DEVELOPMENT OF AN AERONAUTICAL ELECTROMECHANICAL ACTUATOR WITH REAL TIME HEALTH MONITORING CAPABILITY

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ABSTRACT

Development and implementation of EMAs has increased rapidly during the last years in the context of the “more electrical aircraft”.

One of the main technical key issues for the EMA implementation is the jamming. It can appear due to metal-metal contact of load transmission (in gearboxes, bearings and ball/roller screws). This problem penalizes the reliability although with very low failure rate. To overcome this problem in aeronautical EMAs are actually several ways investigated, where one of the most attractive and with more promising is the implementation of advanced monitoring systems.

This implementation of “smart” monitoring systems will imply a clear economical profit in the final product and in the complete system: envisaged benefits will be lower maintenance costs with higher reliability, instead of increasing maintenance costs and decreasing reliability for classical components without Health Monitoring.

At the end, the selection of the Health Monitoring and Management system will be able to establish different levels of validation: failure detection, diagnostic and prognostic; this will provide a proactive maintenance strategy in order to replace EMA before failure.

A demonstrator prototype of an innovative electromechanical actuator with real time health monitoring capability has been designed and developed by SENER. This actuator type can be taken as a reference for typical secondary control surface applications.

This development is based on previous work performed by SENER in AWIATOR project where one of the tasks was the design and calculation of the new flap trailing edge with MINITEDs. In addition, this work included the supports and linkages of the current actuator to the MINITED.

This compact electromechanical actuator shows innovations with respect to current state-of-the-art electrical actuators as lightness and compactness of the resulting actuator, with high power density within small dimensions. As an added value, an additional plug module is under development for real time health monitoring to detect potential working incidents: “smart actuator”.

One of the additional key points will be the health management in order to solve the introduction of these systems in EMAs, and to check the compatibility with the aircraft systems.

KEYWORDS

Health Monitoring, high reliability, electro mechanical actuator (EMA), smart actuation systems, aerospace applications, predictive maintenance.

STATE OF THE ART

The monitoring of mechanical components is well known in the heavy industries like gas sector, railway and energy but the systems architecture is significantly different in aerospace, with very different constraints for weight and robustness. Some of the monitoring strategies may prove a useful technology transfer.

Structural Health Monitoring (SHM) is a very important objective for manufacturers, end-users and maintenance teams, but until now focused primarily in frames, panels, etc.

But Health Monitoring is still in the early stages to be introduced in aeronautical actuators in general and more in EMAs. EMAs architecture offers a very good scenario to develop predictive systems that help end users and maintenance teams.

The addition of Health Monitoring has a stronger economic motivation, principally for end-users. The envisaged benefits are constant maintenance costs and reliability, instead of increasing maintenance costs and decreasing reliability for classical components without Health Monitoring. This economic impact of the introduction of HM for aircraft is not easy to evaluate. It depends on the usage conditions and, furthermore, it is difficult to appreciate the impact on the cost of the final EMA structure. The cost of HM systems must not be so high as to cancel out the expected maintenance cost savings. There are some references about SHM in military A/C that can give a view of the potential economical impact in HM for EMAs: time saved by the new type of maintenance based on the introduction of SHM. Such evaluation for military aircraft reports that, for a modern fighter aircraft featuring either metal or composite structure, an estimated 40% or more can be saved on inspection time through the use of smart monitoring systems. Next table presents the figures resulting from this evaluation.

Inspection type	Current inspection time (% of total)	Estimated potential for smart systems	Time saved (% of total)
Flight line	16	0.40	6.5
Scheduled	31	0.45	14.0
Unscheduled	16	0.10	1.5
Service instructions	37	0.60	22.0
	100		44.0

Figure 1. Estimated time saved on inspection operations by the use of SHM, for modern fighter aircraft

Still in the aeronautic domain, there is also a benefit for manufacturers. Taking into account the permanent presence of sensors at the design stage will permit a reduction in the safety margins in some critical areas. Weight reduction will be then possible, giving higher aircraft performance, lower fuel consumption and higher maximum range.

