:Partial Power Descent to 0.8 Vne
  - 48:Partial Power Descent to 0.9 Vne
  - 44:Right Turn During Climb
  - 55-57:Right Turn in Dive
  - 55:Right Turn in Dive, 15° AoB
  - 56:Right Turn in Dive, 30° AoB
  - 57:Right Turn in Dive, 45° AoB
  - 3:Steady Climb
  - 53:Dive to 1.0 Vne
  - 70-75:Pushover

The entire identified cluster corresponding to a CWC regime event is formed around at least one member of the target set (necessary condition) and members from the cluster set that are of durations less than a user-defined persistence threshold. Figure B-3 shows the basic steps involved in implementation of the clustering algorithm.

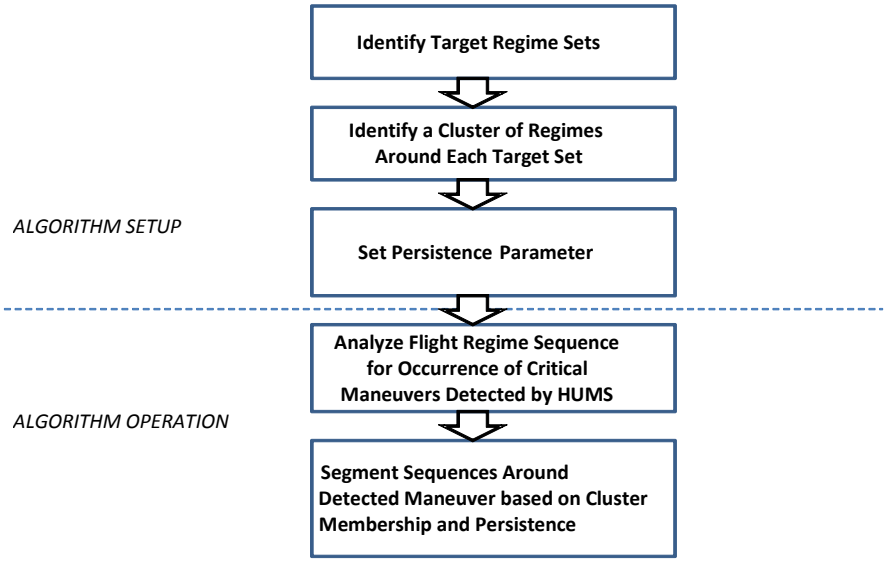


Figure B-3. The MR Clustering Algorithm Implementation

Figure B-4 notionally shows how the clustering algorithm performs, using a 45° AoB turn (left or right) as an example. Each of the three cluster formations are described individually.

- During the first maneuver from left, HUMS first detects a 45° turn (member of the target set), followed by a PPD (member of the cluster set), followed by a second 45° turn. At the end of the second detected 45° turn, HUMS shows a forward-flight regime. On condition that the duration of PPD during the maneuver is smaller than the persistence, it is clustered together with the two detected 45° turn HUMS regimes. Although the forward-flight regime is also a member of the cluster set, the regime duration is longer than the persistence value and indicates that it is indeed a legitimate forward-flight maneuver. As a result, the cluster for a single 45° turn CWC regime is exited and a crossover time of 1 second is added onto each end.

- The second potential cluster formation of HUMS regimes shown is a combination of a PPD right turn and a right turn in dive, followed by forward flight. Although the turn regimes are part of the cluster set and satisfy the persistence requirement, there are no members of the target set before the cluster exit criteria is met by the long-duration, forward-flight regime. This is referred to as an empty cluster and is not considered a legitimate 45° turn CWC regime.

- The third cluster formation is similar to the first with the exception that the cluster formation is exited upon e ncountering a noncluster regime (approach) rather than a sufficiently persistent cluster regime. This results in another 45° CWC regime cluster with the crossover time applied to the duration.

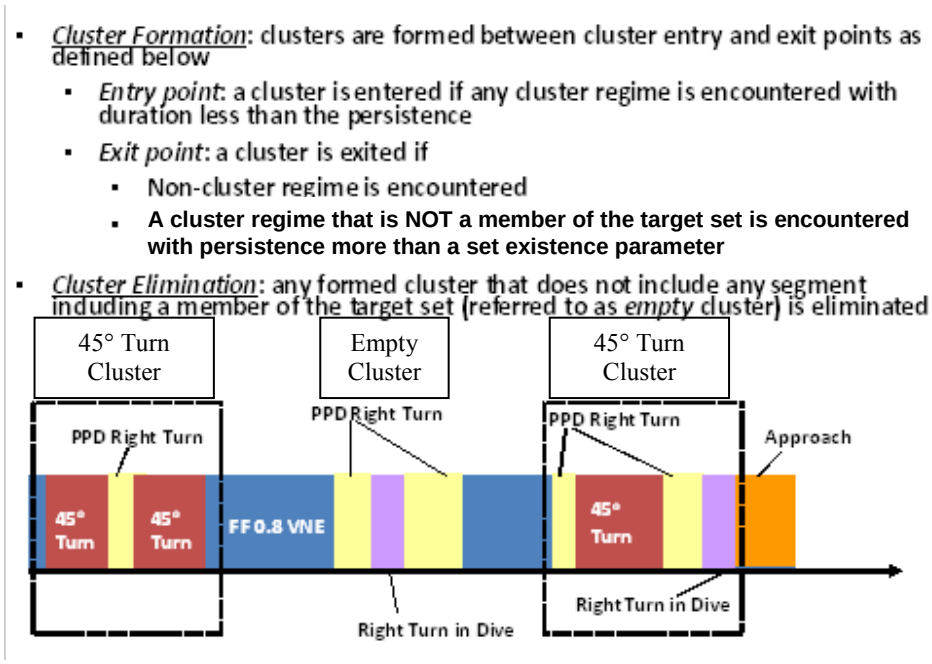
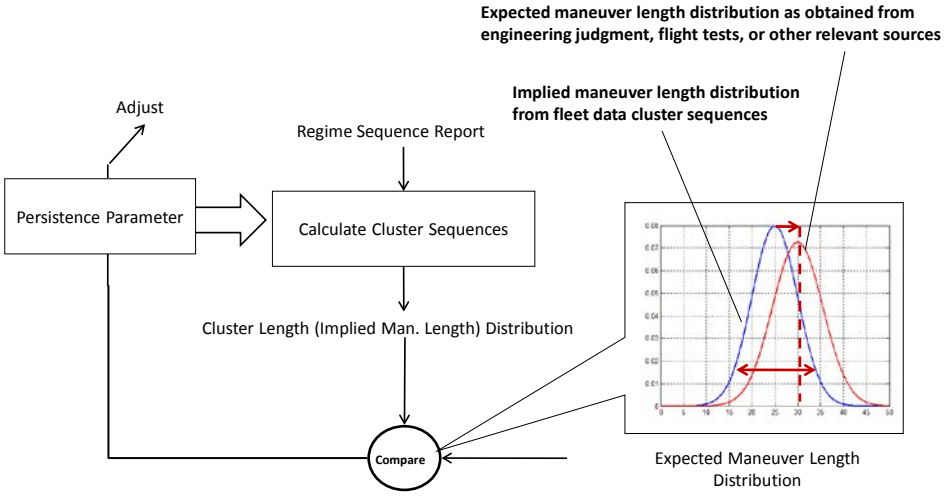


Figure B-4. Clustering of HUMS Regime Sequences

The persistence used to bound the cluster regions is a tunable parameter that can be set by the user. One way to refine this parameter is to run the algorithm on the training data from the fleet with different persistence values, calculate the probability distribution of CWC regime durations implied by the choice of the persistence parameter, and find the value that results in the best match between the obtained distribution and a baseline distribution from flight test data, engineering judgment, analysis of parametric data, or other relevant sources (see figure B-5).



The goal of fine tuning is to best match the (statistical) distribution of maneuver lengths implied by the choice of the persistence parameter with the distribution of maneuver lengths obtained from all relevant sources (engineering judgment, test flights after adjusting for test setup/exit, etc.)

Figure B-5. Tuning of the Persistence Parameter

B.4 THE HUMS DETECTABILITY.

Detectability considers how well HUMS is able to detect damaging CWC regimes when they actually happen. Figure B-6 is an excerpt from flight test data for a 45° AoB, right-turn CWC regime. As shown, HUMS RR detected occurrences of a 45° right-turn target regime, but the detected time in the steady-state portion of the maneuver is underestimated. It is observed that a choice of persistence parameter equal to 16 seconds correctly clustered the entire maneuver. Phase 1 Flight Loads Survey (FLS) test data (see appendix C) and a sample training set of fleet data were used as an example of how to estimate reliability factors to increase the raw CWC regime cluster counts to ensure conservatism during the analysis for CRT adjustments. The number of CWC regimes in flight tests and HUMS detection of a regime in the target set during the maneuver were used to estimate a probability of a CWC regime miss at a desired confidence level using binomial distribution for the number of times HUMS misses the target maneuver within the total number of trials.

	Run #	HUMS Regime	Time	ADAPS Maneuver	
	4	40:Forward Flight to 0.8 Vne	5	RT TRN 80KT/105% ENT	
Cluster Set	4	82-87:Generic Level Right Turn	1	RT TRN 80KT/105% ENT	
	4	82-87:Generic Level Right Turn	1	RT TRN 80KT/105% ENT	Entry*
	4	82-87:Generic Level Right Turn	2	RT TRN 80KT/105% ENT	
	4	82-87:Generic Level Right Turn	5	RT TRN 80KT/105% ENT	
Target Set	4	84:Generic Level Right Turn, 45deg AOB, 0.8 Vne	1	RT TRN 80KT/105% ENT	
	5	84:Generic Level Right Turn, 45deg AOB, 0.8 Vne	2	RT TRN 80KT/105% 45AOB	Steady
Cluster Set	5	51:Partial Power Descent Right Turn	9	RT TRN 80KT/105% 45AOB	
	6	51:Partial Power Descent Right Turn	4	RT TRN 80KT/105% REC	
	6	51:Partial Power Descent Right Turn	1	RT TRN 80KT/105% REC	Recovery*
	6	51:Partial Power Descent Right Turn	1	RT TRN 80KT/105% REC	
	6	51:Partial Power Descent Right Turn	1	RT TRN 80KT/105% REC	
	6	40:Forward Flight to 0.8 Vne	1	RT TRN 80KT/105% REC	

Figure B-6. Occurrence and Duration of Target Set Maneuvers

Out of a truth data set consisting of 11 available 45° turn CWC regimes, HUMS did not miss any target regimes. Similarly HUMS detected target regimes for all 37 symmetric pullout runs conducted during flight tests. A 90% confidence interval led to upper bounds of 19% and 6% for the probability of a single miss for the 45° turn and symmetric pullout CWC regimes, respectively. The derivation of these probabilities was (1) denoting the probability of a single miss by P and (2) the probability of not having a miss in N trials was equal to $(1 - P)^N$. The largest value of P for which $(1 - P)^N$ is less than or equal to $1 - P_C$, where the confidence P_C is chosen as a large number <1; e.g., 0.90 or 0.95, is given by $1-\left(1-P_C\right)^{\frac{1}{N}}$. Inserting $N = 11$ and a $P_C = 0.9$ and gives ~19% and $N = 37$ yields ~6%.

These numbers were then applied to analysis of about 1600 hr of fleet data, resulting in additional four counts of 45° turn CWC regimes (with seven observed maneuvers) and two counts of symmetric pullout maneuvers (with six observed maneuvers).

This simple analysis example was used primarily to show how the reliability factor is dependent on the number of test points flown, even when a target regime is detected 100% of the time. However, it is not desirable or practical to rely solely on flight test data points to establish reliability, as this would result in extremely long and expensive HUMS validation flight test programs. Furthermore, the Phase 3 dedicated, scripted HUMS flight test-quantified detection of target regimes in the form of a hitting average metric and found that 100% detection is not achieved for all turn conditions (see appendix C). In addition to accounting for this effect, the clustering algorithm reliability must account for several other behaviors unique to the onboard RR algorithms, which are discussed in the following sections.

B.5 PROCESS FOR DEFINING TARGET SETS TO REDUCE MISSES.

The overall process for identifying and eliminating possible misses is shown in figure B-7. This process starts with CWC regimes that are determined to be damaging and corresponding key parametric conditions that have led to such a determination. First, an approach for identifying possible misses and a process for handling such cases is shown using two examples that relate to swash plate damaging CWC regimes. In the case of the swash plate, high-AoB right turns and symmetric pullout were identified as damaging CWC regimes with the roll angle and load factor (vertical acceleration) determined to be the key parameters. This analysis uses measured flight loads data as a method to relate damage to HUMS target regimes, which reduces the possibility of missing damaging maneuvers within the current HUMS RR output.

Starting with the roll angle, a training subset of fleet data was mined for any occurrence of roll angle exceeding 20°, and statistics were calculated over all the HUMS regimes that were detected for these simulated true high-AoB, right-turn CWC regimes. The HUMS regimes shown in the first column of table B-2 comprised more than 99% of the turn occurrences from the training set and, therefore, were considered to be a robust set of possible HUMS regimes that could be included in a target set and cluster set for a high-AoB, right-turn CWC regime. To determine the associated probability of missing a damaging event among this set of HUMS regimes, their associated load probabilities were estimated from FLS data. The damaging stationary swash plate component load was considered to be MR swash plate bending moment, which was directly measured in the FLS. The load threshold for a damaging high-AoB, right-turn CWC regime was determined to be 40,000 inch-pounds as obtained from examination of the FLS-measured MR swash plate bending moment values corresponding to all damaging CWC regimes identified in the stationary swash plate fatigue substantiation report.

Table B-2 also summarizes the analysis of 30° and 45° high-AoB, right-turn CWC regimes from the FLS, examining the MR swash plate bending moment load distributions of the corresponding detected HUMS regimes. The results indicated that HUMS regime number 84, a 45° AoB level turn, had the greatest probability of high load levels exceeding the load threshold, P(L>load threshold), at 35.7%. However, HUMS regime number 83, a 30° AoB level turn, was also found to exceed the load threshold with probability 10.7%. Of particular interest are generic level right

turn and PPD right turn (HUMS regime numbers 82 and 51), which have a nontrivial P(L>load threshold) of 8.9% and 15.3%. Moreover they are generic regimes, bundling all cases where AoB exceeds 10°. Another noteworthy observation in table B-2 is HUMS regime number 44, a turn during climb, which is another generic regime, shows no occurrence of high load levels exceeding the load threshold. HUMS regime numbers 82 and 51 were analyzed further for identification of subregimes that exhibit substantial probability of load exceedance above load threshold, as described next.

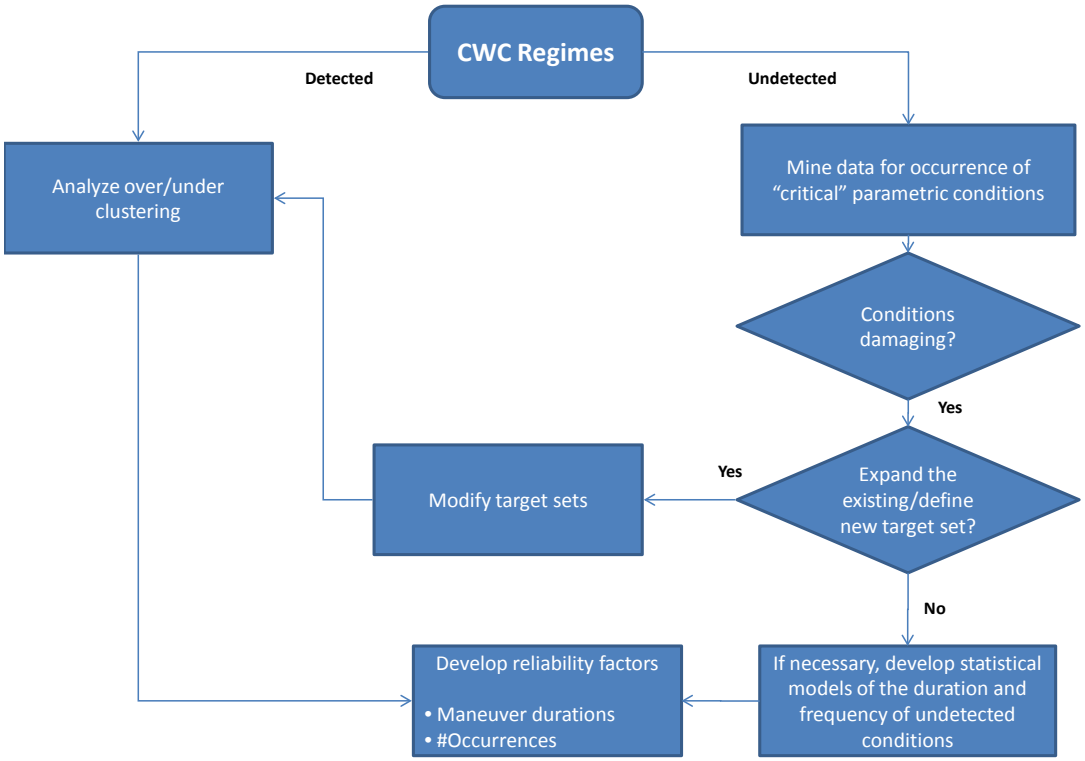


Figure B-7. Process for Redefining Target Sets and Elimination of Maneuver Misses

Table B-2. Potential Damaging Regimes and Load Analysis

			Par. Cond. Holds			Par. Cond. Does NOT Hold		
Regime	**Duration**	**Key Regime Parametric Condition**	**L>TH**	**L<TH**	**P(L>TH)**	**L>TH**	**L<TH**	**Pr(L>TH)**
84:G. Level RT Turn, 45deg, 0.8 Vne	131	RA>35, ABS(ROC)<=400, LF<=1.18	40	72	35.7%	11763	141463	7.7%
83:G. Level RT Turn, 30deg, 0.8 Vne	2117	20<RA<=35, ABS(ROC)<=400, LF<=1.18	136	1140	10.7%	11667	140395	7.7%
86:G. Level Right Turn, 30deg, 1.0 Vne	98	20<RA<=35, ABS(ROC)<=400, LF<=1.18	136	1140	10.7%	11667	140395	7.7%
44:RT Turn During Climb	1883	RA>10, ROC>400, LF<=1.18	0	196	0.0%	11803	141339	7.7%
82-87:G. Level RT Turn	769	RA>10, LF<=1.18, ABS(ROC)<=400	177	1819	8.9%	11626	139716	7.7%
51:Partial Power Descent RT Turn	514	RA>10, LF<=1.18, ROC<=-400	1025	5663	15.3%	10778	135872	7.3%
82:G. Level RT Turn, 15deg, 0.8 Vne	64	10<RA<=20, ABS(ROC)<=400, LF<=1.18	1	607	0.2%	11802	140928	7.7%
85:G. Level RT Turn, 15deg, 1.0 Vne	16	10<RA<=20, ABS(ROC)<=400, LF<=1.18	1	607	0.2%	11802	140928	7.7%
70-75:Pushover	16	LF<=0.85	71	8226	0.9%	11732	133309	8.1%
75:Severe Pushover to 1.0 Vne	118	LF<=0.85	71	8226	0.9%	11732	133309	8.1%

Analyzing the load by separating these generic regimes into smaller subsets limited to roll angles of 10° to 20°, 20° to 35°, and larger than 35°, respectively, there was a significant increase in load exceedance probability for roll angles larger than 35° (35.7% and 34.3% for generic right turn and PPD right turn, respectively). Therefore, if these two HUMS regimes are included in

the target set, the number of CWC regime misses would be greatly reduced, but also result in a high false-alarm rate. The goal would be to count these regimes as damaging, only if the roll angle indicates a turn higher than 30°, which would require additional information concerning the roll angle. The easiest method to implement would be to estimate the roll angle using a representative sample of measured data, as shown above, and apply them to the fleet results. A more precise method would be to use the recorded HUMS roll angle time history in addition to the regime sequence output file. However, this is very computationally intensive and would require much additional effort to manipulate large amounts of data while ensuring data integrity. However, depending on the UBM credit criticality, this may be required to maintain the baseline risk in the CRT adjustment.

Turns are a similar aspect of the clustering algorithm reliability because they are comprised of entry, steady, and recovery portions that cannot be detected individually by the existing HUMS RR software. In the CRT analysis process, the E&R portions are considered as a single transient CWC regime (based on the number of occurrences), while the steady portion is considered a separate CWC regime (based on duration). Once the clustering algorithm has been applied to a usage history, all turn CWC regime clusters are identified in which the counts can be used to quantify E&R occurrences and appropriate count reliability factors can be applied. However, the turn cluster durations include time spent in all three portions. The total duration can be used as is, including the application of corresponding duration reliability factors. However, if it is determined that less conservatism is desired or necessary, the percentage of steady turn portion within in the total duration can be estimated based on the training set of flight test and fleet data, or determined by roll angle fleet time histories, as described above. The complete method for determining reliability factors for counts and durations is described in the next section. These factors are compiled from a training set of fleet and flight test data and are used with HUMS RR sequence output files to compute CRT adjustments (i.e., they do not impose the need to obtain parameter time histories for all prior aircraft usage (described previously) as a potential option).

B.6 RELIABILITY FACTOR METHOD FOR MANEUVER COUNT AND DURATION.

Section B.5 focuses on the possibility of missing damaging maneuvers, and a process was introduced, along with examples, to show how missed maneuvers may be eliminated. This section considers the impact of overclustering and underclustering on the estimated duration and count of damaging maneuvers and presents a method for determining the associated reliability.

A regression equation is built to relate the cluster maneuver lengths (regression explanatory variable) to true maneuver lengths, which are obtained by mining fleet data for occurrences of parametric conditions that conservatively reflect high load occurrences (regression dependent or response variable). In extracting intended CWC regimes from parametric analysis of the fleet, uncertainty may arise about the duration or count of the detected maneuvers; in which case, expert judgment could supplement automated procedures. In other words, the maneuvers extracted from the fleet parametric analysis are used under expert supervision to build truth data for development of regression equations to relate cluster durations to actual maneuver durations. The goodness of the regression fit is then used to compute confidence intervals for true maneuver length predictions as a function of the observed cluster lengths. The predictions of the regression equation are again compared against expert judgment on some selected maneuvers to

ensure adequacy of the predictions. Similarly, probability distributions are built that describe the mismatch between the position of clusters and true maneuvers, as measured by the deviation between cluster and maneuver centers. Although the error distribution of maneuver duration predictions are used to build confidence bounds for total time in damaging maneuvers from cluster durations, the duration and maneuver position predictions are needed to develop reliability factors for damaging maneuver counts from cluster durations and positions. The latter is based on computing the probability of two consecutive maneuvers combining into one from the estimated probability distributions. The mathematical description of the problem is presented here.

The following regression equation relates the length of cluster i, denoted by L_i, to the true length of the corresponding maneuver, denoted by X_i.

$$X_i = aL_i + b + \varepsilon_i \tag{B-1}$$

where ε_i is a sequence of zero-mean independent and identically distributed (i.i.d.) normal random variables with variance, σ^2. From this equation the following is obtained.

$$\begin{aligned} & X_i \Big| L_i \sim N\left(\hat{a}L_i + \hat{b}, \sigma^2\left(1 + \frac{\boldsymbol{u}_i^T \boldsymbol{F}^{-1}\boldsymbol{u}_i}{N_C}\right)\right) \\ & \boldsymbol{u}_i^T = \left(L_i \;\; 1\right), \\ & \boldsymbol{F} = \frac{1}{N_C}\sum_i \boldsymbol{u}_i \boldsymbol{u}_i^T \end{aligned} \tag{B-2}$$

Note that the prediction variance has a fixed component, σ^2, and a variable component, $\sigma^2 N_C^{-1}\boldsymbol{u}_i^T \boldsymbol{F}^{-1}\boldsymbol{u}_i$, which becomes smaller as the number of data points in the training set, N_C, is increased. This leads to

$$\sum_i X_i \Big| \sum_i L_i \sim N\left(\hat{a}\sum_i L_i + N\hat{b}, N\sigma^2 + N_C^{-1}\sigma^2 \sum_i \boldsymbol{u}_i^T \boldsymbol{F}^{-1}\boldsymbol{u}_i\right) \tag{B-3}$$

where N is the observed number of maneuvers (i.e., number of clusters) in the credit evaluation set. This means that a correction of magnitude, $k\hat{\sigma}\sqrt{N + N_C^{-1}\sum_i \boldsymbol{u}_i^T \boldsymbol{F}^{-1}\boldsymbol{u}_i}$, must be added to the total observed duration in the target maneuver (i.e., sum of cluster durations) where k is a suitable multiple; e.g., 1.65 that corresponds to 95% confidence and $\hat{\sigma}$ is the estimate of variance. Similarly, consider the regression equations

$$C_i^* - C_i = c + e_i \tag{B-4}$$

where

C_i^* is the true center of the maneuver matched to cluster i with center C_i (again, applying expert judgment in the matching process when ambiguities arise), and e_i is a sequence of zero-mean i.i.d. normal random variables with variance γ^2. This leads to

$$\hat{c} \sim N\left(c^*, \frac{\gamma^2}{N_C}\right) \tag{B-5}$$

where c^* is the true value of c. As usual, the estimate of γ is denoted by $\hat{\gamma}$.

The results from these equations can be used to build reliability factors for maneuver counts, as described below. This requires probability distributions for the duration of true (unobserved) maneuvers. Such distributions can be built using analysis of parametric data, which are supplemented by application of expert judgment, as needed. Suppose this process leads to a probability density function $P_X(.)$ for the true maneuver distribution. For simplicity, it is also assumed that the number of samples used for training is large, i.e., $NC \to \infty$. With some proper modifications, the analysis below will apply to finite N_C cases but at the expense of much more tedious manipulations.

The undercount analysis consists of the following steps.

1. Scan through the training data set to segment groups of clusters that are close, ending a segment (chain of clusters) if the trailing edge of the last cluster in the group and the leading edge of the first cluster in the next group have a distance that exceeds the cluster group separation threshold (Ψ).

2. One suitable threshold is a percentile (e.g., 95th) of the true maneuver distribution $P_X(.)$, because allowing two clusters to be included in a group implies that the maneuvers they represent to possibly be a part of a larger maneuver that connects them. If the distance between the two clusters is too large to be filled by any likely maneuver, with high confidence, one group can be terminated and a new one started. Note that in many cases, one group may only consist of one cluster.

3. For a group consisting of N clusters, examine the probability of the true number of maneuvers within the group to be N^*.

$$P(N^* | N) = \frac{\Pr(N^*)\Pr(N^*)}{\sum_{N^* \geq 1} \Pr(N | N^*)\Pr(N^*)} \tag{B-6}$$

Let n^- denote the number of maneuvers combined when clusters are formed (undercount) and n^+ denote the number of extra clusters formed due to separation of one or more maneuvers by the clustering algorithm.

$$N = N^* - n^- = n^+ \tag{B-7}$$

From this relation, the following is obtained

$$\begin{aligned} \Pr\left(N \middle| N^*\right) &= \sum_{n^-=0}^{N^*-1} \Pr\left(N = N^* - n^- + n^+ \middle| n^-, N^*\right) \Pr\left(n^- \middle| N^*\right) \\ \Pr\left(N \middle| N^*\right) &= \sum_{n^-=0}^{N^*-1} \Pr\left(N^+ = N - N^* + n^- \middle| n^-, N^*\right) \Pr\left(n^- \middle| N^*\right) \end{aligned} \tag{B-8}$$

The probabilities $\Pr(n^+)$ are precomputed values compiled on the basis of maneuver versus cluster matching results, in particular, from samples where expert judgment is needed to resolve ambiguities in the matching process. Based on the analysis of a number of maneuvers of various durations, the expert determines an average overcount rate, $\hat{\lambda}^+$. Based on maneuver versus cluster matching results and input from an expert, the data in table B-3 was compiled.

Table B-3. Hypothetical Overcount Data

Maneuver Duration	10	15	20	12	25	30	17	29	13	32	Average Overcount Rate
No. of Overcounts	0	1	1	0	2	3	1	3	0	2	
No. of Overcounts/Maneuver Duration	0	1/15	1/20	0	2/25	3/30	1/17	3/29	0	2/32	0.052

The data in table B-3 results in 0.052 as the average overcount rate.

Now, using a Poisson distribution for the number of overcounts, the following is obtained

$$\Pr\left(n^+ = N = N^* + n^- \middle| n^-, N^*, \sum_{i=1}^{N^*} X_i\right) = \begin{cases} \dfrac{\left(\sum_{i=1}^{N^*} X_i \hat{\lambda}^+\right)^{N-N^*+n^-} \exp\left(-\sum_{i=1}^{N^*} X_i \hat{\lambda}^+\right)}{\left(N - N^* = n^-\right)!} & N - N^* = n^- \geq 0 \\ 0 & N - N^* = n^- < 0 \end{cases} \tag{B-9}$$

where $\sum_{i=1}^{N^*} X_i$ is the total duration of the maneuvers spread over the interval T, which is spanned by the segmented group from the beginning of the first cluster minus $\frac{\Psi}{2}$, to the end of the last cluster in the group plus $\frac{\Psi}{2}$. Recall that Ψ is the cluster group separation threshold. The

probability distribution of the sum $\sum_{i=1}^{N^*} X_i$, denoted by $P_{\sum N^* X}(.)$ can be found by N^*-1 fold convolution of $P_X(.)$ onto itself, i.e., $P_{\sum N^* X}(.) = P_X(.) \oplus ... \oplus P_X(.)$. Alternatively, this distribution may be approximated by a normal distribution with mean, $N^* E(X)$, and variance, $N^* Var(X)$, where $E(X)$ and $Var(X)$ are mean and variance terms computed from $P_X(.)$. $\sum_i X_i$ may be eliminated from equation B-9 via integration over its probability distribution.

$$\Pr\left(n^+ = N - N^* + n^- \middle| n^-, N^*\right) = \frac{1}{\int_{T-N^*\Psi}^{T} P_{\Sigma N^* X}(Z)dZ} \int_{T-N^*\Psi}^{T} \Pr(N^+ = N - N^* = n^- \middle| n^-, N^*, Z) P_{\Sigma N^* X}(Z)dZ \quad \text{(B-10)}$$

where the normalization by $\int_{T-N^*\Psi}^{T} P_{\Sigma N^* X}(Z)dZ$ and integration over $T - N^*\Psi \le Z \le T$ takes into account that the maneuvers are apart by no more than Ψ (recall that two consecutive clusters that are apart by more than Ψ will belong to separate groups) and spread over an area that is no greater than T. The calculation of $\Pr\left(N^*\right)$ and $\Pr\left(n^- \middle| N^*\right)$ is discussed below.

$\Pr(N^*)$ is equal to the denominator of equation B-10 as the only available information about N^* is that N^* maneuvers, each following the distribution $P_X(.)$, are spread over an area of length larger than $T - N^*\Psi$ and smaller than T.

$$\Pr\left(N^*\right) = \Pr\left(T - N^*\Psi \le \sum_i X_i \le T\right) = \int_{T-N^*\Psi}^{T} P_{\Sigma N^* X}(Z)dZ \quad \text{(B-11)}$$

From equations B-9, B-10, and B-11, it is concluded that

$$\Pr\left(N^+ \middle| N^*\right)\Pr\left(N^*\right) = \lambda^{N^*} \exp\left(-\lambda\right) \sum_{n^- = \max(0, N^* - N)}^{N^*-1} \left[\frac{\Pr\left(n^- \middle| N^*\right)}{\left(N - N^* + n^-\right)!} \int_{T-N^*\Psi}^{T} \left(\hat{Z}^+\right)^{N - N^* + n^-} \left(-\hat{Z}^+\right) P_{\Sigma N^* X}(Z)dZ \right] \quad \text{(B-12)}$$

Calculation of $\Pr\left(n^- \middle| N^*\right)$ used in equation B-12 involves the following steps

1. Consider two distinct consecutive maneuvers i and $i + 1$ with durations X_i and X_{i+1}, corresponding cluster durations L_i and L_{i+1}, cluster centers C_i and C_{i+1}, and maneuver centers C_i^* and C_{i+1}^*. Denote $\overline{L}_i = \frac{1}{2}\left(L_i + L_{i+1}\right), \overline{X}_i = \frac{1}{2}\left(X_i + X_{i+1}\right)$ and let $N_C \to \infty$. It is found that

$$\bar{L}_i - \left(C_{i+1} - C_i\right) \left| \bar{X}_i, C_{i+1}^* - C_i^* \sim N\left(\frac{1}{\hat{a}}\left(\bar{X}_i - \hat{b}\right) - \left(C_{i+1}^* - C_i^*\right), \frac{\hat{\sigma}^2}{2\hat{a}^2} = 2\hat{\gamma}^2\right)\right.$$

$$\bar{L}_i - \Delta_i \left| \bar{X}_i, \Delta_i^* \sim N\left(\frac{1}{\hat{a}}\left(\bar{X}_i - \hat{b}\right) - \Delta_i^*, \frac{\hat{\sigma}^2}{2\hat{a}^2} = 2\hat{\gamma}^2\right)\right., \tag{B-13}$$

$$\Delta_i = C_{i+1} - C_i, \Delta_i^* = C_{i+1}^* - C_i^*$$

2. Define the indicator function I_i to be 1 if the distinct consecutive maneuvers i and $i + 1$ are merged into one cluster, and 0 otherwise. For any given distance between maneuver centers Δ_i^*, compute the conditional probability of consecutive maneuvers merging into one via the following expression (CDF_N denotes the cumulative distribution function of a normal distribution)

$$\Pr\left(I_i = 1 \middle| \Delta_i^*\right) = \int_{\bar{X}_i \geq \Delta_i^*} \Pr\left(\bar{L}_i \geq \Delta_i \middle| \bar{X}_i, \Delta_i^*\right) P_{\bar{X}_i}\left(\bar{X}_i\right) d\bar{X}_i$$

$$\Pr\left(I_i = 1 \middle| \Delta_i^*\right) = \int_{\bar{X}_i \geq \Delta_i^*} \left[1 - CDF_N\left(\Delta_i \middle| \bar{X}_i, \Delta_i^*\right)\right] P_{\bar{X}_i}\left(\bar{X}_i\right) d\bar{X}_i \tag{B-14}$$

$$P_{\bar{X}_i}(.) = P_{\frac{X}{2}}(.) \oplus P_{\frac{X}{2}}(.)$$

3. The true distance between cluster centers Δ_i^* in equation B-14 is unknown. Postulate an exponential distribution with intensity $\frac{N^*}{T}$ for their values (notice that N^* maneuvers are spread over an area of length T). The (unconditional) probability of the distinct consecutive maneuvers i and $i + 1$ merging into one cluster can then be computed via

$$\eta = \Pr\left(I_i = 1\right) = \frac{N^*}{T} \int_{\Delta_i^* \geq 0} \Pr\left(I_i = 1 \middle| \Delta_i^*\right) \exp\left(-\frac{N^*}{T}\Delta_i^*\right) d\Delta_i^* \tag{B-15}$$

4. Finally, the following is computed

$$\Pr\left(n^- \middle| N^*\right) = \eta \Pr\left(\sum_{i=1}^{N^*-1} I_i = n^-\right) = \left(\frac{n^-}{N^* - 1}\right) \eta^{n^-} \left(1 - \eta\right)^{N^*-1-n^-}$$

with the boundary condition: (B-16)

$$\Pr\left(n^- \middle| N^* = 1\right) = 1$$

Equations B-13 through B-16, and equation B-6 allow the computation of $\Pr\left(N^* \middle| N\right)$ for any postulated value of N^*. Setting a suitable confidence level P_C (e.g., 0.95 or 0.99), a conservative value for undercounts is given by $\bar{n} = \bar{N}^* - N$ where

$$\bar{N}^* = \max\left\{N^*\right\} \text{subject to } \Pr\left(N^* \middle| N\right) \geq 1 - P_C \tag{B-17}$$

B.7 CLUSTERING RELIABILITY FACTOR ILLUSTRATION.

A tail number from the fleet with the highest number of 30° to 45° maneuvers (based on the roll angle parameter) was selected for this illustration to provide the largest data set. A cluster definition was developed for a 30° turn CWC regime. The clustering method was applied to the fleet data and the results were postprocessed. A 10° roll angle threshold was used to define true turn maneuvers to represent the CWC regimes in the training data from the fleet. Figure B-8 shows a comparison of the resulting clusters. Simple turns are shown where the roll angle increases monotonically and returns to a normal, forward-flight attitude. There were also examples of more complex turns that had several nonmonotonic roll angle traces or appeared to be two merged, back-to-back turns without a forward-flight condition in between.

An estimate was performed to determine a cluster length versus true maneuver length regression. Only simple clusters and the associated true maneuvers participated in the regression analysis to extract the following information for use in reliability calculation. There were 48 resulting true maneuver turns. The data was analyzed to determine the following items.

- Regression equation relating cluster lengths and centers to true maneuver lengths and centers plus corresponding error variances
- The intensity by which a true maneuver is broken into several clusters
- Calculation of cluster groups that are close, based on a distance threshold computed from the cluster versus maneuver length and center error variances
- Cluster count within each group
- The time span of each group

Count reliability factors were calculated for 30° to 45° maneuvers in the following way. There were 27 clusters formed and 48 instances of a true maneuver. Because no cases of a maneuver broken into separate clusters (underclustering) were observed, the intensity of the related process was set to a small number.

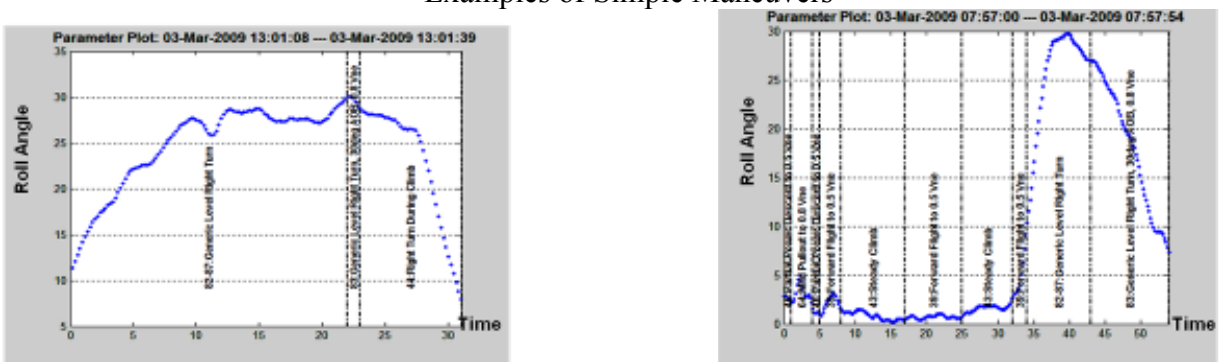
Prior distribution of maneuver lengths was found by fitting a Weibull distribution to maneuver lengths segmented using roll angle threshold of 10 found within simple maneuvers, as shown in figure B-9. From this, the 90th percentile of the posterior count distribution was 56. Although the 90th percentile count was twice the cluster count of 27, it was only 20% above the 48 true maneuvers.

The cluster definition, the 90th percentile Cluster Duration Reliability Factor (CDRF), and the Cluster Count Reliability Factor (CCRF) that were developed from the training set were then applied to two other aircraft. Aircraft 1 had 12.7 flight hours to which the clustering algorithm with given a target set and cluster set, and a set of persistence times was applied to compute 30°

turn maneuvers. Aircraft 2 had 9.3 flight hours. True maneuver E&R points were again defined by a 10° roll angle threshold.

