NINETEENTH EUROPEAN ROTORCRAFT FORUM

Paper n°E2

HELICOPTER USAGE MONITORING SYSTEMS: AIMING AT SAFER OPERATION.

by

M. Spinello, B. Maino

AGUSTA, ITALY

September 14-16, 1993
CERNOBBIO (Como)
ITALY

ASSOCIAZIONE INDUSTRIE AEROSPAZIALI
ASSOCIAZIONE ITALIANA DI AERONAUTICA ED ASTRONAUTICA

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B. MAINO

AGUSTA

The helicopter presents, with respect to airplane, a certain number of penalizing aspects; two among these are particularly important: higher direct operating costs and lower flight safety. The helicopter manufacturers together with the biggest operators are spending a lot of efforts trying to reduce the former and increase the latter. The so called Usage Monitoring Systems could grant significant advantages in that they allow to determine the aircraft real usage spectrum. It is therefore possible to compute the actual residual fatigue life of each critical component and to perform maintenance actions "on condition". Agusta's present activities on the matter are devoted to provide the EH-101 helicopter with a comprehensive Usage Monitoring System. An overview of the system's hardware architecture is presented, followed by a full description of the dedicated software. Special care is devoted in presenting and evaluating early results as well as in highlighting limitations and devised solutions.

1.0. Introduction.

One of the main challenges of aircraft and in particular of helicopter design is certainly the increase of flight safety. Therefore, in addition to new design theories, new topics are being investigated e.g. the "damage tolerance" and new comprehensive numerical routines. Among the new topics, Health and Usage Monitoring Systems (HUMS) [1] must be regarded as a group of hardware and software devices aimed at monitoring the correct functioning of the aircraft major systems, say engines, hydraulic, avionic etc. They advise the operator in case of either detected fault (Health) or impending maintenance threshold (Usage).

The Usage Monitoring Systems, and in particular those devoted to the aircraft structure, could grant the operator great advantages both in safety of operation and in reduction of the direct operating costs [2]. They allow, indeed, to determine the aircraft's real usage spectrum, i.e. the actual loads, to reckon the actual residual life of whatever component and hence to perform maintenance actions "on condition". In addition they give engineers the possibility to assess the effectiveness of the design spectra and to verify the components' predicted fatigue life.

For this is certainly not a consolidated matter, a lot of efforts must be devoted to determine the safest and most reliable methods to perform the envisaged tasks, to test in detail their broad potentialities and also to evaluate their airworthiness implications [3].

Early attempts to develop an effective monitoring system were made by military experts [4-8]. They meant to evaluate as precisely as possible the actual mission spectra performed by their helicopters during different types of mission, such as training, taxiing, attack, etc. They succeeded in assessing the effectiveness of the loads used in the design phase and also in assessing the helicopter capabilities to perform unforeseen missions. The methods used included:

- strain gauge measurements of loads on some significant structural parts,
- parametric evaluations, wherewith it was possible to determine the severity of the helicopter's mission by recording the time history of some significant parameters,
- manoeuvre recognition, consisting in analyzing the time history of some typical flight parameters, such as speed, altitude etc., in order to establish the manoeuvres performed during flight.

An estimation of the aircraft residual life was possible by correlating the obtained results with the components fatigue strength analysis. The evolution of the cited techniques is represented by the modern Usage Monitoring Systems, in which safety is certainly the most important aspect.

The methods used or being developed today include [9-10]:

- exceedances monitoring
- part load monitoring
- events, ground-air-ground cycles, start-stops counts
- histograms (torque, load, speed, temperature, etc.)
- flying hours logging (standard)
- flight condition recognition
- flight load synthesis
- holometrics [11]
- neural network and pattern recognition
- rotor coning/flapping (articulated rotors)
- fixed wing fatigue meters (speed, g, altitude)
- operational profile assessment.

Agusta's Usage Monitoring activity is today devoted to the development and the assessment of both the hardware and software to be fitted on board the EH-101, the first helicopter to be provided with such a systems from the beginning.

2.0. Fatigue substantiation process.

The design of the fatigue loaded components of a helicopter structure is certainly a challenging task, as it involves a great amount of efforts and a great deal of experience. It is also a long-lasting activity: it starts at the beginning of the definition phase and ends together with the operational life of the helicopter [12-13].