I. HEALTH MONITORING APPROACH

SENER is coordinating a Spanish consortium to develop the Health Monitoring approach for EMA systems. In the project Research Centres (TEKNIKER), Universities (Mondragon Univ. and Politechnic University of Madrid), and SMEs (Interlab, Korta) are collaborating for the complete Health Monitoring definition and management.

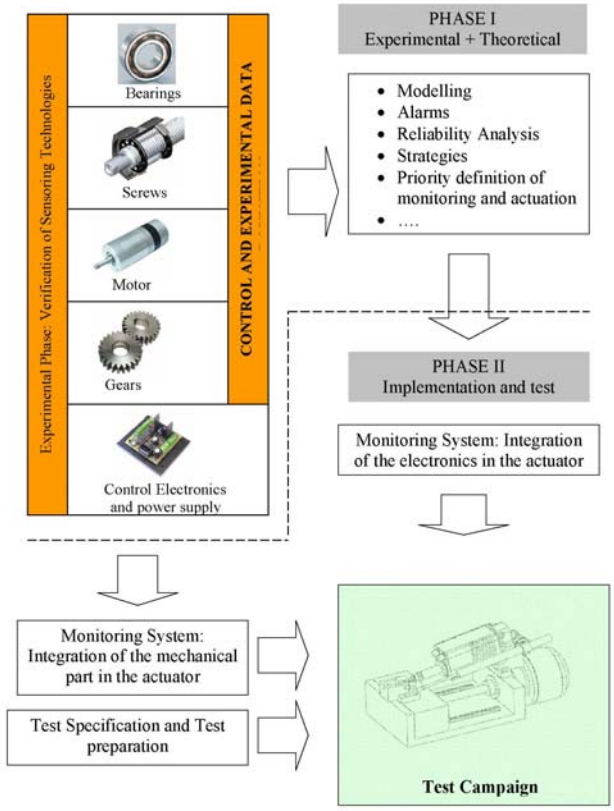

Figure 2. HM approach flow-chart

The project in Phase I defines the more appropriated sensoring for each component of the EMA in order to define sensor-component-type of failure approach.

Using different test bench for each component, un-damaged and damaged parts are being tested with different sensors (industrial and suitable for on A/C on board) in order to obtain different damage laws to be implemented in a second phase by means of algorithm equations.

These mathematical models will be implemented in the actuator through a FPGA module (Phase II), with the aim to be a plug in module, and including diagnostic and prognostic capacities.

The project is focused on the understanding of failure modes on EMA architecture and the definition of a health monitoring strategy in order to answer the following key issues:

- Mechanical failure prediction: The EMA catastrophic failure mode is jamming in during critical flight phase. All the current jamming solution makes the EMA too heavy or to bid to be use on future aircraft. Most of them are based on adding a dual load pass able to drive back the actuator when the regular load passed is jammed.

  The main concept of this project is not to avoid jamming which is a natural main failure for mechanical system under harsh conditions. The concept is to search for a monitoring solution, including some integrated sensors, whose life time performance could be anticipated. This smart EMA shall provide to the system reliable information about its current and future performances

- Monitoring system: Until now, aircraft monitoring is very light, only analogical, fully redundant in order to avoid any inadvertent wrong information and easy fault tree detection. This new concept asks for new type of sensors (load, vibration, temperature...) typically used during flight test campaigns but, in this case, with performance for the full life. Nobody will accept to ground an aircraft on the basis of wrong EMA information

- A/C information: This new concept will be able to evaluate in real time the EMA rest of life and the lead time before mandatory maintenance. The main objective is to introduce different levels of health monitoring (from just an alarm to a detail diagnosis and prognostics). One of the key points will be the health management in order to solve the introduction of these systems in EMAs, and to check the compatibility with the A/C systems

II. CURRENT PROJECT STATUS

2.1 Bearings

Monitoring of bearings is well known in the industry, there are several available commercial solutions based on accelerometers. The failure phase of a bearing is divided on 4 stages. The vibrations produced by the defects in the two earliest stages appear at high frequencies up to 60 KHz and with very low levels. The preliminary defects of these two first stages do not affect seriously to the component performance. In the third stage, the defects increase due to the wear, and in this stage appears the “bearing defect frequencies” like BPFO, BPFI …

The detection of this failure is easy and robust in this stage. The bearing has reached the level where should be replaced to avoid collateral damage to the rest of components. According with the supplier, alarm levels shall be defined for this purpose.