The results are shown in table B-4 for Aircraft 1 and table B-5 for Aircraft 2. For both maneuver durations and counts, raw cluster data was less than the corresponding true maneuver data. However, with the addition of the CDRF and CCRF, the predictions were conservative compared to the true data. To maintain the reliability of the Sikorsky Aircraft Corporation (SAC) standard fatigue life analysis processes, a co nservative prediction is necessary to eliminate risks associated with the clustering algorithm process errors.

Examples of Simple Maneuvers



Examples of Complex Maneuvers

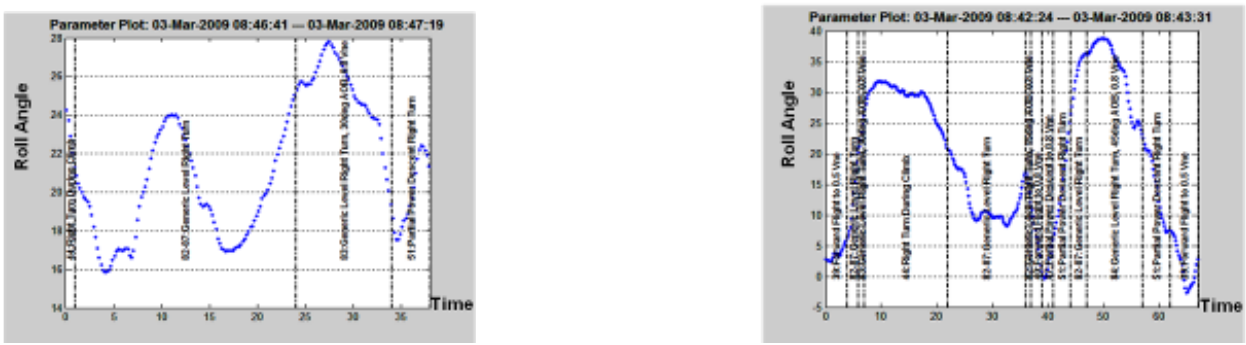


Figure B-8. Example Maneuvers

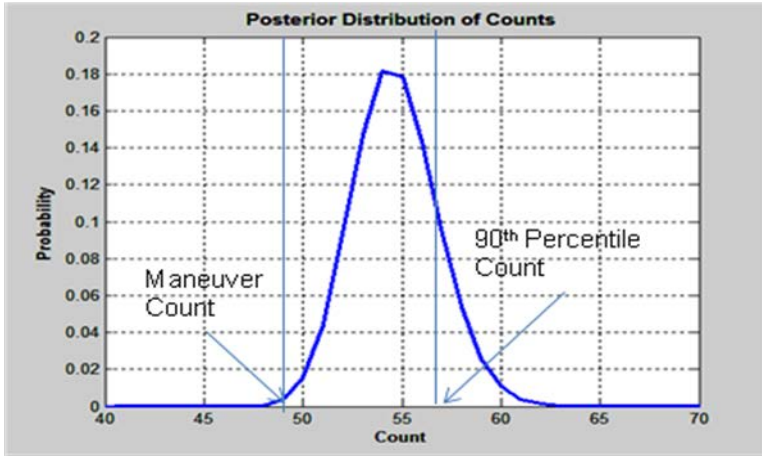


Figure B-9. Posterior Distribution of Counts

Table B-4. Aircraft 1 Maneuver Predictions

Aircraft 1	True Maneuver	Clustered Maneuver Mean Predictions	Clustered Maneuver Prediction and Reliability Factor
Total Duration	921 sec	916* sec	932 sec
Count	48	27**	57

*Obtained by inserting total clusters duration in the regression equation that relates cluster lengths to maneuver lengths
**Obtained by simple count of clusters

Table B-5. Aircraft 2 Maneuver Predictions

Aircraft 2	True Maneuver	Clustered Maneuver Mean Predictions	Clustered Maneuver Prediction and Reliability Factor
Total Duration	379 sec	381* sec	390 sec
Count	18	11**	25

*Obtained by inserting total clusters duration in the regression equation that relates cluster lengths to maneuver lengths
**Obtained by simple count of clusters

B.8 COMPUTATIONAL DETAILS FOR CREDIT EVALUATION.

This section presents the detailed analysis process for calculating actual usage data presented in section 6.3.1 of the main report. The steps involved to determine the regression parameters and other factors used in credit evaluation are explained using a right-turn CWC regime as an example.

There were two kinds of right-turn CWC regimes of interest: 30° and 45° AoB. Furthermore, only the subset of these maneuvers, which is further characterized by 1.0 Vne, was used. When

designing and applying clusters for 30° and 45° maneuvers, several considerations were addressed:

- HUMS regimes for turn in dive 30° AoB and turn in dive 45° AoB do not specify velocity (as function of the Vne airspeed). However, since these regimes did not occur very frequently in the training set of fleet data, it was conservative to add these to the target set without generating a great deal of false positives. These resulted in the following two maneuvers:

  - M30RT with target set defined as 30° level right-turn 1.0 Vne plus right-turn in dive 30° AoB

  - M45RT with target set defined as 45° level right-turn 1.0 Vne plus right-turn in dive 45° AoB

- As discussed previously, many HUMS turn regimes do not specify AoB, including PPD right turn, turn in climb, generic level turn, and turn in dive. Among these regimes, it was established earlier that turn in climb is not damaging; therefore, this regime was excluded from the target set. The other regimes could be potentially damaging depending on their unknown AoB. One conservative assumption would be to assign all occurrences of these generic turns to high AoB (30° and above). However, because these generic turn regimes are detected very frequently, this conservatism will lead to an undesirably large number of false positive clusters. To avoid this problem (as described in section B.4), the user should estimate, based on a training set for which parametric data is available, the percentage of maneuvers within generic turns where the AoB exceeds 30° or 45°, and apply reliability factors to account for 90% confidence bounds. These generic maneuvers were optimized using the training set and procedure explained below. The computed percentages were then applied to the counts and durations of generic turn maneuvers. The generic right-turn maneuver was denoted by MGRT and consisted of the target regimes generic right turn, right turn in dive, and PPD right turn.

- Since the data on M30RT and M45RT is sparse, the data on MGRT was used to train all turn maneuver regression equations and other factors.

The training phase consisted of the following steps.

1. Specify and collect training set consisting of regime and parametric data.

   In the analysis performed for this project, training data was used representing over 1126 flight hours for which parametric and regime data was available. This data covered the period of February to March 2009 for 12 tail numbers presented in section 6.3.1 of the main report. A semiautomated software program developed under this project, known as the UBM regime recognition clustering (RRC) tool was used to define the data for the training set (see section 6.5.5), as shown in figure B-10.

2. Develop cluster and true maneuver data for regression analysis and optimize the algorithm parameters.

   HUMS regimes in the cluster set were defined for the MGRT CWC regime using the RRC tool, as shown in figure B-11. For each selection of the cluster regime persistence parameters, a regression analysis was run to match the duration of the clusters to the duration of a hypothetical true maneuver, which was defined using the parametric data shown in figure B-12. The hypothetical truth was defined as AoB>10° with a hysteresis value of 3°. To simplify the tuning, the persistence parameter of a number of cluster regimes that were more closely related to the target set was set to a higher value to ensure that they remained in the cluster regardless of their time as long as they accompanied a target regime. Dwelling in any of the other regimes in the cluster set will cause exit from the cluster, as described in section B.2, if the time is larger than their persistence, optimized to be 9 seconds for MGRT. Final regression results are shown in figures B-13 and B-14.

3. Compute reliability factors.

   The following adjustments and reliability factors based on 90% confidence intervals were determined by the RRC using regression results for the observed durations and counts.

- Duration

  - Cluster duration regression multiple (0.83 = 1/1.201659)
  - Statistical CDRF (1.06)

- Count

  - Statistical CCRF (1.90)

4. For cluster definitions based on generic regimes, compute a multiple for false positive correction.

   Due to frequent occurrence of MGRT, a greater number of false positives occurs if these occurrences are not corrected by a ratio to estimate only the high-AoB portions of the maneuver. Using the RRC tool HUMS validation graphical user interface (GUI), these ratios were first found to be 0.17 and 0 with the training data set and then further enhanced with CDRF and CCRF reliability factors to result in 0.2300 and 0.0032 ratios for duration and counts, respectively.

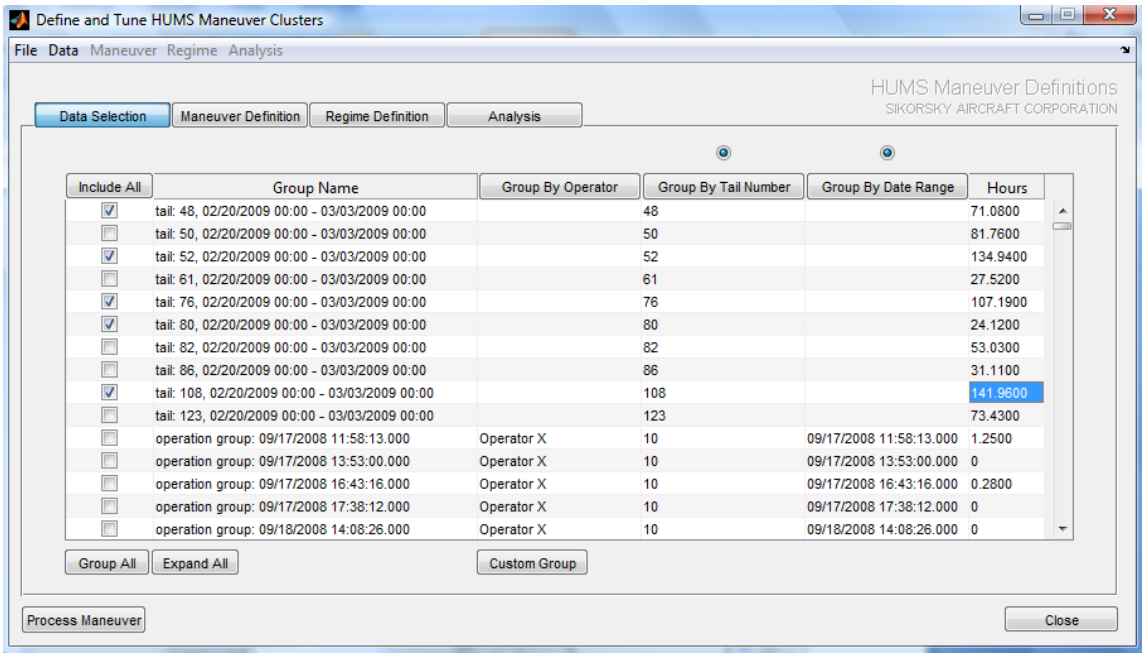


Figure B-10. Definition of Training Data Set

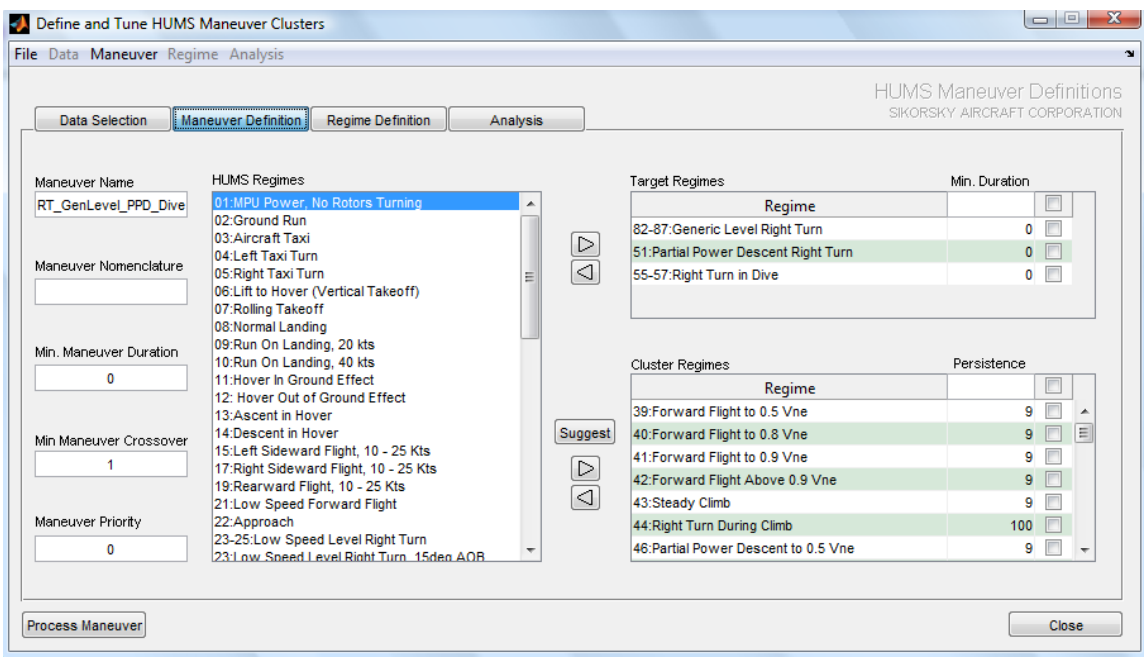


Figure B-11. Target Set and Cluster Set Definition

The evaluation phase applied the clustering algorithm to past fleet usage history for each tail number, as recorded by the HUMS RR regime sequence output files. After computing the durations and counts for the M30RT and M45RT clusters, these results were increased by 23% and 0.32% of the MGRT results, respectively (these correspond to the high-AoB ratios plus confidence calculated for MGRT, based on the training set). Finally, Weibull distributions were

fitted to the computed durations and counts (for each maneuver per 100 hours) for each tail number in the subfleet. For these distributions, the 90th percentile was divided by the 50th percentile to compute a usage monitor reliability factor (UMRF) for duration and count to account for usage variability. The UMRF was calculated as 1.7 for M30RT and 4.3 for M45RT.

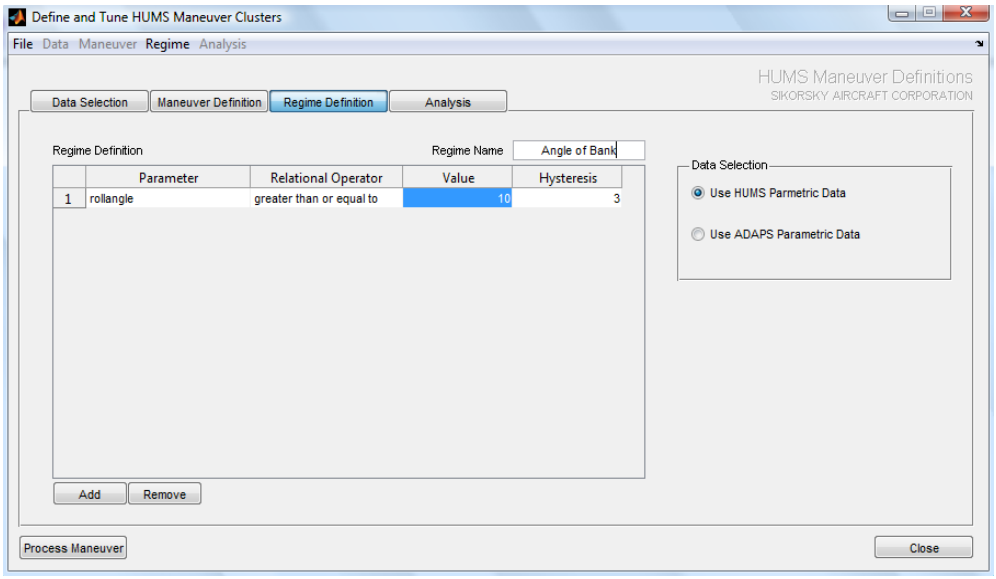


Figure B-12. True Maneuver Definition to Simulate CWC Regime in the RRC

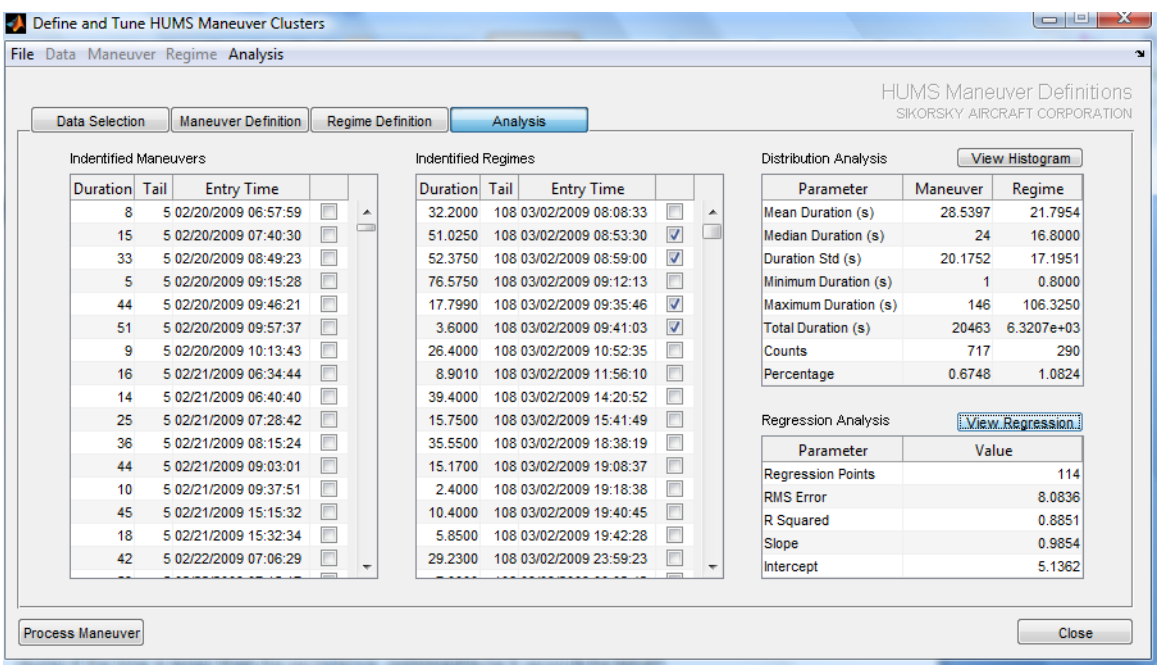


Figure B-13. Posterior Distribution of Counts

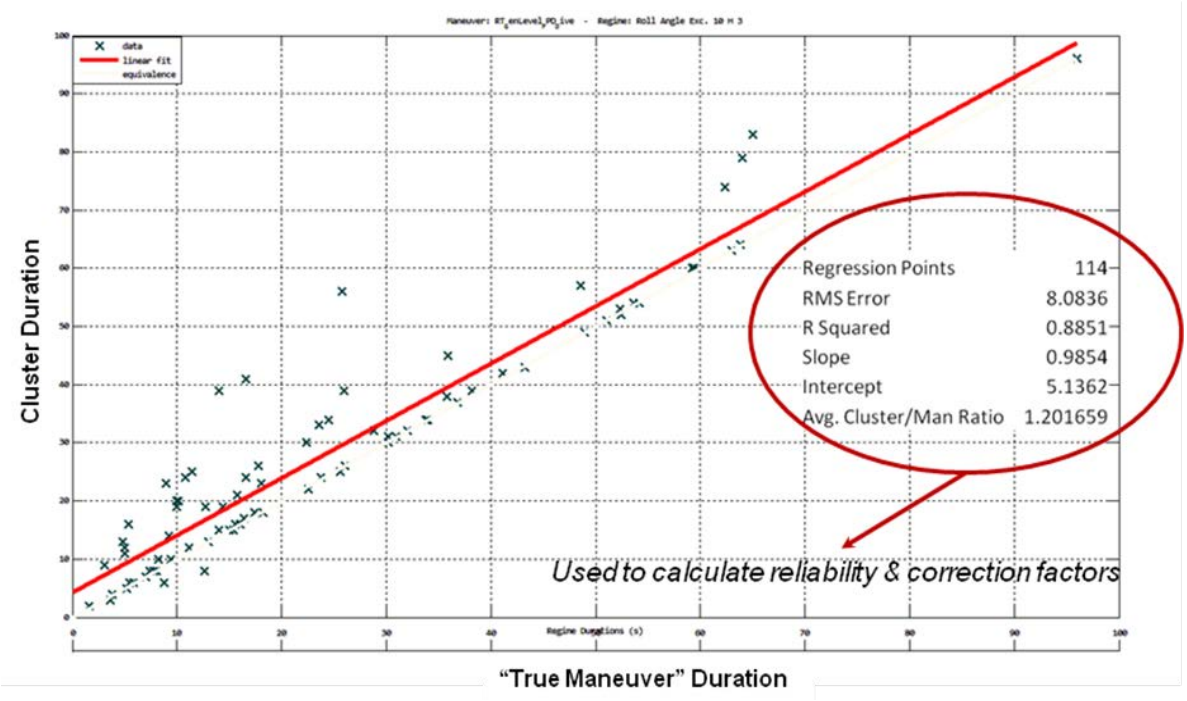


Figure B-14. Regression Results for Turn Cluster vs True Maneuver

APPENDIX C—REGIME RECOGNITION FLIGHT TEST DATA AND HEALTH AND USAGE MONITORING SYSTEM EVALUATION

C.1 PHASE 1 FLIGHT TEST.

An S-92 Flight Loads Survey (FLS) was conducted in the first quarter of 2009 and used for the Phase 1 data set. This test consisted mostly of gross weight expansion (GWE) with limited hours to collect tail pylon loads data for analysis model validation. Health and Usage Monitoring System (HUMS) data was collected simultaneously with independent flight instrumentation.

As part of the regime recognition (RR) verification, it was desired to obtain the composite worst-case (CWC) spectrum maneuver data over a range of gross weight (GW) and center of gravity (CG) to examine algorithm sensitivity to boundaries of the design envelope. Another verification technique is free flight, which simulates operational variability in typical S-92 missions, such as an oil rig, an executive transport, etc. A full, ideal data set for RR purposes was constructed that was comprised of seven GW/CG configurations shown in table C-1. The rationale for regime selection is noted in the last column of the table. It includes the following categories when descending the order of prioritization.

1. Critical regimes that drive component retirement time
2. A regime that HUMS currently cannot recognize
3. Complex maneuvers and free flight
4. Most frequent S-92 operational fleet regimes

Note that this ideal set of test points did not consider program budget, West Palm Beach (WPB) flight test center schedule, or consideration of S-92 Program Office-approved allocation of dedicated flight hours. Rather, it is an overpopulated list to provide data for a broad range of GW and CG; it does not represent the minimum set of test points required to satisfy the objectives of this research project, which has been demonstrated to be much smaller in size for the proposed usage-based maintenance (UBM) credit technical approach.

Table C-2 and figure C-1 summarize the percentage of test points flown compared to the total desired data set. The term “Max” refers to current certified maximum GW for internal loading, “Exp” refers to GWE limit for internal loading, and “Light” refers to less than current maximum GW. As shown in table C-1 and figure C-1, “aft” refers to an extreme rearward CG within the operational envelope, “fwd” refers to extreme forward CG, and “mid” refers to a near-neutral CG location. Of the seven desired configurations, four were flown in the FLS. Two light-weight configurations acquired data for about 25% of the desired ideal maneuver set, and two expanded GW envelope configurations collected data for about 75% of the desired points. Overall, the Phase 1 flight test captured approximately 26% of the total ideal set of approximately 1000 test points for all seven configurations.

Table C-1. Ideal Flight Test Data Set for Regime Recognition

Category	Flight Condition	Multiple Maneuver Details	Justification and Notes
PRIMARY			
Lift to hover			Frequent regime
Hover, IGE		100% NR, 105% NR	Frequent regime
Hover, OGE		100% NR, 105% NR	Frequent regime
Hover, reversals		Longitudinal, lateral, rudder, collective (+/-10%)	Missing regime
Hover, turns	12 sec/360º	Left turn, right turn	Included in UH-60M RR flight test
Paced flight	30 kt	Forward, rearward, left side, right side	Missing regime; Obtain entry, acceleration, steady state and recovery records
Takeoff and climb	VBROC, 120% Q		Critical regime
Climb	VBROC, 120% Q		Frequent regime
Climbing turns	0.8 Vne, 120% Q	15, 30, 45 AoB; Left and right	New algorithm verification
Level flight sweep, speed		0.3, 0.5, 0.7, 0.8, 0.9, 1.0 Vne	Frequent regime
Dive	1.1 Vne		Missing regime; Obtain entry, acceleration, steady state and recovery records
Turns, level flight		0.8 Vne, Vne; 30, 45 AoB; Left and right	Critical regime; Obtain entry, steady state, and recovery records
E/R Turns, level flight	Vne, 30 AoB	Left and right	Missing regime; Benign, Normal, and Aggressive E&R
Pullout, symmetrical		0.8 Vne, 1.0 Vne; 1.5 g, 2.0 g	Critical regime
Pushover, symmetrical		0.8 Vne, Vne; 0.5 g, and 0.0 g	Critical regime
Descent, partial power	Vne, 500 fpm		Missing regime; Obtain entry, descent, and recovery records
Reversals, level flight		0.8 Vne, Vne; Longitudinal, lateral, rudder, collective (+/-10%)	Missing regime
Sideslip		0.8 Vne, Vne; 5º, 10 º Left and right	New algorithm verification
Autorotation		Entry at Vma, Auto at Vma with NRmin, 100% NR and NRmax	Missing regime; Obtain entry, acceleration, steady state records
Autorotation, turns		Vma, 45 AoB, NR max	Included in UH-60M RR flight test
Autorotation, recovery		Vma, NRmax, Recovery to level flight 100% NR	Missing regime
Approach to hover		Normal and rough	Critical regime
Vertical landing		2, 4, and 6 fps	Critical regime
Run-on landing		2, 4, and 6 fps; 30 kt, 60 kt	Critical regime
Taxi			May be critical for heavier GW
Taxi turns		Left and right	May be critical for heavier GW

Table C-1. Ideal Flight Test Data Set for Regime Recognition (Continued)

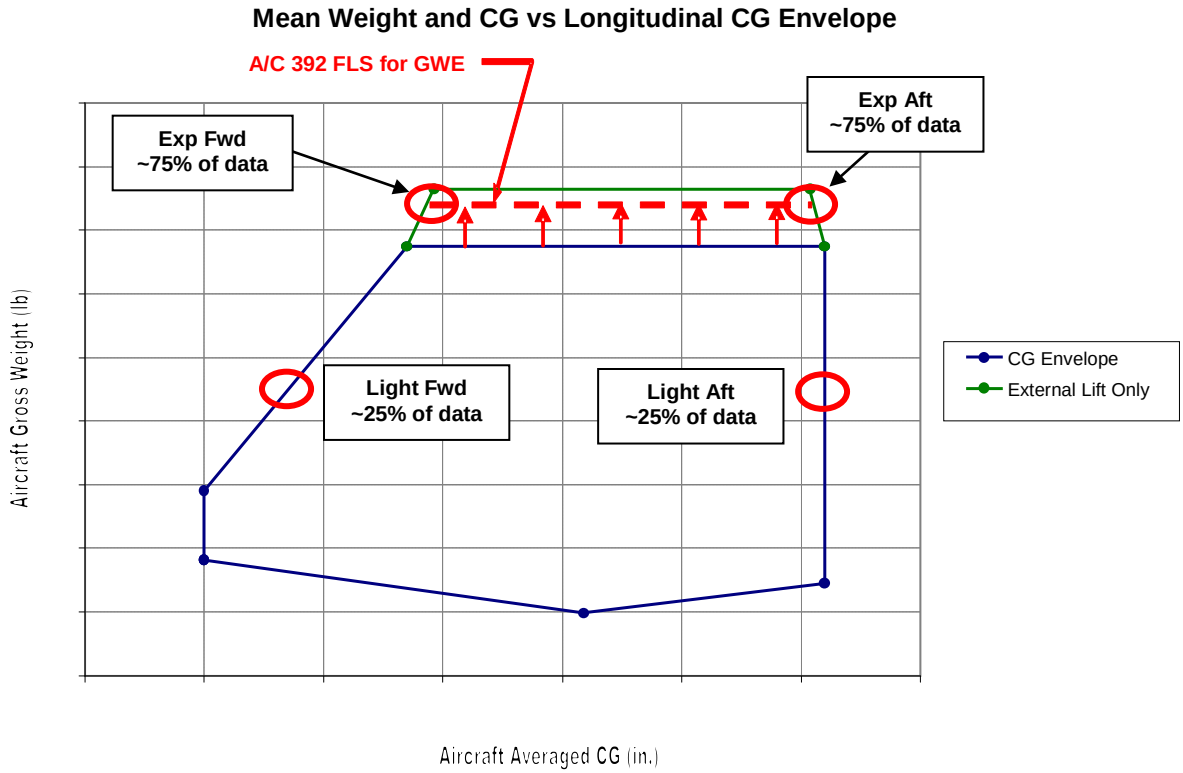
Category	Flight Condition	Multiple Maneuver Details	Justification and Notes
EXPLORATORY			
Free flight		Simulate typical S-92 transport mission	Continuous data collection
Droop stop pounding			UH-60M RR test required telemetry
Rolling pullout	0.8 Vne	1.5 g, 2.0 g; Left and right	UH-60M RR test required telemetry
Rolling pushover	0.8 Vne	0.5 g, 0.0 g; Left and right	UH-60M RR test required telemetry
OEI in hover			UH-60M RR test required telemetry
OEI at altitude			UH-60M RR test required telemetry

AoB = Angle of bank
NR = Design rotor speed
NRmax = Design rotor speed maximum
NRmin = Design rotor speed minimum
E&R = Entry and recovery
VBROC = Velocity at best rate of climb
Vma = Velocity for autorotation
Vne = Velocity not to exceed
OGE = Out-of-ground effect
IGE = In-ground effect
GW = Gross weight

Table C-2. Percentage of Ideal Flight Test Data Set Flown in Phase 1

Maneuver Set	Light Fwd (%)	Light Aft (%)	Max Fwd (%)	Max Mid (%)	Exp Fwd (%)	Exp Mid (%)	Exp Aft (%)
Hover (IGE, OGE, turns, and control reversals)	18	9	none	none		none	100
Paced Flight (fwd, left, right, and reverse)	none	none	none	none		none	100
Climb and climbing turns	13	13	none	none		none	50
Level flight	67	67	none	none		none	100
Level flight turns (entry, steady, recovery, and severities)	40	40	none	none		none	80
Level flight (control reversals)	13	13	none	none		none	100
Sideslips	50	50	none	none		none	100
Pullouts and pushovers (sym and rolling)	25	15	none	none		none	33
Descent (dive, PPD, auto, and auto turns)	27	36	none	none		none	100
Landings (approach, vert, and run-on)	9	18	none	none		none	36
Taxi (fwd and turns)	100	100	none	none		none	100
Exploratory (free flight, OEI, and DSP)	none	none	none	none	none	none	none
Total	27	28	none	none		none	75

IGE = In-ground effect
OGE = Out-of-ground effect
PPD = Partial power descent
OEI = One engine inoperative
DSP = Droop stop pounding



EXP = GWE limit for internal loading

Figure C-1. Summary of Flight Test Data Flown in Phase 1

C.2 PHASE 2 FLIGHT TEST.

The Phase 2 flights on aircraft serial number S920003 (referred to as A/C 392) flew consisted of other test objectives, including additional FLS and global-positioning, system-assisted oil rig approaches that were flown throughout 2009 and the first quarter of 2010. These tests provided information that can be used to further populate the desired data in the exploratory category of table C-1. These data sets were not collected to verify CWC loads and, thus, include data that is closer to scripted free flight than to the carefully performed regimes flown for flight load surveys. However, A/C 392 retained the load instrumentation and, therefore, data from any active channels is available along with HUMS parametric and RR data.

C.3 PHASE 3 FLIGHT TEST.

The Phase 3 flight test objective was to obtain data for S-92 RR algorithm development and validation. There are no existing data sets that contain a full complement of simultaneously recorded data for aircraft state parameters, HUMS regimes, and a comprehensive set of rotor and airframe loads. A single, dedicated HUMS RR flight was conducted using A/C 392 on June 28, 2010 at the WPB facility. Flight 1243 assessed variability in the HUMS RR algorithms for selected turn and pull-up maneuvers. Variables included turns of varying roll rates, rates of climb, and different pilot techniques. Although A/C 392 had a comprehensive set of loads instrumentation, much of it was not active at the time of the flight.

Figure C-2 presents the run log for Flight 1243. This run log is the official declaration of the maneuvers flown. Each run is identified by a distinct number and maneuver description. The pilot flew most of the maneuvers per the plan. A copilot (CP) designation in the maneuver description indicates maneuvers that were repeated by the CP to quantify effects of pilot variability. Table C-3 is a top-level summary of turns, pullouts, and time in maneuvers resembling free flight. These summaries quantify the number of maneuvers that the pilot declared were flown in the three flight test phases.

The Phase 3 data were examined more in depth for HUMS RR statistics. Top-level statistics are shown in figures C-3 through C-5 as bar charts representing the percentage of time that HUMS identified each regime out of the total time each respective maneuver was flown. These data were grouped according to maneuver type.

There were 38 maneuvers flown at a 30° angle of bank (AoB) turn. Because of the sensitivity of the current onboard HUMS algorithms and associated toggling phenomenon, several regimes were declared by HUMS during the turns. Histograms were constructed from the data to display the time distribution of the HUMS regimes within the duration of the true maneuvers flown. As shown in figure C-3, the 30° AoB turn subregime is declared approximately 35% of the during the actual turn duration. Turns are generic regimes with the AoB used as a prorate parameter to determine the subregime category. When the generic turn regime without AoB was included in the statistic, the percentage of time that HUMS detects a turn during the actual turn duration increased to approximately 60%.

Figure C-4 shows a bar chart for the six 45° AoB turns flown in Phase 3. The corresponding 45° subregime was detected about 20% of the actual maneuver time. When the generic turn was included, the detection increased to about 46%. There were also large amounts of time (~32%) declared as partial power descent (PPD) turns.

Symmetric pullouts are shown in figure C-5 for the 11 maneuvers flown. Because the pullout maneuvers are generic regimes with load factor as the prorate parameter, the severity is not established until the load factor reaches a peak value. Consequently, the percentage of time recognized was fairly low at approximately 30%. However, pullouts are CWC transient maneuvers, so the count of occurrences must be monitored rather than the duration.

To further examine the ability of the clustering algorithm to map HUMS RR output into CWC regimes, a "hitting average" metric was established to determine how often HUMS declared a target regime for the critical CWC turn and pullout maneuvers (see table C-4). If a selected target regime is detected by HUMS at least once at any time during the maneuver, it is declared a "hit" because a cluster can be formed from it. Note that this metric does not consider duration or counts of the target regime, only whether it is detected at least one time during the maneuver by the current onboard HUMS RR software. Also note that the clustering algorithm reliability factors for this study are based on simplified single parameter definitions of truth data (i.e., roll angle or load factor) and do not use this metric. However, the hitting average could be useful for reliability assessments of more complex cluster definitions where the truth data cannot be parametrically represented very well.

Table C-4 shows the percentage that the appropriate target regime (e.g., a 30° AoB turn subregime) was identified by HUMS (a hit) out of the set consisting of the total number of times the true maneuver was flown in flight test (attempts). If the target set is expanded to include the generic regime (i.e., no bank angle or load factor specified), the new number of hits for each maneuver set is given in the next column. The hitting average for the set of maneuvers is presented in the last column.

Hitting averages for level turns were quite high. In typical FLS tests from Phase 1, they were 100%. A similar result was observed in Phase 3, except for a few instances where the onboard HUMS RR did not declare some of the 30° AoB turns when multiple, back-to-back, single-direction repeats (e.g., two left turns in a row or three right turns in a row). Even when an intentional pullout or pushover was flown during a level turn, HUMS still properly declared the turn.

Several hitting averages of 0% for turns without the generic regime in the target set were observed for the dive maneuvers and are attributed to the nature of the respective HUMS algorithm. The current onboard HUMS RR algorithms define a dive maneuver only when the engine torque is above a threshold, which is defined as 75% of maximum engine torque. If the engine torque is less than 75% of maximum engine torque, the regime is declared to be a PPD.

