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TRANSMISSION USAGE MONITORING FOR THE EH101; A COMPREHENSIVE APPROACH

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__Abstract.__ *Time has come for substantial enhancements in the helicopter maintenance processes. This paper presents a brief survey on the current ideas, particularly concerning Transmission Usage Monitoring (TUM) applications. Follows a description of the TUM application for the EH101 helicopter, the undergoing development activity and targets. System validation and maintenance credits aspects are then explored.*

Symbols.

af	bearing life adjustment factor
b	number of torque bands
C	bearing basic dynamic load rating
D_C	cumulative damage of component C
D_{CO}	initialised damage total for component C
F	number of flight conditions
F_a	applied thrust load
F_r	applied radial load
f_{ra}	corrective factor to take account for both accessories torque absorption and the drive system efficiency
K_C	gear ratio of component C
L_C	calculated life of component C
L_{na}	bearing life
m	exponent in the RMC formula
n	rotation speed
N	number of cycles
N_i	allowable cycles for the i-th torque band
NR	rotor speed
p	period

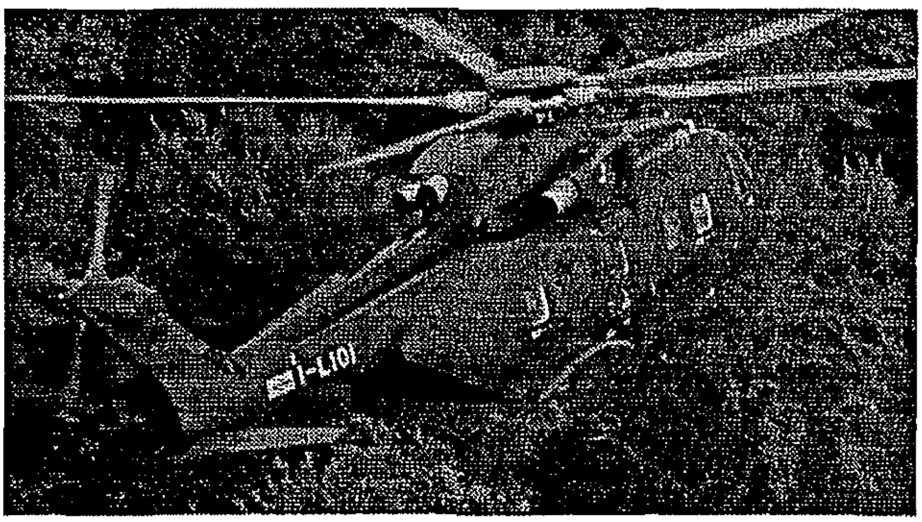

Figure 1. EH101 PP9 utility variant.

P dynamic equivalent load

P_i Power of i-th flight condition

RMC Root mean cube power spectrum

S stress

t_i time accumulated within torque band i

T torque

T_{EF} highest torque for infinite fatigue life (endurance limit)

T_{ES} endurance limit reduced by a safety factor

T_{E1i} engine 1 torque (i-th sample)

T_{E2i} engine 2 torque (i-th sample)

T_{E3i} engine 3 torque (i-th sample)

T_{MRi} main rotor torque (i-th sample)

T_{TRi} tail rotor torque (i-th sample)

x exponent in the bearing life formula

X_i duration of i-th flight condition

A B C and X Y are constants.

Abbreviations.

AMC - Aircraft Management Computer
AMDB - Aircraft Management Data Bus
AMS - Aircraft Management System
CAA - Civil Aviation Authority
CPU - Central Processing Unit
DTC - Data Transfer Cartridge
DTD - Data Transfer Device
FAA - Federal Aviation Administration
GBDS - Ground Based Data System
HARP - Helicopter Airworthiness Review Panel
HHMAG - Helicopter Health Monitoring Advisory Group
HUMS - Health and Usage Monitoring Systems
LRU - Line Replaceable Unit
MCWG - Maintenance Credit Working Group
MoD - Ministry of Defence
N - Newtons
RMC - Root Mean Cube
rpm - rotations per minute
SIU - Sensor Interface Unit
SUM - Structural Usage Monitoring
TBO - Time Between Overhauls
TUM - Transmission Usage Monitoring
TUMS - Transmission Usage Monitoring System
UDB - Usage Data Base

1. Introduction.

1.1 Growing interest in HUMS.

Helicopter Health and Usage Monitoring Systems (HUMS) have been rapidly developing over the past several years, with the purposes of enhancing safety, reducing maintenance costs and increasing availability.