Tests were carried out on a Falex test machine and sensor measurements taken for developing a bearing health monitoring system.

Two types of bearings (angular contact ball bearings and cylindrical roller thrust bearings) and four types of faults were tested. First lubrication fault, consisting in the bearing having no lubricating grease or degraded grease. Second, a race fault. Ball bearings with the inner-race, outer-race or one ball scratched were tested. For roller bearings, electro-erosion machining was used to make a hole in one roll. Third, an overloading failure. Excessive load was applied to the bearings. Finally, fatigue damage for ball bearing only. The test rig was left running and the bearing was under controlled temperature and lubrication conditions.

The Falex test machine measured load, speed, bearing temperature and torque. Besides this, accelerometers were used. Two small accelerometers of 2 and 4 grams weight, suitable for integrating within the actuator, were adhesively mounted to the external, static ring of the bearing with cyanoacrilate glue. A third, industrial accelerometer, was mounted to the bearing housing with a mounting stud. Measurements were taken at various speeds and loads on normal and faulty bearings. For lubrication fault and fatigue damage, measurements were also taken during the degradation process.

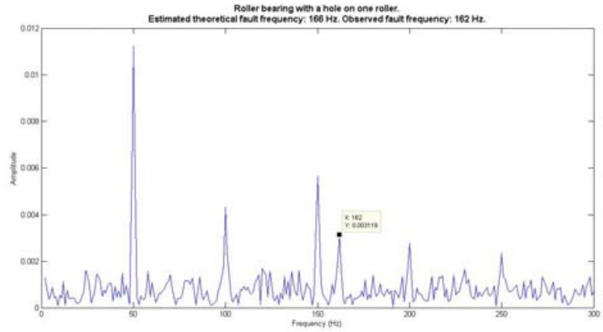

Figure 3. Vibration spectrum for a roller bearing with a fault in one roll. A peak can be clearly observed at the fault/roll frequency.

Bearing fault signal detection and recognition [3], [11] should be accomplished by different methods of pattern recognition, Neural Networks [12], Hidden Markov Models [4], [5], fuzzy logic [7] or probabilistic models [9].

There are two different methods to extract features, the short Fourier transform or wavelet time-scale decomposition.

Here, a fault diagnosis method is implemented using short Fourier transform. Vibration signals for normal and faulty bearings are preprocessed to extract relevant features and used to automatically detect and classify various types of defects as overload, outer race or faultness which may occur in a rolling bearing.

The data used are vibration signals coming from different type of bearings (axial, angular). Vibration signals coming from two different accelerometers (Dytran, Pcb) have been used and the data was recorded for time intervals of ten minutes and changing the conditions in this way: 1kn (600 rpm, 1500 rpm), 4kn (600, 1500), 5kn(600, 1500) and 8.5kn (600, 1500) for the angular bearing and 1kN (400 rpm, 1200 rpm,1500 rpm), 5kN (400 rpm, 1200 rpm, 1500 rpm), 8kN (400 rpm, 1200 rpm,1500 rpm) for the axial bearing.

It is possible to distinguish the different conditions examining the magnitude of the vibration but the signal changes as the fault progresses and the method is not very robust.

Figure 4 and 5 show different signals in temporal domain and the normalized histograms.