Run Log

Date	2010-06-28	**Facility**	DFC WPB FL	**Aircraft**	003
Model	S92A	**Test Type**	FLIGHT	**Testno**	1243

TestPlan	S92/G23	**Flight**	993	**Plan**	
Cond					

FltSeq	1	**TO Time**	10:50:00	**FltHrs**	1.8	**GndHr**	0.2
NomGw		**ESGW**	23223	**TOFue**	3700	**HP**	40
NomCg		**ESCG**	353.3	**LDFue**	1800	**OAT**	32
NomLatC		**ESLatCG**		**VhDay**		**Wind**	
NomHd		**Pilot**	J. BISCAINO	**CoPil**	R. DOEPPNER	**Obs**	
Config	HUMS Regime Recognition						

RUN CLASSIFED AS 22K MID

1	AMBIENT	GRND	0	1
5	AMBIENT	GRND	0	1
6	NO.1 EPAC	GRND	1	1
7	NO.2 EPAC	GRND	1	1
8	LIFT TO HOVER	CLMB	1	1
9	HOVER IGE	HOV	0	1
10	LVL FLT 80KT	LF	0	1
11	LVL LT 80KT ENT	LF	1	1
12	LVL LT 80KT 30AOB	LF	0	1
13	LVL LT 80KT REC	LF	1	1
14	LVL LT 80KT SLOW ENT		1	1
15	LT 80KT 30AOB & SLOW REC		1	1
16	LEVEL LT 80KT FAST ENT			1
17	LT 80KT 30AOB & FAST REC			1
18	LVL RT 80KT ENT			1
19	LVL RT 80KT 30AOB			1
20	LVL RT 80KT REC			1
21	LVL RT 80KT SLOW ENT			1
22	RT 80K 30AOB S REC F ENT			1
23	RT 80KT 30AOB & FAST REC			1
24	CP LVL LT 80KT ENT			1
25	CP LVL LT 80KT 28AOB			1
26	CP LVL LT 80KT 30AOB			1
27	CP LVL LT 80KT REC			1
28	CP LVL FLT 80KT			1
29	CP LVL LT 80KT SLOW ENT			1
30	CP LVL LT 80KT 30AOB			1
31	CP LVL LT 80KT SLOW REC			1
32	CP LVL LT 80KT FAST ENT			1
33	CP LVL LT 80KT 30AOB			1
34	CP LVL LT 80KT FAST REC			1
35	CP LVL RT 80KT ENT			1
36	CP LVL RT 80KT 30AOB			1
37	CP LVL RT 80KT REC			1
38	CP LVL RT 80KT SLOW ENT			1
39	CP LVL RT 80KT 30AOB			1
40	CP LVL RT 80KT SLOW REC			1

Figure C-2. Flight 1243 Run Log

41	CP LVL RT 80KT SLOW ENT	1
42	CP LVL RT 80KT 30AOB	1
43	CP LVL RT 80KT FAST REC	1
44	LVL LT 80KT ENT	1
45	LVL LT 80KT 45AOB	1
46	LVL LT 80KT REC	1
47	LVL LT 80KT SLOW ENT	1
48	LVL LT 80KT 45AOB	1
49	LVL LT 80KT SLOW REC	1
50	LT 80KT 45AOB F E/STD/R	1
51	LVL RT 80KT ENT	1
52	LVL RT 80KT 45AOB & REC	1
53	LVL RT 80KT SLOW ENT	1
54	RT 80KT 45AOB & SLOW REC	1
55	LVL RT 80KT FAST ENT	1
56	LVL RT 80KT 30AOB	1
57	LVL RT 80KT FAST REC	1
58	DIVE LT 130KT ENT	1
59	DIVE LT 130KT 30AOB	1
60	DIVE LT 130KT REC	1
61	D LT 130KT S ENT 30AOB	1
62	DIVE LT 130KT SLOW REC	1
63	DLT 130K 30AOB F E/STD/R	1
64	DIVE RT 130KT ENT	1
65	DIVE RT 130K 30AOB & REC	1
66	DRT 130K 30AOB S E/STD/R	1
67	DRT 130K 30AOB F E/STD/R	1
68	DIVE LT 130KT ENT	1
69	DIVE LT 130KT 45AOB	1
70	DIVE LT 130KT REC	1
71	DIVE LT 130KT SLOW ENT	1
72	DIVE LT 130KT 45AOB	1
73	DIVE LT 130KT SLOW REC	1
74	D LT 130KT F ENT & 45AOB	1
75	DIVE LT 130KT FAST REC	1
76	DIVE RT 130KT ENT	1
77	D RT 130KT 45 AOB & REC	1
78	DIVE RT 130KT SLOW ENT	1
79	DIVE RT 130KT 45AOB	1
80	DIVE RT 130KT SLOW REC	1
81	DIVE RT 130KT FAST ENT	1
82	DIVE RT 130KT 45 AOB	1
83	DIVE RT 130KT FAST REC	1
84	PPD ROD 500FPM	1
85	PPD LT 80KT ENT	1
86	PPD LT 80KT 30AOB	1
87	PPD LT 80KT REC	1
88	PPD LT 80K S ENT & 30AOB	1
89	PPD LT 80KT SLOW REC	1
90	PPD LT 80K F ENT & 30AOB	1
91	PPD LT 80KT FAST REC	1
92	PPD RT 80K 30AOB E/STD/R	1

Figure C-2. Flight 1243 Run Log (Continued)

93	PPD RT 80KT SLOW ENT	1
94	PPD RT 80K 30AOB & S REC	1
95	PPDRT 80K30AOB F E/STD/R	1
96	PPD LT 80KT ENT	1
97	PPD LT 80KT 45AOB	1
98	PPD LT 80KT REC	1
99	PPD LT 80KT SLOW ENT	1
100	PPD LT 80KT 45AOB	1
101	PPD LT 80KT SLOW REC	1
102	PPD LT 80KT FAST ENT	1
103	PPD LT 80KT 45AOB	1
104	PPD LT 80KT FAST REC	1
105	PPD RT 80KT ENT & 45AOB	1
106	PPD RT 80KT REC	1
107	PPD RT 80K S ENT & 45AOB	1
108	PPD RT 80KT SLOW REC	1
109	PPD RT 80K F ENT & 45AOB	1
110	PPD RT 80KT FAST REC	1
111	LEVEL FLT 80KT	1
112	LVL LT 80KT 30AOB E/R X2	1
113	LVL LT 80KT 30AOB E/R X3	1
114	LVL RT 80KT 30AOB E/R X2	1
115	LVL RT 80KT 30AOB E/R X3	1
116	30AOB LT 80KT SLOW E/RX2	1
117	30AOB RT 80KT SLOW E/RX2	1
118	30AOB LT 80KT FAST E/RX2	1
119	30AOB RT 80KT FAST E/RX2	1
120	30AOB 80KT LT/RT E/R	1
121	30AOB 80KT RT/LT E/R	1
122	30AOB 80KT LT/RT S E/R	1
123	30AOB 80KT RT/LT S E/R	1
124	30AOB 80KT LT/RT F E/R	1
125	30AOB 80KT RT/LT F E/R	1
126	CP LT 80KT 30AOB E/R X2	1
127	CP RT 80KT 30AOB E/R X2	1
128	CP 30AOB LT 80KT S E/RX2	1
129	CP 30AOB RT 80KT S E/RX2	1
130	CP 30AOB LT 80KT F E/RX2	1
131	CP 30AOB RT 80KT F E/RX2	1
132	CP 30AOB 80KT LT/RT E/R	1
133	CP 30AOB 80KT RT/LT E/R	1
134	CP 30AOB 80K LT/RT S E/R	1
135	CP 30AOB 80K RT/LT S E/R	1
136	CP 30AOB 80K LT/RT F E/R	1
137	CP 30AOB 80K RT/LT F E/R	1
138	0/30/15/45/0 LT 80KT E/R	1
139	0/30/15/45/0 RT 80KT E/R	1
140	0/45/15/30/0 LT 80KT E/R	1
141	0/45/15/30/0 RT 80KT E/R	1
142	0/45/30/45/0 LT 80KT E/R	1
143	0/45/30/45/0 RT 80KT E/R	1
144	0/45/15/45/0 LT 80KT E/R	1

Figure C-2. Flight 1243 Run Log (Continued)

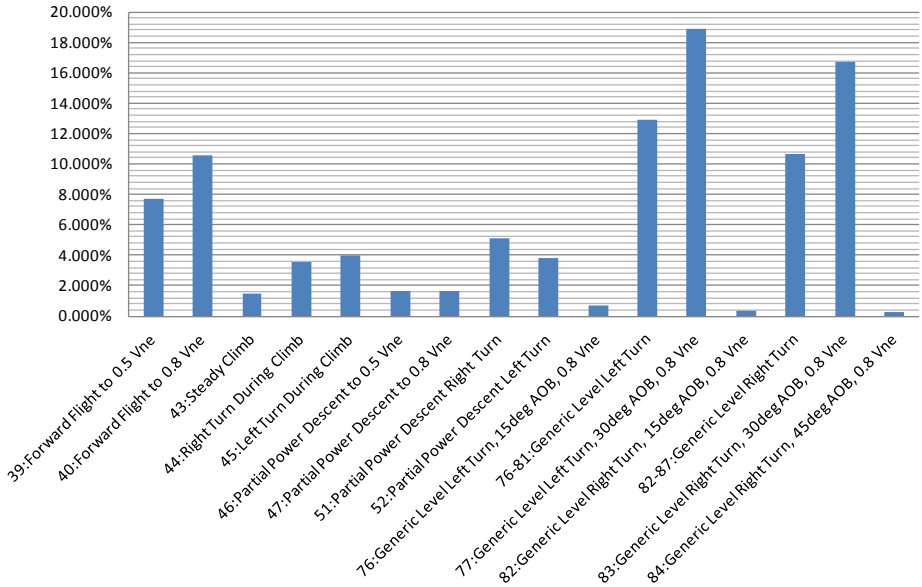
145	0/45/15/45/0 RT 80KT E/R	1
146	LT +PO 80KT 30AOB 1.2G	1
147	LT +PO 80KT 30AOB 1.5G	1
148	RT +PO 80KT 30AOB 1.2G	1
149	RT +PO 80KT 30AOB 1.5G	1
150	30AOB LT +PSHOVR 80KT .8G	1
151	30AOB RT +PSHOVR 80KT .8G	1
152	CP LT +PO 80KT 30AOB 1.2G	1
153	CP LT +PO 80KT 30AOB 1.5G	1
154	CP RT +PO 80KT 30AOB 1.2G	1
155	CP RT +PO 80KT 30AOB 1.5G	1
156	CP 80K 30AOB LT +PSOV .8G	1
157	CP 80K 30AOB RT +PSOV .8G	1
158	80K PO+PSOV 1/1.2/.8/1G	1
159	80K PO+PSOV 1/1.5/.5/1G	1
160	80K PO+PSOV 1/1.5/.5/1G	1
161	80K PO+PSOV 1/1.5/.5/1G	1
162	80 KT 1.2G SYM PO	1
163	80 KT 1.5G SYM PO	1
164	80 KT 2.0G SYM PO	1
165	130 KT 1.2G SYM PO	1
166	130 KT 1.5G SYM PO	1
167	130 KT 1.85G SYM PO	1
168	CP 80 KT 1.2G SYM PO	1
169	CP 80 KT 1.5G SYM PO	1
170	CP 80 KT 1.72G SYM PO	1
171	CP 80 KT 1.88G SYM PO	1
172	CP 130 KT 1.2G SYM PO	1
173	CP 130 KT 1.5G SYM PO	1
174	CP 130 KT 1.8G SYM PO	1
175	CP 130 KT 2.0G SYM PO	1
176	AMBIENT	1
177	ZCAL	1
178	RCAL	1
179	XCAL	1
180	AMBIENT	1

Figure C-2. Flight 1243 Run Log (Continued)

Table C-3. Critical Turn and Pullout Maneuver Counts and Free Flight for RR

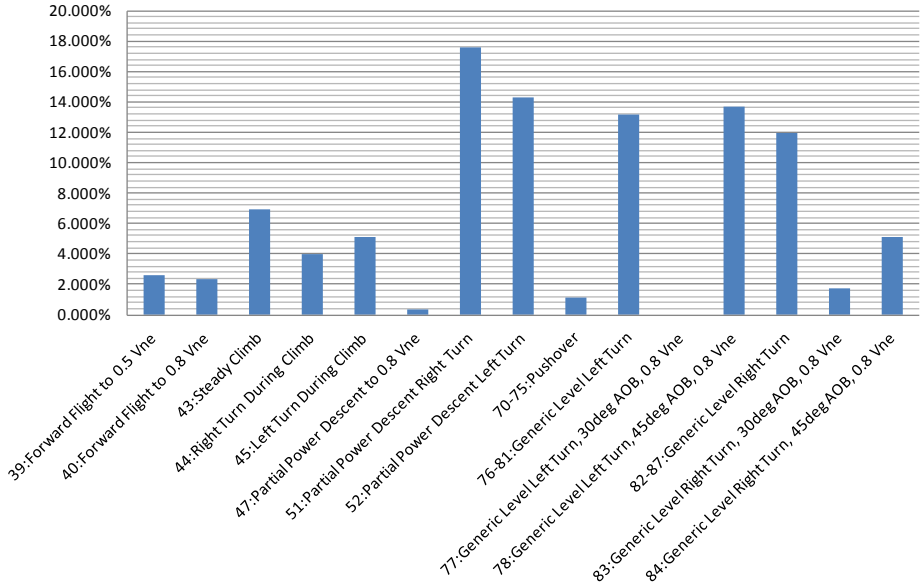
Flight Number	Run Description																						
	High-Bank Turns																Pullout/Pushover				Similar to Free Flight		
	80 kt				VH				Vne				Dive - 130 kt				Pullout		Pushover				
	30° AoB LT	30° AoB RT	45° AoB LT	45° AoB RT	30° AoB LT	30° AoB RT	45° AoB LT	45° AoB RT	30° AoB LT	30° AoB RT	45° AoB LT	45° AoB RT	30° AoB LT	30° AoB RT	45° AoB LT	45° AoB RT	Symmetric	During Turn	Symmetric	During Turn	Oil Rig - Minutes	OEI - Minutes	Other Free Flight - Minutes
1083								2															
1085								4									16						
1086								2									2						
1087																	5						
1091								2				2					9						
1095												1					2						
1097												1					2						
1107																					162		
1150																					66		
1165																							36
1168	2	2	2	2	1	1	1	1															
1169	2	2	2	2	1	1	1	1	1	1	1	1					2		2				
1190																						3.5	
1206			2	2													2						
1215									1	1													
1243	20	20	2	2									3	3	3	3	2	4		4			
Total	24	24	8	8	2	2	2	12	2	2	1	5	3	3	3	3	42	4	2	4	228	3.5	36

Vne = Velocity not to exceed



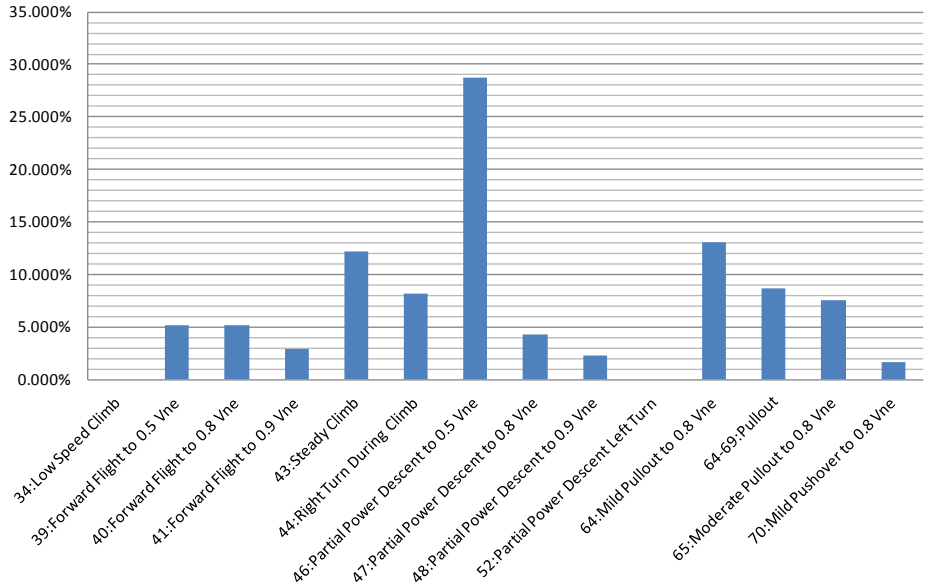
Vne = Velocity not to exceed

Figure C-3. Histogram Summary, 30° AoB Level Turns



Vne = Velocity not to exceed

Figure C-4. Histogram Summary, 45° AoB Level Turns



Vne = Velocity not to exceed

Figure C-5. Histogram Summary, Symmetric Pullouts

Table C-4. Hitting Average Metric Results

Maneuver Description	Attempts	Subregime Hits	With Generic	Hitting Average Without Generic (%)	Hitting Average With Generic (%)
LVL 30° AoB, Normal	18	16	18	89	100
LVL 30° AoB, Benign	12	12	12	100	100
LVL 30° AoB, Aggressive	12	10	11	83	92
LVL 45° AoB, Normal	2	2	2	100	100
LVL 45° AoB, Benign	2	2	2	100	100
LVL 45° AoB, Aggressive	2	2	2	100	100
LVL 30° AoB and 1.2G pullout	4	4	4	100	100
LVL 30° AoB and 1.5G pullout	4	4	4	100	100
LVL 30° AoB and 0.8G pushover	4	4	4	100	100
DIVE 30° AoB, Normal	2	0	2	0	100
DIVE 30° AoB, Benign	2	0	2	0	100
DIVE 30° AoB, Aggressive	2	0	2	0	100
DIVE 45° AoB, Normal	2	0	2	0	100
DIVE 45° AoB, Benign	2	0	2	0	100
DIVE 45° AoB, Aggressive	2	2	2	100	100
PPD 30° AoB, Normal	2	n/a	2	n/a	100

Table C-4. Hitting Average Metric Results (Continued)

Maneuver Description	Attempts	Subregime Hits	With Generic	Hitting Average Without Generic (%)	Hitting Average With Generic (%)
PPD 30° AoB, Benign	2	n/a	2	n/a	100
PPD 30° AoB, Aggressive	2	n/a	2	n/a	100
PPD 45° AoB, Normal	2	n/a	2	n/a	100
PPD 45° AoB, Benign	2	n/a	2	n/a	100
PPD 45° AoB, Aggressive	2	n/a	2	n/a	100
LVL 30° AoB, Rev, Norm	4	3	4	75	100
LVL 30° AoB, Rev, Benign	4	3	4	75	100
LVL 30° AoB, Rev, Aggressive	4	2	4	50	75
Complex Turns	8	2	6	25	75
Sym Pullout, 1.2G	3	0	0	0	0
Sym Pullout, 1.5G	4	4	4	100	100
Sym Pullout, >1.5G	4	4	4	100	100
PO + PSH, 1.0/1.2/0.8/1.0	1	0	0	0	0
PO + PSH, 1.0/1.5/0.5/1.0	3	3	3	100	100

PO = Pullout
PSH = Pushover

Further examination of the output data from the Advanced Data Acquisition and Processing System (ADAPS) shows that during all maneuvers declared by the run log to be DIVE 30 AoB (Normal, Benign, and Aggressive), the N1QCOR:D:1C1 (engine 1 torque percentage) parameter was below the 75% threshold; thus, this maneuver is actually a PPD according to the HUMS RR definition. Sample data plots of this parameter from the ADAPS data for a maneuver declared by the pilot as "DIVE 30 AoB, Normal" are shown in figure C-6. This corresponds to runs 64 and 65 in the run log for Flight Test no. 1243. The figures show that the run log declared a dive maneuver, but the engine torque was lower than the threshold, and HUMS correctly declared the maneuver as a PPD. Further examination of component loads for these maneuvers was beyond the scope of this project, but is recommended to determine if they should be counted with full-power turns or with PPD turns.

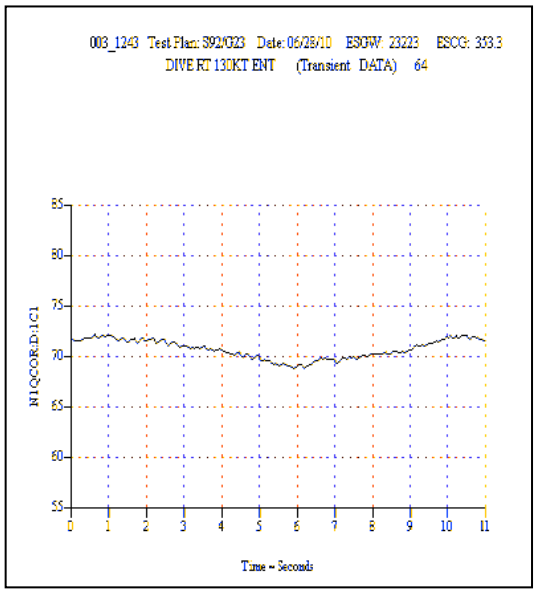


Figure 4 – Flight Test 1243 – Run 64 – DIVE RT 130 KT ENT

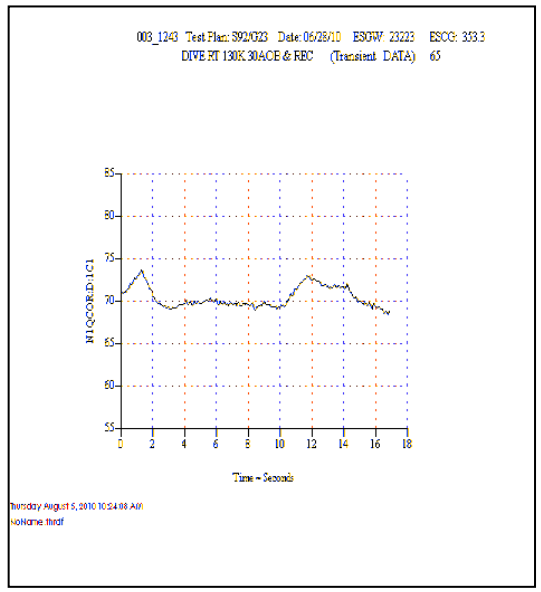


Figure 5 – Flight Test 1243 – Run 65 – DIVE RT 130 KT 30 AOB & REC

Figure C-6. Engine Torque in Phase 3 Dive Maneuvers

Table C-5 lists the Phase 3 runs where a dive maneuver was intended, but was flown with a power setting less than the threshold for a PPD. When the PPD turns were included as a generic regime, the hitting average for the dive turns was 100%.

Table C-5. Runs Labeled DIVE With PPD Regime Identified

Run	Declared Maneuver
58-60	DIVE LT 30 AoB, Normal
61-62	DIVE LT 30 AoB, Benign
63	DIVE LT 30 AoB, Aggressive
64-65	DIVE RT 30 AoB, Normal
66	DIVE RT 30 AoB, Benign
67	DIVE RT 30 AoB, Aggressive
68-70	DIVE LT 45 AoB, Normal
71-73	DIVE LT 45 AoB, Benign

Maneuvers that were intentionally flown as PPD turns had a hitting average of 100%. Note that there are no subregimes that specify the AoB in a PPD turn, so the subregime hit column is labeled n/a. The challenge from these examples is that if the power setting crosses the threshold into the PPD parameter space, the HUMS RR algorithms do not specify the AoB. Further examination of loads for UBM candidate components is recommended to determine the appropriate cluster definitions but was beyond the scope of this project.

Several maneuvers were flown for a 30° AoB turn reversal. These were flown as reversals from left to right and right to left. The hit criterion was that HUMS identified both the left and right 30° turns. HUMS performed well in most cases for the normal and benign roll rates. For aggressive roll rates, the target and generic regimes were sometimes missed.

The complex turn category combined two different AoB turns in the same direction, as shown in figure C-7. There were two basic types of complex turns. The first type, shown in the left-side figure, overlapped two consecutive 45° AoB turns at a small level where the intermediate AoB returns to 15° and at a large level where the intermediate AoB is 30°. The other type of complex turn was where the pilot wobbles the AoB on the way up to a maximum of 45° AoB (wobble-up) and on the way down from a maximum 45° AoB (wobble-down). The hitting average for these very complex turns that have rapidly changing conditions was understandably the lowest. However, these types of fluctuations have been observed in fleet data, so they are conceivably realistic operational conditions. If the 45° AoB turn subregime is specified as the target regime, the hitting average is only 25%. However, this increases to 75% when the generic turns are included in the target set.

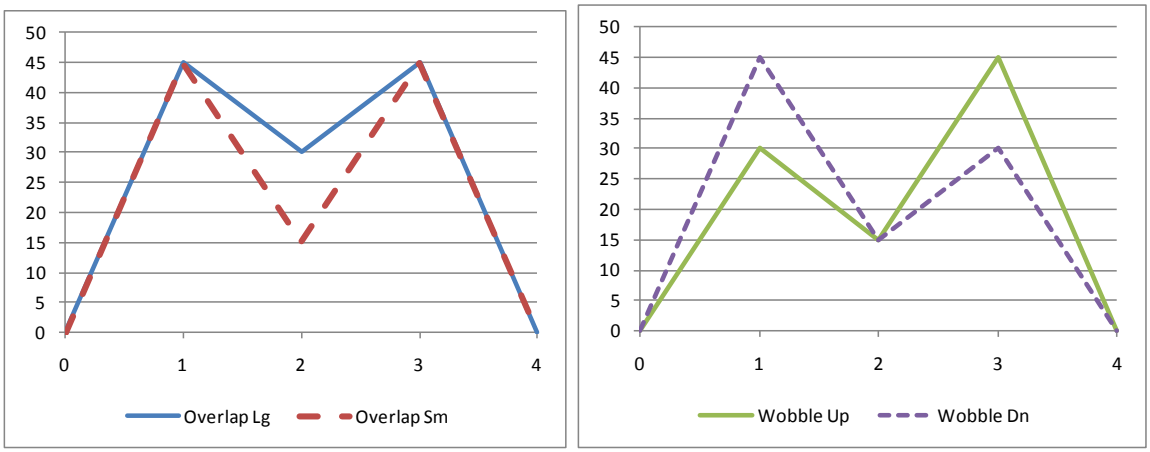


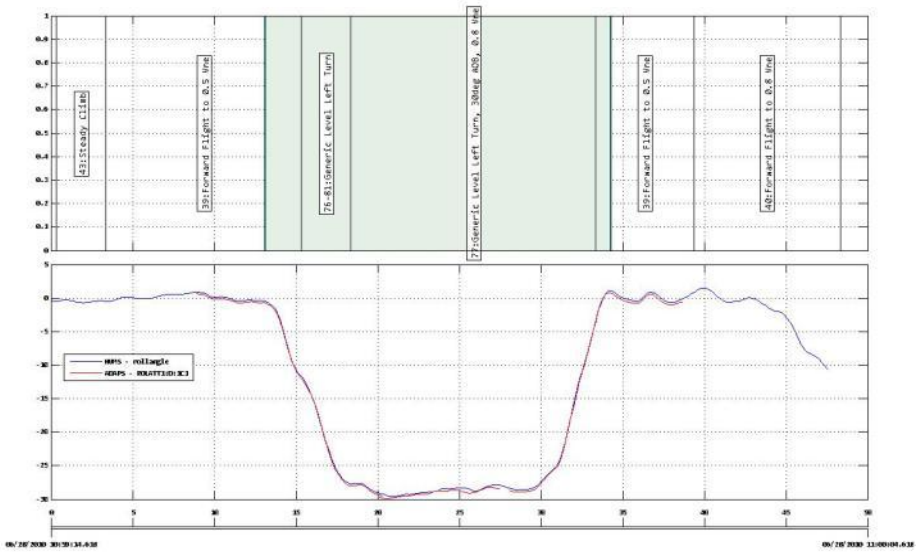
Figure C-7. Complex Turn Maneuvers

Various symmetric pullout maneuvers were flown at different load factors. The HUMS threshold for recognizing a pullout maneuver is 1.3 g. The hitting average for those above the HUMS threshold was 100%. Even when combined with a pushover condition, whose threshold is 0.7 g, the hit rates were 100% for all conditions above threshold.

C.4 PHASE 3 RUN PLOTS AND STATISTICS.

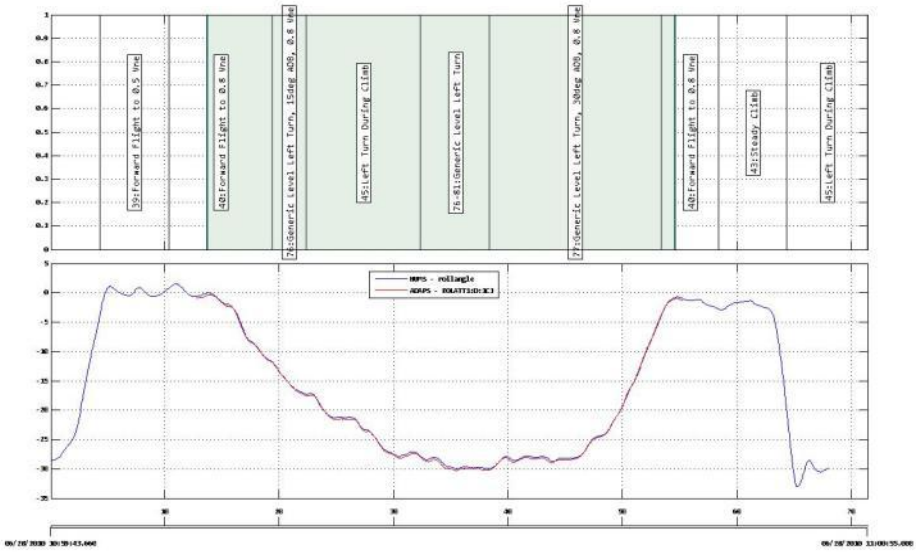
Figures C-8 through C-110 show the Phase 3 scripted flight test results with plotted HUMS RR data output and statistics. The data from both the HUMS and ADAPS sources are shown on the same axis. All data are shown as two plots consisting of a chosen parameter gathered from both the HUMS and ADAPS, specifically roll attitude for turn maneuvers and load factor for pullout or pushover maneuvers, and the regime that was identified by the HUMS at each time step. The plots and statistics were produced using the semiautomated UBM regime recognition Clustering (RRC) tool developed in this project, described in section 6.5.5 of the main report. This

powerful software tool allowed easy alignment of HUMS and ADAPS data. Each plot shows the overlay of a common parameter in each data set (i.e., roll angle for turn maneuvers and load factor for pullouts). Statistics were automatically generated in a window highlighted by the user to trim away data that was recorded during setup and exit of the flight test maneuver. This enabled the most accurate statistics to be generated, rather than using raw flight test start and stop times for the maneuver. A time window was chosen in which the suggested maneuver was taking place, and statistics for this time window are given below the plots. Regimes within the highlighted time window are shown in green in the HUMS regime subplot. The corresponding results and statistics were used to generate the top-level bar charts and metric table of hitting averages that were presented previously in this appendix. In figures C-8 through C-110, Vne is defined as velocity not to exceed.



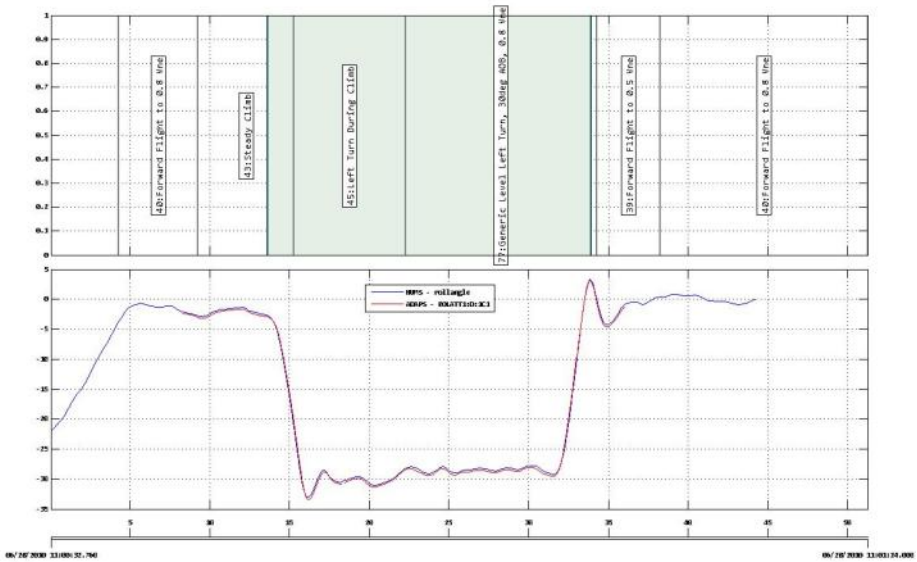
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
39:Forward Flight to 0.5 Vne	2	14.954	3.17
76-81:Generic Level Left Turn	1	14.174	3
77:Generic Level Left Turn, 30°AoB, 0.8 Vne	1	70.872	15

Figure C-8. Runs 11-13: 0.8 Vne, Level Left-Turn 30° AoB, Normal



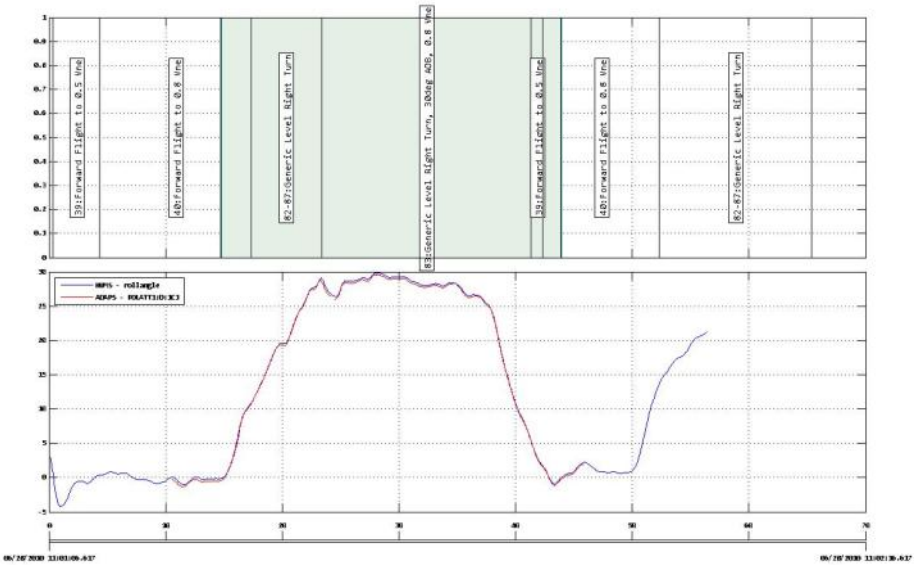
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
40:Forward Flight to 0.8 Vne	2	16.799	6.86
45:Left Turn During Climb	1	24.471	10
76-81:Generic Level Left Turn	1	14.683	6
76:Generic Level Left Turn, 15° AoB, 0.8 Vne	1	7.341	3
77:Generic Level Left Turn, 30° AoB, 0.8 Vne	1	36.707	15

Figure C-9. Runs 14-15: 0.8 Vne, Level Left-Turn 30° AoB, Benign



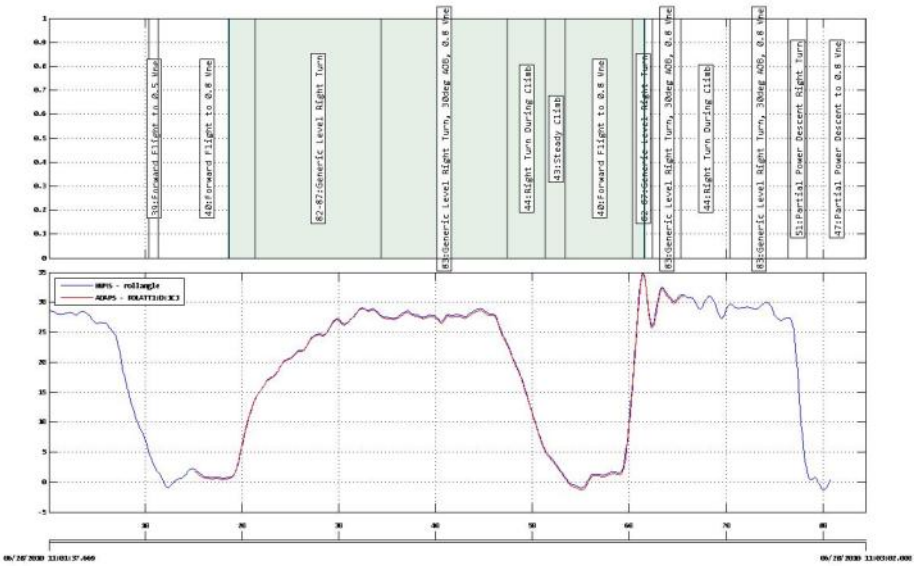
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
43:Steady Climb	1	8.051	1.63
45:Left Turn During Climb	1	34.488	7
77:Generic Level Left Turn, 30° AoB, 0.8 Vne	1	57.462	11.66

Figure C-10. Runs 16-17: 0.8 Vne, Level Left-Turn 30° AoB, Aggressive



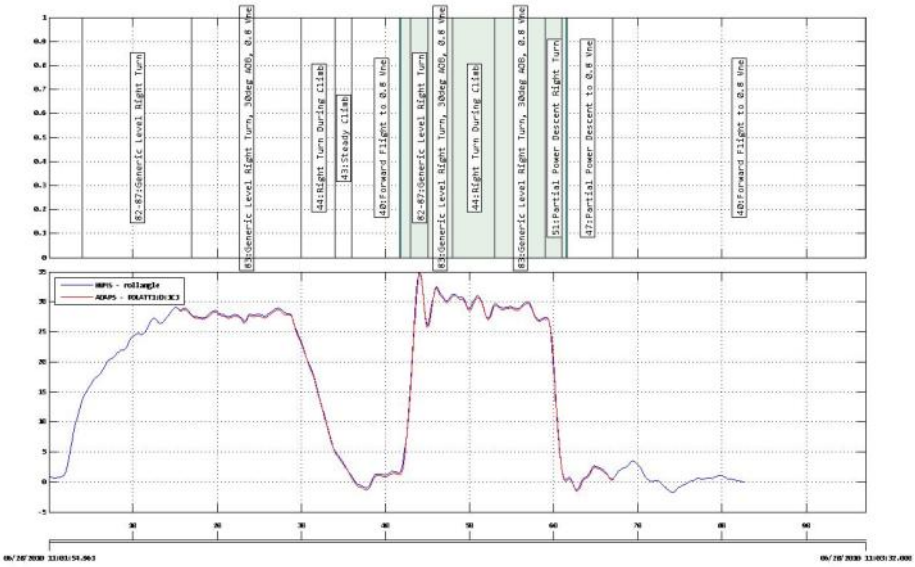
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
39:Forward Flight to 0.5 Vne	1	3.43	1
40:Forward Flight to 0.8 Vne	2	14.252	4.16
82-87:Generic Level Right Turn	1	20.579	6
83:Generic Level Right Turn, 30° AoB, 0.8 Vne	1	61.738	18

Figure C-11. Runs 18-20: 0.8 Vne, Level Right-Turn 30° AoB, Normal



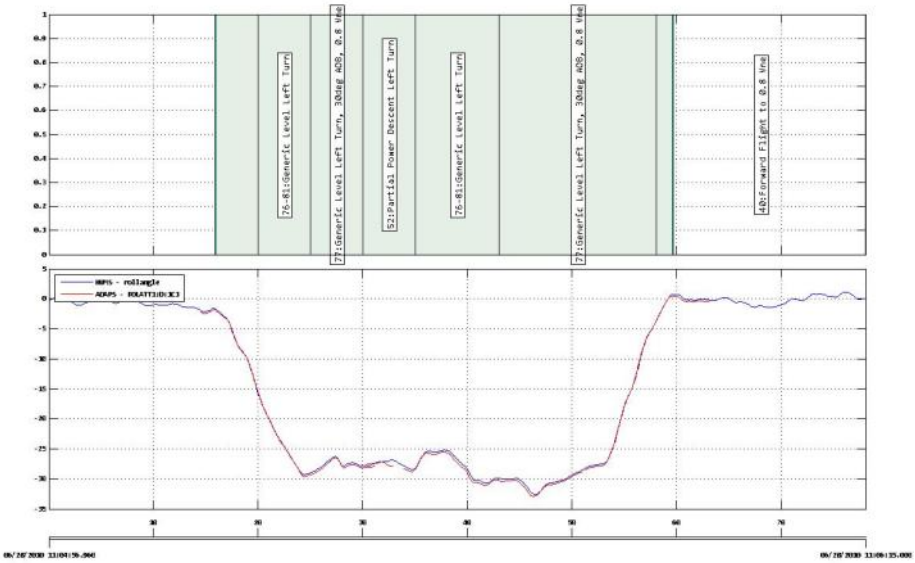
Regime	Counts	Time (%)	Time (sec)
40:Forward Flight to 0.8 Vne	2	22.62	9.7
43:Steady Climb	1	4.662	2
44:Right Turn During Climb	1	9.323	4
82-87:Generic Level Right Turn	2	33.093	14.2
83:Generic Level Right Turn, 30° AoB, 0.8 Vne	1	30.301	13

Figure C-12. Runs 21-22: 0.8 Vne, Level Right-Turn 30° AoB, Benign



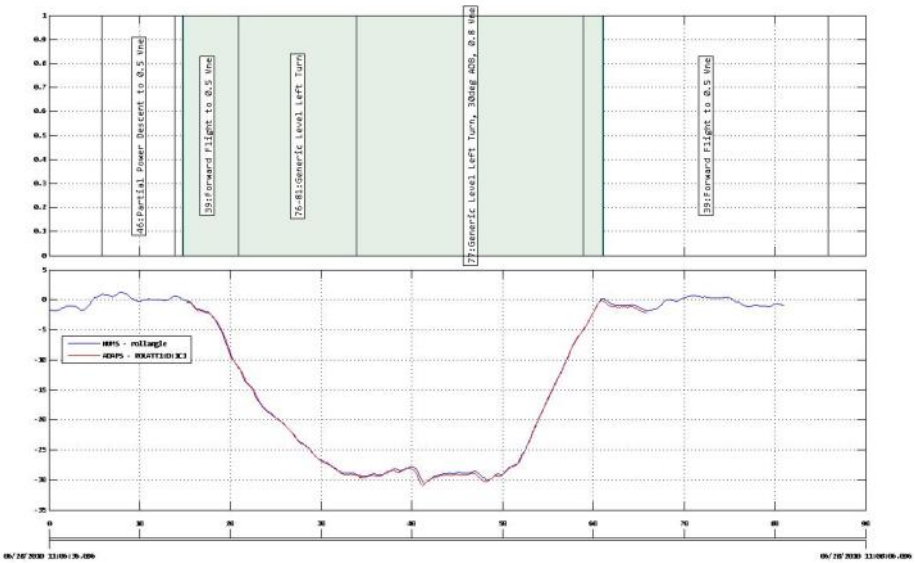
Regime	Counts	Time (%)	Time (sec)
40:Forward Flight to 0.8 Vne	1	6.347	1.26
44:Right Turn During Climb	1	25.272	5
47:Partial Power Descent to 0.8 Vne	1	2.673	0.53
51:Partial Power Descent Right Turn	1	10.109	2
82-87:Generic Level Right Turn	1	10.109	2
83:Generic Level Right Turn, 30° AoB, 0.8 Vne	2	45.49	9