During the definition phase, the designers, making use of both engineering judgement and helicopter mission requirements, try to determine an operating spectrum, as close as possible to reality, to which refer to during the whole design phase. Once the components are thoroughly designed, they are verified by fatigue tests in order to establish if they fulfil the design strength requirements. Flight load survey is then employed to assess whether the predicted design loads correspond to the real ones. Though further refinement be introduced, based on the development and maturity experiences, in the fatigue substantiation process it is always necessary to take into account also a certain degree of uncertainty, because it is unlikely that all the aircraft of the same fleet will undergo the same life. Therefore a system capable of recognizing each helicopter real flight envelope could grant great advantages both to the designers, as they can verify the hypothesis made, and to the customers, allowing an increased safety and a reduced cost of ownership. Maintenance schedules, indeed, would no longer be established on the assumption of flying the worst loading spectrum, but the "on-condition" maintenance concept can be introduced.

2.1. EH-101 flight spectrum.

The EH-101 flight spectrum is subdivided into the following main flight conditions:

- ground operations
- hover
- climb and descent
- autorotation
- level flight.

Each flight condition is characterized by the weight, the centre of gravity position, the altitude at which it takes place and by one or more parameters to thoroughly estimate its severity. For instance it is necessary to take into account also speed value or speed and acceleration values in case of a uniform level flight or an accelerated level flight respectively.

Parameters to be monitored to fully describe all the most significative manoeuvres of the flight envelope are:

- weight
- centre of gravity position
- altitude
- speed
- yaw rate
- climb and descent rate
- bank angle
- longitudinal acceleration
- load factor.

As weight and centre of gravity position are not precisely measured, but are estimated by the pilot before flight and thus subject to error or manipulation, it is always considered that each flight condition is flown with the most damaging combination of them.

3.0. Agusta's Structural Usage Monitoring System.

3.1. Structural Usage Monitoring System development.

The logical consequence of such a flight spectrum subdivision was to think of a Structural Usage Monitoring System capable of discriminating between the predefined flight conditions. A flight condition recognition method was then developed.

The aggressiveness of each manoeuvre depends both on the percentage of time spent by the helicopter in that condition and on its severity. Manoeuvres were then sorted and attention was first centred on those having the greater fatigue life consumption (See Table 1). A modular software was written, where each module is devoted to the analysis of one of the latter flight conditions. This procedure allowed us to:

- develop the software considering the flight conditions separately and one by one
- cover the flight spectrum starting from the fatigue most significant part of it
- achieve and evaluate early results obtained by running first modules.

3.2. Structural Usage Monitoring System architecture.

The production standard Structural Usage Monitoring System architecture is composed by an on-board and an on-ground computer. The on-board unit must get all the necessary data from dedicated sensors, roughly analyze them, store results in a data transfer device and manage any message could be useful to the crew. Once back to the base, the data transfer device will be connected to the ground station to down-load all data and information gathered during flight. The ground operator can then proceed to update the usage data of the helicopter through dedicated algorithms that take into account both the mission flight time and the spectrum actually flown.

For developing purposes a different data acquisition and analysis system was arranged, because it is certainly easier to develop on-ground the whole system and related software and fit it on-board when its performances are fully tested. Moreover the production standard aircraft computer will be available in the first half of 1994 and the present one has not the capabilities to perform as needed. Therefore a portable 16-channels analog cassette recorder was used to record flight data directly on the helicopter or from the flight data base of Agusta's flight data acquisition facility. Data are then down-loaded in a PC or a work-station by means of an analog to digital converter fitted with anti-aliasing filters. The data sampling frequency is very low, because the typical input or reaction period of a pilot is about half a second and the inertia of the helicopter is such that it is not reasonable to consider shorter manoeuvre's periods. Flight data are thus ready to be analyzed.

3.3. Usage Monitoring Analysis Program.

Usage Monitoring Analysis Program was written in order to recognize EH-101 helicopter most significant flight conditions. It is subdivided into four main sections:

- opening data and output files
- recognizing flight phases
- updating results' matrices
- writing results in output files.

The first and last sections are specific to the on-ground development version, while the other two were written envisaging their implementation on-board.

3.3.1. First section: opening data files.

At the beginning the program opens all the necessary data files. Each one of them must contain the time history of each flight parameter to be considered. The data values must be in engineering units as follows:

• roll attitude	degrees
• pitch attitude	degrees
• yaw attitude (heading)	degrees
• indicated airspeed (IAS)	Knots
• pressure altitude	feet
• load factor	'g' units
• 'TOP' channel	volts.