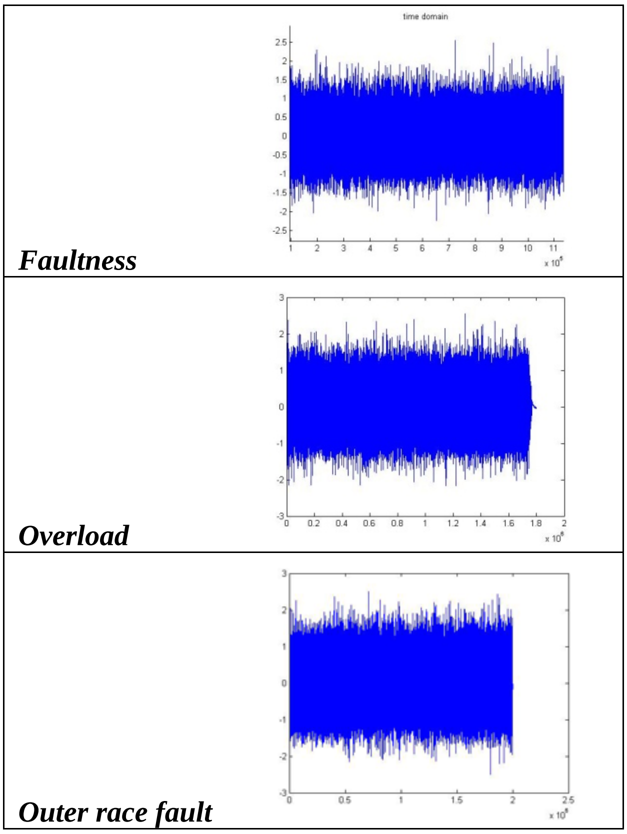

Figure 4. Temporal domain

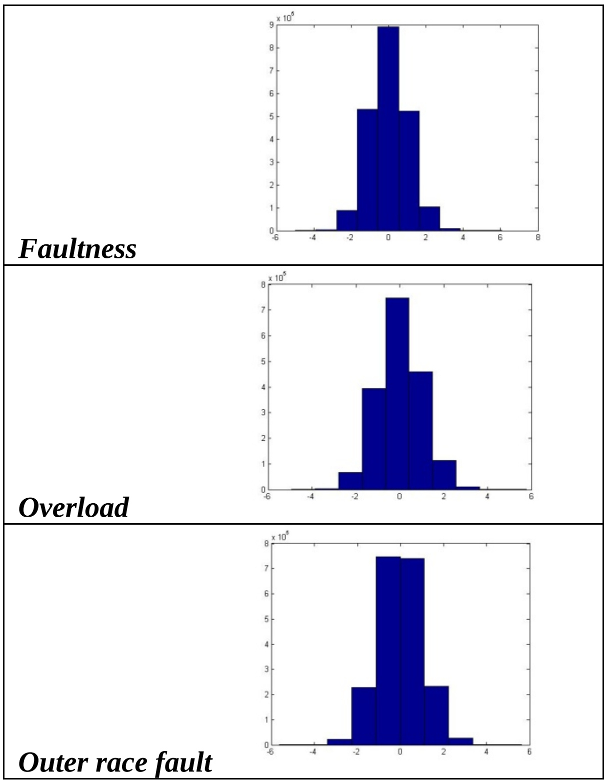

Figure 5. Histogram in the time domain

Signals can be better understood in the frequency domain. In a rolling bearing there are five basic motions to demonstrate dynamics of elements and each has its specific frequency. These frequencies are: shaft rotational frequency (Fs=25), fundamental cage frequency (Fc=48), ball pass inner raceway frequency (FBPI=149), ball pass outer raceway frequency (FBPO=101) and ball rotational frequency (FB=96.1). The Fourier transform with the position of the highest frequencies are shown on figure 6. The presence of some of these frequencies shows that there is some error, but they can appear when the failure is imminent and some other frequencies can also be seen.