In 1985 the Helicopter Airworthiness Review Panel (HARP) identified helicopter health monitoring as an emerging technology capable of contributing to the enhancement of helicopter safety.

Although, of course, primarily concerned with safety and therefore safety credit from HUMS in helping meeting Design Assessment requirements, CAA recognised that other more visibly quantifiable forms of payback from HUMS would be generally desired. For many of the helicopter critical systems and components, safety and reliability are highly correlated.

The Helicopter Health Monitoring Advisory Group (HHMAG) was formed following a recommendation of HARP to further investigate HUMS technologies and its implementations. The HHMAG is representative of the wide interest on this topic by seeing as participants most of the European and US helicopter manufacturers, many important helicopter operators, system suppliers, and airworthiness authorities such as the MoD, the FAA and, of course, the CAA.

The number of HUMS applications is growing among the helicopter operators, but the picture is unbalanced. There is a clear dominance of the health monitoring functions, while the usage information is often limited to automatic flight time recording and exceedance counters.

1.2 Data management.

This sort of unbalance is probably generated by problems involved in data management. While health monitoring functions usually perform completely on-board the helicopter, the usage monitoring functions require a more strategic approach. These relate to the detection of the actual flight spectrum and its impact on the life of critical components. It is then necessary to track each aircraft, flight after flight, and to track components with limited life, even if relocated on different aircraft. This requires the capability to download data to a ground station after a limited number of flights, to provide data synthesis and maintenance reports. Moreover, the ground station may need to exchange data with other ground systems for configuration updates, maintenance procedures' changes, software improvements, etc. Also, it is necessary to provide recovery techniques in case of usage data loss, otherwise a failure of the on-board usage data recorder could reduce confidence on all the recorded flight spectrum data and all the life expenditure evaluations for that aircraft.

The Transmission Usage Monitoring is rather peculiar for this kind of difficulties since it deals with a number of Line Replaceable Units (LRUs) that can be removed and re-installed several times, on an aircraft, during their life. Hence, the flight spectrum history of each LRU can be different from that of the aircraft where it is installed. Then, each LRU requires a record that has to continuously represent its status. Such record will include an identification code of the LRU and the current life expenditure or usage rate, if the LRU includes limited life components. However to better represent the status of the LRU, additional information may be required, like its actual load spectrum, relevant exceedances or specific events occurred that may allow correlation with the failure modes of the LRU.

The handling of this kind of records for each LRU of each transmission system operated by a fleet of helicopters may represent a strong data management effort for an operator. The effort is even stronger if it's the manufacturer that aims at tracking all the transmission systems delivered, but it is here where we have the opportunity to reap the best results from the transmission usage monitoring. As a matter of fact, only the manufacturer can analyse component overhaul records and assess usage data to establish inspections, and other maintenance actions.

1.3 Impact on maintenance processes.

The proper application of this technology can have desirable effect on maintenance and inspection programs. Maintenance credit potential exists for all major dynamic components of rotorcraft, including the transmission system. Maintenance credits can range from the extension of a component life limit to the adjustment of inspection intervals, TBOs, or modification of other maintenance actions. Unlikely, specific approval procedures of applications for maintenance credit have not yet been defined by the airworthiness authorities.

To better identify and review all the aspects related to maintenance credits for HUMS, the HHMAG spawned the Maintenance Credit Working Group (MCWG). Meanwhile, an FAA working group has distributed the final draft of an Advisory Circular to provide guidance to obtain maintenance credits when using aircraft equipped with HUMS.

1.4 Cost reductions.

Maintenance credits can really affect the helicopter's direct operating cost, thus presenting this technology as a very attractive option for the operators.

Out of the benefits directly associated with maintenance credits, others may derive from improved maintenance procedures or equipment, thanks to the availability of usage data. These benefits may be in the form of reduced cost, workload, or turn-round time.