The 'TOP' is a two-levels signal operated in flight by a flight test engineer. When high, it indicates that the helicopter is in a defined flight condition. It is useful because it permits to precisely locate the significant flight conditions and so to verify how they should be characterized and if the Usage Monitoring program is able to detect all of them.

3.3.2. Second section: flight phase recognition.

To perform the flight phases recognition, the program computes the mean value and the first derivative mean value of each channel in a given period of time.

As a computed first derivative is not null even if practically it can be considered so, a lower and upper limit must be considered and a first derivative value is set to zero when it is comprised between the two. Each channel has its own first derivative limits that can be conveniently and independently modified.

According to each channel mean and first derivative values, the program identifies the different flight phases. For example for a level flight condition all the channels' first derivatives have a null mean value, while for an accelerated level flight condition only the speed channel's first derivative exceeds stated limits. The same logic is used to recognize all the other flight conditions.

3.3.3. Updating results' matrices.

Once the flight condition is recognized, it is necessary to store all the information useful to classify it according to the stress department needs. So, for instance, when a level flight condition is detected, it is necessary to record the altitude and the speed at which it took place. Similarly for an accelerated flight condition also the acceleration value must be recorded. As it is impractical to store each significant value as it is, parameters' variation intervals are subdivided into "variation bands" (see Table 2) and the program counts the time the helicopter spent in each considered flight condition with a given combination of parameters.

The output data are then a group of matrices, one for each considered flight condition. Each matrix has a number of dimensions that equa's the number of parameters necessary for thoroughly characterize each flight condition and a number of elements depending on the number of bands each parameter is subdivided into. For example the level flight condition is characterized by altitude and speed, so the level flight matrix has two dimensions and a number of elements obtained by multiplying the number of altitude bands for the number of speed ones, i.e. 7x3=21. Each element is an integer number indicating the cumulative time the helicopter flew in that condition. In Table 3 there is a list of all the result's matrices together with their dimensions.

As only some flight conditions are considered and also data acquisition problems may prejudice flight condition recognition, an output matrix is devoted to "anomalous" flight conditions. It has only one element indicating the total time spent in such conditions.

3.3.4. Fourth section: writing results in the output files.

When all the analysis tasks are over, the program calls the dedicated subroutine to write the results in the output files. There is one file for each considered flight condition. Each file contains a list of the values of the result matrix elements to which it is referred to, the mean and the first derivative values of all the channels during all the recognized flight conditions.

3.3.4.1. The "Active TOP" output file.

The "Active TOP" output file is a list of all channels' mean and first derivative values during the flight periods in which the "TOP" signal is activated. In addition to this, it also contains the type of flight condition the program recognized during the "active TOP" flight periods.

The file is very helpful for the evaluation of the software capabilities. It is in fact possible to assess the typical mean and first derivative values of each of the selected flight conditions and consequently to choose and eventually refine the first derivative limits. Moreover it allows the evaluation of the software capabilities to recognize the flight conditions by comparing the program results with the manoeuvre really flown by the helicopter during the "active TOP" phase of flight.

3.4. Results' analysis.

The program was run with different flights' input data files and it demonstrated to satisfactorily perform the flight phases recognition in each case. Results were almost the same for each considered flight, so that it is convenient to concentrate the attention on only one of them to evaluate the program performances. As showed on Table 4, flight 394 of EH-101 prototype number two was chosen. It is a "load survey" flight and contains all the fatigue significant manoeuvres repeated more times with different combination of parameters.

Apart from small discrepancies attributable to the natural impossibility of the pilot in achieving exactly the desired values of speed or bank angle, uniform and accelerated level flights, banked turns and control reversals are all recognized and properly characterized.

Some problems arise with ascending and descending flight conditions, as they are correctly detected, but it is quite impossible to discriminate among different rates of climb. This is attributable to the typical high fluctuations of the pressure altitude signal, that prejudice the signal first derivative calculation. So, having considered a sufficient number of samples for calculation, the altitude mean value is certainly acceptable and reliable for our applications, while an alternative way is necessary for the determination of the rate of climb. One envisaged solution is to use the variometer signal to achieve the rate of climb. Though simple, it is not an easily applicable solution, because the variometer signal is not usually acquired in the EH-101. It is then necessary to arrange the needed wiring and the eventual modifications to include also this signal in the acquisition system.

Other problems came from the unreliability of the normal acceleration ("g") signal preventing us from recognizing manoeuvres such as the cyclic and collective pull-ups or push-overs. These are to be assessed in the near future.

