Effectiveness of Structural Usage Monitoring (SUM) and Transmission Usage Monitoring (TUM) in Military and Civil Applications

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ABSTRACT

Permanently installed Health and Usage Monitoring System (HUMS) combine a range of health and usage monitoring functions within common equipment. These systems have the potential to significantly improve aircraft safety and maintainability.

The Structural Usage Monitoring (SUM) and the Transmission Usage Monitoring (TUM) are integral parts of the multifunctional Health and Usage Monitoring System (HUMS), whose purposes include vibration and drive system diagnostics, exceedance monitoring and rotor track and balance.

While these functions have already been implemented on different AgustaWestland helicopter models, providing quite consolidated results for the establishment of more efficient fleet maintenance procedures, the structural usage monitoring and the transmission usage monitoring system still requires some efforts in order to achieve reliable and advantageous results for the operator.

AgustaWestland current intent is to focus the attention on the SUM and TUM program, already installed on the AW101 fleet, in order to thoroughly assess potential to lead to component reliability improvement in terms of safety and cost reduction.

1 INTRODUCTION

While certified Health & Usage Monitoring Systems have been in operational service since the early 1990s, the origins of HUMS can be traced back to the early 1970s when the UK Ministry of Defence (MoD) began research into the use of vibration monitoring to improve the detection of helicopter drive-train faults. Since the early 1990s, the adoption of HUMS has been rapid and widespread. However, the technology has evolved significantly in the past decade to encompass far more than just “monitoring”.

Originally developed to improve the safety of civil helicopters operating in the hostile North Sea environment, HUMS technology has now been credited with providing safety and significant maintenance benefits to both civil and military operations.

The primary objective of this study is to evaluate the feasibility of the helicopter usage monitoring system for monitoring critical helicopter components in an operational and maintenance environment.

HUMS provides diagnostic and usage information to the maintenance and flight crews on the condition of critical components in the rotors, engines and drive train. The HUMS monitoring functions and parameters are summarized in Figure 1 and Figure 2.

The benefits promised by the application of HUMS technology are of great interest to the helicopter operator, because of the potential to enhance safety while reducing operating costs that is greatly needed to continue to operate profitably.

This report contains an evaluation of a state of the art SUM and TUM system.

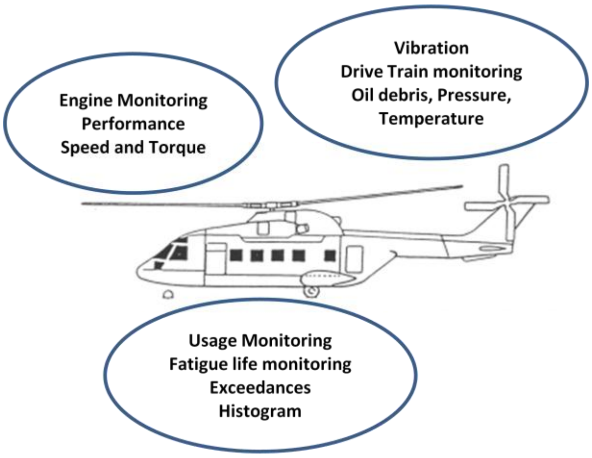


Figure 1 – Hums Monitoring Function

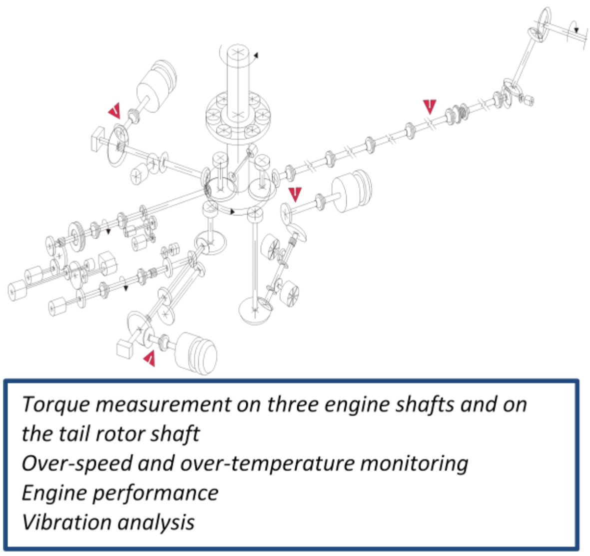


Figure 2 – Engine and Transmission Monitoring

2 HUMS DESCRIPTION AND OPERATING PROCEDURES

The HUMS components are illustrated in Figure 3.