Figure C-13. Runs 22-23: 0.8 Vne, Level Right-Turn 30° AoB, Aggressive



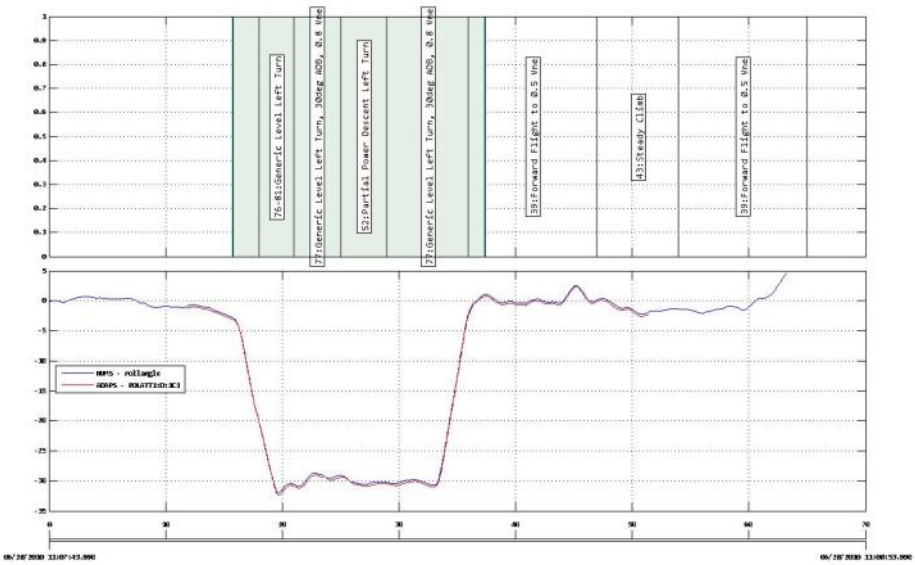
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
40:Forward Flight to 0.8 Vne	1	3.72	1.63
52:Partial Power Descent Left Turn	1	11.437	5
76-81:Generic Level Left Turn	2	29.736	13
77:Generic Level Left Turn, 30° AoB, 0.8 Vne	2	45.748	20

Figure C-14. Runs 24-27: CP, 0.8 Vne, Level Left-Turn 30° AoB, Normal



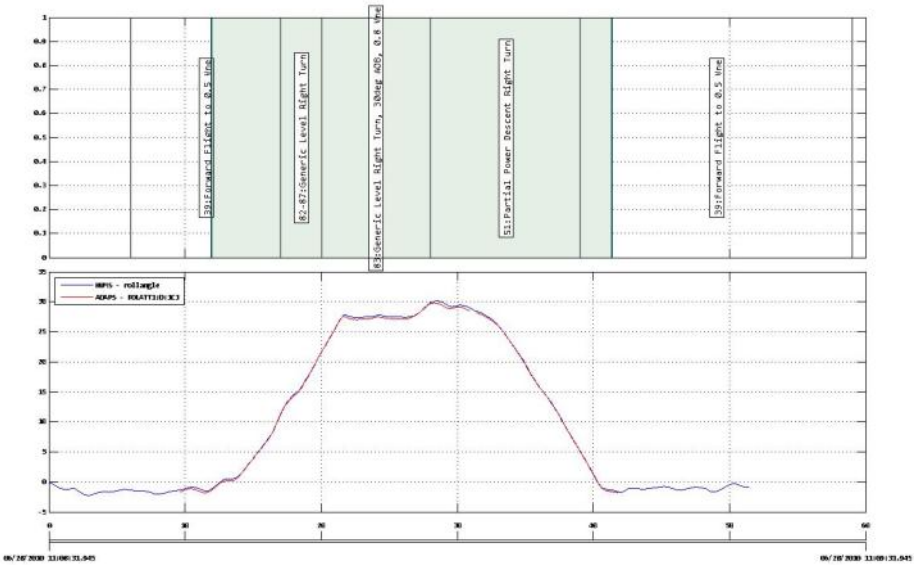
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
39:Forward Flight to 0.5 Vne	2	17.946	8.31
76-81:Generic Level Left Turn	1	28.071	13
77:Generic Level Left Turn, 30° AoB, 0.8 Vne	1	53.983	25

Figure C-15. Runs 29-31: CP, 0.8 Vne, Level Left-Turn 30° AoB, Benign



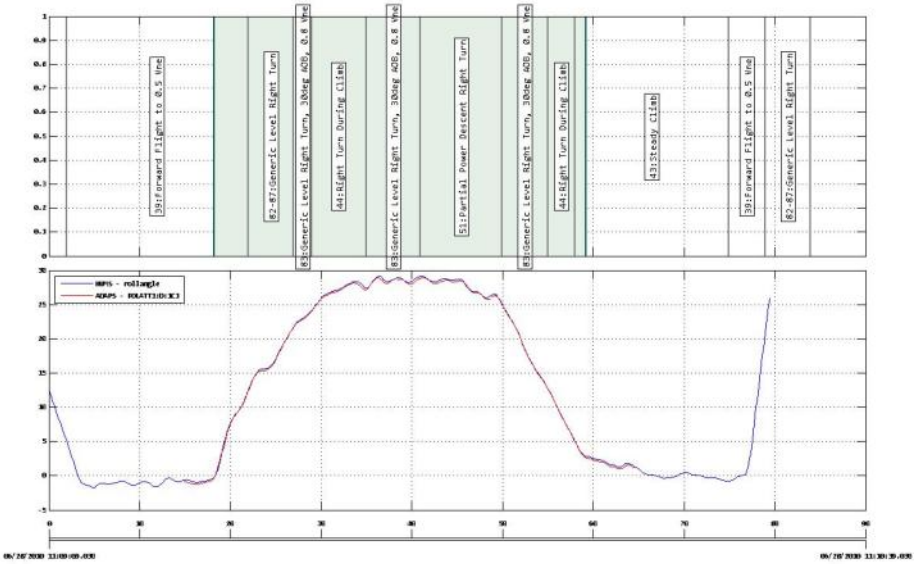
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
39:Forward Flight to 0.5 Vne	1	6.491	1.4
52:Partial Power Descent Left Turn	1	18.509	4
76-81:Generic Level Left Turn	1	13.881	3
77:Generic Level Left Turn, 30° AoB, 0.8 Vne	2	50.898	11

Figure C-16. Runs 32-34: CP, 0.8 Vne, Level Left-Turn 30° AoB, Aggressive



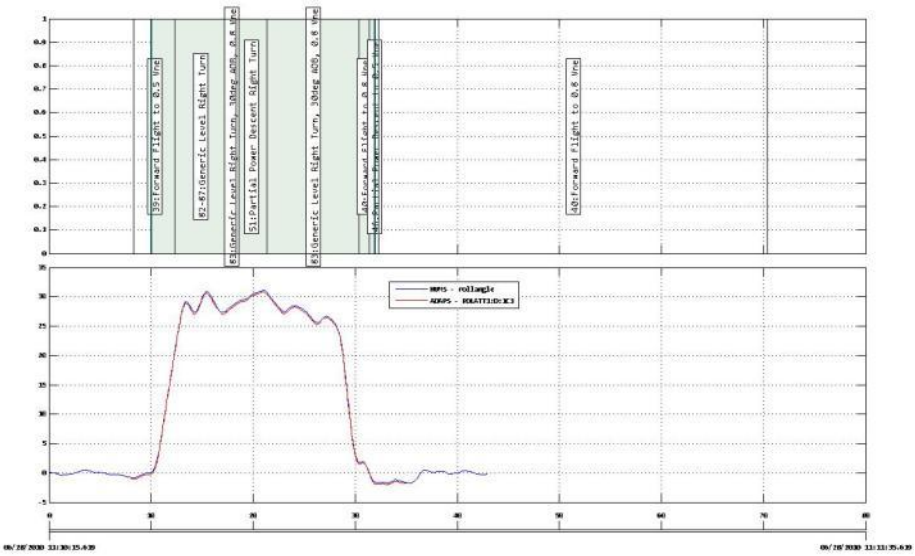
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
39:Forward Flight to 0.5 Vne	2	25.215	7.42
51:Partial Power Descent Right Turn	1	37.393	11
82-87:Generic Level Right Turn	1	10.198	3
83:Generic Level Right Turn, 30° AoB, 0.8 Vne	1	27.195	8

Figure C-17. Runs 35-37: CP, 0.8 Vne, Level Right-Turn 30° AoB, Normal



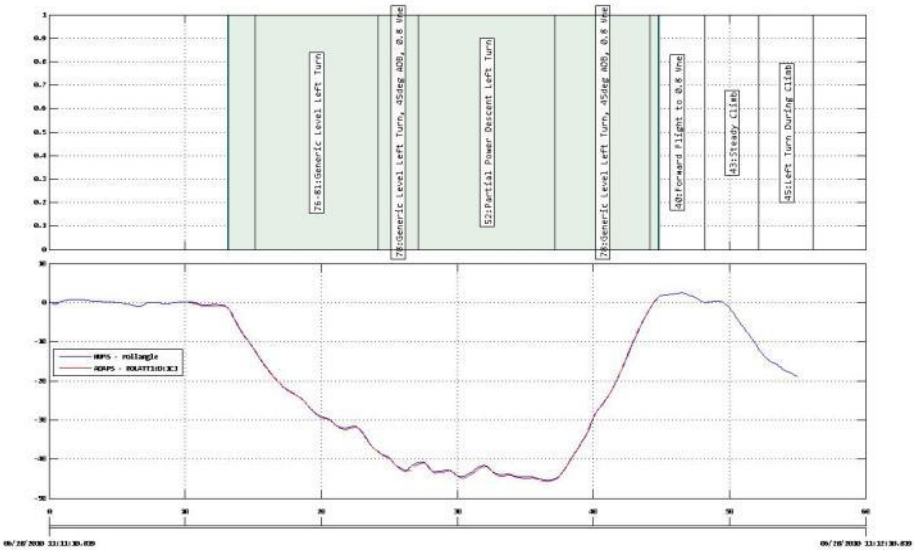
Regime	Counts	Time (%)	Time (sec)
39:Forward Flight to 0.5 Vne	1	9.155	3.75
43:Steady Climb	1	2.998	1.23
44:Right Turn During Climb	2	21.962	9
51:Partial Power Descent Right Turn	1	21.962	9
82-87:Generic Level Right Turn	1	12.201	5
83:Generic Level Right Turn, 30° AoB, 0.8 Vne	3	31.722	13

Figure C-18. Runs 38-40: CP, 0.8 Vne, Level Right-Turn 30° AoB, Benign



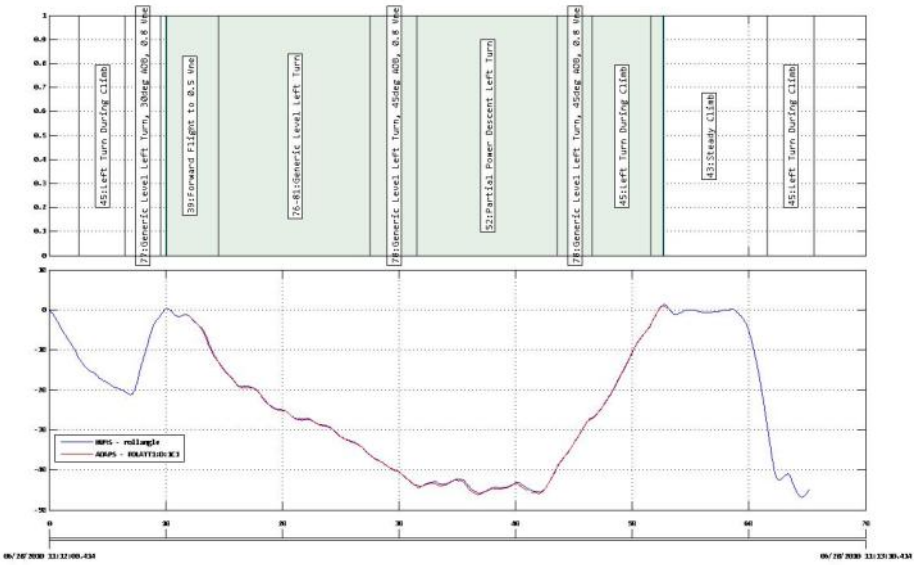
Regime	Counts	Time (%)	Time (sec)
39:Forward Flight to 0.5 Vne	1	10.603	2.32
40:Forward Flight to 0.8 Vne	1	4.566	1
46:Partial Power Descent to 0.5 Vne	1	2.651	0.58
51:Partial Power Descent Right Turn	1	13.697	3
82-87:Generic Level Right Turn	1	22.828	5
83:Generic Level Right Turn, 30° AoB, 0.8 Vne	2	45.656	10

Figure C-19. Runs 41-43: CP, 0.8 Vne, Level Right-Turn 30° AoB, Aggressive



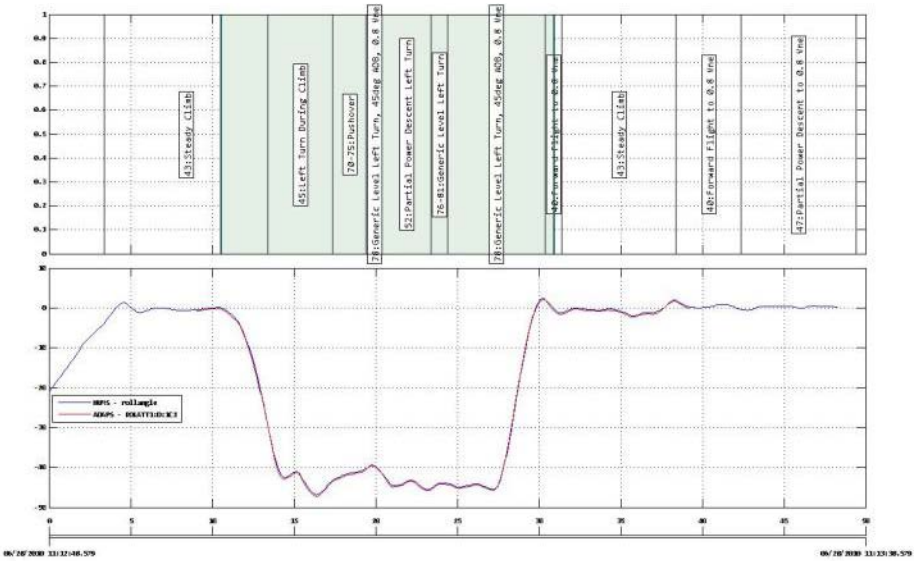
Regime	Counts	Time (%)	Time (sec)
40:Forward Flight to 0.8 Vne	1	2.037	0.64
52:Partial Power Descent Left Turn	1	31.614	10
76-81:Generic Level Left Turn	1	28.453	9
78:Generic Level Left Turn, 45° AoB, 0.8 Vne	2	31.615	10

Figure C-20. Runs 44-46: 0.8 Vne, Level Left-Turn 45° AoB, Normal



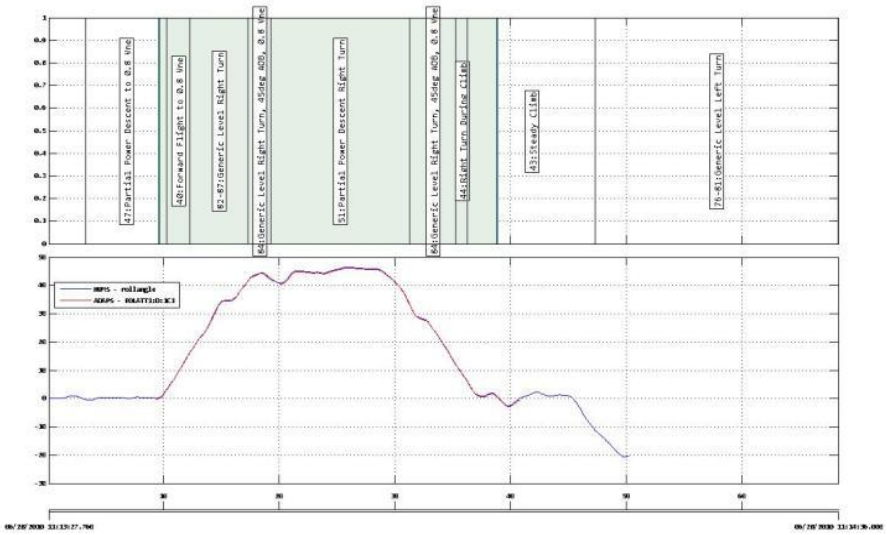
Regime	Counts	Time (%)	Time (sec)
39:Forward Flight to 0.5 Vne	1	10.546	4.49
43:Steady Climb	1	2.623	1.12
45:Left Turn During Climb	1	11.734	5
52:Partial Power Descent Left Turn	1	28.161	12
76-81:Generic Level Left Turn	1	30.508	13
78:Generic Level Left Turn, 45° AoB, 0.8 Vne	2	16.427	7

Figure C-21. Runs 47-49: 0.8 Vne, Level Left-Turn 45° AoB, Benign



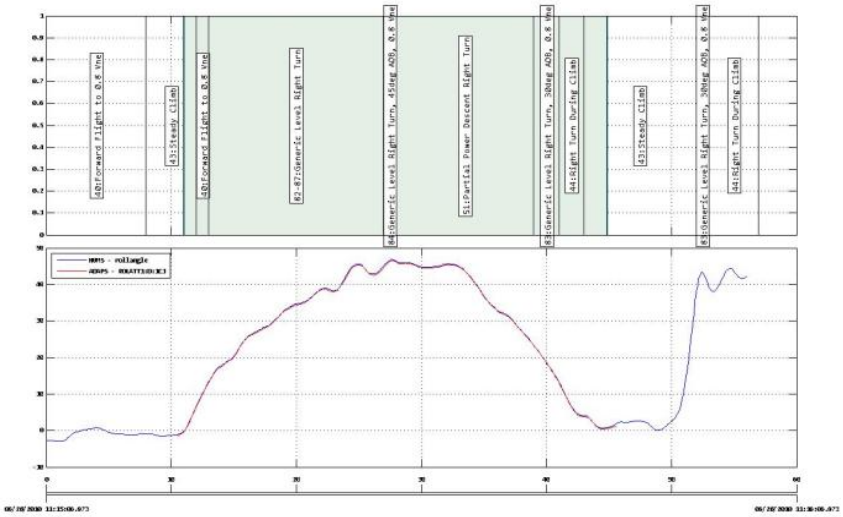
Regime	Counts	Time (%)	Time (sec)
40:Forward Flight to 0.8 Vne	1	2.576	0.53
43:Steady Climb	1	14.043	2.86
45:Left Turn During Climb	1	19.619	4
52:Partial Power Descent Left Turn	1	14.714	3
70-75:Pushover	1	9.81	2
76-81:Generic Level Left Turn	1	4.905	1
78:Generic Level Left Turn, 45° AoB, 0.8 Vne	2	34.333	7

Figure C-22. Run 50: 0.8 Vne, Level Left-Turn 45° AoB, Aggressive



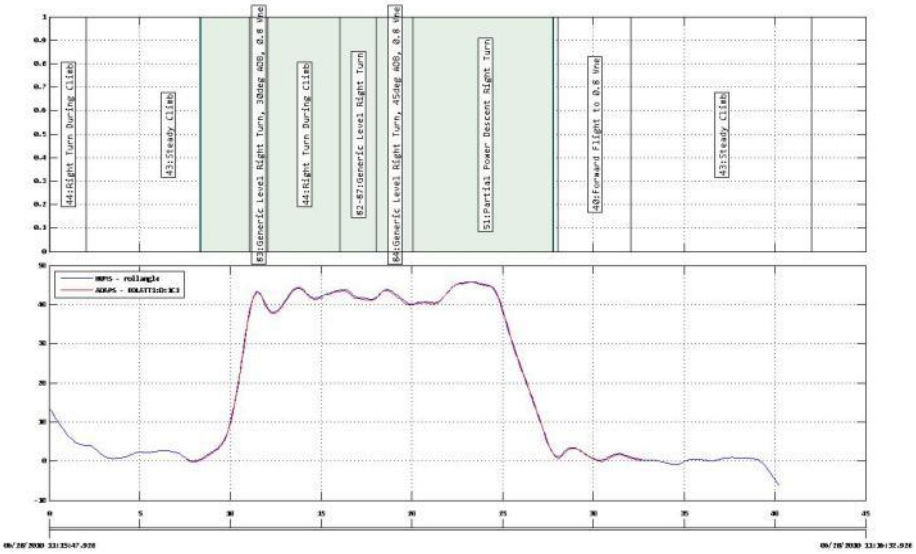
Regime	Counts	Time (%)	Time (sec)
40:Forward Flight to 0.8 Vne	1	6.845	2
43:Steady Climb	1	8.73	2.55
44:Right Turn During Climb	1	3.423	1
47:Partial Power Descent to 0.8 Vne	1	2.281	0.67
51:Partial Power Descent Right Turn	1	41.072	12
82-87:Generic Level Right Turn	1	17.113	5
84:Generic Level Right Turn, 45° AoB, 0.8 Vne	2	20.536	6

Figure C-23. Run 51-52: 0.8 Vne, Level Right-Turn 45° AoB, Normal



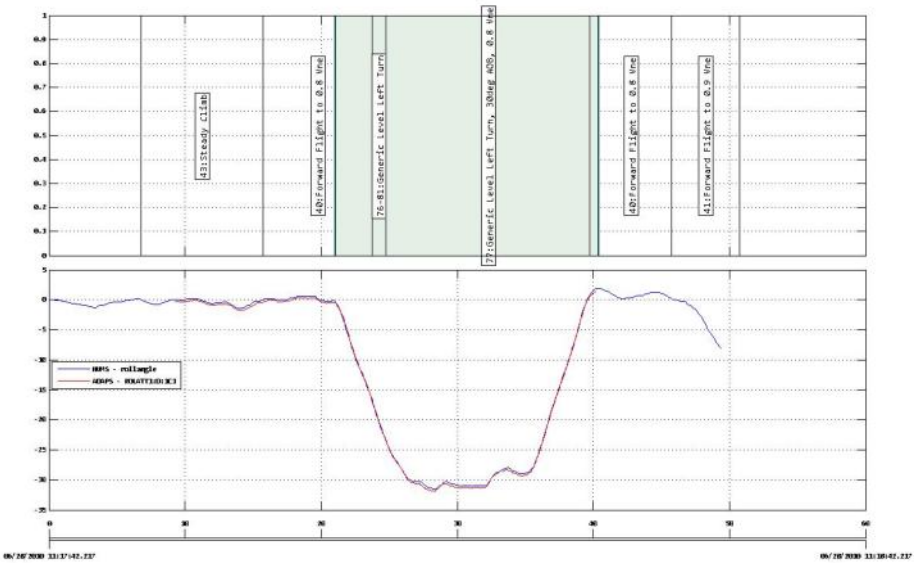
Regime	Counts	Time (%)	Time (sec)
40:Forward Flight to 0.8 Vne	1	2.955	1
43:Steady Climb	2	8.405	2.84
44:Right Turn During Climb	1	5.909	2
51:Partial Power Descent Right Turn	1	32.501	11
82-87:Generic Level Right Turn	1	41.365	14
83:Generic Level Right Turn, 30° AoB, 0.8 Vne	1	5.909	2
84:Generic Level Right Turn, 45° AoB, 0.8 Vne	1	2.955	1

Figure C-24. Runs 53-54: 0.8 Vne, Level Right-Turn 45° AoB, Benign



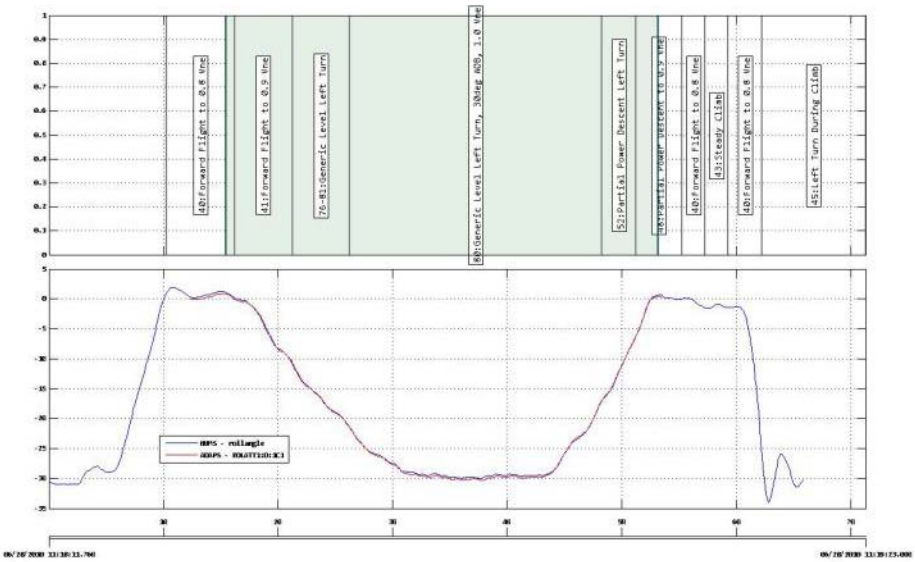
Regime	Counts	Time (%)	Time (sec)
43:Steady Climb	1	13.918	2.71
44:Right Turn During Climb	1	20.574	4
51:Partial Power Descent Right Turn	1	39.79	7.74
82-87:Generic Level Right Turn	1	10.287	2
83:Generic Level Right Turn, 30° AoB, 0.8 Vne	1	5.144	1
84:Generic Level Right Turn, 45° AoB, 0.8 Vne	1	10.287	2

Figure C-25. Runs 55-57: 0.8 Vne, Level Right-Turn 45° AoB, Aggressive



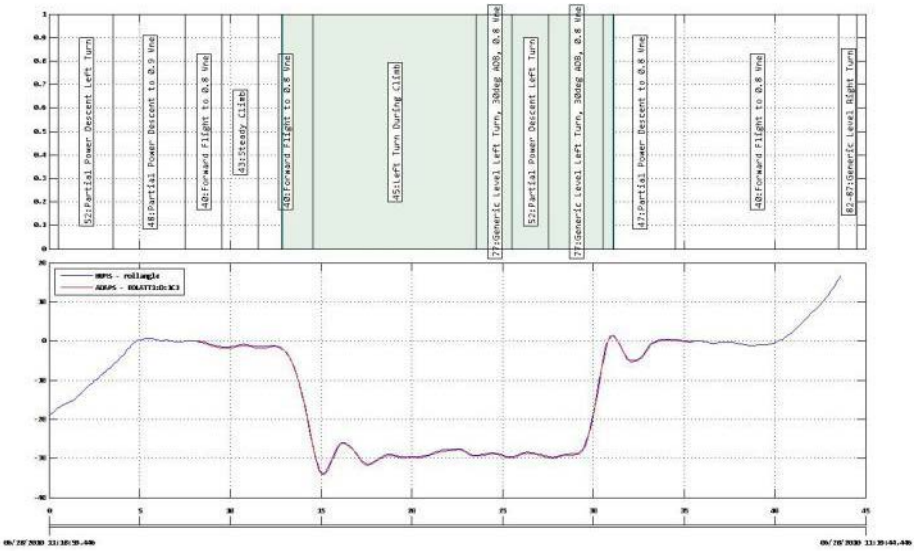
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
76-81:Generic Level Left Turn	1	5.171	1
77:Generic Level Left Turn, 30° AoB, 0.8 Vne	1	77.56	15

Figure C-26. Runs 58-60: 130 kt, Dive Left-Turn 30° AoB, Normal



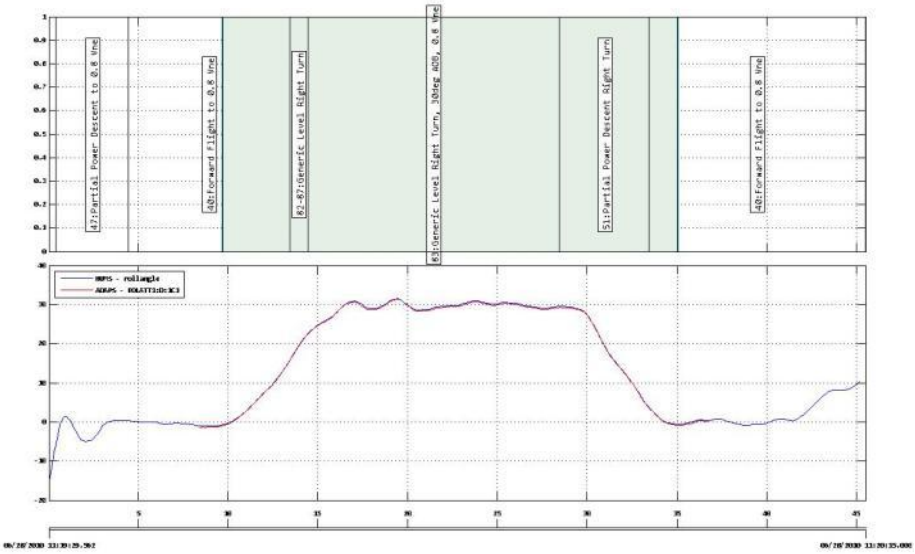
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
40:Forward Flight to 0.8 Vne	1	2.074	0.78
41:Forward Flight to 0.9 Vne	1	13.264	5
48:Partial Power Descent to 0.9 Vne	1	5.076	1.91
52:Partial Power Descent Left Turn	1	7.959	3
76-81:Generic Level Left Turn	1	13.264	5
80:Generic Level Left Turn, 30° AoB, 1.0 Vne	1	58.363	22

Figure C-27. Runs 61-62: 130 kt, Dive Left-Turn 30° AoB, Benign



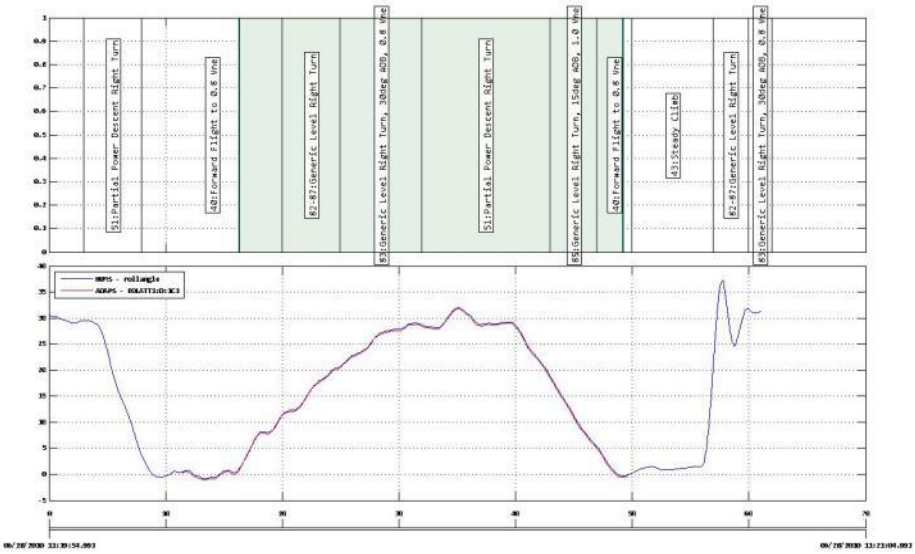
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
40:Forward Flight to 0.8 Vne	1	9.238	1.69
45:Left Turn During Climb	1	49.282	9
47:Partial Power Descent to 0.8 Vne	1	3.149	0.58
52:Partial Power Descent Left Turn	1	10.952	2
77:Generic Level Left Turn, 30° AoB, 0.8 Vne	2	27.379	5

Figure C-28. Run 63: 130 kt, Dive Left-Turn 30° AoB, Aggressive



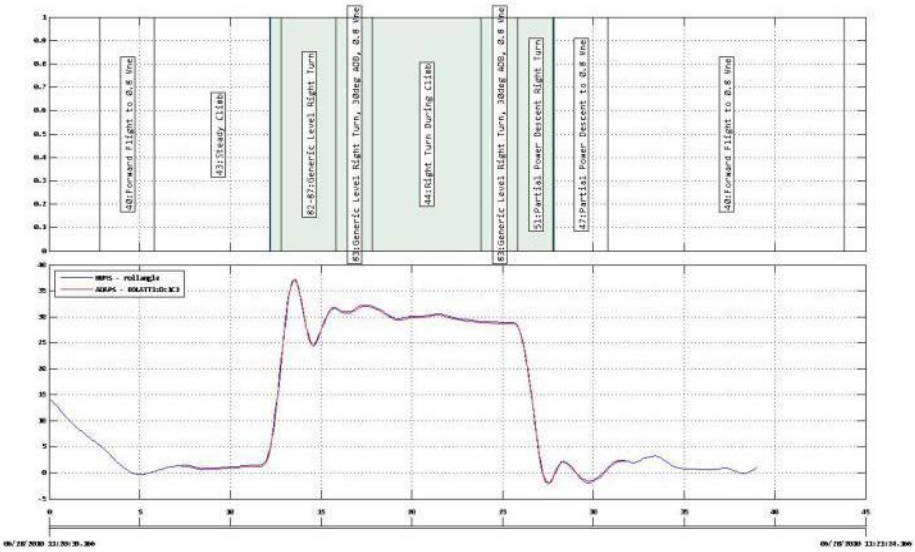
Regime	Counts	Time (%)	Time (sec)
40:Forward Flight to 0.8 Vne	2	21.017	5.32
51:Partial Power Descent Right Turn	1	19.746	5
82-87:Generic Level Right Turn	1	3.949	1
83:Generic Level Right Turn, 30° AoB, 0.8 Vne	1	55.288	14

Figure C-29. Runs 64-65: 130 kt, Dive Right-Turn 30° AoB, Normal



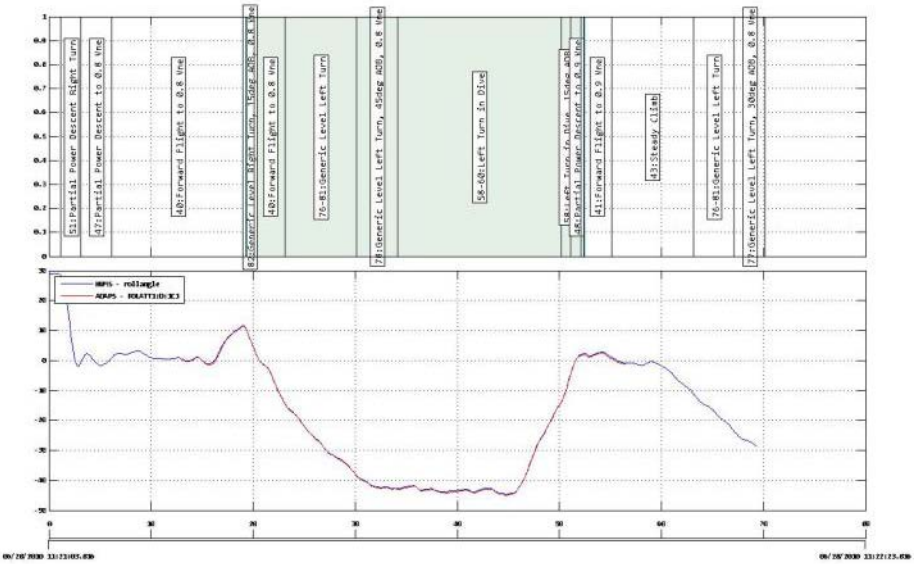
Regime	Counts	Time (%)	Time (sec)
40:Forward Flight to 0.8 Vne	2	17.916	5.89
51:Partial Power Descent Right Turn	1	33.442	11
82-87:Generic Level Right Turn	1	15.201	5
83:Generic Level Right Turn, 30° AoB, 0.8 Vne	1	21.281	7
85:Generic Level Right Turn, 15° AoB, 1.0 Vne	1	12.161	4

Figure C-30. Run 66: 130 kt, Dive Right-Turn 30° AoB, Benign



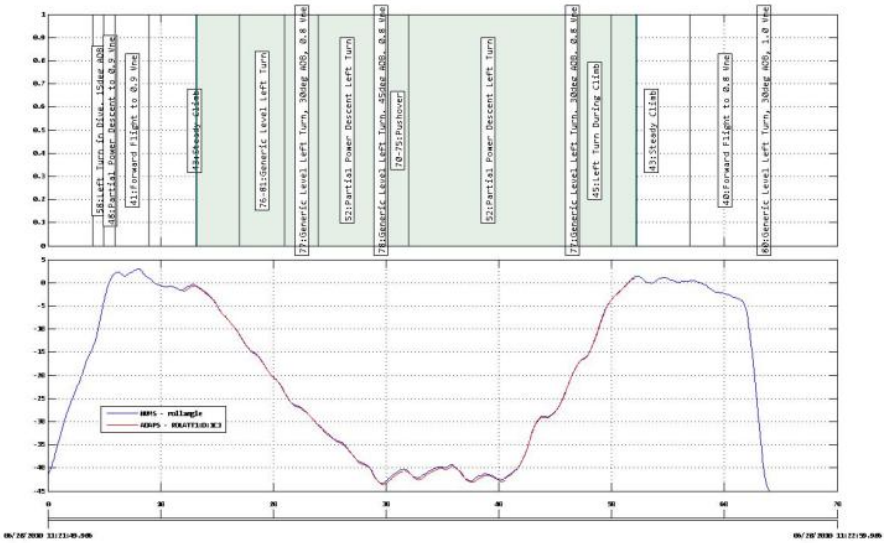
Regime	Counts	Time (%)	Time (sec)
43:Steady Climb	1	3.992	0.62
44:Right Turn During Climb	1	38.461	6
51:Partial Power Descent Right Turn	1	12.676	1.98
82-87:Generic Level Right Turn	1	19.23	3
83:Generic Level Right Turn, 30° AoB, 0.8 Vne	2	25.64	4