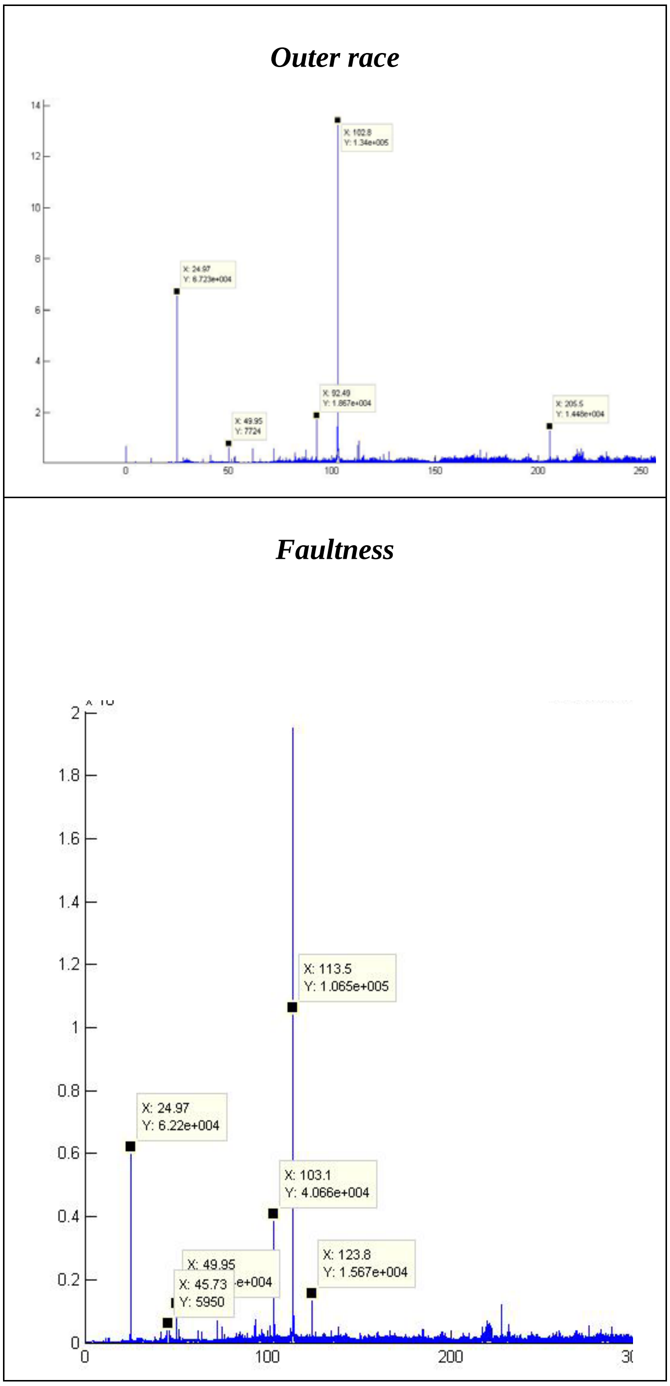

Figure 6. Frequency spectrum

The data can be preprocessed to extract the positions of the Fourier transform with fewest changes for each condition [7]. Figure 7 shows this difference.