On board function provides an algorithm for the flight condition recognition implemented into the system management computer (SMC). It makes use of a set of flight parameters to identify in real time the helicopter's current flight condition.

The algorithm output is then provided in the data transfer cartridge (DTC) in the system log file, for download purposes and in a more synthetic form on the common control unit (CCU).

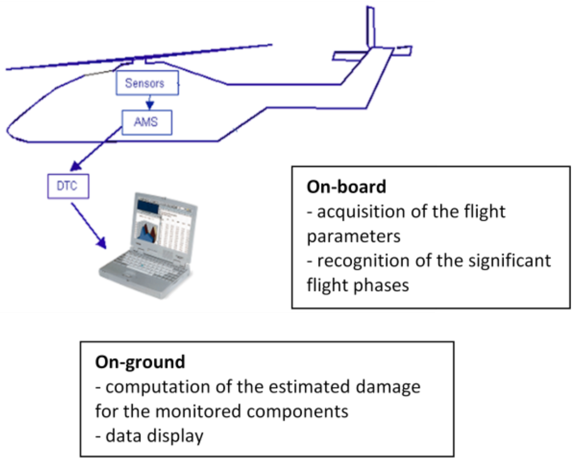


Figure 3 – On-board and On-ground Function

Namely the download should take place after each flight, but the usage function are designed to operate up to 15 hours between two downloads without loss of data.

Since the ground station contains the configuration of the components on board the helicopter, once the aircraft usage data are in the ground station it's possible to assign them to the relevant life limited components.

In this way the ground station generates a usage history for any single component and computes a usage rate and consequently an estimation of the remaining life, assuming that the recorded usage spectrum is representative of the future one.

The main characteristic of the software is that the flight phase recognition is performed in real time. A very short period of flight (2.96 seconds) is analysed each time. Once the flight phase is recognised, the whole process is repeated for the following time interval.

No time delay must exist between two consecutive intervals, in this way the flight is thoroughly analysed without losing information. The different flight phases are recognised according to each channel's mean and first derivate mean values.

As a computed first derivate is not null even if it can practically be considered so, a lower and an upper limit must be considered. A first derivate mean value must be set to zero when it is comprised between the two limits. Each channel must have its own limits

The data recording shall start when at least one engine is in ground-idle, it shall stop when all engines are shut down and weight on wheels (WOW) signal is 'yes'. The software shall acquire the parameters in Figure 4.

	Signal	Measuring unit
Group A	Pitch, roll and yaw attitude True airspeed Load factor	Degrees Knots G unit
Group B	Engine 1, 2 and 3 torque Barometric radar altitude	% Feet
Group C	Vertical speed	Feet/second
Group D	Weight on wheels	Yes/No
Group F	Outside temperature	°C

Figure 4 – List of parameters

Group A parameters shall be subjected to the calculation of the mean value and the first derivate mean value in each considered time interval.

Furthermore the mean value calculation shall be executed for group B and C parameters. For group D parameters, the software shall detect, in each considered time interval, only the state or the changing state. Group F parameters are considered constant during the time interval hence the current value is used directly.

3 ON-BOARD SOFTWARE OUTPUT DATA FORMAT

The on-board software is designed to recognise each significant flight condition together with the value of all parameters necessary to thoroughly characterise it. In addition to the time spent in each flight condition, the output data also contains the value of the significant parameters. The output data are a list of records, one for each time interval. Each record has a number of fields that equals the number of parameters necessary to fully characterise the identified flight condition in the corresponding time interval, reference [1].

For example, if in a certain time interval it is identified that the helicopter is flying a level flight condition this shall be characterized by the centre of gravity position, the helicopter weight, altitude, speed, ACSR (Active Control of Structural Response) status and hook load code. The ACSR system employed on the AW101 helicopter was introduced to improve passenger comfort and to meet vibration targets.