Figure C-31. Run 67: 130 kt, Dive Right-Turn 30° AoB, Aggressive



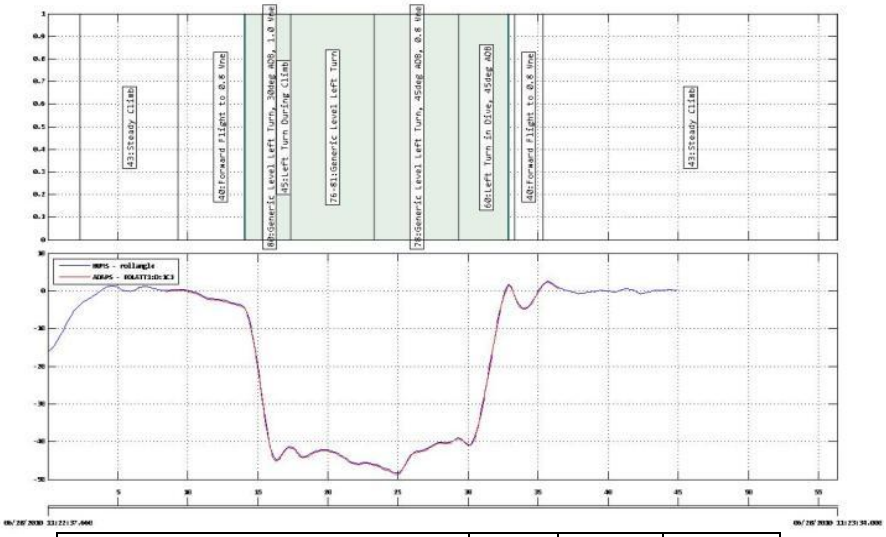
Regime	Counts	Time (%)	Time (sec)
40:Forward Flight to 0.8 Vne	1	9.067	3
41:Forward Flight to 0.9 Vne	1	0.852	0.28
48:Partial Power Descent to 0.9 Vne	1	3.022	1
58-60:Left Turn in Dive	1	48.357	16
58:Left Turn in Dive, 15° AoB	1	3.022	1
76-81:Generic Level Left Turn	1	21.156	7
78:Generic Level Left Turn, 45° AoB, 0.8 Vne	1	12.089	4
82:Generic Level Right Turn, 15° AoB, 0.8 Vne	1	2.434	0.81

Figure C-32. Runs 68-70: 130 kt, Dive Left-Turn 45° AoB, Normal



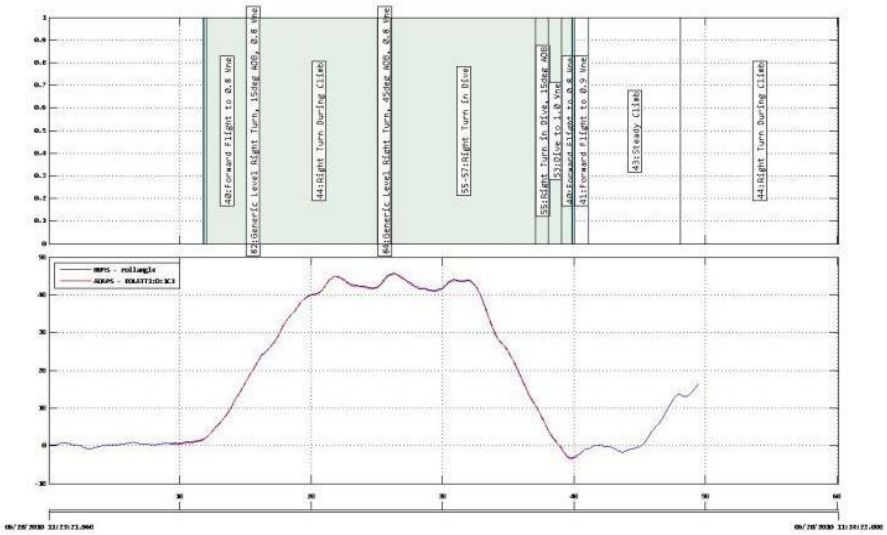
Regime	Counts	Time (%)	Time (sec)
43:Steady Climb	2	15.406	6.01
45:Left Turn During Climb	1	7.69	3
52:Partial Power Descent Left Turn	2	48.706	19
70-75:Pushover	1	5.127	2
76-81:Generic Level Left Turn	1	10.254	4
77:Generic Level Left Turn, 30° AoB, 0.8 Vne	2	10.254	4
78:Generic Level Left Turn, 45° AoB, 0.8 Vne	1	2.563	1

Figure C-33. Runs 71-73: 130 kt, Dive Left-Turn 45° AoB, Benign



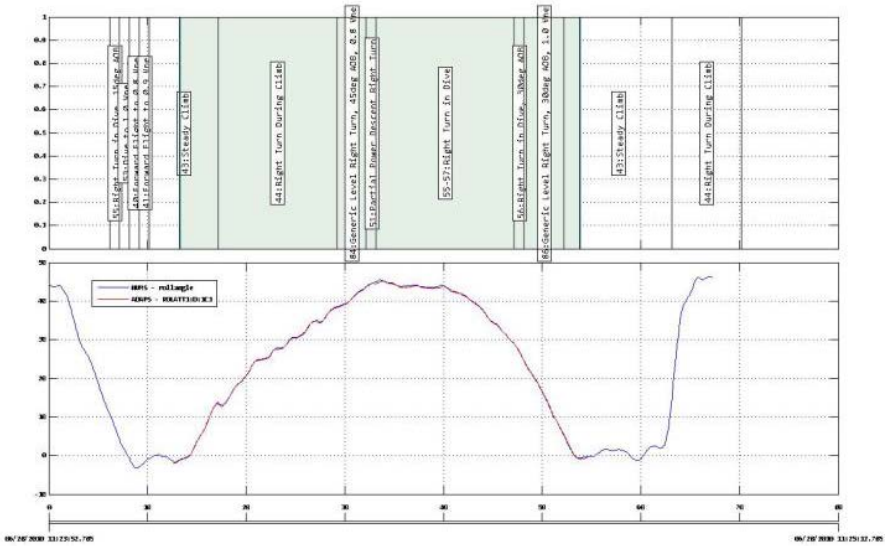
Regime	Counts	Time (%)	Time (sec)
40:Forward Flight to 0.8 Vne	1	6.67	1.26
45:Left Turn During Climb	1	5.314	1
60:Left Turn in Dive, 45° AoB	1	18.927	3.56
76-81:Generic Level Left Turn	1	31.887	6
78:Generic Level Left Turn, 45° AoB, 0.8 Vne	1	31.887	6
80:Generic Level Left Turn, 30° AoB, 1.0 Vne	1	5.315	1

Figure C-34. Runs 74-75: 130 kt, Dive Left-Turn 45° AoB, Aggressive



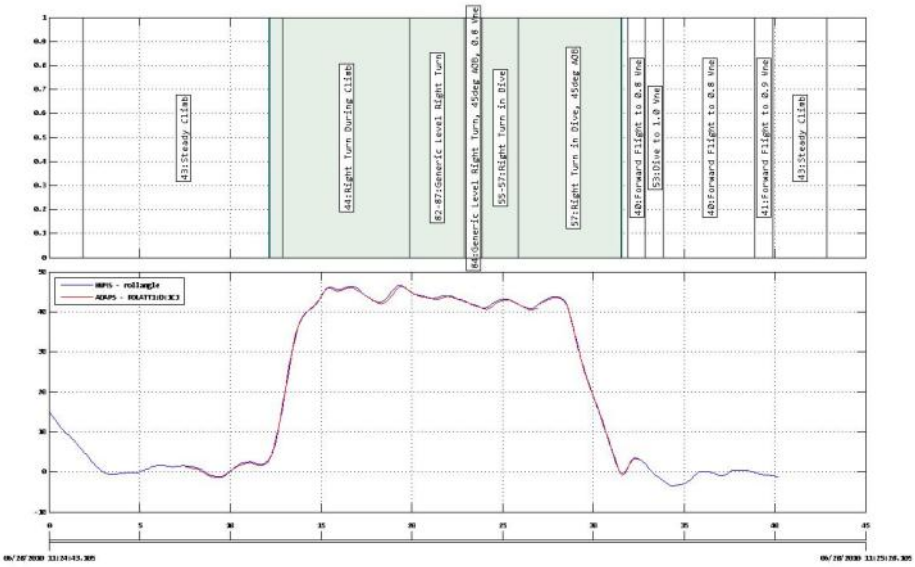
Regime	Counts	Time (%)	Time (sec)
40:Forward Flight to 0.8 Vne	2	13.56	3.8
44:Right Turn During Climb	1	32.099	9
53:Dive to 1.0 Vne	1	3.567	1
55-57:Right Turn in Dive	1	39.232	11
55:Right Turn in Dive, 15° AoB	1	3.567	1
82:Generic Level Right Turn, 15° AoB, 0.8 Vne	1	3.567	1
84:Generic Level Right Turn, 45° AoB, 0.8 Vne	1	3.567	1

Figure C-35. Runs 76-77: 130 kt, Dive Right-Turn 45° AoB, Normal



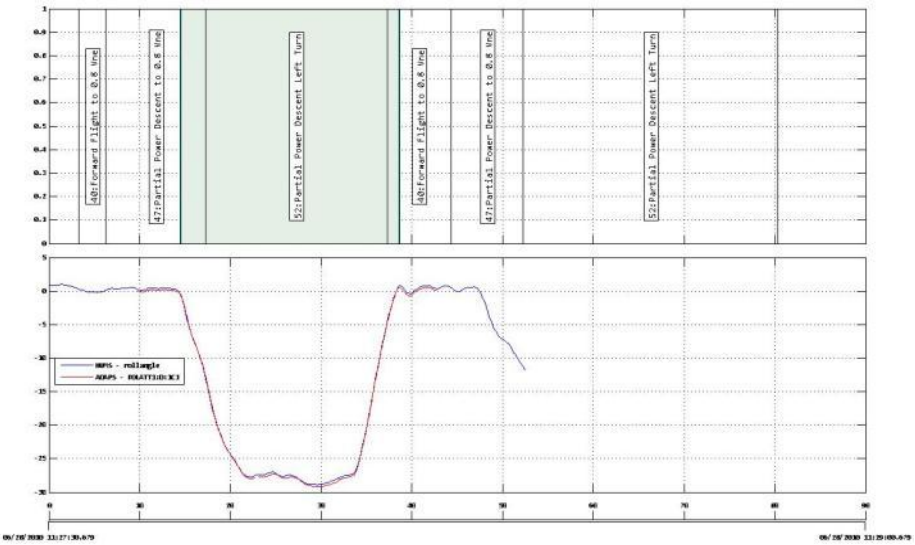
Regime	Counts	Time (%)	Time (sec)
43:Steady Climb	2	13.673	5.54
44:Right Turn During Climb	1	29.598	12
51:Partial Power Descent Right Turn	1	2.466	1
55-57:Right Turn in Dive	1	34.531	14
56:Right Turn in Dive, 30° AoB	1	2.466	1
84:Generic Level Right Turn, 45° AoB, 0.8 Vne	1	7.399	3
86:Generic Level Right Turn, 30° AoB, 1.0 Vne	1	9.866	4

Figure C-36. Runs 78-80: 130 kt, Dive Right-Turn 45° AoB, Benign



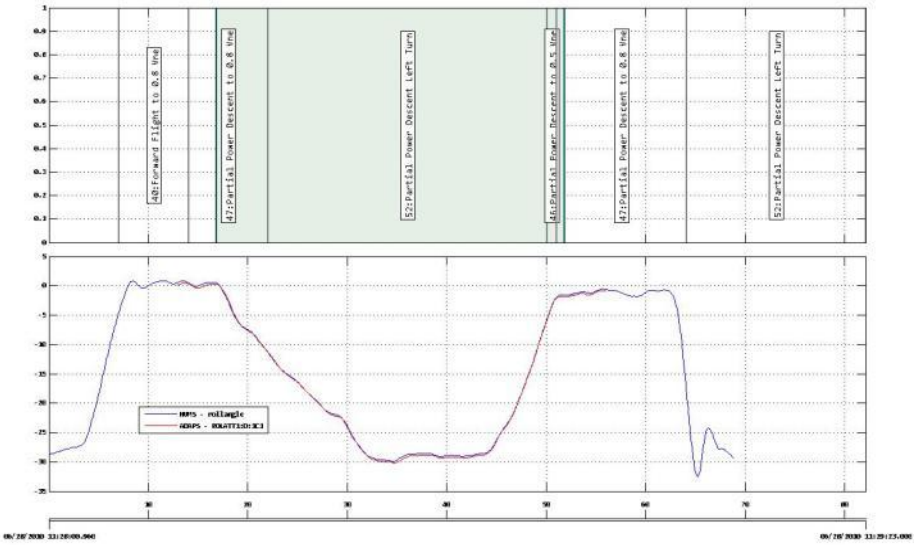
Regime	Counts	Time (%)	Time (sec)
43:Steady Climb	1	3.752	0.73
44:Right Turn During Climb	1	36.086	7
55-57:Right Turn in Dive	1	10.31	2
57:Right Turn in Dive, 45° AoB	1	29.231	5.67
82-87:Generic Level Right Turn	1	15.465	3
84:Generic Level Right Turn, 45° AoB, 0.8 Vne	1	5.155	1

Figure C-37. Runs 81-83: 130 kt, Dive Right-Turn 45° AoB, Aggressive



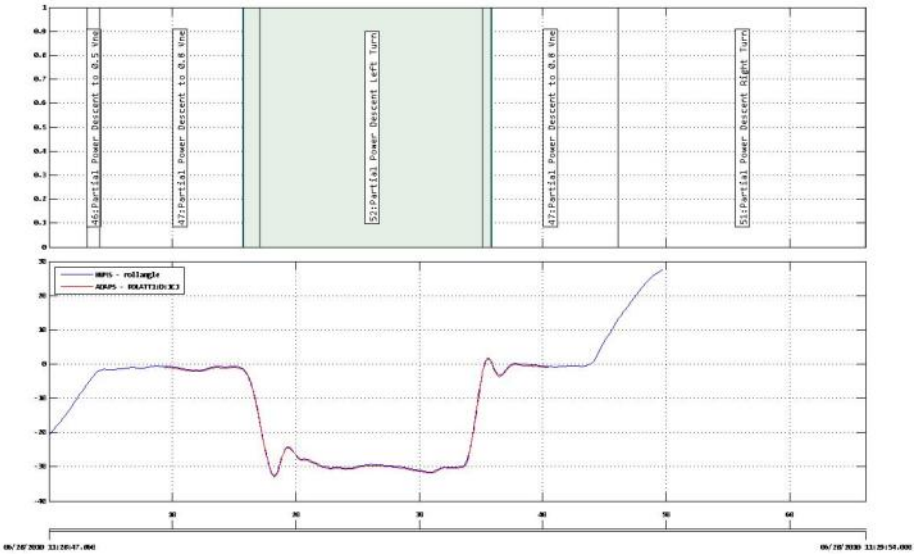
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
40:Forward Flight to 0.8 Vne	1	5.572	1.34
47:Partial Power Descent to 0.8 Vne	1	11.497	2.77
52:Partial Power Descent Left Turn	1	82.931	20

Figure C-38. Runs 85-87: 80 kt, PPD Left-Turn 30° AoB, Normal



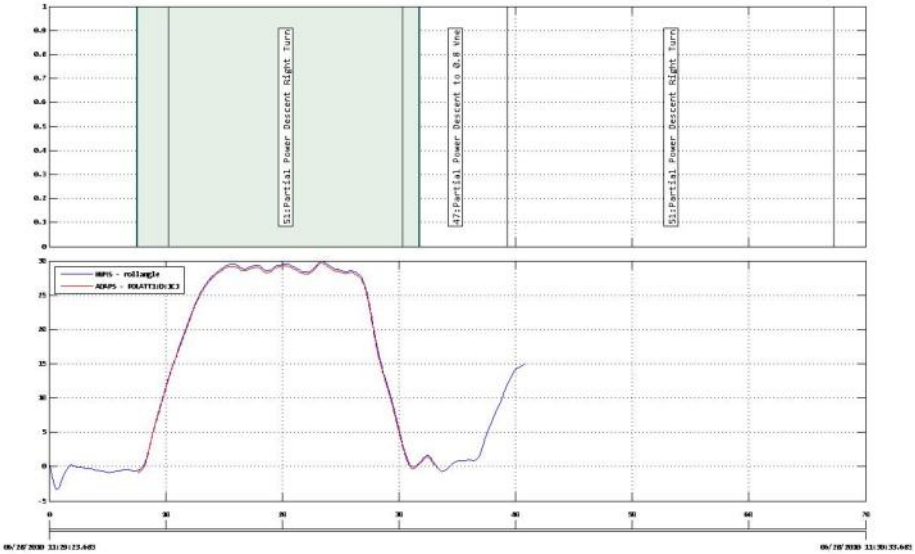
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
40:Forward Flight to 0.8 Vne	0	0	0
46:Partial Power Descent to 0.5 Vne	1	2.86	1
47:Partial Power Descent to 0.8 Vne	2	17.064	5.97
52:Partial Power Descent Left Turn	1	80.077	28

Figure C-39. Runs 88-89: 80 kt, PPD Left-Turn 30° AoB, Benign



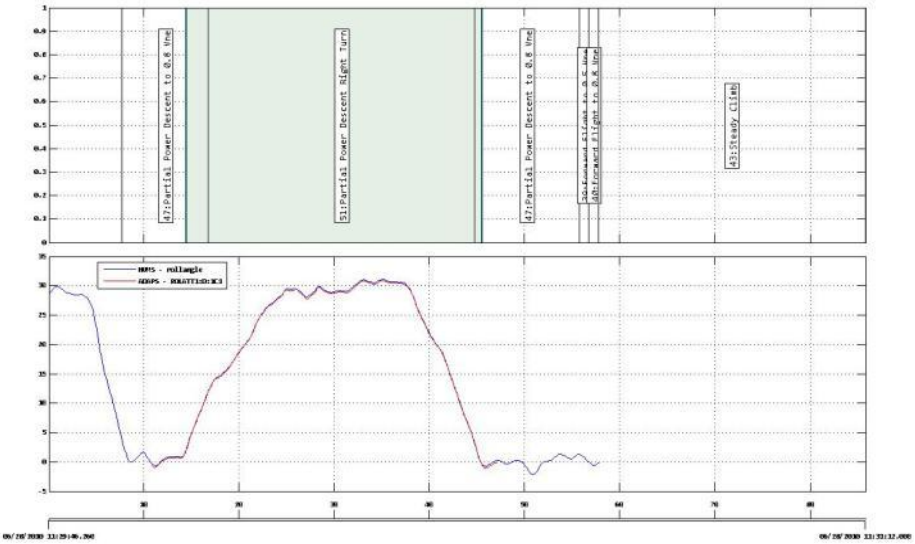
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
47:Partial Power Descent to 0.8 Vne	2	10.443	2.1
52:Partial Power Descent Left Turn	1	89.557	18

Figure C-40. Runs 90-91: 80 kt, PPD Left-Turn 30° AoB, Aggressive



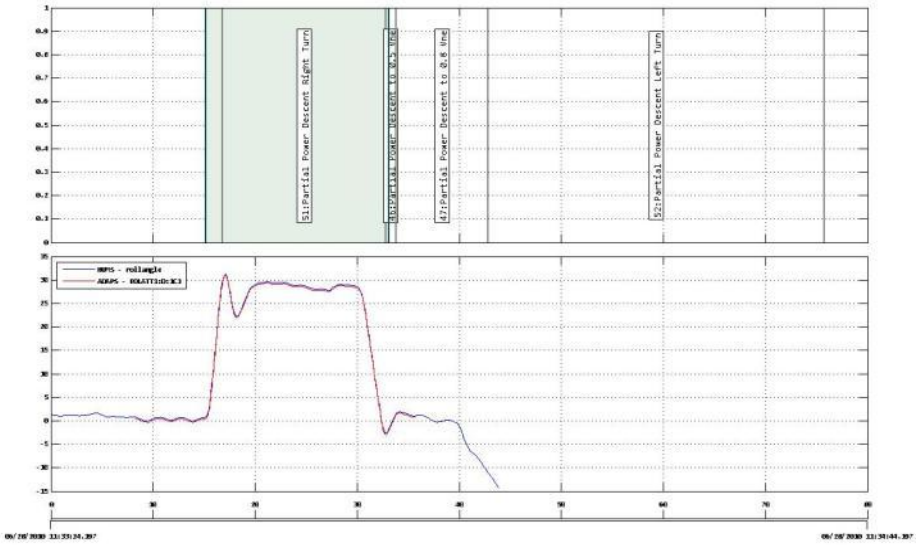
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
47:Partial Power Descent to 0.8 Vne	1	6.014	1.46
51:Partial Power Descent Right Turn	1	82.665	20

Figure C-41. Run 92: 80 kt, PPD Right-Turn 30° AoB, Normal



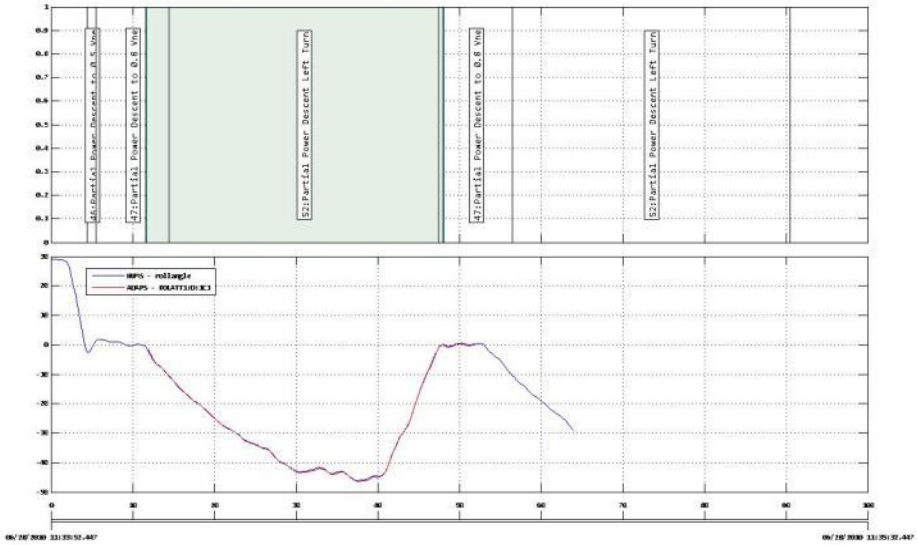
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
47:Partial Power Descent to 0.8 Vne	2	9.822	3.05
51:Partial Power Descent Right Turn	1	90.178	28

Figure C-42. Run 93-94: 80 kt, PPD Right-Turn 30° AoB, Benign



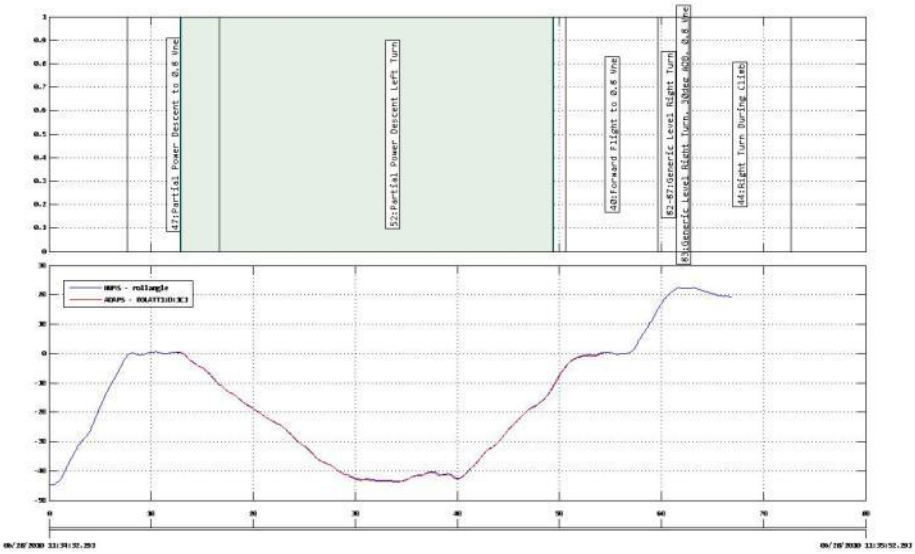
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
46:Partial Power Descent to 0.5 Vne	1	1.801	0.32
51:Partial Power Descent Right Turn	1	89.177	16

Figure C-43. Runs 95: 80 kt, PPD Right-Turn 30° AoB, Aggressive



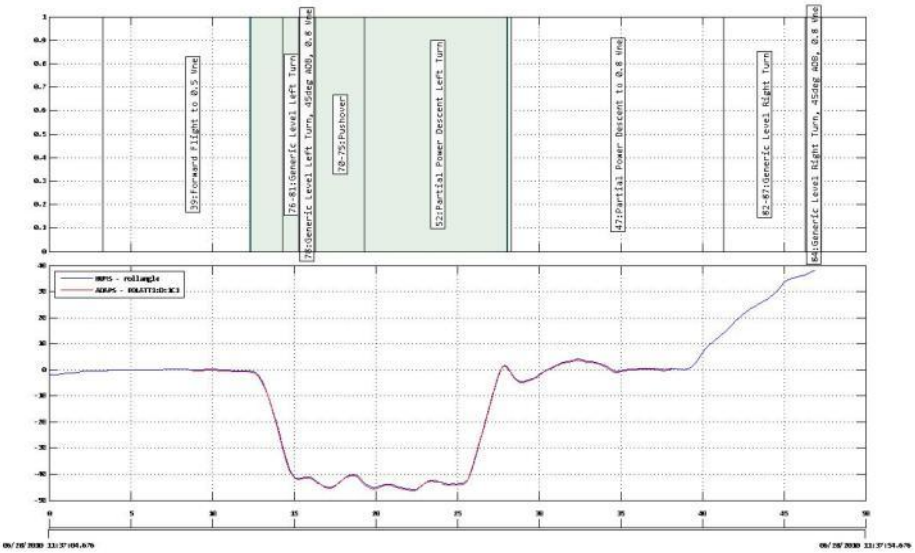
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
47:Partial Power Descent to 0.8 Vne	2	9.36	3.41
52:Partial Power Descent Left Turn	1	90.64	33

Figure C-44. Runs 96-98: 80 kt, PPD Left-Turn 45° AoB, Normal



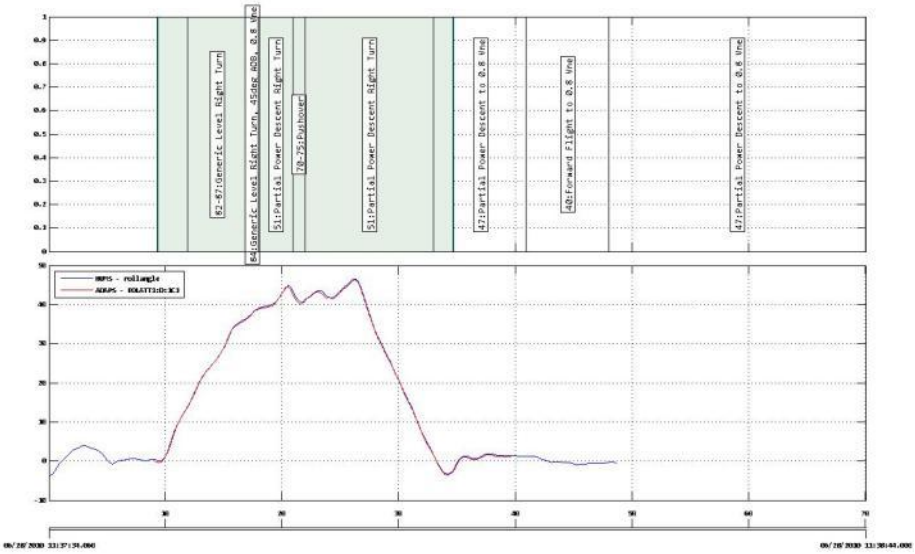
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
47:Partial Power Descent to 0.8 Vne	1	10.343	3.78
52:Partial Power Descent Left Turn	1	89.657	32.73

Figure C-45. Runs 99-101: 80 kt, PPD Left-Turn 45° AoB, Benign



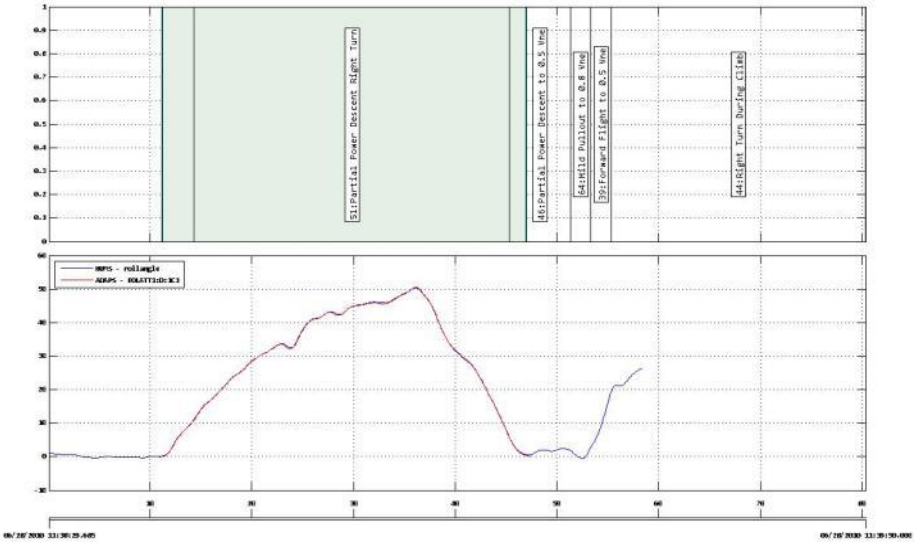
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
39:Forward Flight to 0.5 Vne	1	12.525	1.97
52:Partial Power Descent Left Turn	1	55.685	8.76
70-75:Pushover	1	19.074	3
76-81:Generic Level Left Turn	1	6.358	1
78:Generic Level Left Turn, 45° AoB, 0.8 Vne	1	6.358	1

Figure C-46. Runs 102-104: 80 kt, PPD Left-Turn 45° AoB, Aggressive



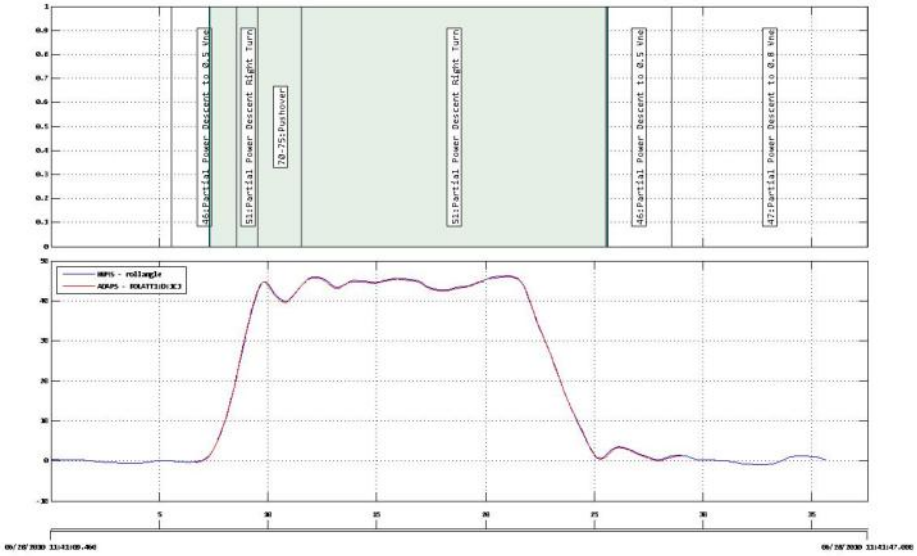
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
47:Partial Power Descent to 0.8 Vne	1	6.808	1.72
51:Partial Power Descent Right Turn	2	55.275	14
70-75:Pushover	1	3.948	1
82-87:Generic Level Right Turn	1	19.741	5
84:Generic Level Right Turn, 45° AoB, 0.8 Vne	1	3.948	1

Figure C-47. Runs 105-106: 80 kt, PPD Right-Turn 45° AoB, Normal



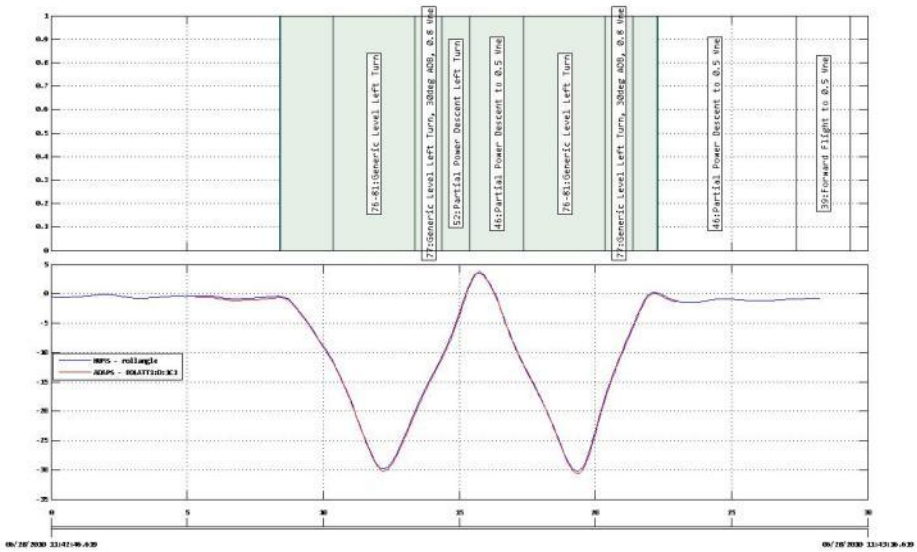
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
46:Partial Power Descent to 0.5 Vne	1	4.653	1.67
51:Partial Power Descent Right Turn	1	86.614	31

Figure C-48. Runs 107-108: 80 kt, PPD Right-Turn 45° AoB, Benign



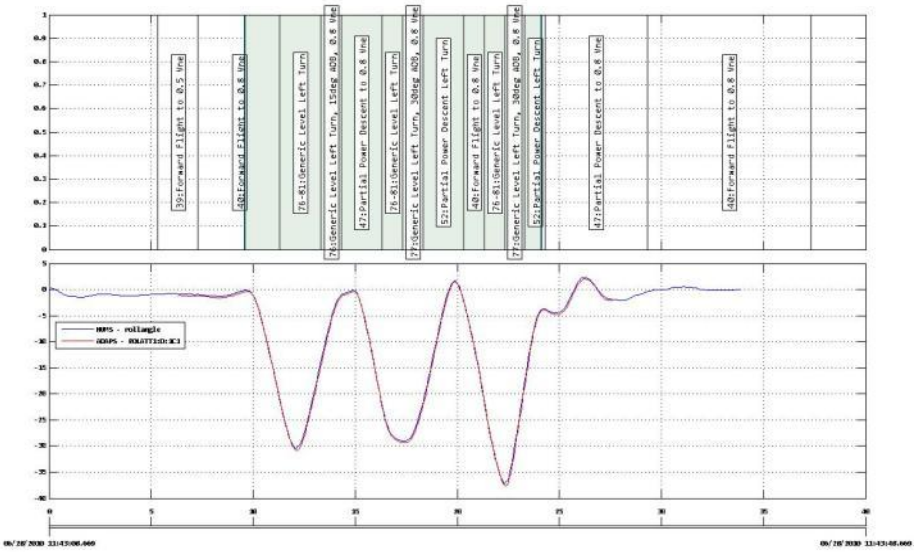
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
46:Partial Power Descent to 0.5 Vne	2	7.085	1.3
51:Partial Power Descent Right Turn	2	81.984	15
70-75:Pushover	1	10.931	2

Figure C-49. Runs 109-110: 80 kt, PPD Right-Turn 45° AoB, Aggressive



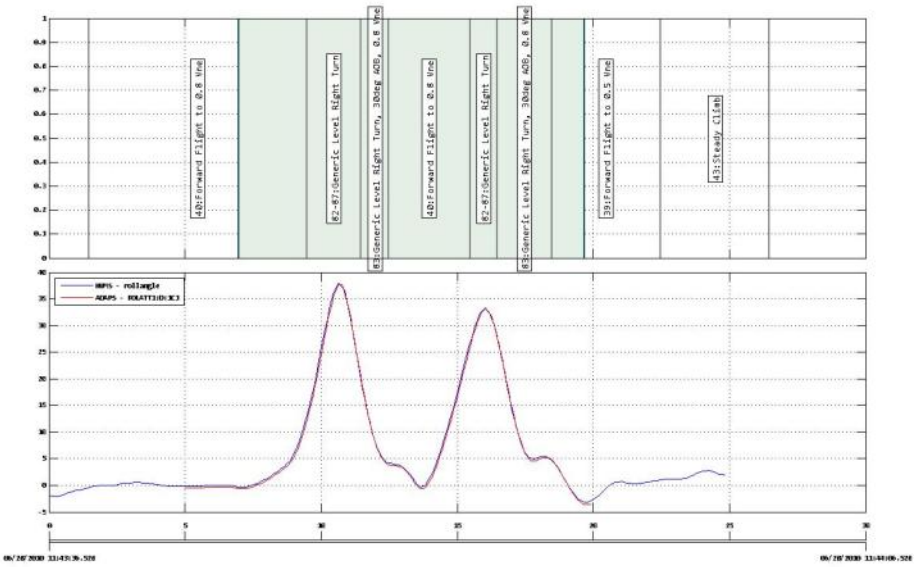
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
46:Partial Power Descent to 0.5 Vne	2	21.025	2.91
52:Partial Power Descent Left Turn	1	7.213	1
76-81:Generic Level Left Turn	2	43.277	6
77:Generic Level Left Turn, 30° AoB, 0.8 Vne	2	14.426	2

Figure C-50. Run 112: 80 kt, Two Repeats Level Left-Turn 30° AoB, Normal



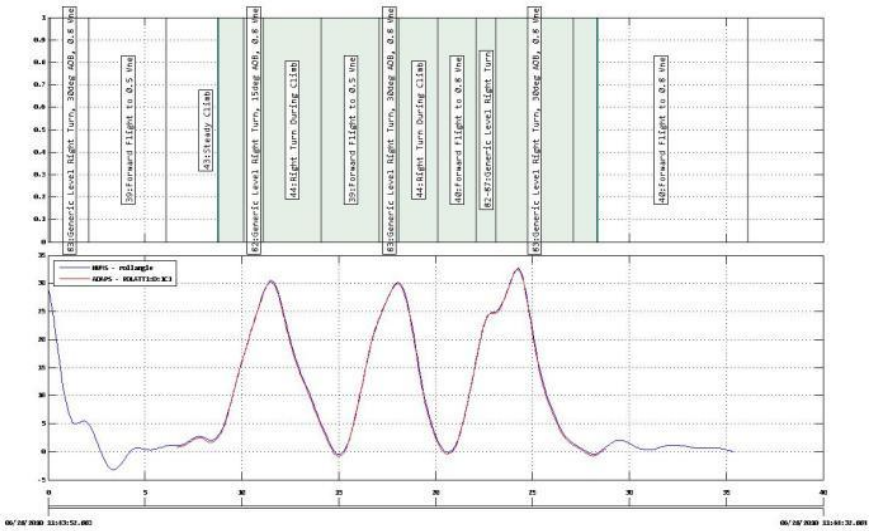
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
40:Forward Flight to 0.8 Vne	2	18.725	2.72
47:Partial Power Descent to 0.8 Vne	1	13.77	2
52:Partial Power Descent Left Turn	2	19.31	2.8
76-81:Generic Level Left Turn	3	27.54	4
76:Generic Level Left Turn, 15° AoB, 0.8 Vne	1	6.885	1
77:Generic Level Left Turn, 30° AoB, 0.8 Vne	2	13.77	2