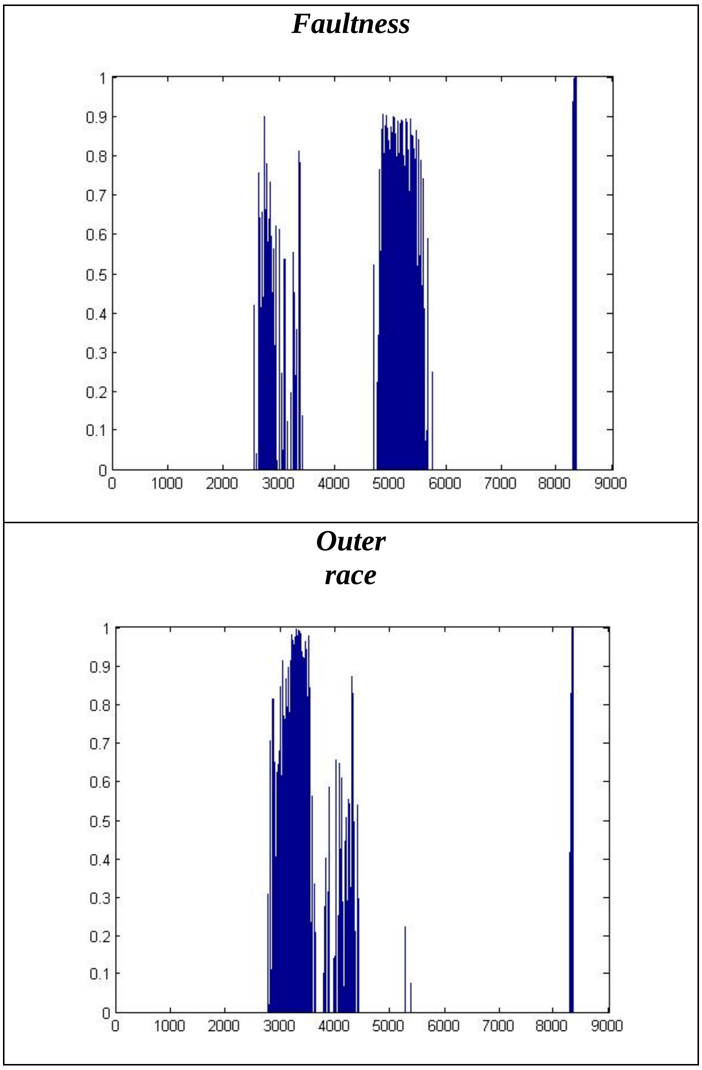

Figure 7. Difference in relevant positions shown as a bar plot

After this step, a pattern mixture of characteristic positions of different fault is obtained (discarding duplicates), put them together and measure the feasibility of the method using the Euclidean distance to classify the signals. Three steps have been taken into account: a) detect the presence of a defect, b) recognize the specific kind of a defect and c) recognize the severity of the defect. These steps are currently on progress.

2.2 Screw / Nut assembly

The screw/nut assembly has the particularity that one of the both components (screw or nut) depending on the used configuration moves along the actuator stroke.

This characteristic makes difficult the component monitoring. The most feared event for screw/nut assembly is the jamming, that is produced usually by a severe heating of both mentioned components over the operation ranges defined by the supplier. The common failures that could produce this temperature increment are:

- Lubrication failure
- Recirculating jam of rotating elements
- Degradation of races / rolling element surfaces due to wear

The two first events demand an immediate corrective action and could be produced by manufacturing defects or operation overloads. The last one (degradation) is the consequence of the normal use up to the useful life.

To analyse these events, both direct and indirect measurements will be used:

- Direct: Accelerometers, thermocouples, position sensors (rotary, lineal)
- Indirect: Current sensors

In order to study these effects in detail, a dedicated test rig (Figures 8 and 9) is under development with directly collaboration of the screw supplier.

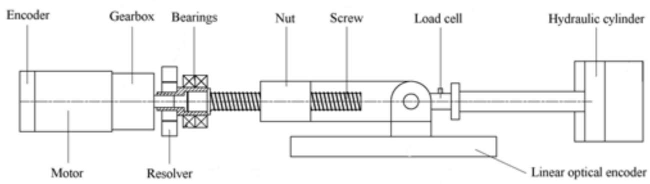

Figure 8. Screw/ Nut assembly test rig (scheme)

The lubrication and recirculation jam failures appear as a sudden increment of the friction torque; meanwhile the fatigue failure appears as a gradual increment of the backlash. The friction torque increments can be measured using the current values (indirect sensor) and the backlash comparing the input position (resolver) with the lineal position (linear optical encoder). All these signals have to be stored at high frequency in order to achieve a high accuracy because backlash magnitude order in terms of microns.

Figure 9 shows the screw / nut assembly rig test set up.

Figure 9. Screw/ Nut assembly test rig (set up)

2.3 Electronics

The electronic subsystem includes the power converters and switching bridges for motor operation (brushless three -winding DC motor) and also secondary power sources for the control system, as well as for the health monitoring system itself. So, all these are also a possible source of failure.