Therefore the record has a number of significant fields that is the sum of the fields representing the parameters plus ACSR status field and the one containing the flight condition code. Each parameter field is an integer value indicating the "variation band" corresponding to the parameter's value.

All the results records shall contain the following data:

- centre of gravity (CG) and weight
- density altitude
- ACSR status and Hook load code

All flight conditions are identified as anomalous flight conditions when one of their relevant parameters (speed, load factor, bank angle, ascending/descending rate, weight, etc.) is not detected, so the interval shall be classified as a type anomalous flight condition.

Figure 5 shows a list of all the flight conditions together with their relevant parameter.

Description	A	B	C	D	E	F	G	H	I	L
Low speed flare	•	•	•	•	•		•			
Vertical take-off	•	•	•	•	•					
Vertical landing	•	•	•	•	•		•			
Rolling take-off	•	•	•	•	•	•				
Rolling landing	•	•	•	•	•	•	•			
Ground operations	•	•	•	•	•					
Taxiing on-ground	•	•	•	•	•	•				
Hovering IGE	•	•	•	•	•					
Hovering OGE	•	•	•	•	•					
IGE operations	•	•	•	•	•	•				
Autorotation	•	•	•	•	•		•			
Level flight	•	•	•	•	•	•				
Longitudinal reversal	•	•	•	•	•	•				
Lateral reversal	•	•	•	•	•	•				
Pedal reversal	•	•	•	•	•	•				
Uniform banked turn	•	•	•	•	•	•		•		
Accelerated banked turn	•	•	•	•	•	•		•	•	
Asc./Desc. banked turn	•	•	•	•	•	•		•		•
Asc./Desc. accel. banked turn	•	•	•	•	•	•		•	•	•
Collective pull-up or push- over	•	•	•	•	•	•	•			
Level accel. Flight	•	•	•	•	•	•				
Asc./Desc. accel. flight	•	•	•	•	•	•				•
Uniform asc./desc. Flight	•	•	•	•	•	•				•
Anomalous flight conditions	•	•	•	•	•					

A - ACSR Status
B - Hook load
C - CG Position
D - Weight
E - Density attitude
F - TAS speed
G - Load factor
H - Bank angle
I - Long. acceleration
L - Asc./Desc. rate

Figure 5 – Flight conditions and relevant parameters

4 USAGE MONITORING OVERVIEW

For most current helicopters, rotating dynamic components (rotors and controls) are certified for fatigue using the safe-life methodology.

This section presents an overview of the system to be used to determine the fatigue life usage for dynamic components.

Usage parameter data can be used to determine the time in each manoeuvres category (spectrum) for each HUMS equipped aircraft.

All measured flight stresses above the reduced endurance limit produce some fatigue damage.

Using Miner's rule, a fatigue life, in flight hours, is calculated using the flight stresses and the certification flight spectrum developed for the aircraft. A fatigue life is established by assessing the frequency and magnitudes of oscillatory stresses above the reduced endurance limit giving the fatigue strength of the part. A retirement life can then be established for the part, so that the part can be removed from service before the safe life of the part has been reached.

The Figure 6 presents a diagram of this methodology

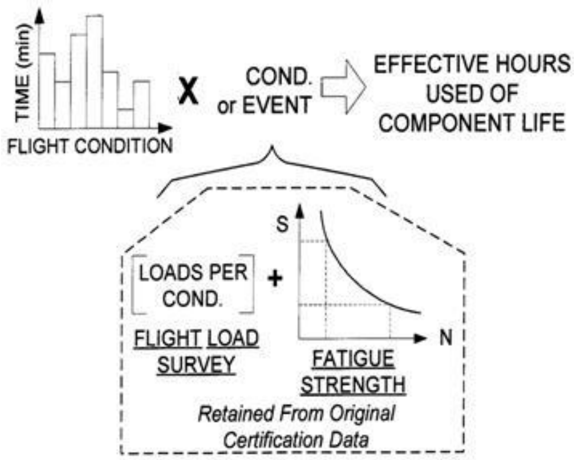


Figure 6 – Component life determination process using flight condition recognition

The major benefit of usage monitoring is an accurate accounting of how the aircraft has been operated. This information may allow an increased time in service for components on aircraft that were operated less severely than the assumed spectrum used in certification calculations.