2. EH101 TUM implementation guidelines.

The EH101 is an Agusta-Westland joint-program for a mid-weight, three-engine helicopter in three basic variants, naval, utility and civil.

The EH101 logistic support system includes a ground facility called Ground Based Data System (GBDS). This is designed to support several aircraft and offers multiple management functions, like flight set up, maintenance scheduling, HUMS related tasks, etc. The maintenance functions of the GBDS are targeted to provide support for first line operation of the EH101, with the capability of seamless co-operation with other logistics and support systems. This feature gives us the opportunity of collecting the usage data of each transmission system and updating them after each flight, eventually providing first line maintenance information and forecasting. Moreover, it is possible to transfer the usage data recorded by all the operators onto a centralised manufacturer Usage Data Base (UDB), thus providing assessment of the usage monitoring performance, data and algorithm validation, and system substantiation for maintenance credit claim.

The EH101 Transmission System is conventionally designed, though, it contains some advanced features. It is compound by a main gearbox, an accessory gearbox, an intermediate gearbox, a tail

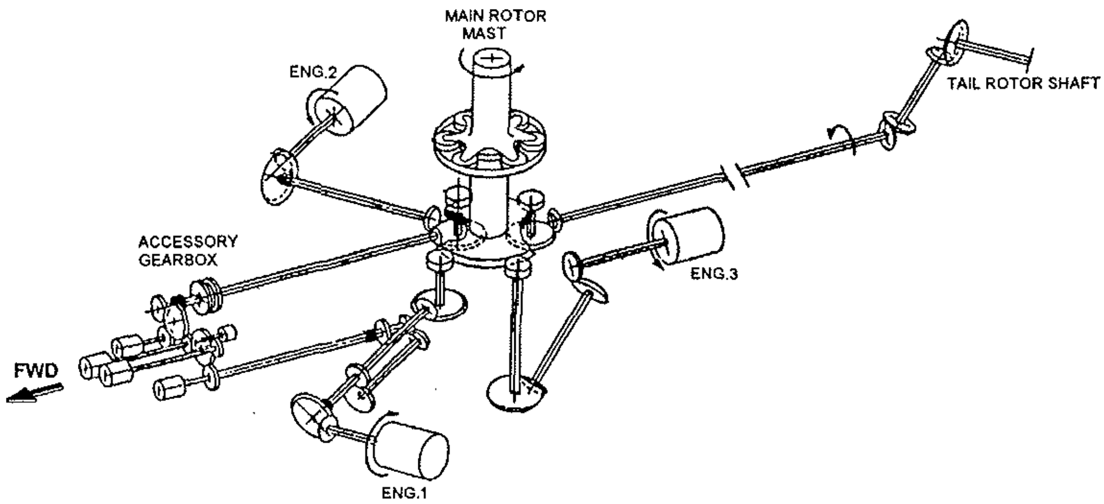

Figure 2. EH101 Transmission System.

gearbox and tail drive shafts. The main gearbox collects torque from the three gas turbine engines and drives the main rotor mast, the accessory gearbox, the tail rotor drive and some accessories. The accessory gearbox drives the remaining accessories, and the intermediate and tail gearboxes drive the tail rotor mast.

The Transmission System is compliant with the naval, utility and civil variants with minor differences.

The stringency of both military and civil helicopter specifications has increased the difficulties of satisfying the specific requirements based on traditional design procedures. Hence, the need for alternative methods of safeguarding the aircraft and its systems has led to a monitoring system having the capability of detecting malfunctions, forecasting incipient failures, evaluating true usage spectrum and supporting the achievement of the TBO objectives.

The most relevant critical components taken into account by the TUM are gears, shafts and bearings, though, a list of life limited components for the transmission system is not yet available, since fatigue tests and type tests are still ongoing at the time of this paper writing. Rotor masts, cases, case supports and drive shaft supports are object of the Structural Usage Monitoring (SUM) instead, since their loads are heavily affected by the occurring flight manoeuvres and not or not only by the torque.

The transmission usage computations are mainly based on individual usage spectrum collected for each single component by means of the data management described hereafter and without direct reference to any standard spectrum.