4.0. Future objectives.

Usage Monitoring analysis program development efforts are certainly not over. It will therefore be necessary to even broadly test and optimize the program, in order to minimize the memory occupation and the computer workload so as to be properly installed on the EH-101 on-board unit. First tests on at least two prototypes are already scheduled for the next year.

After all the fatigue significant analysis routines are developed and sufficiently tested, it is necessary to correlate their results with the helicopter's fatigue life consumption. This will be done by means of dedicated algorithms capable of determining the residual life of each fatigue critical component.

The last and however demanding activity is the certification of the whole system. It will be certainly an interesting and onerous task as no rules today exist on the argument. Agusta, together with other main helicopter manufacturers and operators, is actively collaborating with the regulatory authorities, especially the CAA, in the assessment of all Structural Usage Monitoring related matters, to produce a document to be considered as a guide-line for the establishment of the certification rules.

5.0. Conclusions.

The results so far obtained are certainly encouraging and indicate that significative advantages could be gained through the application of Usage Monitoring Systems. Nevertheless, still some work remain to be done in the assessment of the system's whole potentialities and reliability, in the establishment of fatigue lifing algorithms and mainly in determining the new maintenance procedures, that broadly interfere with safety, costs and certification issues. However the foreseen improvements both in safety of operation and in reduction of life cycle costs undoubtedly justify all those efforts.

6.0. References.

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CLIMB AND DESCENT :
climb + descent 500 ft/min
climb + descent 1000 ft/min
climb + descent 1500 ft/min
LEVEL FLIGHT :
level flight 0.3 Vne
level flight 0.4 Vne
level flight 0.5 Vne
level flight 0.6 Vne
level flight 0.7 Vne
level flight 0.8 Vne
level flight 0.9 Vne
level flight 1.0 Vne
level flight 1.1 Vne
normal acceleration + deceleration
rapid acceleration + deceleration
20° banked left and right turn
30° banked left and right turn
45° banked left and right turn
cyclic and collective pull-up 1.3 g
cyclic and collective pull-up 1.7 g
longitudinal reversal (1 second)
lateral reversal (1 second)
pedal reversal (1 second)

Table 1 EH-101 most fatigue significant flight conditions.

ROLL ATTITUDE (bank angle):					
1			value	≤	-35 deg
2	-35 deg	<	value	≤	-25 deg
3	-25 deg	<	value	≤	-15 deg
4	-15 deg	<	value	≤	15 deg
5	15 deg	<	value	≤	25 deg
6	25 deg	<	value	≤	35 deg
7			value	>	35 deg
AIRSPEED:					
1			value	≤	0.25 Vne
2	0.25 Vne	<	value	≤	0.45 Vne
3	0.45 Vne	<	value	≤	0.65 Vne
4	0.65 Vne	<	value	≤	0.75 Vne
5	0.75 Vne	<	value	≤	0.85 Vne
6	0.85 Vne	<	value	≤	0.95 Vne
7			value	>	0.95 Vne
ALTITUDE:					
1	0 ft	<	value	≤	3000 ft
2	3000 ft	<	value	≤	10000 ft
3	10000 ft	<	value	≤	15000 ft
LOAD FACTOR:					
1			value	≤	0.9 g
2	0.9 g	<	value	≤	1.1 g
3	1.1 g	<	value	≤	1.4 g
4			value	>	1.4 g
CLIMB/DESCENT RATE:					
1			value	≤	-1100 ft/min
2	-1100 ft/min	<	value	≤	-550 ft/min
3	-550 ft/min	<	value	≤	f' min. lim.
4	f' min. lim.	<	value	≤	f' max. lim.
5	f' max. lim.	<	value	≤	550 ft/min
6	550 ft/min	<	value	≤	1100 ft/min
7			value	>	1100 ft/min
LONGITUDINAL ACCELERATION:					
1			value	≤	-2.5 Kts/s
2	-2.5 Kts/s	<	value	≤	f' min. lim.
3	f' min. lim.	<	value	≤	f' max. lim.
4	f' max. lim.	<	value	≤	2.5 Kts/s
5			value	>	2.5 Kts/s

Table 2 List of "variation bands" in which each parameter's variation interval is subdivided in.

flight condition:	parameter	variation bands	results matrix dim.
Climb and descent			
	altitude speed c/d rate	3 7 7	147
Level flight			
	altitude speed	3 7	21
Banked turn			
	altitude speed bank angle	3 7 7	147
Collective pull-up			
	altitude speed load factor 'g'	3 7 4	84
Reversal			
	altitude speed long./lat./pedal	3 7 3	63
Accelerated level flight			
	altitude speed acceleration value	3 7 5	105

Table 3 List of all the result's matrices together with their dimensions.