Of even more importance, an increase in safety is achieved for those aircraft operated more severely than assumed certification spectrum because their parts will be retired from service earlier than the initial certification calculation would allow

5 STRUCTURAL USAGE MONITORING

Since the certification method establishes part retirement lives based on a conservative usage spectrum, it is easy to see that if the actual spectrum were found to be less severe or specific flight conditions were performed for a lesser flight time, a part could be allowed to be used for a longer period of time.

The HUMS recognizes and records different flight conditions such as ground, in ground effect manoeuvres, level flight, power on manoeuvres, power transitions, autorotation, take-off and landings at actual weight, altitude and airspeed and time spent in each of these conditions.

The HUMS monitors the parameters listed in Figure 5 and determines actual recognized flight conditions flown by the aircraft and compares these to the flight spectrum used for certification to determine the effect on established part lives

The HUMS system is designed to confirm the life calculation as well as provide a better spectrum of data to determine when the component should be retired based on the many parameters monitored, time spent in each condition, aircraft weight, and altitude in each condition. The typical flight missions included in the usage spectra utilized for fatigue life evaluation have been compared to the parameters that SUM is able to recognise, reference [1].

Flight data have been obtained by using SUM log of various flights of AW101 helicopters.

The analysis is based on a high number of flight hours monitoring on AW101 fleet and it's articulated into:

- ➢ comparison between the design usage spectrum and the flight conditions recognized by the SUM and TUM system
- ➢ an assessment of fatigue lives for the components for which the usage deviations are significant.

For these helicopters, a sample analysis of the time and number of start-stop an AW101 has spent in flight regimes during operational usage and at different weight/centre of gravity is shown in Figure 7 to Figure 13.

The coloured bars are an aggregate of the percentage of time or number of events per 100 running hours of the actual monitored usage for the helicopters considered in this analysis.

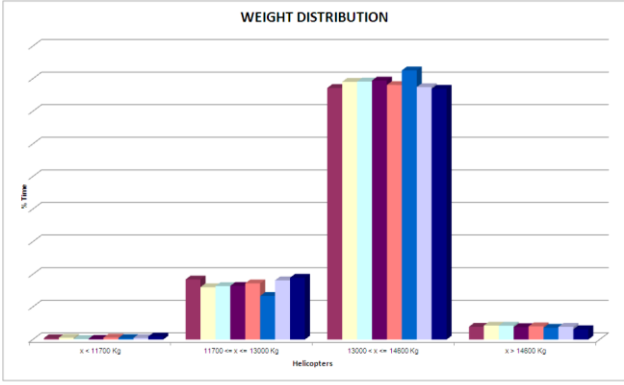


Figure 7 – Weight distribution

The operative range is around 13000÷14600 kg, the actual weight distribution could be positive on the fatigue lives for some components as main and tail rotors and controls, transmission and supports and drive system, if the design is conservative in the highest weight band.

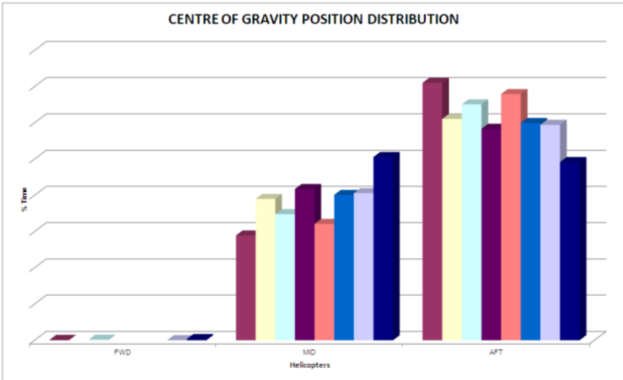


Figure 8 – CG distribution

The design CG distribution is in line to the actual usage taking account AW101 missions and configurations.