3. EH101 TUM architecture.

The EH101 TUM concept is structured on three main levels:

- single aircraft level: on-board torque data gathering;
- fleet level: integration of TUM data into the Ground Base Data System (GBDS);
- whole production level: comprehensive usage data base of all the transmission systems ever operated.

Such a concept is developed in a system architecture based on the following major items:

- the Transmission Usage Monitoring System (TUMS) subdivided into two subsystems, both under customer operation, one on-board the helicopter as part of the avionics, and the other as a software application in the GBDS.

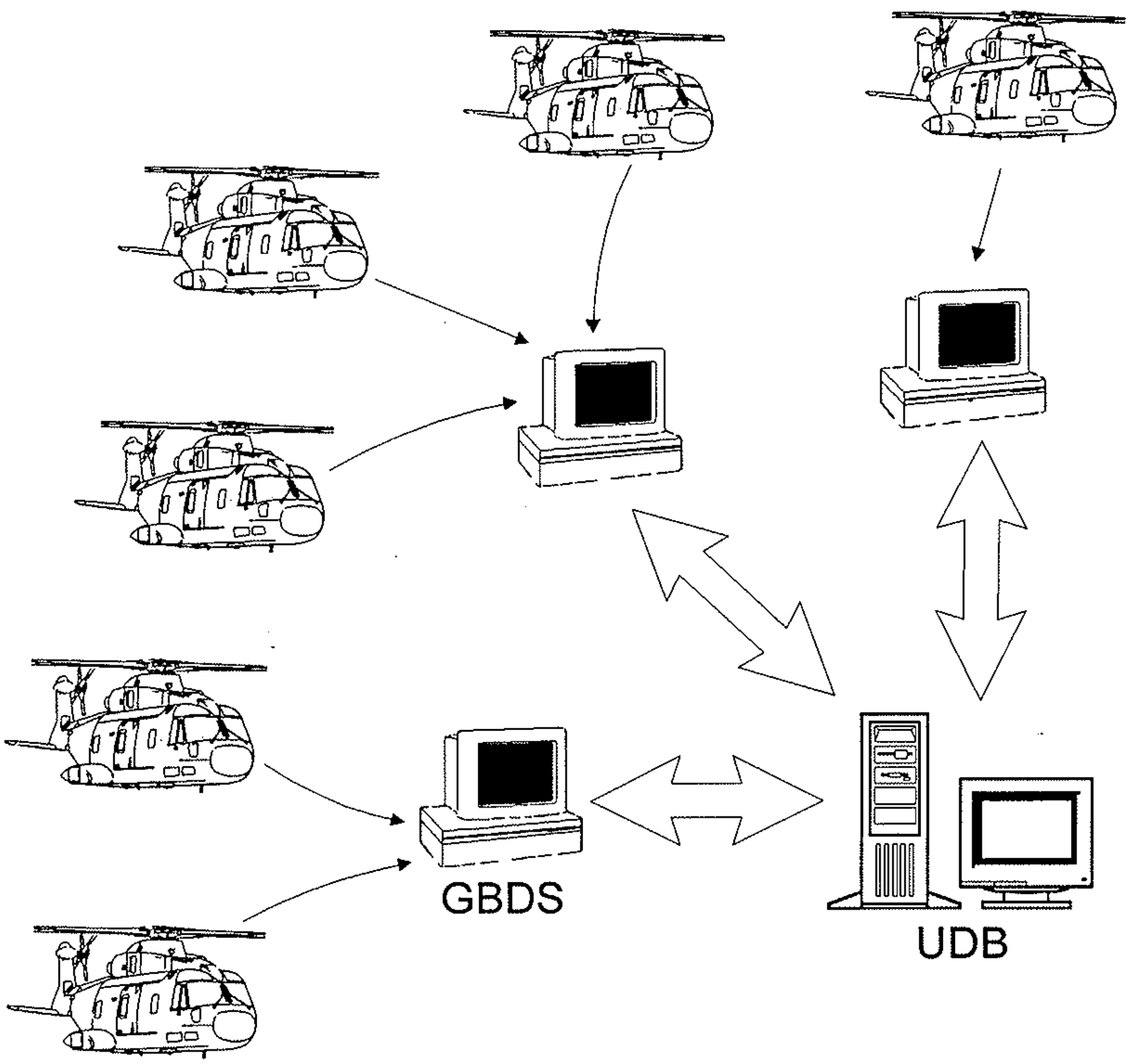

Figure 3. TUM data flow.