Flight nr. 394 helicopter PP2		
TOP	real flight condition	recognized flight condition
3	transition level flight 75 KIAS - climb 75 KIAS	level flight + climb mean speed 77 KIAS
4	uniform climb 75 KIAS	ascending uniform flight
5	transition climb 75 KIAS - 75 KIAS level flight	climb 78 KIAS + level flight 79 KIAS
6	level flight 0.5 Vne (79 KIAS)	level flight 84 KIAS
7	level flight 0.4 Vne (63 KIAS)	level flight 68 KIAS
8	level flight 0.3 Vne (47 KIAS)	level flight 52 KIAS
9	level flight 0.6 Vne (95 KIAS)	level flight 97 KIAS
10	level flight 0.7 Vne (110 KIAS)	level flight 111 KIAS
11	level flight 0.8 Vne (126 KIAS)	level flight 126 KIAS
12	level flight 0.9 Vne (142 KIAS)	level flight 142 KIAS
13	normal deceleration from 142 to 75 KIAS - level	2.5 kts/s decelerated level flight 137 - 74 KIAS
14	normal acceleration from 75 to 142 KIAS - level	2.1 kts/s accelerated level flight 80 - 139 KIAS
15	rapid deceleration from 142 to 75 KIAS - level	4.1 kts/s decelerated level flight 143 - 73 KIAS
16	climb 1000 ft/min 75 KIAS	climb 1800 ft/min 78 KIAS
17	transition from level flight 95 KIAS to descent 500 ft/min 95 KIAS	level flight 96 KIAS + descent 1200 ft/min 97 KIAS
18	steady descent 500 ft/min 95 KIAS	descending flight 1500 ft/min 96 KIAS
19	transition from descent 500 ft/min 95 KIAS to level flight 95 KIAS	descending flig ht 780 ft/min 98 KIAS + level flight 97 KIAS
20	climb Maximum Continuous Power 95 KIAS	climb 1000 ft/min 96 KIAS
21	steady descent 1500 ft/min 95 KIAS	descending flight 1380 ft/min 97 KIAS
22	45° bank right turn 95 KIAS	39° bank right turn 90 KIAS
23	45° bank left turn 95 KIAS	42° bank left turn 92 KIAS
24	30° bank right turn 47 KIAS	28° bank right turn 56 KIAS
25	30° bank left turn 47 KIAS	31° bank left turn 53 KIAS
26	45° bank right turn 63 KIAS	38° bank right turn 67 KIAS
27	45° bank left turn 63 KIAS	38° bank left turn 67 KIAS
28	30° bank right turn 142 KIAS	27° bank right turn 135 KIAS
29	30° bank left turn 142 KIAS	29° bank left turn 135 KIAS
30	45° bank right turn 142 KIAS	38° bank right turn 135 KIAS
31	45° bank left turn 142 KIAS	37° bank left turn 129 KIAS
32	longitudinal reversal 142 KIAS	longitudinal reversal 143 KIAS
33	lateral reversal 142 KIAS	lateral reversal 142 KIAS
34	pedal reversal 142 KIAS	pedal reversal 140 KIAS
35	cyclic and collective pull-up 1.3 g 142 KIAS	anomalous flight condition
36	cyclic and collective pull-up 1.7 g 142 KIAS	anomalous flight condition
37	cyclic and collective push-over 0.6 g 142 KIAS	longitudinal reversal
38	longitudinal reversal 95 KIAS	longitudinal reversal 97 KIAS
40	pedal reversal 95 KIAS	pedal reversal 97 KIAS
41	lateral reversal 95 KIAS	lateral reversal 97 KIAS
42	cyclic and collective pull-up 1.3 g 95 KIAS	collective pull-up flight 1.1 g 95 KIAS
43	cyclic and collective pull-up 1.7 g 95 KIAS	anomalous flight condition
44	cyclic and collective push-over 0.6 g 95 KIAS	anomalous flight condition

Table 4 EH-101 PP2 flight 394 "Active TOP" flight conditions and correspondent Usage Monitoring analysis program results.