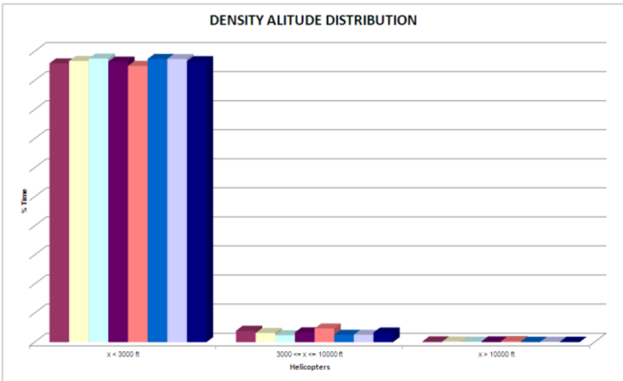


Figure 9 – Altitude distribution

Based on AW101 mission profiles, the design distribution is in line with the actual usage and it's conservative for high altitude; this aspect could have a positive impact on some components influence by high altitude as main rotor controls.

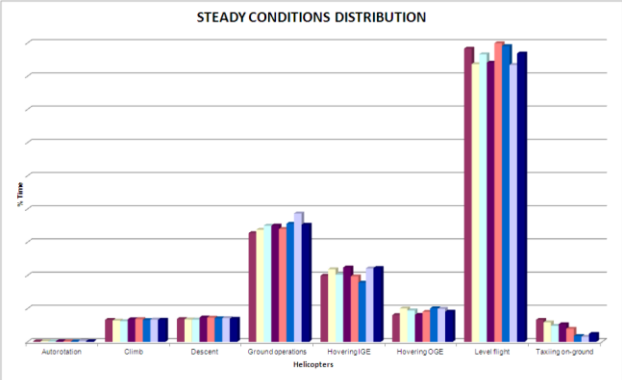


Figure 10 – Steady conditions

The low occurrence in hovering conditions could have a positive impact on some TR components.

The distributions shown in Figure 11 and Figure 12 give a good indication of the typical macro-conditions used to create the design usage spectrum.

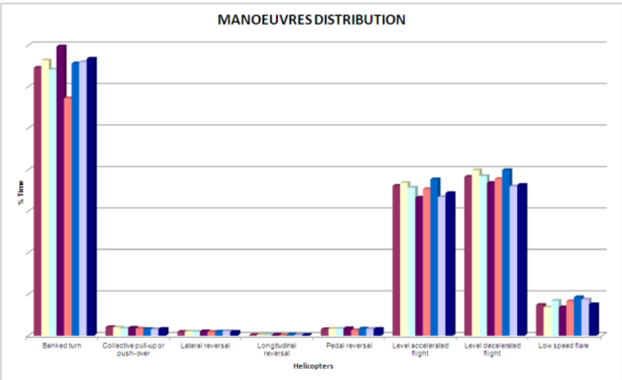


Figure 11 – Manoeuvres conditions

The operative speed range shown in Figure 12 is around high speed; the level flight distribution and the manoeuvre associated to this speed are very important for the fatigue life of the component.

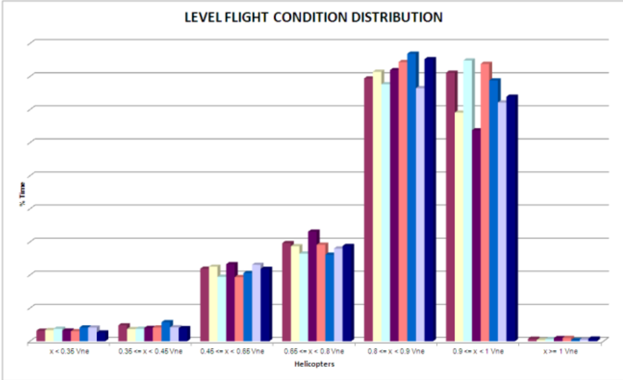


Figure 12 – Level flight conditions

The design assumption of considering accelerations and decelerations at high speed is conservative because they are more critical than the ones at low speed.

The number of ground-air-ground and start-stop performed, Figure 13 influence the fatigue life of many components, as blades, transmission fittings and rods etc. The number of landings has influence on the fatigue lives of the main gear box supports and attachment.

For the tension link an increased of the number of start-stops could have a negative impact on the low frequency life while the low occurrence of the flight conditions at high speed could have a positive impact on the high frequency life.

Only a recalculation of the fatigue live of the tension link could highlight the impact of the combination of high and low frequency.