- the UDB, implemented into a workstation in the manufacturer's network for multiple access;

The TUMS on-board part is formed by components of the Aircraft Management System (AMS):

- 2 Aircraft Management Computers (AMCs);
- 2 Sensor Interface Units (SIUs);
- 4 torquemeters;
- a Data Transfer Device (DTD).

These items communicate through the Aircraft Management Data Bus (AMDB).

The two SIUs provide interfacing to the AMCs for the signals coming from the torquemeters. The DTD receives the torque data from the AMC and stores them in a non-volatile memory, thus allowing the operator to download the torque data to an external equipment, i.e., the GBDS.

The GBDS part dedicated to the TUM function receives usage data from the DTD, by means of a Data Transfer Cartridge (DTC), and stores them in an inner database. Thus, it computes the damage level reached by each life limited component and, eventually, displays relevant warnings for those components that need inspection or substitution. Load spectrum data and event counters are stored into the GBDS as well, but not for local use. Instead, they are transferred, by means of specific procedures, to the UDB storage.

The UDB provides a concentration of the usage information regarding all the manufactured transmission assemblies and their identified components. Major functions of the UDB are the component life expenditure evaluation, RMC power spectrum evaluation, statistical analysis, configuration tracking, histori-

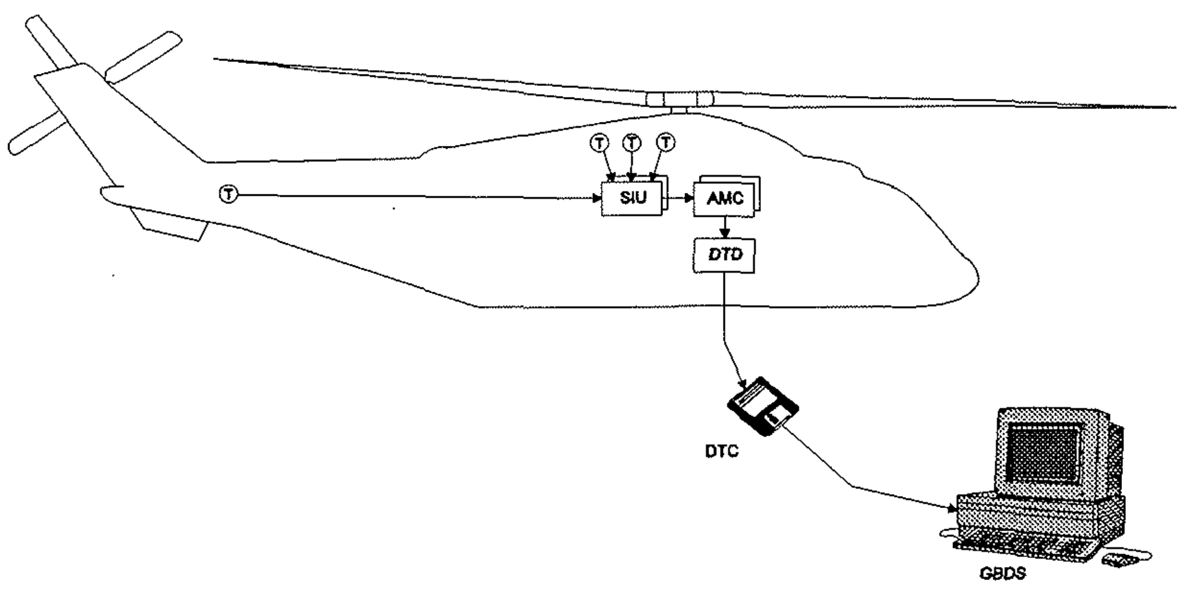

Figure 4. Transmission Usage Monitoring System.

cal data tracking, GBDS data exchange.

The UDB shall be accessed by specific analysis tools to allow reviews of the effectiveness of the usage algorithms and correlation between usage spectra and inconveniences. This includes review of the algorithm parameters and corrective factors, evaluation of maintainability factors and trends, production quality assessments.