Figure C-51. Run 113: 80 kt, Three Repeats Level Left-Turn 30° AoB, Normal



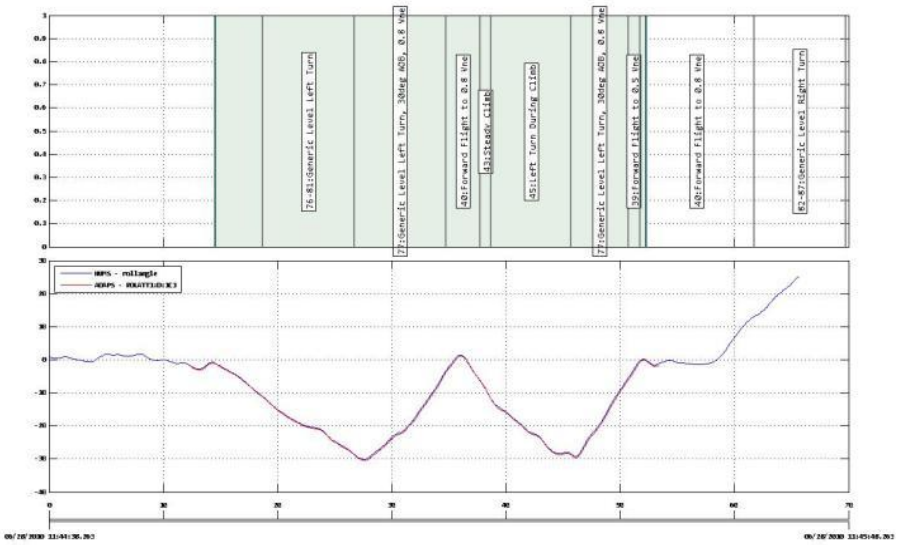
Regime	Counts	Time (%)	Time (sec)
39:Forward Flight to 0.5 Vne	1	9.475	1.2
40:Forward Flight to 0.8 Vne	2	43.277	5.5
82-87:Generic Level Right Turn	2	23.624	3
83:Generic Level Right Turn, 30° AoB, 0.8 Vne	2	23.624	3

Figure C-52. Run 114: 80 kt, Two Repeats Level Right-Turn 30° AoB, Normal



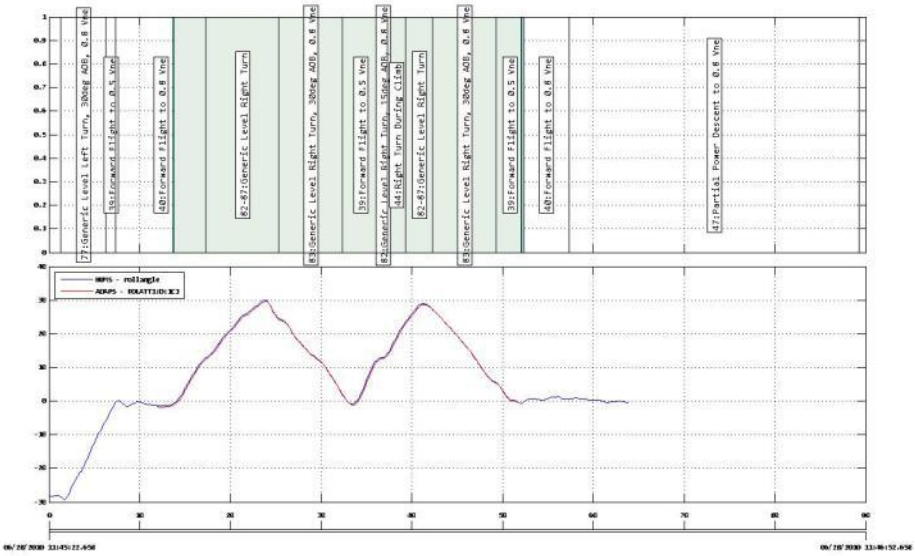
Regime	Counts	Time (%)	Time (sec)
39:Forward Flight to 0.5 Vne	1	15.327	3
40:Forward Flight to 0.8 Vne	2	16.617	3.25
43:Steady Climb	1	6.746	1.32
44:Right Turn During Climb	2	25.546	5
82-87:Generic Level Right Turn	1	5.109	1
82:Generic Level Right Turn, 15° AoB, 0.8 Vne	1	5.109	1
83:Generic Level Right Turn, 30° AoB, 0.8 Vne	2	25.546	5

Figure C-53. Run 115: 80 kt, Three Repeats Level Right-Turn 30° AoB, Normal



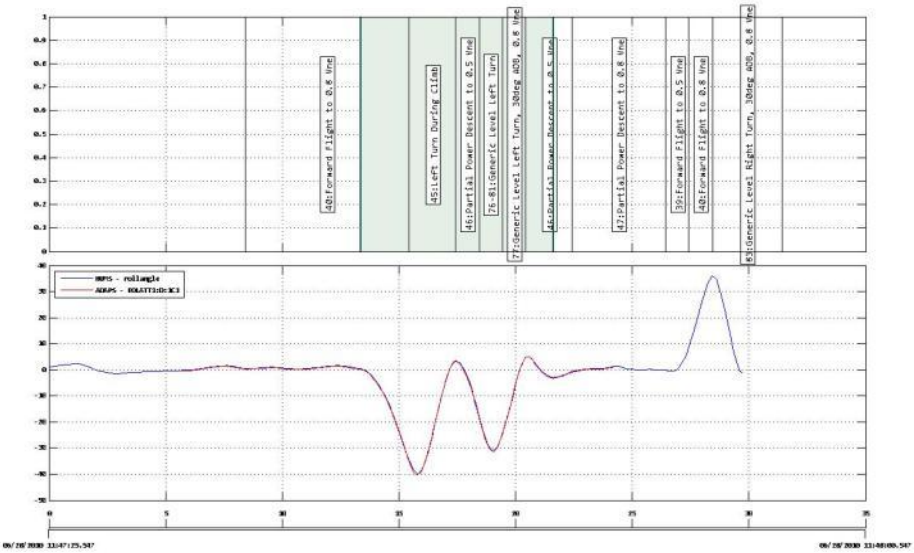
Regime	Counts	Time (%)	Time (sec)
39:Forward Flight to 0.5 Vne	1	2.651	1
40:Forward Flight to 0.8 Vne	2	9.436	3.56
43:Steady Climb	1	2.651	1
45:Left Turn During Climb	1	18.559	7
76-81:Generic Level Left Turn	1	21.21	8
77:Generic Level Left Turn, 30° AoB, 0.8 Vne	2	34.466	13

Figure C-54. Run 116: 80 kt, Two Repeats Level Left-Turn 30° AoB, Benign



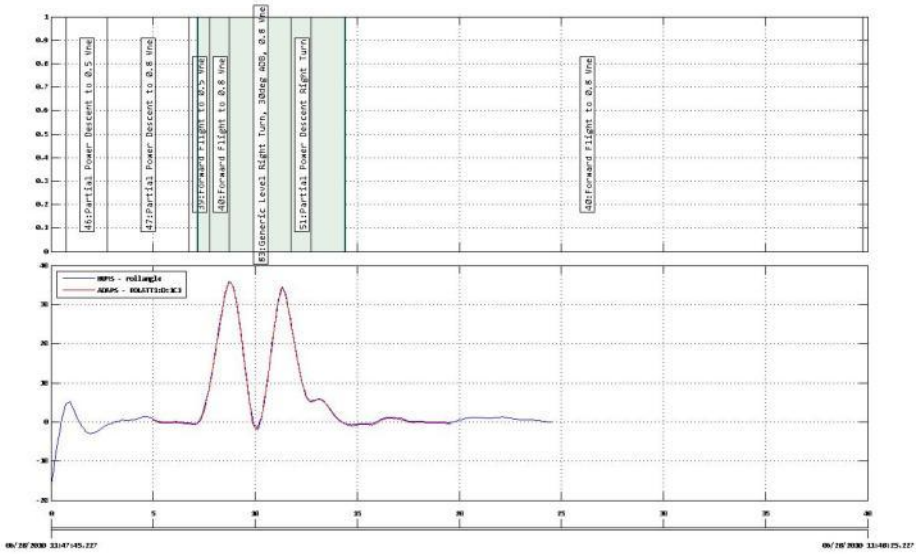
Regime	Counts	Time (%)	Time (sec)
39:Forward Flight to 0.5 Vne	2	17.673	6.78
40:Forward Flight to 0.8 Vne	1	9.333	3.58
44:Right Turn During Climb	1	5.214	2
82-87:Generic Level Right Turn	2	28.676	11
82:Generic Level Right Turn, 15° AoB, 0.8 Vne	1	2.607	1
83:Generic Level Right Turn, 30° AoB, 0.8 Vne	2	36.497	14

Figure C-55. Run 117: 80 kt, Two Repeats Level Right-Turn 30° AoB, Benign



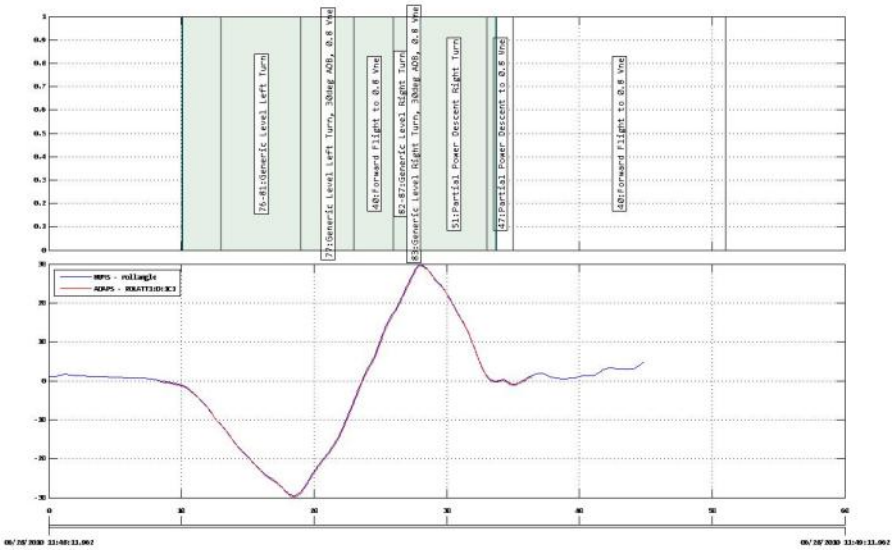
Regime	Counts	Time (%)	Time (sec)
40:Forward Flight to 0.8 Vne	1	25.222	2.08
45:Left Turn During Climb	1	24.206	2
46:Partial Power Descent to 0.5 Vne	2	26.366	2.18
76-81:Generic Level Left Turn	1	12.103	1
77:Generic Level Left Turn, 30° AoB, 0.8 Vne	1	12.103	1

Figure C-56. Run 118: 80 kt, Two Repeats Level Left-Turn 30° AoB, Aggressive



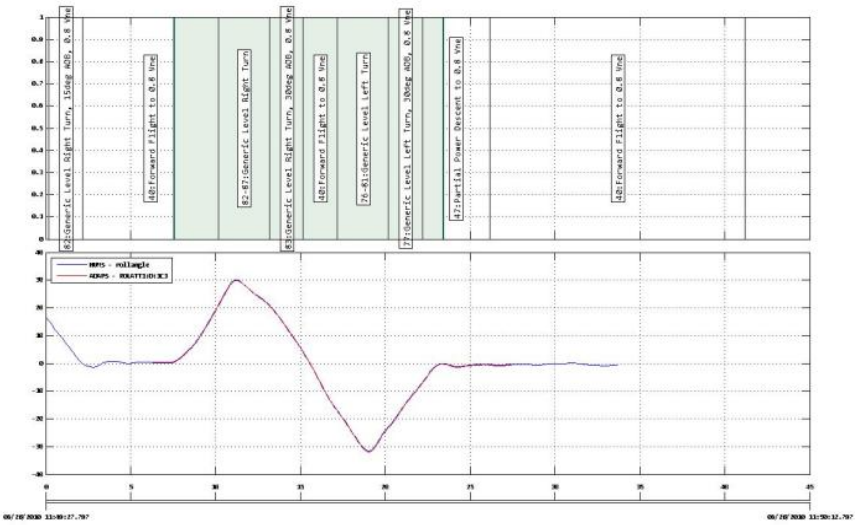
Regime	Counts	Time (%)	Time (sec)
39:Forward Flight to 0.5 Vne	1	7.876	0.57
40:Forward Flight to 0.8 Vne	2	36.747	2.65
51:Partial Power Descent Right Turn	1	13.844	1
83:Generic Level Right Turn, 30° AoB, 0.8 Vne	1	41.532	3

Figure C-57. Run 119: 80 kt, Two Repeats Level Right-Turn 30° AoB, Aggressive



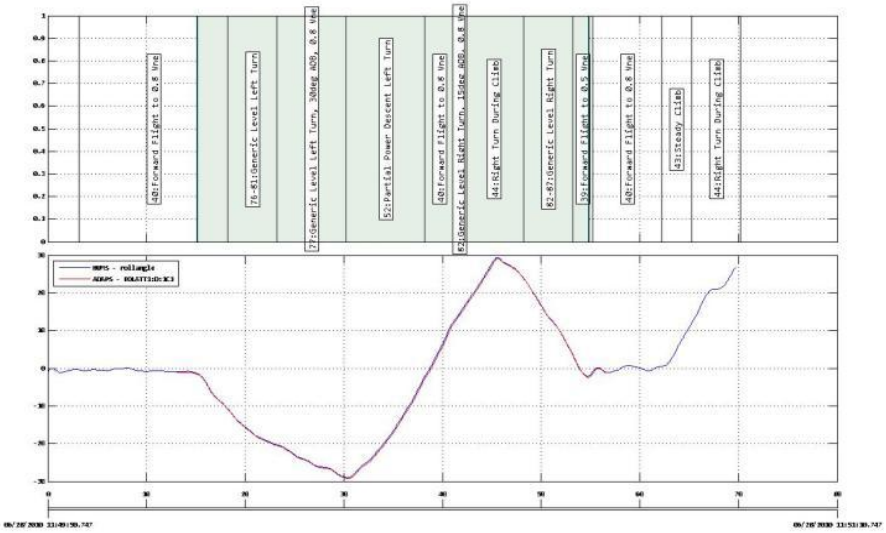
Regime	Counts	Time (%)	Time (sec)
40:Forward Flight to 0.8 Vne	1	12.685	3
47:Partial Power Descent to 0.8 Vne	1	3.041	0.72
51:Partial Power Descent Right Turn	1	21.141	5
76-81:Generic Level Left Turn	1	25.369	6
77:Generic Level Left Turn, 30° AoB, 0.8 Vne	1	16.913	4
82-87:Generic Level Right Turn	1	4.228	1
83:Generic Level Right Turn, 30° AoB, 0.8 Vne	1	4.228	1

Figure C-58. Run 120: 80 kt, Level Left-Turn, Right-Turn 30° AoB, Normal



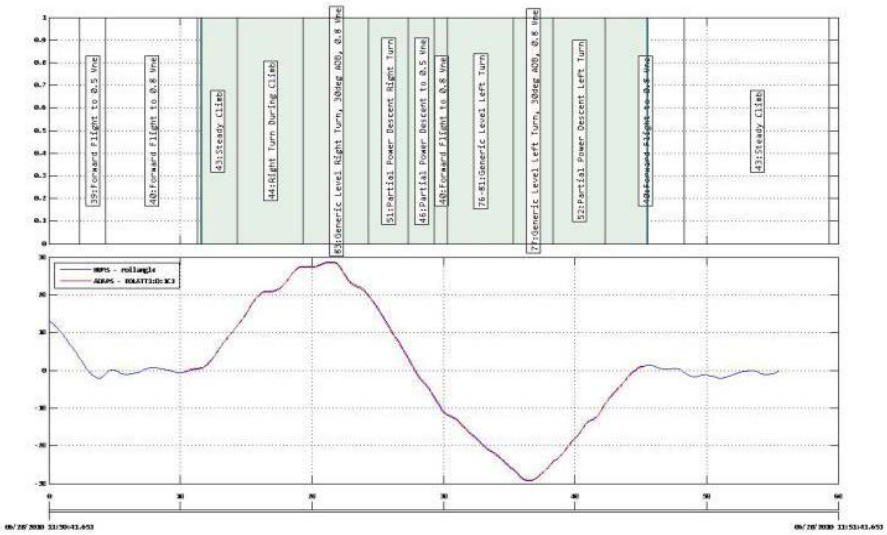
Regime	Counts	Time (%)	Time (sec)
40:Forward Flight to 0.8 Vne	2	29.152	4.62
47:Partial Power Descent to 0.8 Vne	1	7.793	1.24
76-81:Generic Level Left Turn	1	18.916	3
77:Generic Level Left Turn, 30° AoB, 0.8 Vne	1	12.611	2
82-87:Generic Level Right Turn	1	18.916	3
83:Generic Level Right Turn, 30° AoB, 0.8 Vne	1	12.611	2

Figure C-59. Run 121: 80 kt, Level Right-Turn, Left-Turn 30° AoB, Normal



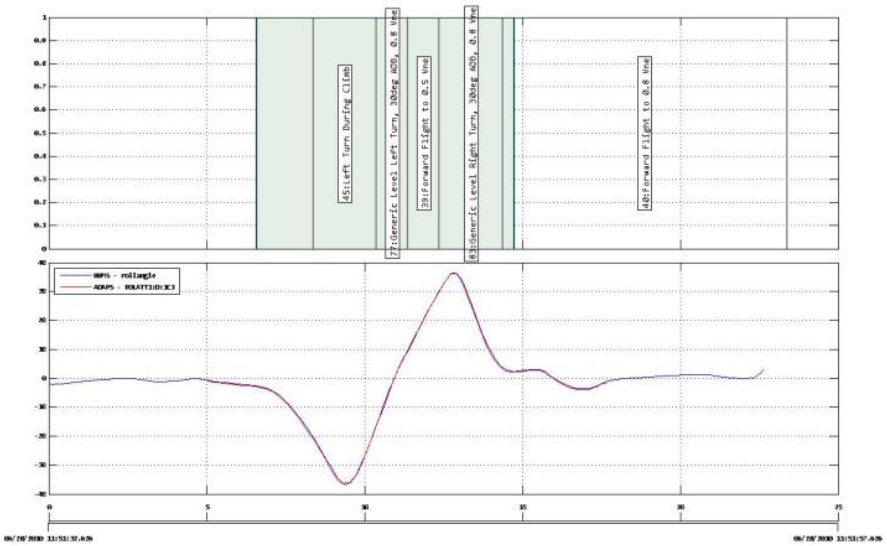
Regime	Counts	Time (%)	Time (sec)
39:Forward Flight to 0.5 Vne	1	4.082	1.62
40:Forward Flight to 0.8 Vne	2	15.291	6.07
44:Right Turn During Climb	1	15.117	6
52:Partial Power Descent Left Turn	1	20.157	8
76-81:Generic Level Left Turn	1	12.598	5
77:Generic Level Left Turn, 30° AoB, 0.8 Vne	1	17.637	7
82-87:Generic Level Right Turn	1	12.598	5
82:Generic Level Right Turn, 15° AoB, 0.8 Vne	1	2.52	1

Figure C-60. Run 122: 80 kt, Level Left-Turn, Right-Turn 30° AoB, Benign



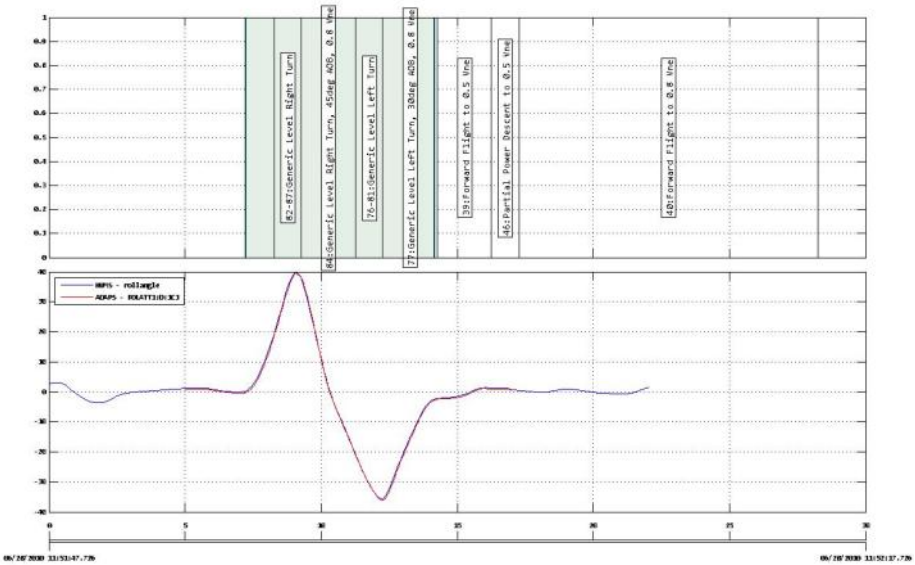
Regime	Counts	Time (%)	Time (sec)
40:Forward Flight to 0.8 Vne	2	12.316	4.18
43:Steady Climb	1	8.045	2.73
44:Right Turn During Climb	1	14.748	5
46:Partial Power Descent to 0.5 Vne	1	5.899	2
51:Partial Power Descent Right Turn	1	8.849	3
52:Partial Power Descent Left Turn	1	11.798	4
76-81:Generic Level Left Turn	1	14.748	5
77:Generic Level Left Turn, 30° AoB, 0.8 Vne	1	8.849	3
83:Generic Level Right Turn, 30° AoB, 0.8 Vne	1	14.748	5

Figure C-61. Run 123: 80 kt, Level Right-Turn, Left-Turn 30° AoB, Benign



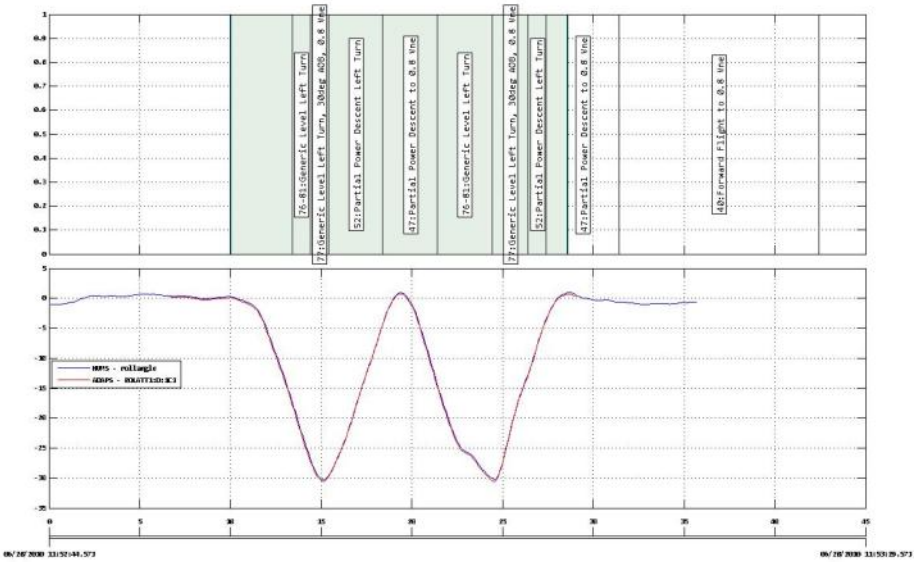
Regime	Counts	Time (%)	Time (sec)
39:Forward Flight to 0.5 Vne	1	12.262	1
40:Forward Flight to 0.8 Vne	1	4.55	0.37
45:Left Turn During Climb	1	24.524	2
77:Generic Level Left Turn, 30° AoB, 0.8 Vne	1	12.262	1
83:Generic Level Right Turn, 30° AoB, 0.8 Vne	1	24.524	2

Figure C-62. Run 124: 80 kt, Level Left-Turn, Right-Turn 30° AoB, Aggressive



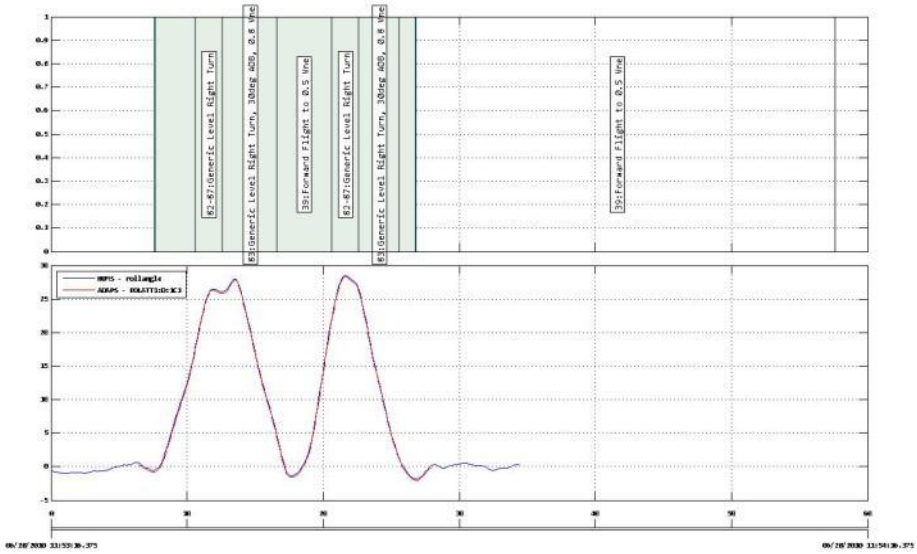
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
76-81:Generic Level Left Turn	1	14.426	1
77:Generic Level Left Turn, 30° AoB, 0.8 Vne	1	27.348	1.9
82-87:Generic Level Right Turn	1	14.426	1
84:Generic Level Right Turn, 45° AoB, 0.8 Vne	1	28.852	2

Figure C-63. Run 125: 80 kt, Level Right-Turn, Left-Turn 30° AoB, Aggressive



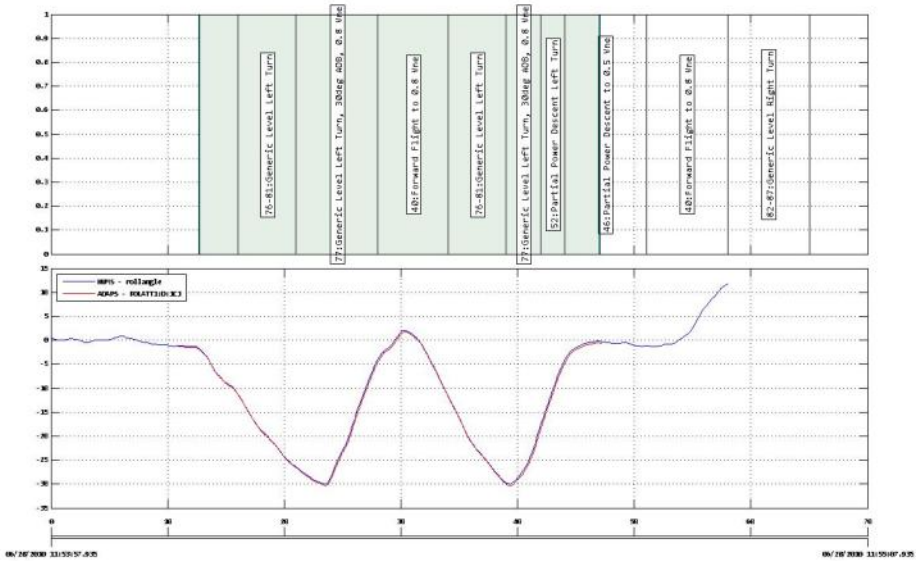
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
47:Partial Power Descent to 0.8 Vne	2	22.432	4.17
52:Partial Power Descent Left Turn	2	21.542	4
76-81:Generic Level Left Turn	2	21.542	4
77:Generic Level Left Turn, 30° AoB, 0.8 Vne	2	16.157	3

Figure C-64. Run 126: CP, 80 kt, Two Repeats Level Left-Turn 30° AoB, Normal



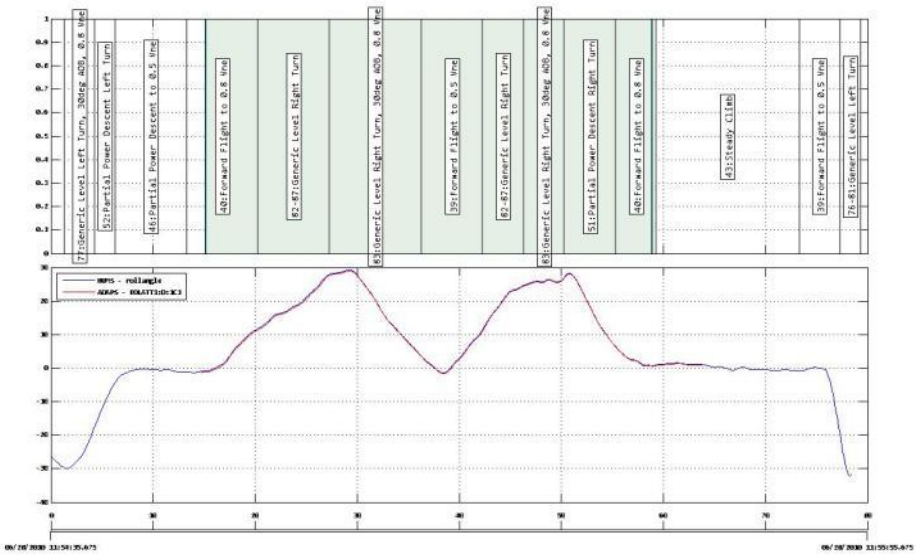
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
39:Forward Flight to 0.5 Vne	2	27.136	5.2
82-87:Generic Level Right Turn	2	20.871	4
83:Generic Level Right Turn, 30° AoB, 0.8 Vne	2	36.525	7

Figure C-65. Run 127: CP, 80 kt, Two Repeats Level Right-Turn 30° AoB, Normal



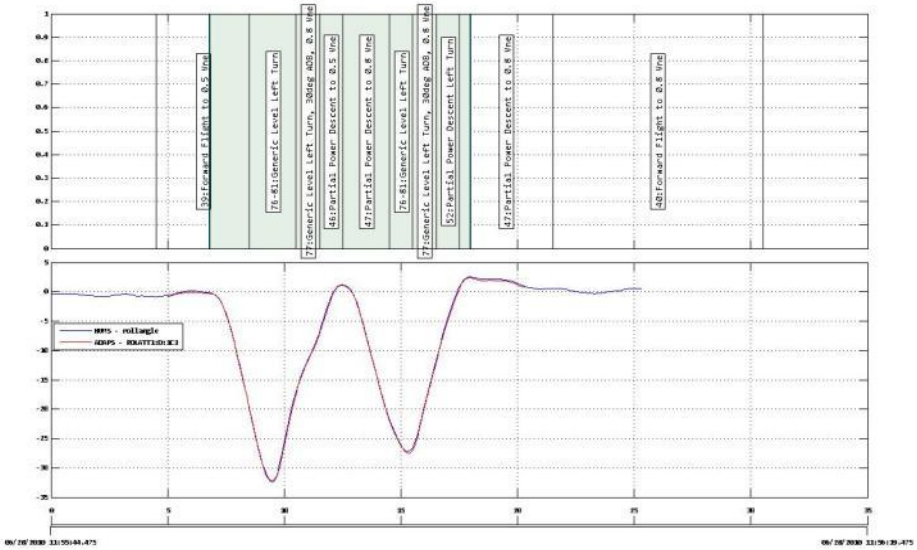
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
40:Forward Flight to 0.8 Vne	1	17.482	6
46:Partial Power Descent to 0.5 Vne	1	8.736	3
52:Partial Power Descent Left Turn	1	5.827	2
76-81:Generic Level Left Turn	2	29.137	10
77:Generic Level Left Turn, 30° AoB, 0.8 Vne	2	29.137	10

Figure C-66. Run 128: CP, 80 kt, Two Repeats Level Left-Turn 30° AoB, Benign



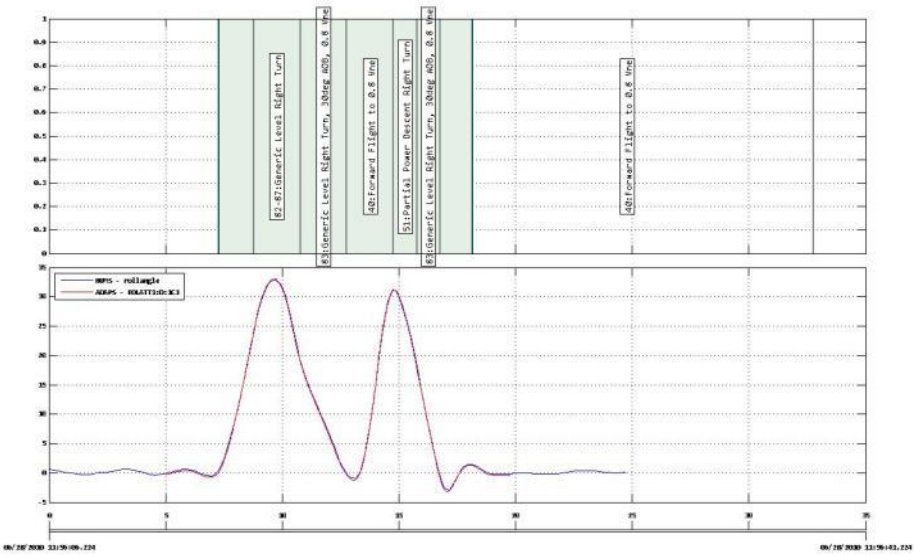
Regime	Counts	Time (%)	Time (sec)
39:Forward Flight to 0.5 Vne	1	13.721	6
40:Forward Flight to 0.8 Vne	2	19.96	8.73
51:Partial Power Descent Right Turn	1	11.434	5
82-87:Generic Level Right Turn	2	25.155	11
83:Generic Level Right Turn, 30° AoB, 0.8 Vne	2	29.729	13

Figure C-67. Run 129: CP, 80 kt, Two Repeats Level Right-Turn 30° AoB, Benign



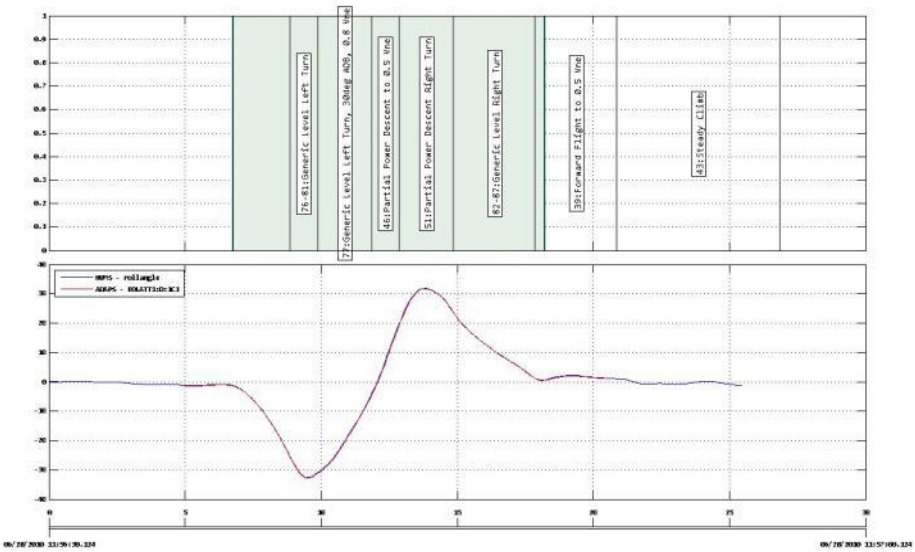
Regime	Counts	Time (%)	Time (sec)
39:Forward Flight to 0.5 Vne	1	15.316	1.71
46:Partial Power Descent to 0.5 Vne	1	8.945	1
47:Partial Power Descent to 0.8 Vne	2	22.07	2.47
52:Partial Power Descent Left Turn	1	8.945	1
76-81:Generic Level Left Turn	2	26.835	3
77:Generic Level Left Turn, 30° AoB, 0.8 Vne	2	17.89	2

Figure C-68. Run 130: CP, 80 kt, Two Repeats Level Left-Turn 30° AoB, Aggressive



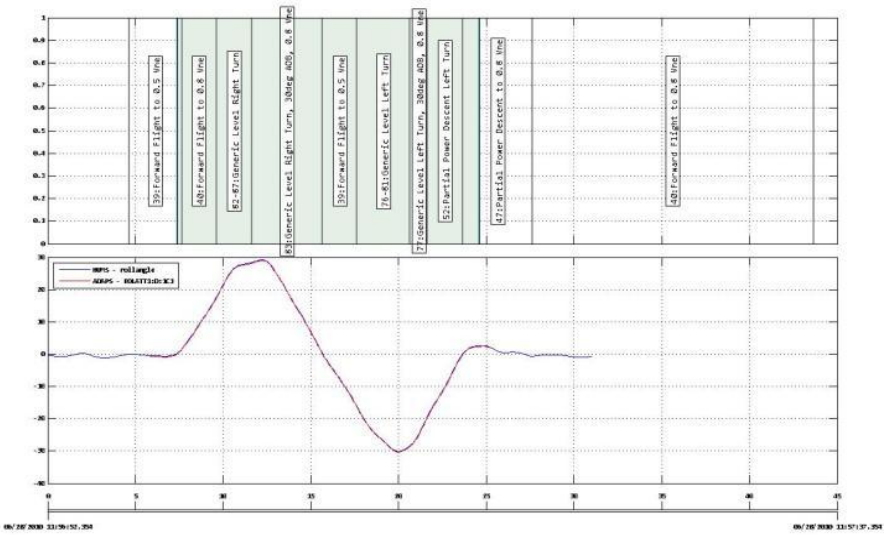
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
40:Forward Flight to 0.8 Vne	2	31.149	3.39
51:Partial Power Descent Right Turn	1	9.196	1
82-87:Generic Level Right Turn	1	18.393	2
83:Generic Level Right Turn, 30° AoB, 0.8 Vne	2	27.589	3

Figure C-69. Run 131: CP, 80 kt, Two Repeats Level Right-Turn 30° AoB, Aggressive



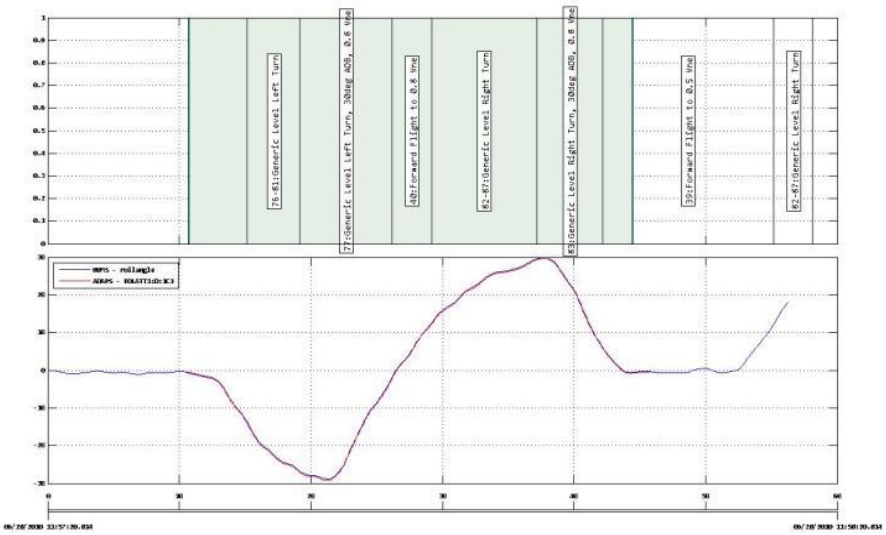
Regime	Counts	Time (%)	Time (sec)
39:Forward Flight to 0.5 Vne	1	2.995	0.34
46:Partial Power Descent to 0.5 Vne	1	8.736	1
51:Partial Power Descent Right Turn	1	17.472	2
76-81:Generic Level Left Turn	1	8.736	1
77:Generic Level Left Turn, 30° AoB, 0.8 Vne	1	17.472	2
82-87:Generic Level Right Turn	1	26.209	3