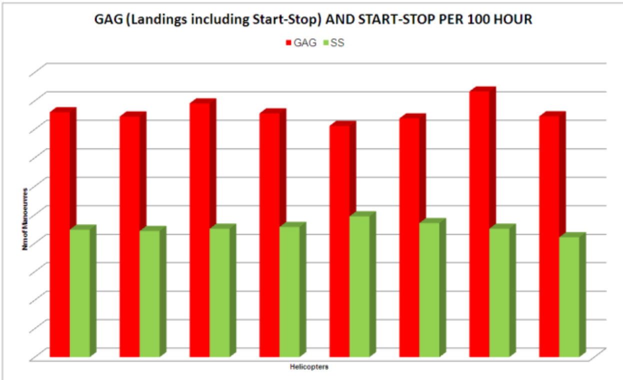


Figure 13 – Manoeuvres conditions

The number of landings/start-stops and the ground operations occurrence give a good indication of the typical duration of the missions.

Based on the revised usage data the calculation of safe lives of critical parts will be repeated in order to assess the severity of the actual spectrum and consequently take the proper actions.

6 TRANSMISSION USAGE MONITORING

The Transmission Usage Monitoring on board function collects five torque spectra, during flight, one for each engine and one for each rotor. Each torque spectrum is defined as a set of 36 torque intervals where, for each interval, a time counter, expressed in seconds, is recorded. The torque inputs are provided by the engine and tail drive shaft torquemeters. These inputs are also used, in real time, to compute the main rotor torque estimate value.

The TUM log files in the DTC are then transferred to and decoded by the ground station computer, where the torque spectra are allocated to each monitored component by means of its torque path code, i.e. for each component a specific torque spectrum shall be calculated based on its position inside the transmission system and its nominal rotating speed.

Some transmission system gears in some helicopters are fatigue life-limited. Furthermore it is fairly common for gear durability to limit the engine power available to the rotor system over much of the helicopter operating envelope.

The most common fatigue failure mode for gear is fracture at the tooth root for which the cyclic bending load at shaft frequency is the significant fatigue load. The bending loads are proportional to transmitted torque.

Engine torque thus provides a direct load measurement parameter for main rotor gearbox gear although tail take-off torque needs to be deducted for some.

In helicopters where gear durability is of significant concern, gear monitoring may provide a number of benefits.

These include:

- performance enhancement by allowing torque limits to be exceeded on the basis that the effect of such exceedances are monitored and taken account
- avoidance of some gearbox removal which, without usage monitoring, would have been required on the basis of the uncertainly associated with pilot reporting of the magnitude and duration
- life extension of individual gears if the their lives are based on the actual severity of in-service usage. Component lives are functions of geometry, materials, speed and force.
  These parameters are generally fixed by design except torque. Torque is a characteristic of transmission operation that greatly affects life and reliability.

The results are that a factor of Maximum Continuous Power (MCP) for each type of component has been developed. This factor is known as the Life Equivalent Power (LEP) factor.

This factor applies to the torque or horsepower used in determining the life of a component. The LEP factor accounts for the reaction of the component to the spectrum of loads that the component sees over its life.

The Figure 14 shows the MR mast distribution for AW101 fleet.

The design spectra and the fatigue test consider the maximum power mainly, so the distribution indicates lower power rating.

This aspect could have a positive impact on the fatigue lives of the drive system components such as gears.

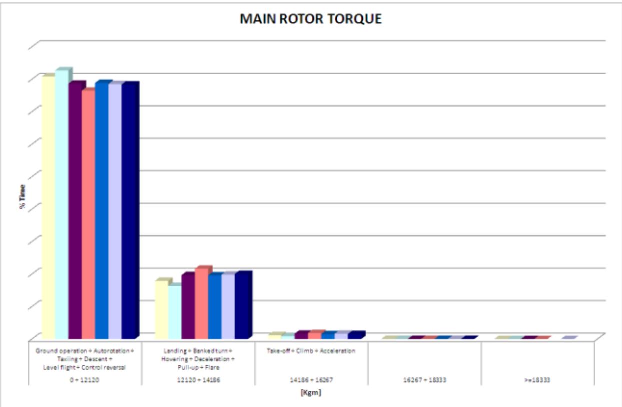


Figure 14 – MR torque distribution

7 NH90 HELICOPTERS

Military helicopter operators are actively examining the airworthiness and cost benefit of permanently installed usage monitoring system.