The individual load spectra and the root mean cube (RMC) power spectra evaluations will support maintenance inspection and overhauls with additional information, allowing time reduction during components screening. Moreover, the RMC power spectra provide substantiation for review of the inspection intervals and TBOs, eventually on a case by case basis.

4. Usage Algorithms.

4.1 Torque data gathering.

Synchronised acquisition of the torque signals is provided for the three engines and the tail rotor. After each sampling the main rotor torque sample is calculated as:

$$T_{MRi} = f_{ra}(T_{E1i} + T_{E2i} + T_{E3i} + T_{TRi})$$

Where f_{ra} is a corrective factor to account for both accessories torque absorption and the drive system efficiency. The torque samples are used to increment time counters. There are b time counters corresponding to b torque bands for each engine and for each rotor. Each time counter indicates the seconds spent in a certain interval of torque values for the relevant engine or rotor.

But, while the torquemeters error is less than ±1%, a term that heavily affects the accuracy of the spectra collected is the number of torque bands. This number is limited by the on-board non-volatile memory and CPU utilisation requirements. A compromise is reached by analysing how the number of bands can affect the torque spectra and the RMC power spectra of a reference flight spectrum built by a set of recorded experimental flight conditions. Each flight condition is normalised, to take into account its occurrences allocation in the reference flight spectrum.

4.2 RMC power spectra evaluation.

To determine the RMC power spectrum the following formula is applied:

$$RMC = \left[\frac{\sum_{i=1}^{N} P_i^n \cdot X_i}{100} \right]^{\frac{1}{n}}$$

Where P_i is the power (in hp) of flight condition i, X_i is the duration (in percentage) of condition i, F is the number of flight conditions and $m = \frac{10}{3}$ is the exponent, which provides a balanced spectrum that is equally representative for gear and bearing stress.

4.3 Gear and shaft fatigue life expenditure.

4.3.1 Cumulative damage.

The formula of the cumulative damage for each component, D_C is expressed as by Miner's summation law:

$$D_c = D_{co} + K_c \cdot NR \cdot \sum_{i=1}^{B} \frac{t_i}{N_i}$$

where D_{CO} is an initialised damage total relating to previous service history, t_i is the time accumulated within torque band i (min.), N_i is a constant for each torque band being the allowable cycles (or mean safe cycles within the torque interval), K_C is a constant (the gear ratio), NR is the rotor speed (rpm), and b is the total number of torque bands to be considered.

Note that $\frac{t_i}{N_i} = 0$ for $i < T_{EF}$ (highest torque for infinite fatigue life corresponding to endurance limit).

4.3.2 Calculated life.

Being the cumulative damage calculated over the period p:

$$p = \sum_{i=1}^{b} t_i$$

the calculated life will be expressed by the equation:

$$L_C = \frac{1}{D_C} \cdot p.$$

4.3.3 T-N curve shape.

The T-N curve is equivalent to an S-N curve since the stress S is proportional to the applied torque T. The T-N curve can be established by the manufacturer by drawing a best-fit curve through the medians of the logarithms of the endurance at each test torque level. The curve is expressed in the four parameters Weibull form:

$$T = T_{EF} + A \cdot (N + C)^B$$

Values of A, B, C are constants depending on material, geometry and loading environment, T_{EF} is the endurance limit.

A "safe" working relationship may be derived by applying a suitable safety factor to the computed mean endurance limit:

$$T = T_{ES} + A \cdot (N + C)^B$$

being T_{ES} the endurance limit taking care of the safety factor.

4.4 Bearing life consumption algorithm.

4.4.1 Bearing fatigue life formula.

Using the basic load rating obtained either from a catalog supplied by a bearing manufacturer or from the appropriate equation, bearing rolling-contact fatigue life in a given application can be determined using the following equation:

$$L_{na} = af \cdot \left(\frac{C}{P}\right)^x$$

where L_{na} is the bearing life (in millions of revolutions), af is a life adjustment factor (for reliability, special bearing properties and operating conditions), C is the basic dynamic load rating(or basic dynamic capacity, in N), P is the dynamic equivalent load (in N). The exponent $x = 3$ for ball bearings and $x = 10/3$ for roller bearings.