Figure C-70. Run 132: CP, 80 kt, Level Left-Turn, Right-Turn 30° AoB, Normal



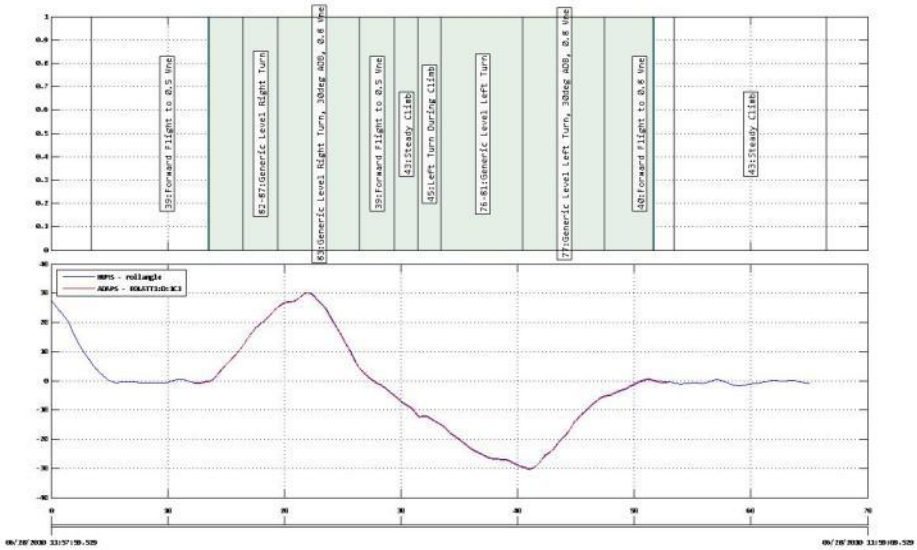
Regime	Counts	Time (%)	Time (sec)
39:Forward Flight to 0.5 Vne	2	13.015	2.24
40:Forward Flight to 0.8 Vne	1	11.619	2
47:Partial Power Descent to 0.8 Vne	1	5.653	0.97
52:Partial Power Descent Left Turn	1	11.619	2
76-81:Generic Level Left Turn	1	17.428	3
77:Generic Level Left Turn, 30° AoB, 0.8 Vne	1	5.809	1
82-87:Generic Level Right Turn	1	11.619	2
83:Generic Level Right Turn, 30° AoB, 0.8 Vne	1	23.237	4

Figure C-71. Run 133: CP, 80 kt, Level Right-Turn, Left-Turn 30° AoB, Normal



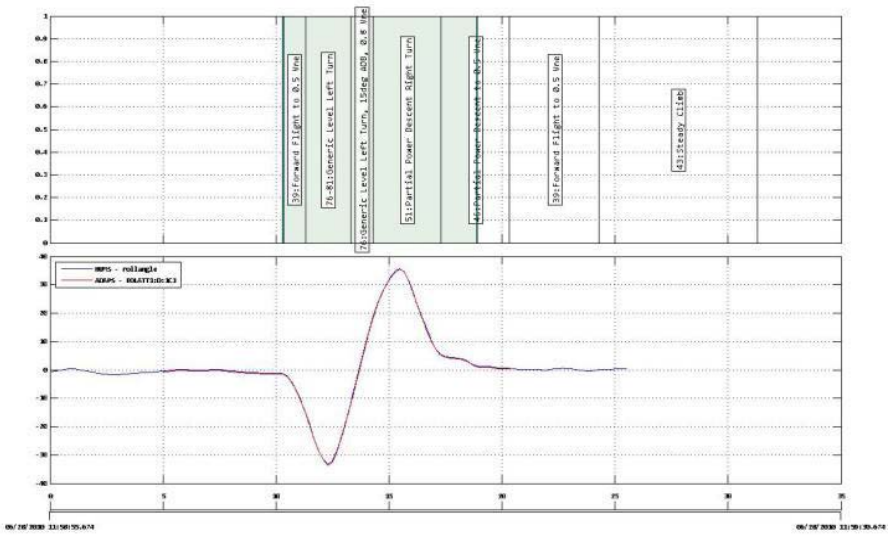
Regime	Counts	Time (%)	Time (sec)
39:Forward Flight to 0.5 Vne	1	6.789	2.29
40:Forward Flight to 0.8 Vne	1	8.895	3
76-81:Generic Level Left Turn	1	11.86	4
77:Generic Level Left Turn, 30° AoB, 0.8 Vne	1	20.754	7
82-87:Generic Level Right Turn	1	23.719	8
83:Generic Level Right Turn, 30° AoB, 0.8 Vne	1	14.824	5

Figure C-72. Run 134: CP, 80 kt, Level Left-Turn, Right-Turn 30° AoB, Benign



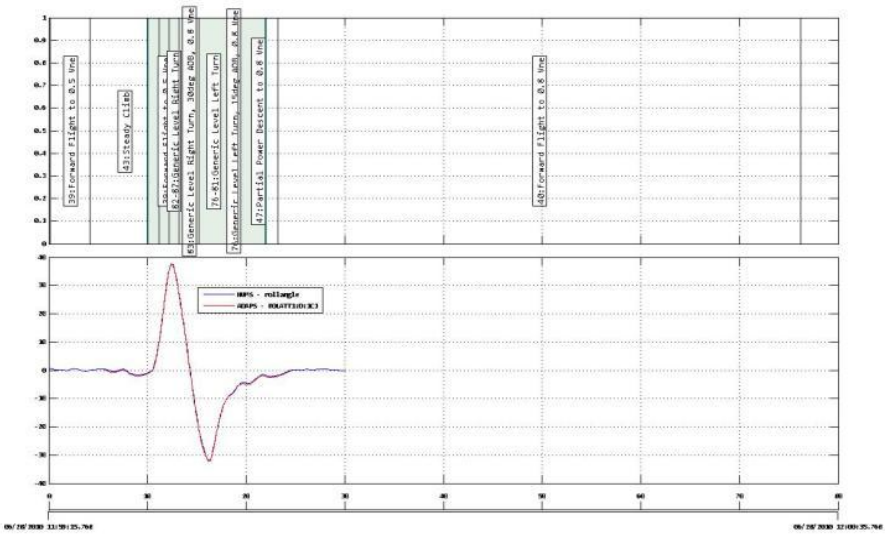
Regime	Counts	Time (%)	Time (sec)
39:Forward Flight to 0.5 Vne	2	15.509	5.91
40:Forward Flight to 0.8 Vne	1	11.051	4.21
43:Steady Climb	1	5.246	2
45:Left Turn During Climb	1	5.246	2
76-81:Generic Level Left Turn	1	18.36	7
77:Generic Level Left Turn, 30° AoB, 0.8 Vne	1	18.36	7
82-87:Generic Level Right Turn	1	7.869	3
83:Generic Level Right Turn, 30° AoB, 0.8 Vne	1	18.36	7

Figure C-73. Run 135: CP, 80 kt, Level Right-Turn, Left-Turn 30° AoB, Benign



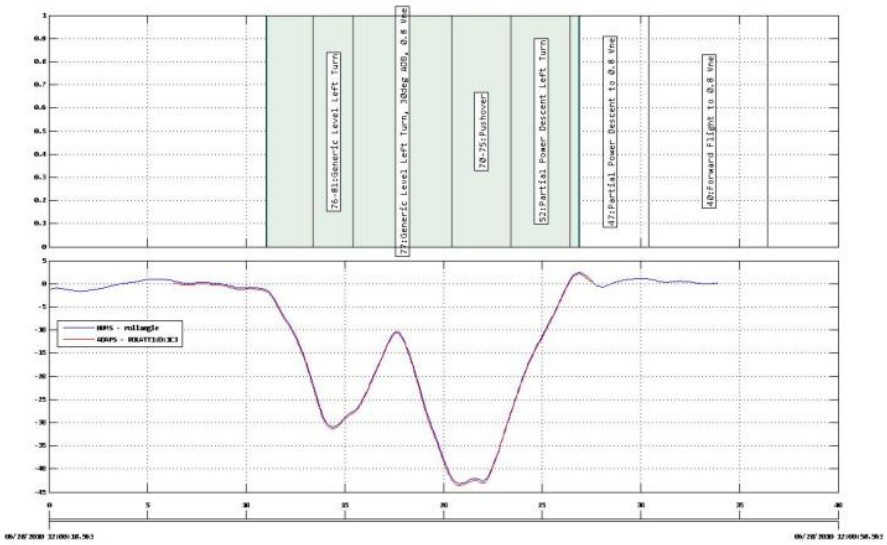
Regime	Counts	Time (%)	Time (sec)
39:Forward Flight to 0.5 Vne	1	11.437	0.98
46:Partial Power Descent to 0.5 Vne	1	18.495	1.58
51:Partial Power Descent Right Turn	1	35.034	3
76-81:Generic Level Left Turn	1	23.356	2
76:Generic Level Left Turn, 15° AoB, 0.8 Vne	1	11.678	1

Figure C-74. Run 136: CP, 80 kt, Level Left-Turn, Right-Turn 30° AoB, Aggressive



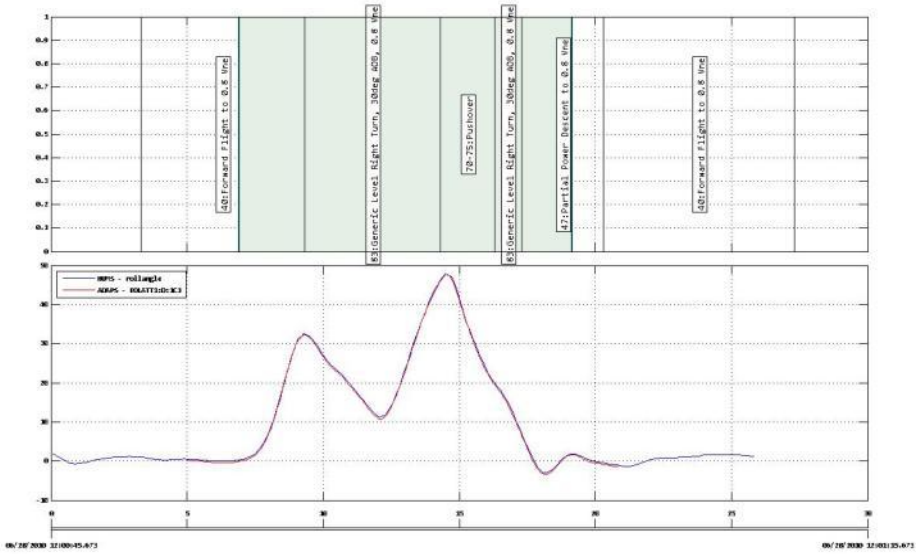
Regime	Counts	Time (%)	Time (sec)
39:Forward Flight to 0.5 Vne	1	8.36	1
43:Steady Climb	1	9.809	1.17
47:Partial Power Descent to 0.8 Vne	1	23.307	2.79
76-81:Generic Level Left Turn	1	25.081	3
76:Generic Level Left Turn, 15° AoB, 0.8 Vne	1	8.36	1
82-87:Generic Level Right Turn	1	8.36	1
83:Generic Level Right Turn, 30° AoB, 0.8 Vne	1	16.721	2

Figure C-75. Run 137: CP, 80 kt, Level Right-Turn, Left-Turn 30° AoB, Aggressive



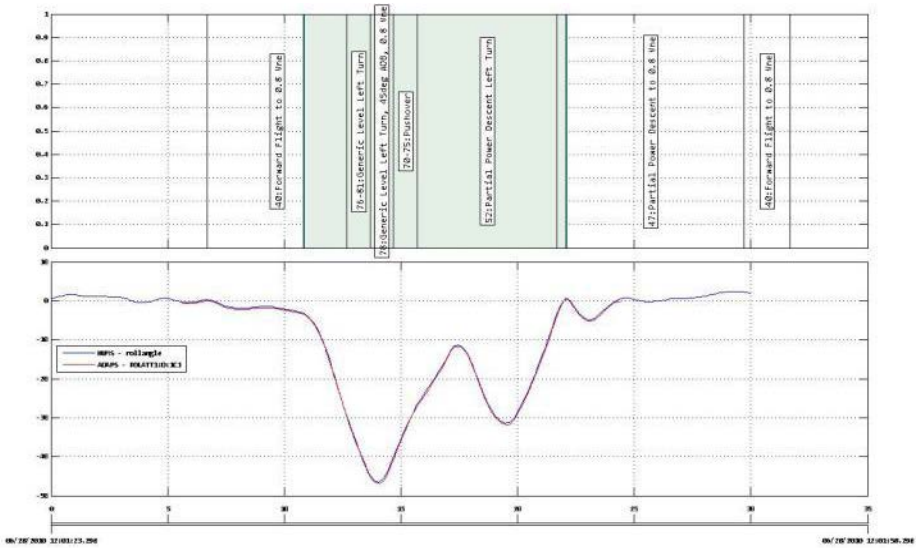
Regime	Counts	Time (%)	Time (sec)
47:Partial Power Descent to 0.8 Vne	1	2.88	0.46
52:Partial Power Descent Left Turn	1	18.934	3
70-75:Pushover	1	18.934	3
76-81:Generic Level Left Turn	1	12.623	2
77:Generic Level Left Turn, 30° AoB, 0.8 Vne	1	31.556	5

Figure C-76. Run 138: 80 kt, 0/30/15/45/0 AoB Left Turn



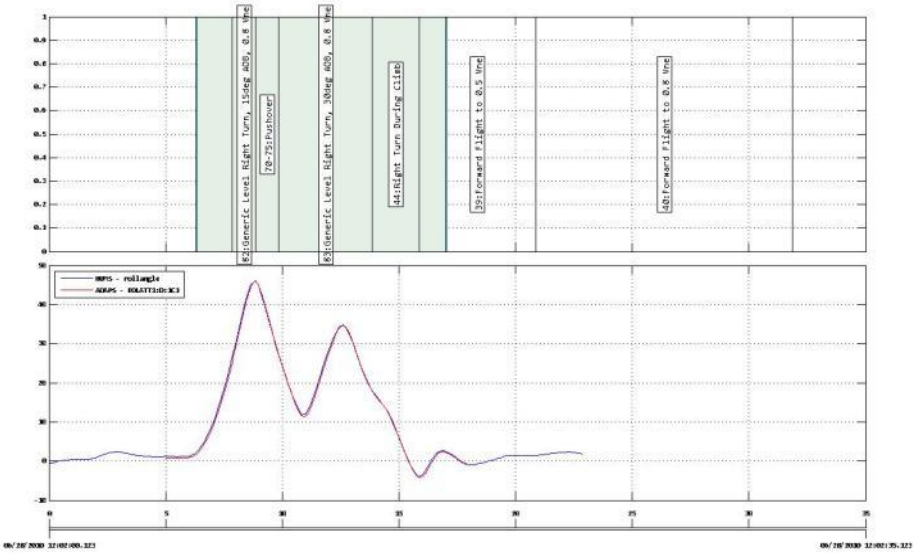
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
40:Forward Flight to 0.8 Vne	1	19.697	2.41
47:Partial Power Descent to 0.8 Vne	1	14.906	1.82
70-75:Pushover	1	16.349	2
83:Generic Level Right Turn, 30° AoB, 0.8 Vne	2	49.048	6

Figure C-77. Run 139: 80 kt, 0/30/15/45/0 AoB Right Turn



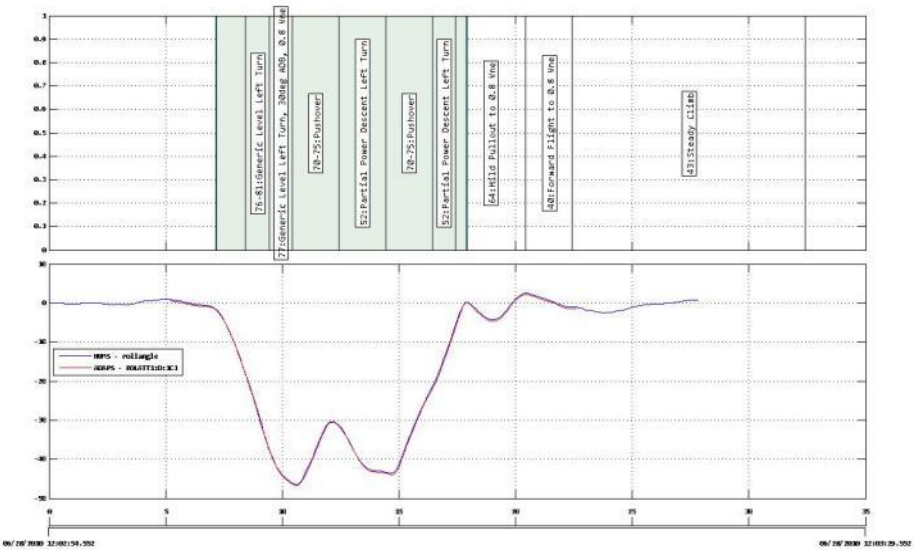
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
40:Forward Flight to 0.8 Vne	1	16.408	1.85
47:Partial Power Descent to 0.8 Vne	1	3.575	0.4
52:Partial Power Descent Left Turn	1	53.345	6
70-75:Pushover	1	8.891	1
76-81:Generic Level Left Turn	1	8.891	1
78:Generic Level Left Turn, 45° AoB, 0.8 Vne	1	8.891	1

Figure C-78. Run 140: 80 kt, 0/45/15/30/0 AoB Left Turn



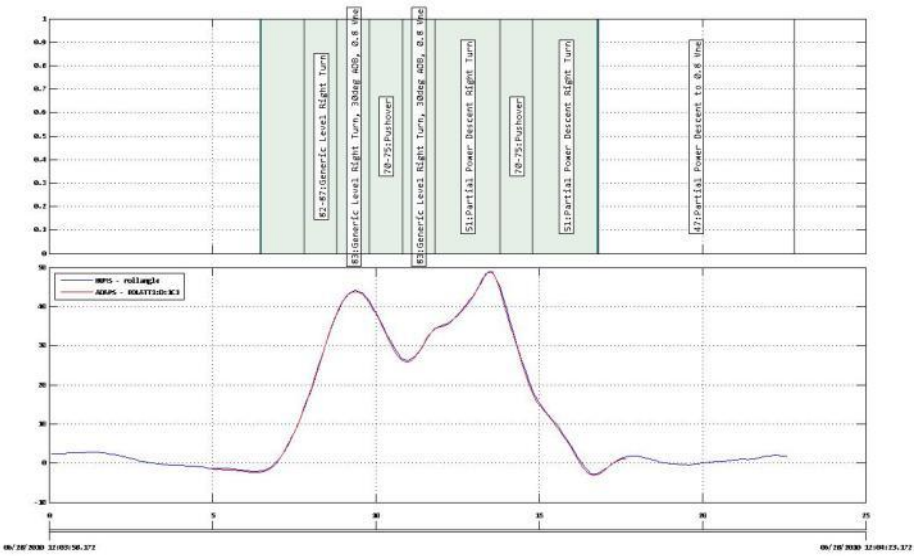
Regime	Counts	Time (%)	Time (sec)
39:Forward Flight to 0.5 Vne	1	10.873	1.16
44:Right Turn During Climb	1	18.685	2
70-75:Pushover	1	9.342	1
82:Generic Level Right Turn, 15° AoB, 0.8 Vne	1	9.342	1
83:Generic Level Right Turn, 30° AoB, 0.8 Vne	1	37.37	4

Figure C-79. Run 141: 80 kt, 0/45/15/30/0 AoB Right Turn



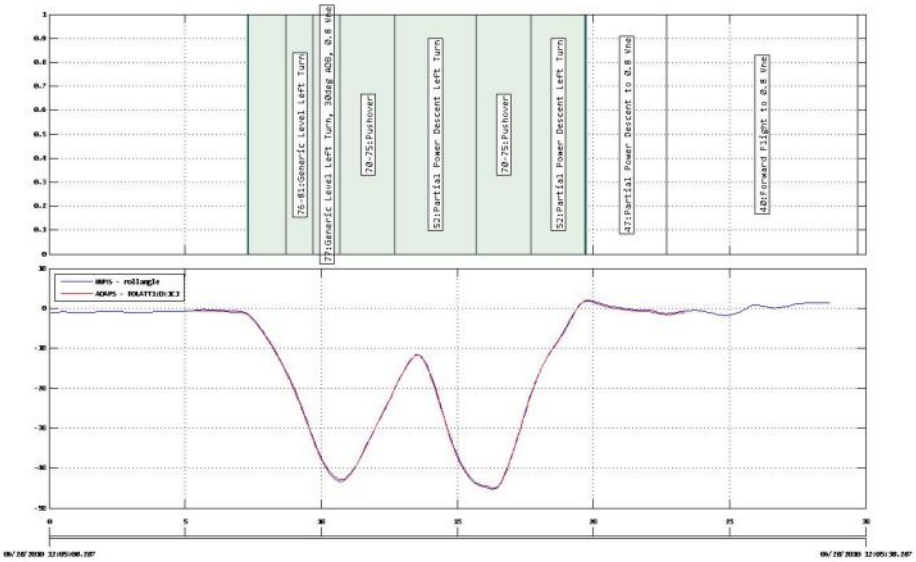
Regime	Counts	Time (%)	Time (sec)
52:Partial Power Descent Left Turn	2	27.939	3
64:Mild Pullout to 0.8 Vne	1	4.442	0.48
70-75:Pushover	2	37.251	4
76-81:Generic Level Left Turn	1	9.313	1
77:Generic Level Left Turn, 30° AoB, 0.8 Vne	1	9.313	1

Figure C-80. Run 142: 80 kt, 0/45/30/45/0 AoB Left Turn



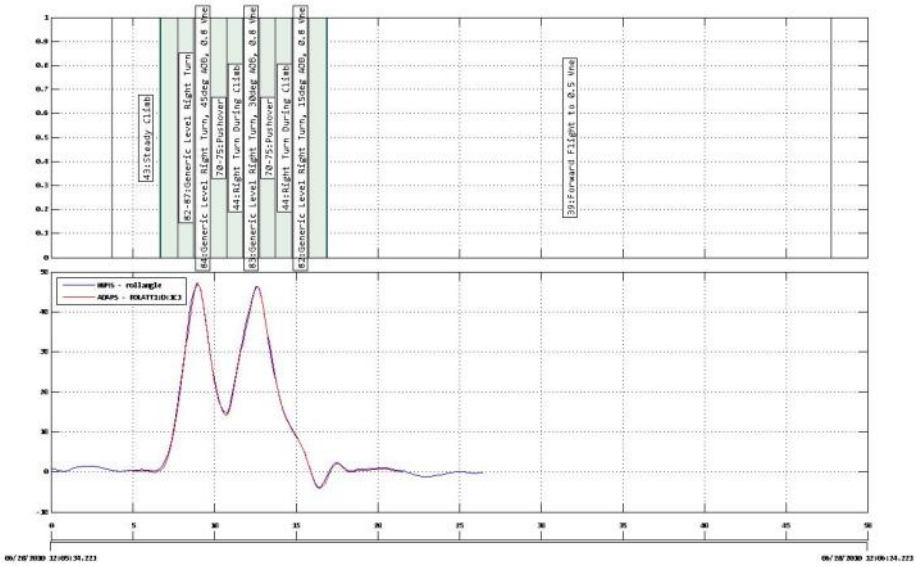
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
51:Partial Power Descent Right Turn	2	38.584	3.98
70-75:Pushover	2	19.388	2
82-87:Generic Level Right Turn	1	9.694	1
83:Generic Level Right Turn, 30° AoB, 0.8 Vne	2	19.388	2

Figure C-81. Run 143: 80 kt, 0/45/30/45/0 AoB Right Turn



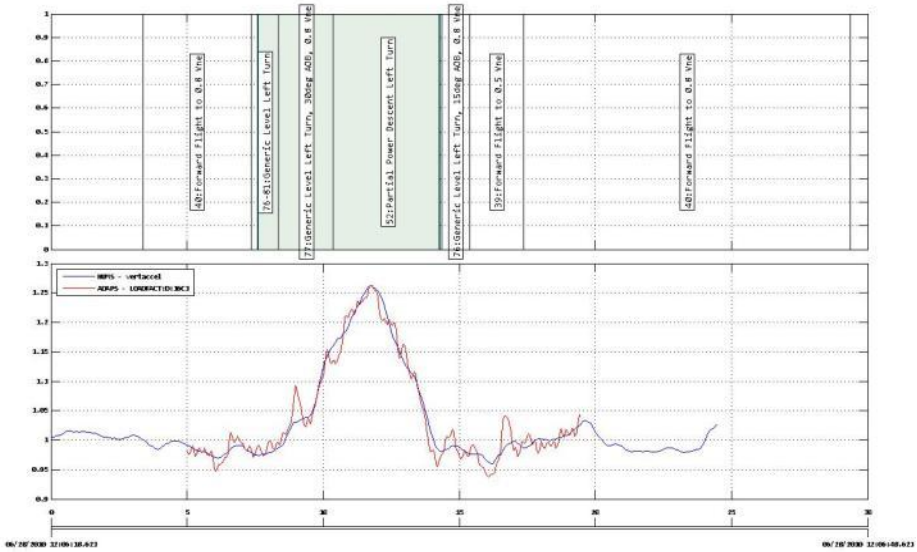
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
47:Partial Power Descent to 0.8 Vne	1	0.157	0.02
52:Partial Power Descent Left Turn	2	40.297	5
70-75:Pushover	2	32.238	4
76-81:Generic Level Left Turn	1	8.059	1
77:Generic Level Left Turn, 30° AoB, 0.8 Vne	1	8.06	1

Figure C-82. Run 144: 80 kt, 0/45/15/45/0 AoB Left Turn



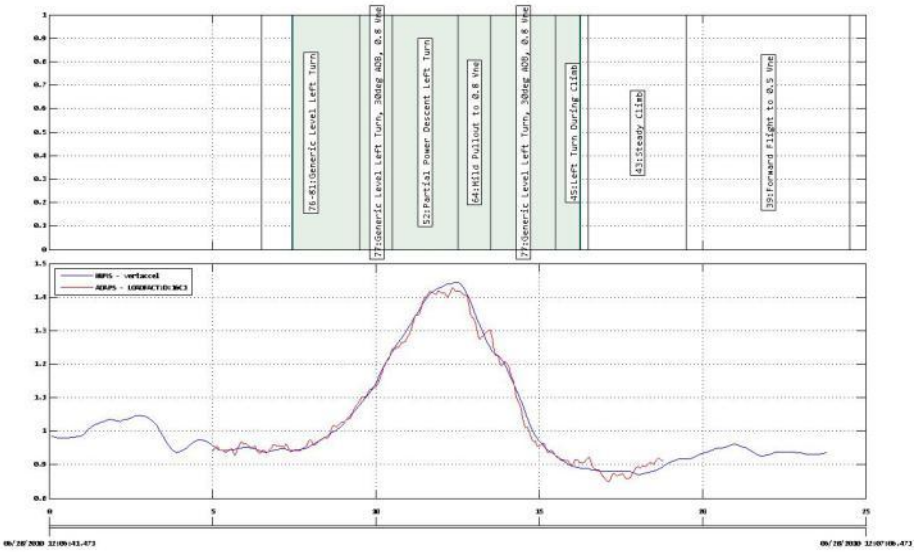
Regime	Counts	Time (%)	Time (sec)
39:Forward Flight to 0.5 Vne	1	11.172	1.14
43:Steady Climb	1	10.352	1.06
44:Right Turn During Climb	2	19.619	2
70-75:Pushover	2	19.619	2
82-87:Generic Level Right Turn	1	9.81	1
82:Generic Level Right Turn, 15° AoB, 0.8 Vne	1	9.81	1
83:Generic Level Right Turn, 30° AoB, 0.8 Vne	1	9.809	1
84:Generic Level Right Turn, 45° AoB, 0.8 Vne	1	9.81	1

Figure C-83. Run 145: 80 kt, 0/45/15/45/0 AoB Right Turn



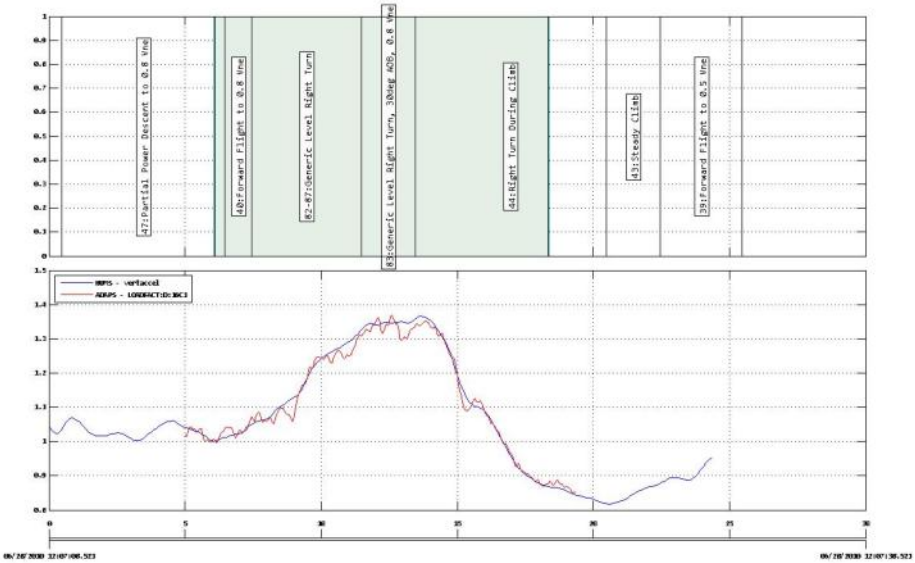
Regime	Counts	Time (%)	Time (sec)
52:Partial Power Descent Left Turn	1	58.585	3.91
76-81:Generic Level Left Turn	1	11.43	0.76
77:Generic Level Left Turn, 30° AoB, 0.8 Vne	1	29.985	2

Figure C-84. Run 146: 80 kt, Pullup With Left-Turn 30° AoB, 1.2 g



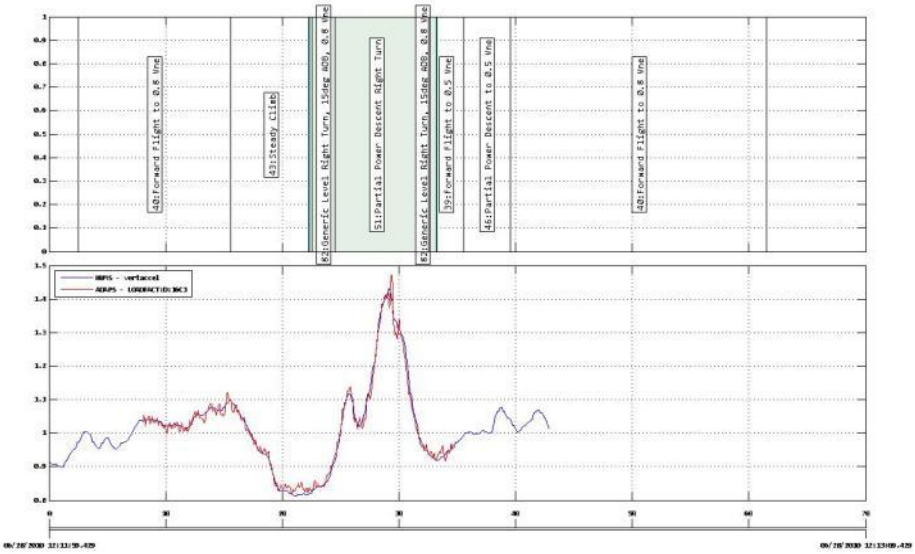
Regime	Counts	Time (%)	Time (sec)
45:Left Turn During Climb	1	8.459	0.75
52:Partial Power Descent Left Turn	1	22.7	2
64:Mild Pullout to 0.8 Vne	1	11.35	1
76-81:Generic Level Left Turn	1	23.442	2.07
77:Generic Level Left Turn, 30° AoB, 0.8 Vne	2	34.05	3

Figure C-85. Run 147: 80 kt, Pullup With Left-Turn 30° AoB, 1.5 g



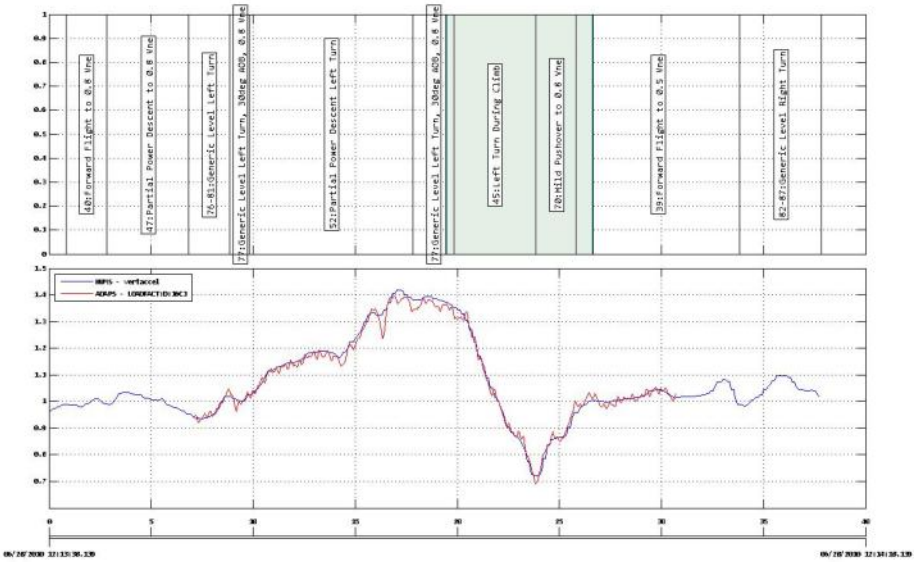
Regime	Counts	Time (%)	Time (sec)
40:Forward Flight to 0.8 Vne	1	8.155	1
44:Right Turn During Climb	1	39.838	4.88
47:Partial Power Descent to 0.8 Vne	1	3.076	0.38
82-87:Generic Level Right Turn	1	32.621	4
83:Generic Level Right Turn, 30° AoB, 0.8 Vne	1	16.31	2

Figure C-86. Run 148: 80 kt, Pullup With Right-Turn 30° AoB, 1.2 g



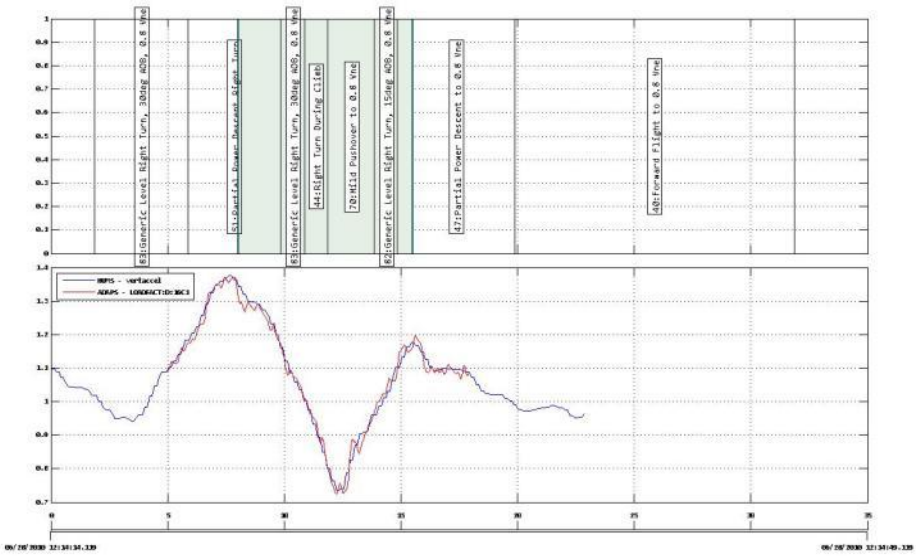
Regime	Counts	Time (%)	Time (sec)
39:Forward Flight to 0.5 Vne	1	6.363	0.7
43:Steady Climb	1	2.244	0.25
51:Partial Power Descent Right Turn	1	63.975	7
82:Generic Level Right Turn, 15° AoB, 0.8 Vne	2	27.418	3

Figure C-87. Run 149: 80 kt, Pullup With Right-Turn 30° AoB, 1.5 g



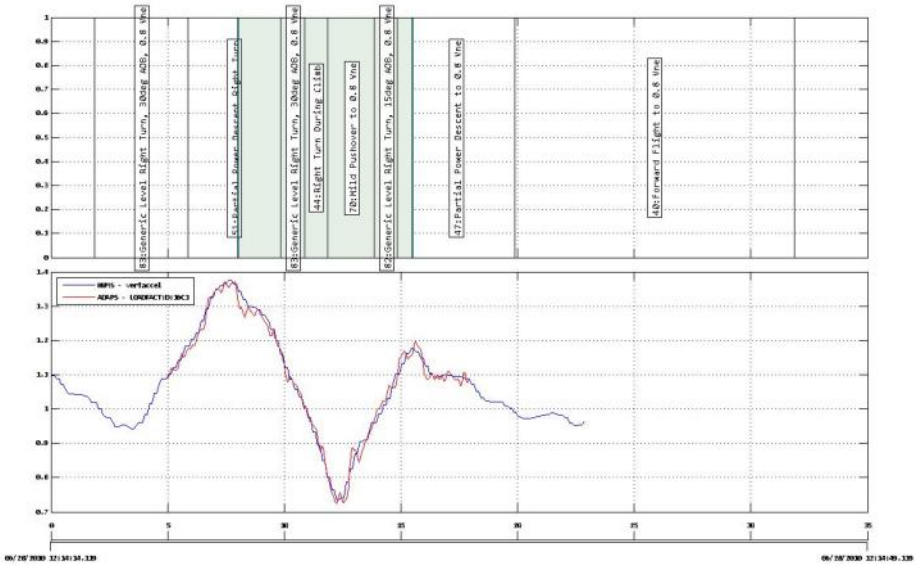
Regime	Counts	Time (%)	Time (sec)
39:Forward Flight to 0.5 Vne	1	11.121	0.8
45:Left Turn During Climb	1	55.676	4
70:Mild Pushover to 0.8 Vne	1	27.838	2
77:Generic Level Left Turn, 30° AoB, 0.8 Vne	1	5.366	0.39