Component life extension, based on the results of a substantiation program, is viable only if a reliable and sufficiently large data set is available.

NH90 HUMS also has the capability to perform flight condition recognition and present counts of occurrences in defined manoeuvres per flight.

ESUM flight recognition is performed on-board the aircraft. AgustaWestland believes that there is the potential to be able to compare each aircraft operational usage with the rest of the fleet, and perhaps, more importantly, with the design usage spectrum.

By doing this there may be benefits in terms of flight safety, by assessing the actual usage compared with the design usage.

A commitment from the customer has been required, providing data feedback and assisting in developing the customer interface and the data feedback procedures.

On-board usage data gathering can provide a comparison between expected usage and actual usage.

In addition to aircraft usage, the output of TUM will provide data on torque usage and on the simple usage metrics, rotor start/stops, landing etc, which are all part of the design usage spectrum

8 CIVIL APPLICATIONS

Implementation of HUMS in civil helicopter is definitely leading that in military helicopters.

While some civil helicopter missions would be rated severe, the majority would be considered less severe than many military operations. Usually, the content of missions tend to be repeatable from day-to-day. In such instances it should be easier to ensure that the aircraft are being operated within the design usage spectrum, which provides the basis for the retirement schedule for fatigue life-limited components.

It is common for civil helicopters to fly for many hours per annum. This can significantly affect the frequency of maintenance actions. Generally, the higher the rate of effort the greater the financial benefits per annum which can be attributed to HUMS.

The certification process for HUMS is more complex than traditional certifications because ground-based equipment is usually involved and new technologies are employed.

The HUMS certification process has three aspects that are all equally important.

These three aspects are: installation, credit validation and continuing airworthiness:

- installation for a HUMS encompasses all areas of certification required to develop a new system and to install it at an operator's facility. If the system includes a ground-based portion, then that is also included. Everything from airborne equipment design and installation to ground-processing methods and equipment is covered under this aspect of certification
- credit validation requires supplying objective evidence that the physics involved in detection, recognition, isolation or other technology related to the maintenance credit being sought is sufficiently understood
- continuing airworthiness documents and demonstrates the operator's ability to successfully operate the HUMS, the operator's procedures and training, the minimum equipment list, how unavailability of the minimum equipment affects the HUMS and maintainer actions and procedures.

For each aspect, certain steps are needed to accomplish the certification.

The experience gained with the research activity on data coming from military operators has allowed applying all that to the civil field, by using the data collected by the HUMS installed on board the AW139.

The research activity is currently in progress at AgustaWestland to verify how the actual usage of the rotorcraft compares to the assumed design spectrum as agreed with the Airworthiness Authority.

9 FUTURE CHALLENGES

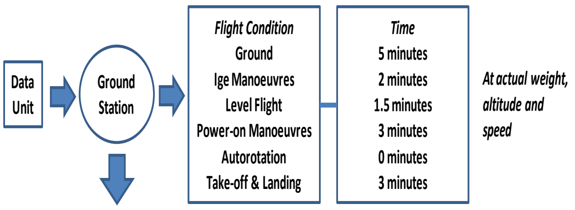
Life limited parts installed on a HUMS aircraft will be handled in the same manner as a part on an aircraft without a HUMS. The only difference would be that the actual part time on a HUMS installation aircraft will be adjusted up or down based on HUMS usage data. The value used to adjust time is called the 'Usage Index', UI.

The UI is applied to establish the actual time credited or debited to the part. For instance a part with a retirement life of 5000 hours has the same retirement life on a HUMS installed aircraft or on a non HUMS installed aircraft, although the time charged to the part per flight hour may be different.

The rate at which life is being consumed relative to certification is referred to as the component clock rate. If usage indicates that the part is using life faster than certification (i.e., it has a reduced life), then the part is said to have a fast clock.

The non HUMS installed aircraft part will always be charged one hour for each hour the aircraft flies. The HUMS installed aircraft part will be charged a percentage of the actual time flown on the part if the part has been approved for HUMS credit.