The bearing life can be expressed in hours instead of millions of revolutions by the following:

$$L_{na_h} = af \cdot \left(\frac{C}{P}\right)^x \cdot \frac{10^6}{60 \cdot n}$$

where L_{na_h} is the bearing life in hours and n is the rotation speed (in rpm).

4.4.2 Dynamic equivalent load evaluation.

From a general point of view, the dynamic equivalent load for bearings subjected to combined radial and thrust loading can be determined from:

$$P = XF_r + YF_a$$

where F_r is the applied radial load (in N), F_a is the applied thrust load (in N). The factors X and Y are obtained from manufacturer tables.

F_r and F_a are linearly dependent by power.

5. Events logging and trends.

All specific events affecting transmission components such as hard landing, sudden stoppage, overspeed and overtorque are recorded by UDB, together with the power spectrum, for correlation with component failures. Additionally, events recording and power spectra can be used on the UDB for assessment of safety, reliability and availability figures and their trends, eventually separated for each customer or mission type.

6. Software validation.

While the hardware validation is rather straightforward and relies on the same validation methods applied for the other HUMS functions, it is even more important to validate the processing procedures and the means of interpretation of the output data and information. Special care is required in the validation of the data exchange procedures between on-board system and GBDS, and between GBDS and UDB, to guarantee error free handling and data protection. Data cross-checks between DTD, GBDS and UDB and proper back-up strategies shall be part of these procedures.

In case of data loss or TUMS inoperativeness for a limited time, conservative criteria shall be applied to provide data estimate and reconstruction, possibly by means of other available information.

Usage algorithms validation will rely on longer term experience, strip examination of gearboxes and regular inspections.

Since the TUM is not a flight critical function the software criticality level will refer to the maintenance credits envisaged.

7. Maintenance credits.

The implementation of TUM on the EH101 aims at improving the maintenance philosophy as well as gaining maintenance credits.

As soon as the TUM becomes operative, it will affect maintenance operation as a source for support information on maintenance activities, only.

At medium-term, as experience on the TUM grows, two basic approaches are considered for maintenance credit claim: a) extension of component fatigue life limits (major Maintenance Credits); b) review of inspection intervals and TBOs (minor Maintenance Credits).

On a long-term basis, it is foreseen to substitute the Hard Time maintenance process of the EH101 Transmission System by an On-Condition one, as the Health Monitoring function shall demonstrate its continued airworthiness. In this new maintenance environment, the TUM will play an important role, by providing a Condition Monitoring maintenance process capability that integrates and improves the On-Condition process, including quality surveillance, evaluation of aircraft reliability performances and identification of components or LRUs that can be operated with the required safety, though they are maintained on condition, supporting scheduling of LRU removals and spare parts management.

Of course, almost all the tasks listed above require approval by the airworthiness authorities. To obtain such approvals the following manufacturer/operator capability must be provided:

1. Specific training in maintenance and operation;
2. An approved maintenance organisation and programme;
3. Specific operating procedures;
4. Minimum equipment list;
5. Component data tracking;
6. HUMS data validation;
7. HUMS data history.

8. Concluding remarks.

HUMS, in general, might be described as a process of continuous improvement with increasing benefits as experience and the data base grow.

This is particularly true for the TUM function as its major benefits depend on the maintenance credits that it can achieve, and this requires a consistent demonstration of capability during all the aircraft operative life. The EH101 TUM design represents a cost effective solution that takes the advantage of new tools, like the GBDS and the UDB, to take care of each operated transmission and to spread the experience gathered by every one to provide an accurate computation of the accumulated fatigue damage, wider load spectrum statistics, events tracking and correlation.

Moreover, to achieve direct operating cost reductions, mainly in the form of maintenance credits, it is necessary to identify and introduce usage monitoring procedures in co-ordination with the regulatory agencies and the operators, since only an integrated process can assure the accuracy of the usage information.

At last, TUM data can reveal a possible design weakness. By means of an improved knowledge of sequences of events and specific operating conditions, TUM data can help understand the problem and develop an effective design modification, that maintains the required airworthiness level.

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