Figure C-88. Run 150: 80 kt, Pushover With Left-Turn 30° AoB, 0.8 g



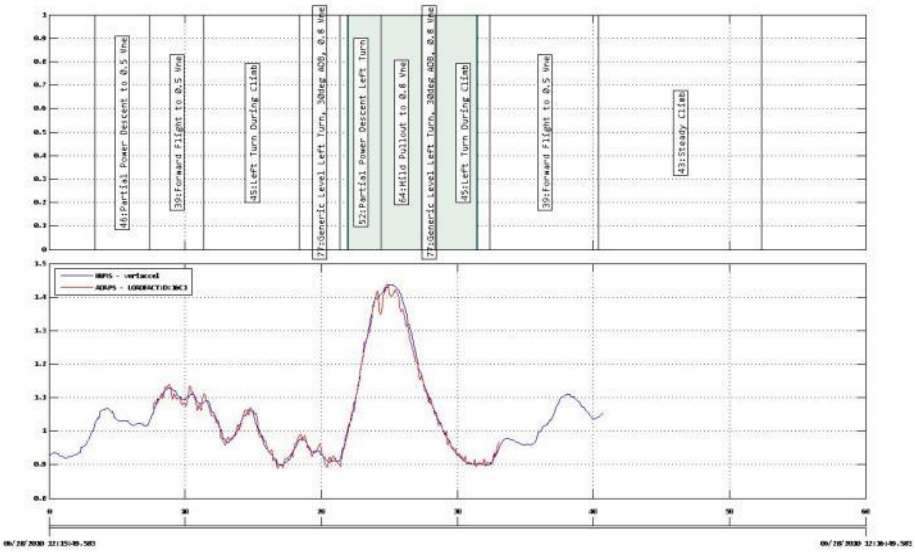
Regime	Counts	Time (%)	Time (sec)
44:Right Turn During Climb	1	13.377	1
47:Partial Power Descent to 0.8 Vne	1	8.437	0.63
51:Partial Power Descent Right Turn	1	24.68	1.85
70:Mild Pushover to 0.8 Vne	1	26.753	2
82:Generic Level Right Turn, 15° AoB, 0.8 Vne	1	13.377	1
83:Generic Level Right Turn, 30° AoB, 0.8 Vne	1	13.377	1

Figure C-89. Run 151: 80 kt, Pushover With Right-Turn 30° AoB, 0.8 g



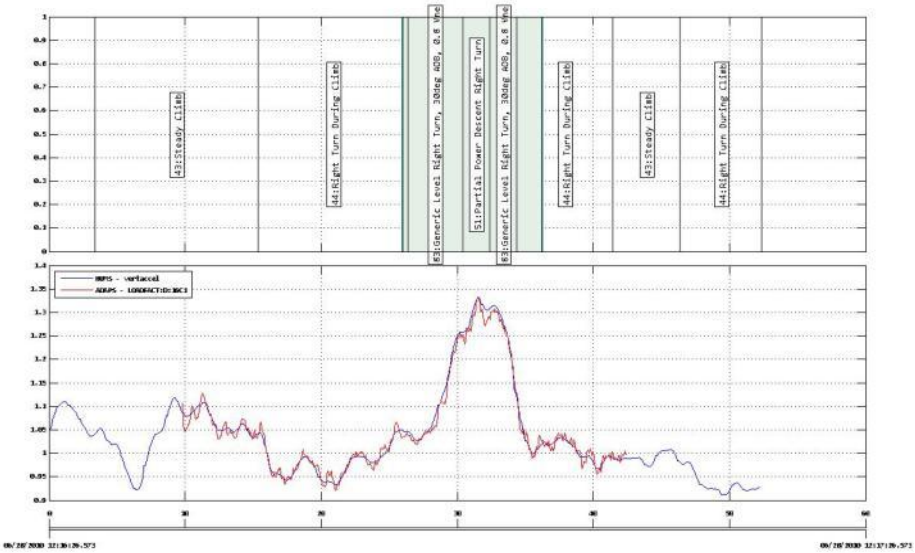
Regime	Counts	Time (%)	Time (sec)
39:Forward Flight to 0.5 Vne	1	8.134	1.61
45:Left Turn During Climb	1	1.161	0.23
52:Partial Power Descent Left Turn	1	75.587	15
76:Generic Level Left Turn, 15° AoB, 0.8 Vne	1	5.039	1
77:Generic Level Left Turn, 30° AoB, 0.8 Vne	1	10.078	2

Figure C-90. Run 152: CP, 80 kt, Pullout With Left-Turn 30° AoB, 1.2 g



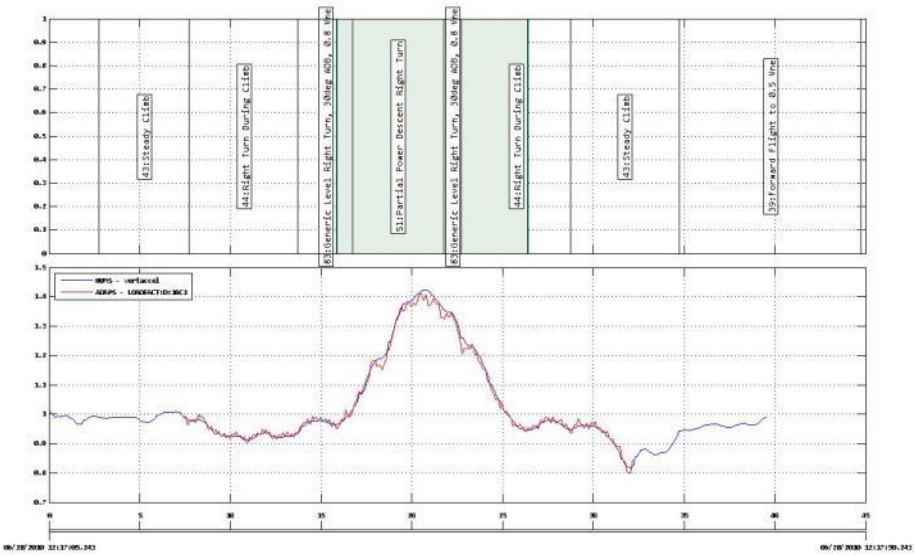
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
45:Left Turn During Climb	1	32.316	3.07
46:Partial Power Descent to 0.5 Vne	0	0	0
52:Partial Power Descent Left Turn	1	25.557	2.43
64:Mild Pullout to 0.8 Vne	1	31.595	3
77:Generic Level Left Turn, 30° AoB, 0.8 Vne	1	10.532	1

Figure C-91. Run 153: CP, 80 kt, Pullout With Left-Turn 30° AoB, 1.5 g



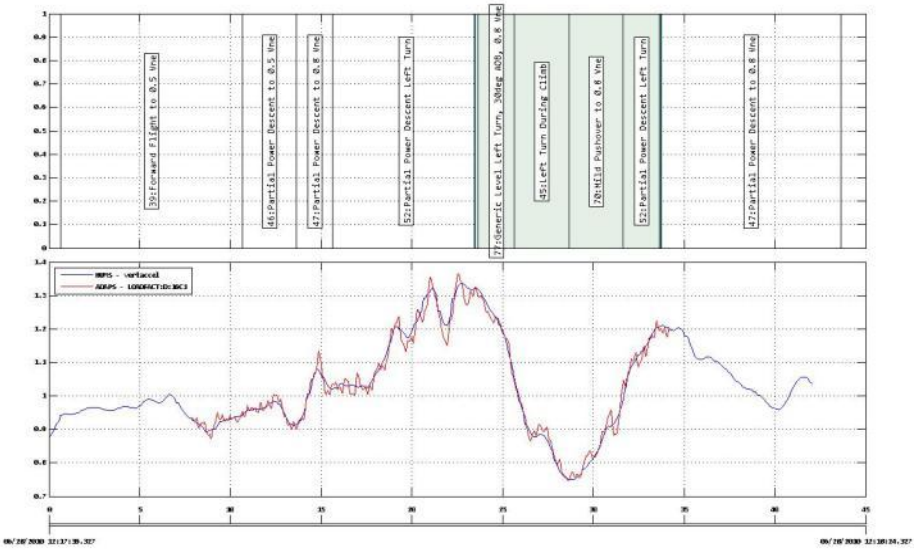
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
44:Right Turn During Climb	2	21.97	2.25
51:Partial Power Descent Right Turn	1	19.508	2
83:Generic Level Right Turn, 30° AoB, 0.8 Vne	2	58.523	6

Figure C-92. Run 154: CP, 80 kt, Pullout With Right-Turn 30° AoB, 1.2 g



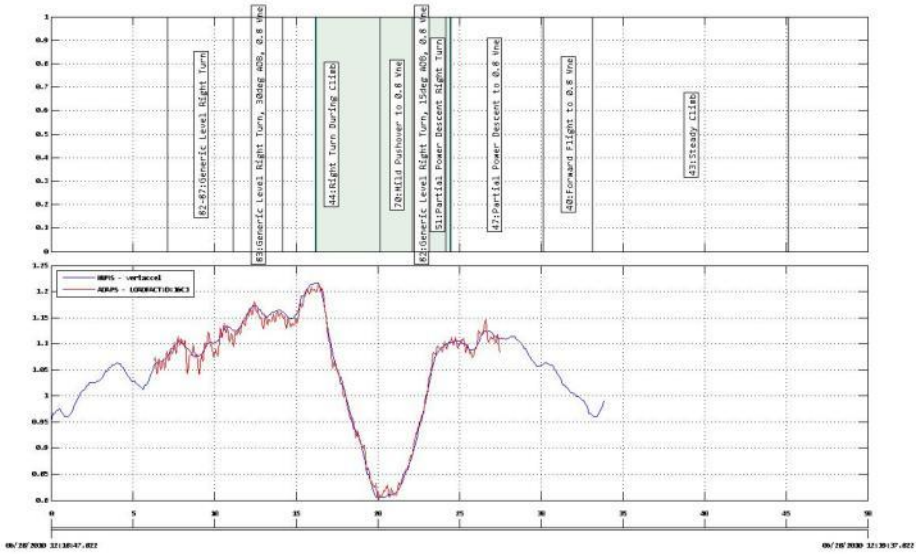
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
44:Right Turn During Climb	1	34.693	3.65
51:Partial Power Descent Right Turn	1	47.487	5
83:Generic Level Right Turn, 30° AoB, 0.8 Vne	2	17.82	1.88

Figure C-93. Run 155: CP, 80 kt, Pullout With Right-Turn 30° AoB, 1.5 g



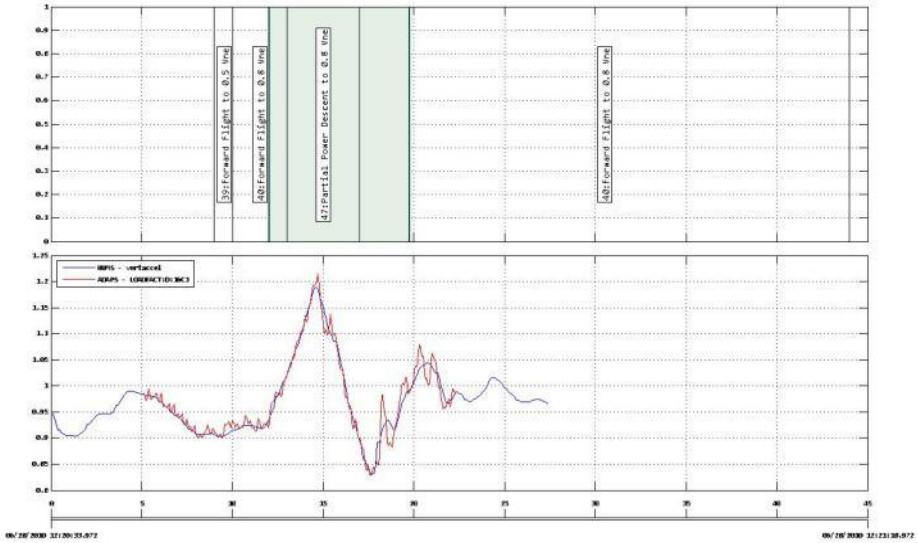
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
45:Left Turn During Climb	1	29.22	3
47:Partial Power Descent to 0.8 Vne	1	0.754	0.08
52:Partial Power Descent Left Turn	2	21.326	2.19
70:Mild Pushover to 0.8 Vne	1	29.22	3
77:Generic Level Left Turn, 30° AoB, 0.8 Vne	1	19.48	2

Figure C-94. Run 156: CP, 80 kt, Pushover With Left-Turn 30° AoB, 0.8 g



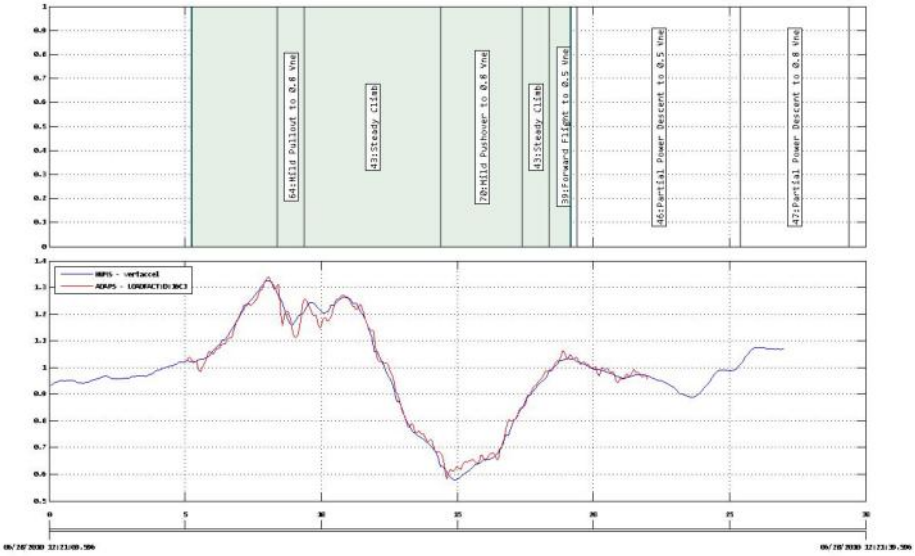
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
44:Right Turn During Climb	1	47.744	3.94
47:Partial Power Descent to 0.8 Vne	1	3.785	0.31
51:Partial Power Descent Right Turn	1	12.118	1
70:Mild Pushover to 0.8 Vne	1	24.235	2
82:Generic Level Right Turn, 15° AoB, 0.8 Vne	1	12.118	1

Figure C-95. Run 157: CP, 80 kt, Pushover With Right-Turn 30° AoB, 0.8 g



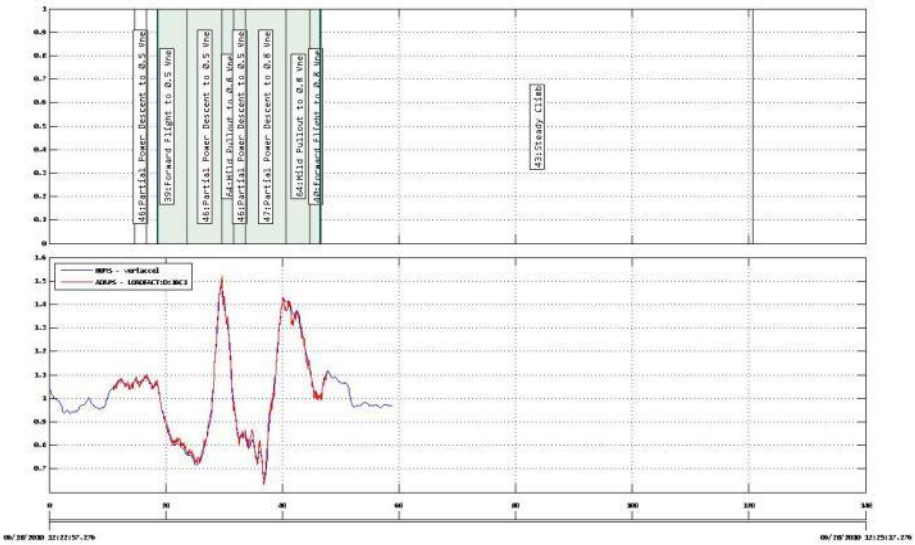
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
40:Forward Flight to 0.8 Vne	2	48.274	3.73
47:Partial Power Descent to 0.8 Vne	1	51.726	4

Figure C-96. Run 158: 80 kt, Pullup With Pushover, 1/1.2/0.8/1.0 g



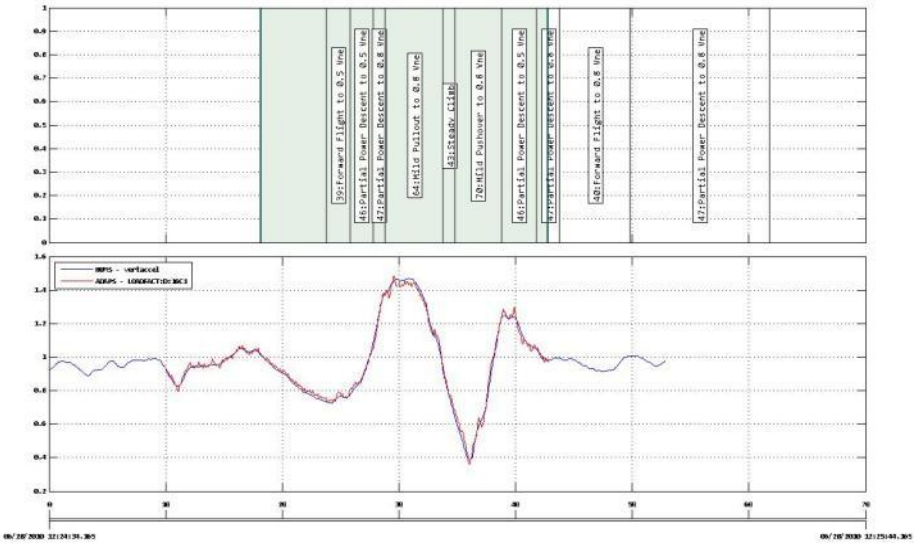
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
39:Forward Flight to 0.5 Vne	1	5.573	0.78
43:Steady Climb	2	43.096	6
64:Mild Pullout to 0.8 Vne	1	7.183	1
70:Mild Pushover to 0.8 Vne	1	21.548	3

Figure C-97. Run 159: 80 kt, Pullup With Pushover, 1.0/1.5/0.5/1.0 g



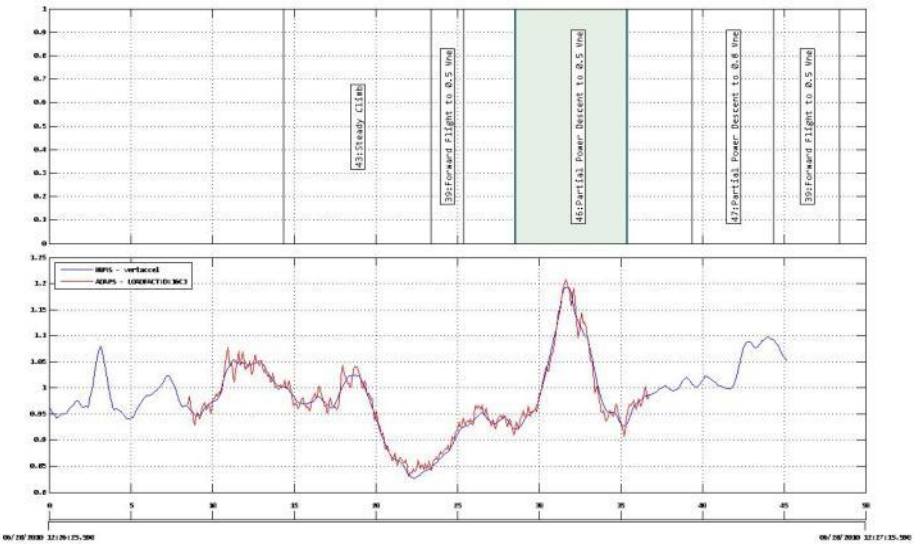
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
39:Forward Flight to 0.5 Vne	1	18.07	5.04
40:Forward Flight to 0.8 Vne	1	6.564	1.83
46:Partial Power Descent to 0.5 Vne	2	28.711	8
47:Partial Power Descent to 0.8 Vne	1	25.122	7
64:Mild Pullout to 0.8 Vne	2	21.533	6

Figure C-98. Run 160: 80 kt, Pullup With Pushover, 1.0/1.5/0.5/1.0 g



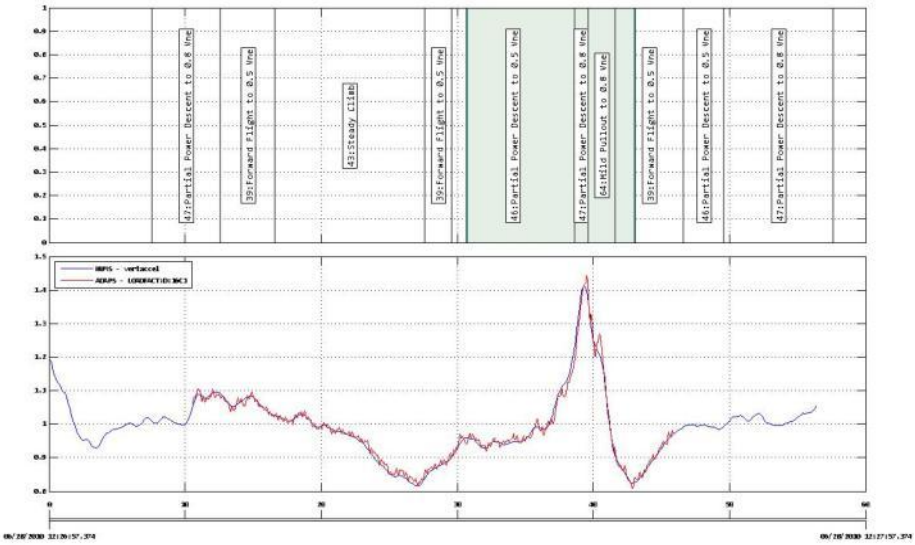
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
39:Forward Flight to 0.5 Vne	1	8.129	2
43:Steady Climb	1	4.065	1
46:Partial Power Descent to 0.5 Vne	2	20.324	5
47:Partial Power Descent to 0.8 Vne	2	7.913	1.95
64:Mild Pullout to 0.8 Vne	1	20.324	5
70:Mild Pushover to 0.8 Vne	1	16.259	4

Figure C-99. Run 161: 80 kt, Pullup With Pushover, 1.0/1.5/0.5/1.0 g



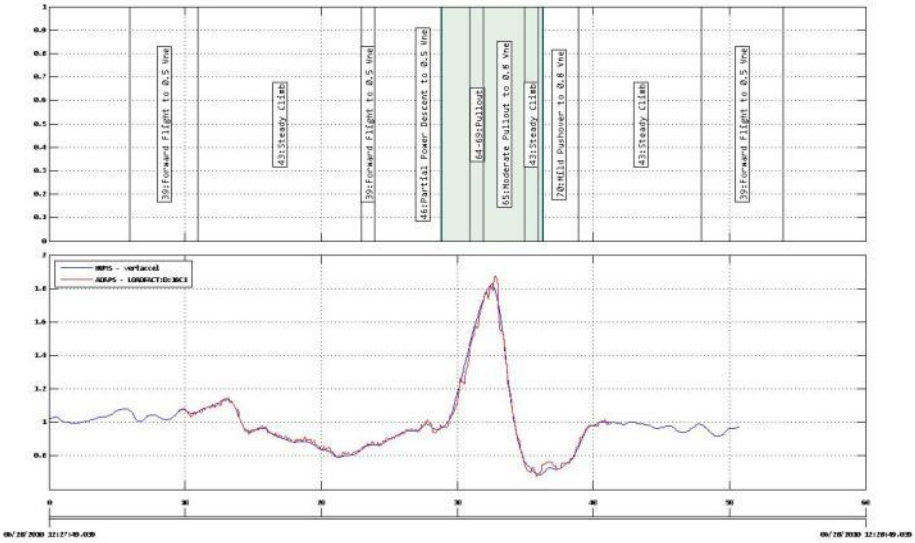
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
46:Partial Power Descent to 0.5 Vne	1	100	6.84

Figure C-100. Run 162: 80 kt, Symmetric Pullout, 1.2 g



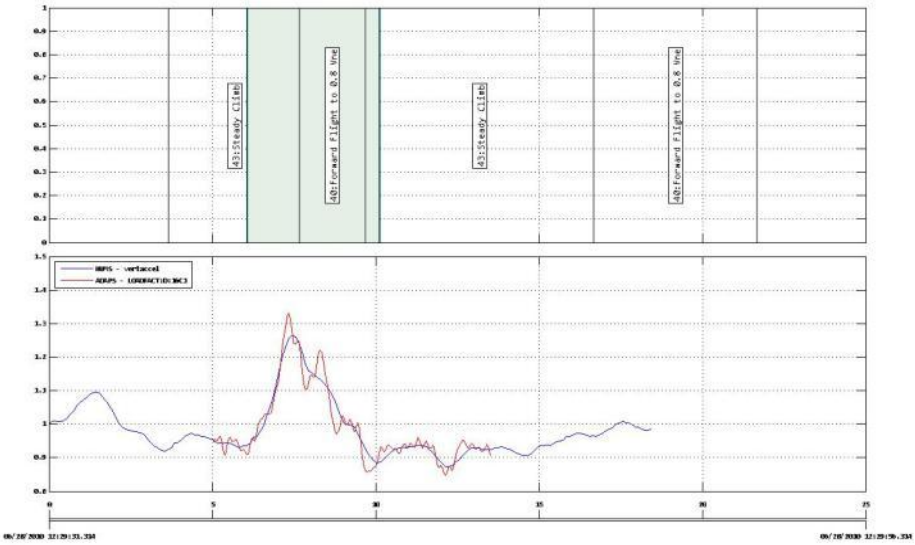
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
39:Forward Flight to 0.5 Vne	1	11.758	1.45
46:Partial Power Descent to 0.5 Vne	1	63.949	7.9
47:Partial Power Descent to 0.8 Vne	1	8.098	1
64:Mild Pullout to 0.8 Vne	1	16.195	2

Figure C-101. Run 163: 80 kt, Symmetric Pullout, 1.5 g



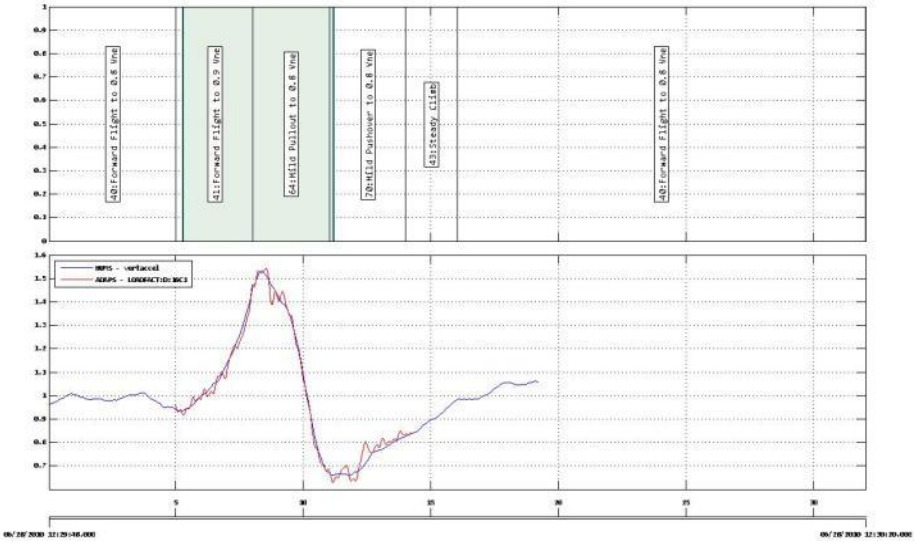
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
43:Steady Climb	1	13.411	1
46:Partial Power Descent to 0.5 Vne	1	28.121	2.1
64-69:Pullout	1	13.411	1
65:Moderate Pullout to 0.8 Vne	1	40.234	3
70:Mild Pushover to 0.8 Vne	1	4.822	0.36

Figure C-102. Run 164: 80 kt, Symmetric Pullout, 2.0 g



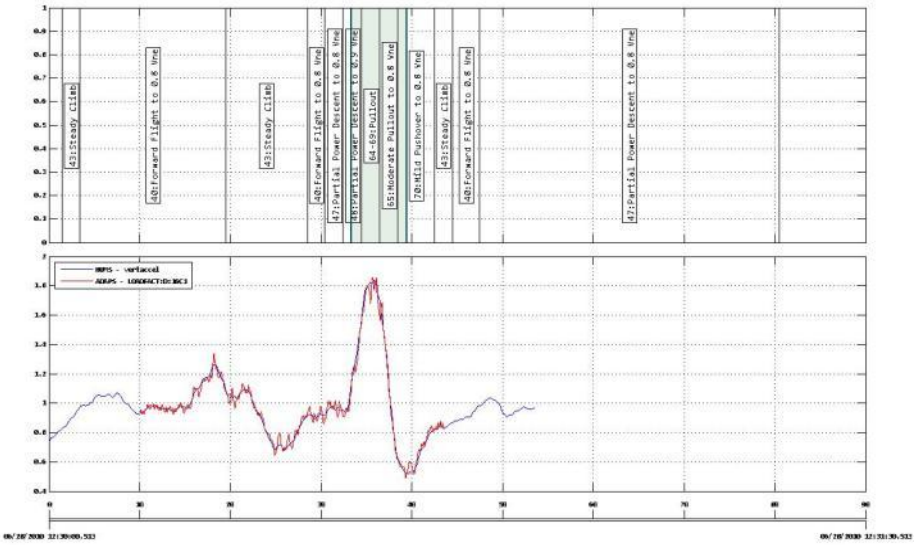
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
40:Forward Flight to 0.8 Vne	1	49.341	2
43:Steady Climb	2	50.659	2.05

Figure C-103. Run 165: 130 kt, Symmetric Pullout, 1.2 g



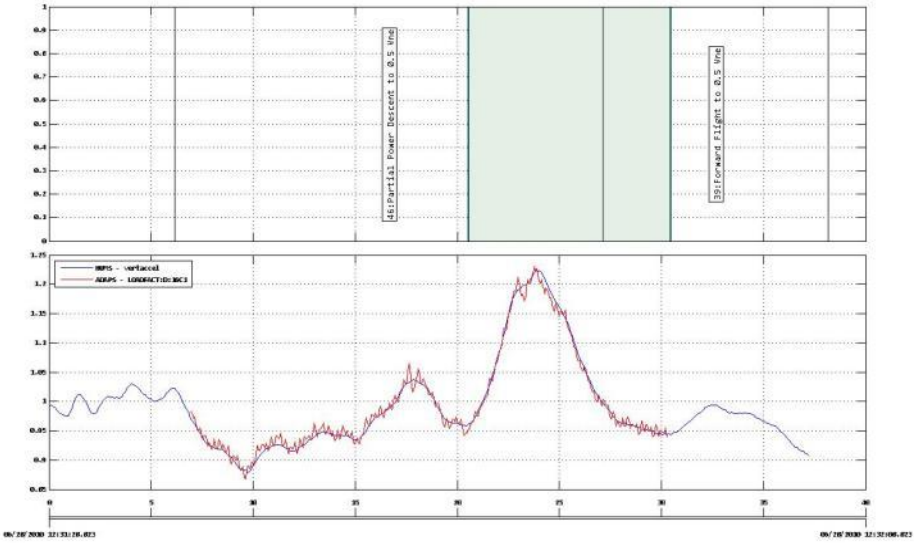
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
41:Forward Flight to 0.9 Vne	1	46.316	2.73
64:Mild Pullout to 0.8 Vne	1	50.822	3
70:Mild Pushover to 0.8 Vne	1	2.862	0.17

Figure C-104. Run 166: 130 kt, Symmetric Pullout, 1.5 g



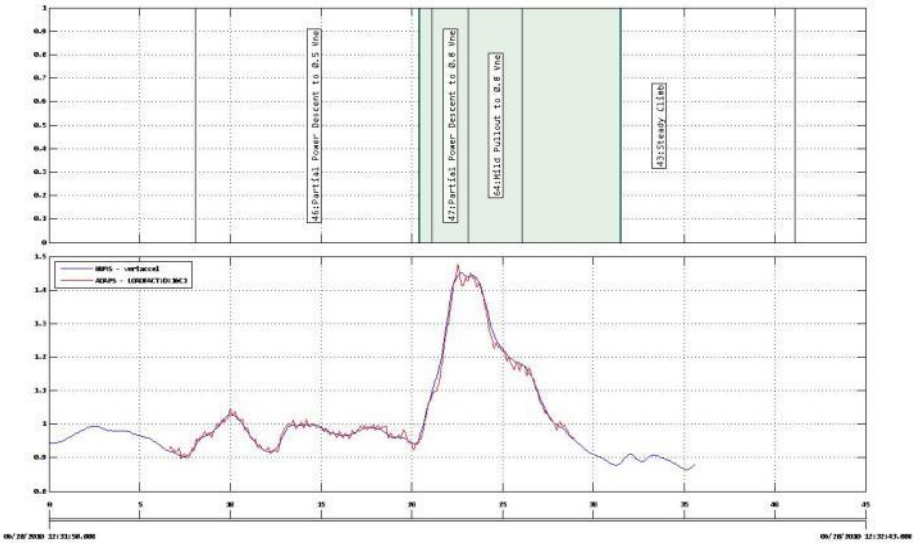
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
48:Partial Power Descent to 0.9 Vne	1	18.828	1.15
64-69:Pullout	1	32.698	2
65:Moderate Pullout to 0.8 Vne	1	32.698	2
70:Mild Pushover to 0.8 Vne	1	15.775	0.96

Figure C-105. Run 167: 130 kt, Symmetric Pullout, 1.85 g



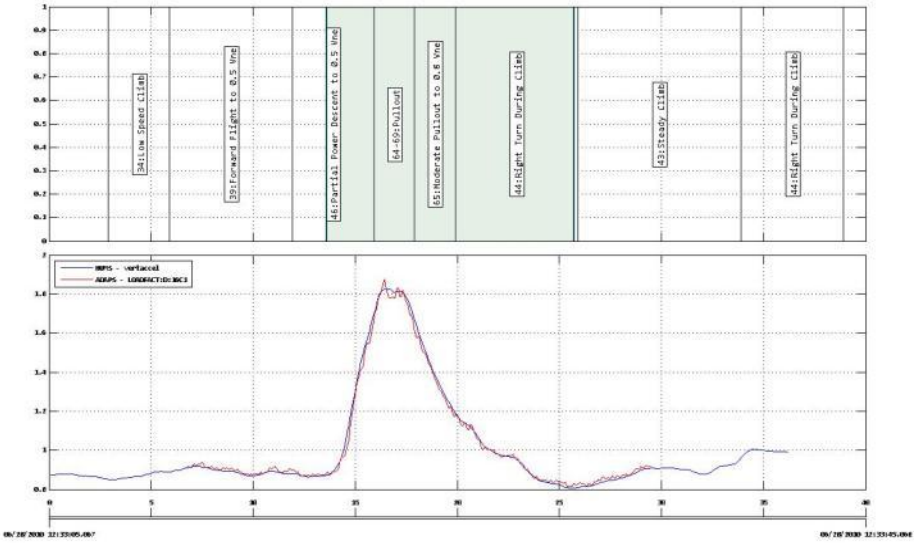
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
39:Forward Flight to 0.5 Vne	1	33.212	3.29
46:Partial Power Descent to 0.5 Vne	1	66.788	6.61

Figure C-106. Run 168: CP, 80 kt, Symmetric Pullout, 1.2 g



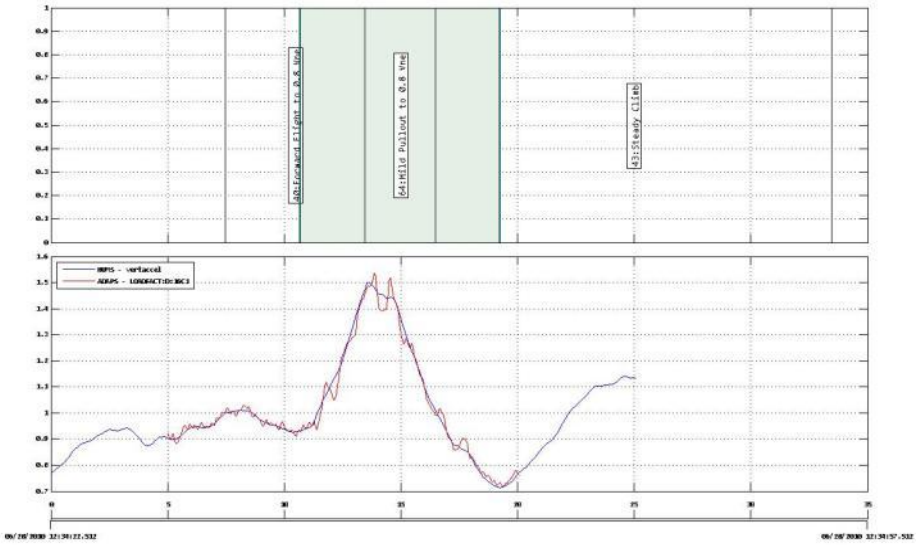
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
43:Steady Climb	1	48.748	5.41
46:Partial Power Descent to 0.5 Vne	1	6.195	0.69
47:Partial Power Descent to 0.8 Vne	1	18.023	2
64:Mild Pullout to 0.8 Vne	1	27.034	3

Figure C-107. Run 169: CP, 80 kt, Symmetric Pullout, 1.5 g



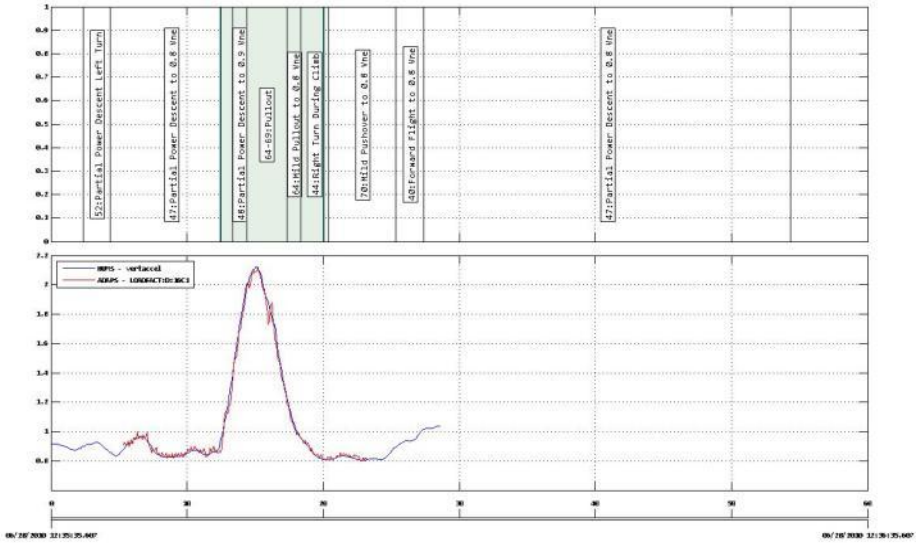
Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
44:Right Turn During Climb	1	47.832	5.8
46:Partial Power Descent to 0.5 Vne	1	19.155	2.32
64-69:Pullout	1	16.506	2
65:Moderate Pullout to 0.8 Vne	1	16.506	2

Figure C-108. Run 171: CP, 80 kt, Symmetric Pullout, 1.88 g



Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
40:Forward Flight to 0.8 Vne	1	32.711	2.8
43:Steady Climb	1	32.255	2.76
64:Mild Pullout to 0.8 Vne	1	35.034	3

Figure C-109. Run 173: CP, 130 kt, Symmetric Pullout, 1.5 g



Highlight Window HUMS Regime Statistics			
Regime	Counts	Time (%)	Time (sec)
44:Right Turn During Climb	1	22.113	1.67
47:Partial Power Descent to 0.8 Vne	1	11.861	0.9
48:Partial Power Descent to 0.9 Vne	1	13.205	1
64-69:Pullout	1	39.615	3
64:Mild Pullout to 0.8 Vne	1	13.205	1

Figure C-110. Run 175: CP, 130 kt, Symmetric Pullout, 2.0 g