For example, the aircrew may have flown ten actual hours but the part is charged 50% or only five hours based on the actual flight spectrum being 50% of the severity of the certification flight spectrum as determined by the HUMS usage monitoring system.



Part Number	Usage Index	Actual AC Hours flown	Time to add to part	Service life of the part	Time remaining
P/N XX-YY Upper cone	50%	10 hours	5 hours	5000 Hrs	4995 Hrs

Figure 15 – Usage Index & Time remaining

By adjusting part usage time using this method the operator can treat parts on and off HUMS installed aircraft in the same manner.

The historical record card for the individual part installed on a HUMS aircraft should indicate the part was installed on a HUMS aircraft to clarify time accumulation.

On a non HUMS installation, the part may be installed at aircraft total time new and removed at 5000 hours which would calculate to time used on the part equals to 5000 hours.

On a HUMS installed aircraft, the time used on the part would not be calculated as on a non HUMS installation, therefore the historical record card must indicate that this part was a HUMS credited part. In the event the HUMS becomes inoperative the transition back to the previous method become as simple as returning the penalty applied to the part to 100%.

Spare components and parts for HUMS aircraft require the same established procedures regarding inventory, tracking and ordering as non HUMS aircraft.

Every component on a helicopter has a safe life limit.

Upon reaching this age, the component must be overhauled. The safe life limit of each component is derived from an expected usage spectrum of the aircraft, and then given a substantial margin.

Consequently, most retired parts are in a perfectly good condition.

However, if an aircraft is exposed to more severe usage than what it was designed, components might be exposed to more damage, Figure 16.

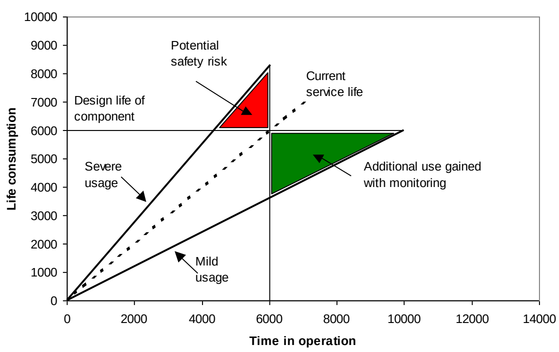


Figure 16 – Effect on retirement of usage monitoring

The reactive approach allows the HUMS to detect any faults present in the rotorcraft, while the proactive methods allow faults to be anticipated before they occur.

10 CONCLUSION

Helicopters are potentially more vulnerable to catastrophic mechanical failures than fixed wing air-craft because of the number of single load path critical parts within the rotor and transmission systems. The capability of HUMS has been shown to be a practical means of reducing the rate of hazardous and catastrophic failures that prevent continued safe flight and landing.

The operational assessment of the integrated HUM System installed on the AW101 has demonstrated a high level of reliability.

The approach used for AW101 is the basis of the philosophy of NH90 and AW39 usage monitoring.

HUMS acts as a sentinel over the state of critical components offering the latest in technology, contributing to a safer aviation environment.

The utilization of the Usage Monitoring data allows knowing the real helicopter spectrum, identifying more or less demanding usages in comparison with the design, confirming or not the current inspection intervals and the retirement lives limitations of the Maintenance Manual.

A continuous feedback between Users and AgustaWestland would reflect on the maintenance programs improvement also in the viewpoint of a condition based maintenance and costs reduction policy, both in terms of usage extension and criticality anticipation for more demanding usage.

Maintenance can be defined as ‘any one or combination of overhaul, repair, inspection, replacement, modification or defect rectification of an aircraft/aircraft component’. After completion of any package of maintenance a ‘certificate of release to service’ is necessary before flight.

In addition to increased safety, HUMS was seen as the technology that would revolutionize rotorcraft maintenance and shift rotorcraft maintenance strategy from time based maintenance to condition based maintenance.

Up till now, the analyses and studies of the usage monitoring potential in the field of safety and reliability have been carried out in a research program financed by AgustaWestland.

11 References

[1] Mariani U., Molinaro R., Mancin S., Maino B. (2007), Structural Usage Monitoring for Helicopter Fatigue Durability Validation, 24th ICAF Symposium - Naples, 16-18 May 2007