Some works about reliability and health monitoring issues for power converters appear, like [13], even for avionics [14]. Failure probabilities have been characterized, showing that filtering capacitors and power transistors are the main elements that could present failure. Different failures occur depending on the environment conditions and modes of operation. For instance, a transistor presents radically different faults depending on whether it is more stressed by over-voltages (mainly from dielectric perforation at the gate oxide), or by over-currents (with effects related more on thermal issues), apart from mechanical ones (soldering, etc.)

For this application, the voltage stabilizing capacitors at the main power source input are to be monitored. Manufacturers provide models and formulas for life prediction, based on the average voltage they support, but more efficient models are based also on ripple variation (produced by the switching frequency of the power source), as defined in [15]. A predictive model based on the measured ripple (once conveniently filtered) will be applied.

Also, switching transistors for winding supply control are monitored so that the on-resistance is measured. Power stress is calculated combining this resistance with the current through the channel, which give an indication of dissipated power.

Furthermore, the application of a ’canaries’ to these transistors is foreseen. The use of the term 'canary' resembles the use of these birds in mines in order to detect the presence of gases with more sensitivity than humans. The canary is based on a down-sized transistor which operates in down-sized, but similar, conditions as for the main transistors. The break-down of this transistor is a precursor event for the damage in the main transistors.

Environmental protection and inadequate operation conditions in electronics might in mid to long-term damage the electronics. To solve this, an integrated temperature and humidity sensor is mounted on the electronics board so that condensation points are calculated, thus warning about inadequate isolation protection for reparation.

2.4 Motor

The actuator is based on a three-winding brushless DC motor. Brushless motors have higher reliability than other options, but still there may be some failures, caused mainly by thermal issues in overload conditions, winding wire breakdowns, as well as mechanical problems.

Main fault mechanisms in brushless motors [16] are:

- Rotor faults (magnets)
- Stator faults (windings)
- Bearing faults
- Inverter faults

Bearing faults and inverter faults are already considered in the health monitoring strategy of the project. Since rotor faults are relatively infrequent [16], our strategy targets the windings faults as the main mechanism to be predicted.

Most winding faults result from breakdown of the winding isolation [17], which occurs from the over-heating of the coil due to Joule effect heating. Fail prediction is achieved through the monitoring of winding temperature over the time. This could raise fast, in terms of seconds, to a value that could cause damage to the coil isolation. In order to obtain fast and accurate readings, avoiding thermal inertia, the temperature of the windings is calculated from the measuring of winding currents. A model gives the relationship between temperature and current for a brushless DC motor working in intermittent operation, taking winding current as an input [18].

Windings may be built using parallel wires, and under some circumstances, some of these wires may break. This produces a current asymmetry that may be observed by frequency analysis of the current.

Windings current measurement also offers a wide amount of information about mechanical problems since, for this type of motors, torque is related to current (speed is mostly controlled, up to a limit, by the winding trigger sequence). This way, resistive torque may be measured by the current drained by the motor. Under this basic circumstance, failures or abnormalities that produce torque losses can also be measured. For instance, wear-out of the mechanical couplings (mechanical hysteresis) may be measured when changing rotating direction by measuring the time where the resistive torque is low because most of the mechanical couplings are being engaged in the opposite direction, with no real resistive torque (this test should be done with load in the actuator).

III. COST-BENEFIT ANALYSIS OF THE HM APPROACH

The cost-benefit analysis is based on estimating maintenance cost per usage hour of the electro-mechanical actuator with and without HM technology. A maintenance strategies simulator developed by Fundación Tekniker was used [1].

Replacement of the actuator is identified as the primary maintenance action. Currently, actuator maintenance consists in maintenance inspections on the aircraft. Occasionally, the actuator can be repaired. The rest of maintenance actions take place outside the aircraft (overhaul or replacement).

The following maintenance strategies were simulated:

- Corrective maintenance: to wait until the actuator fails and replace it.
- Preventive maintenance: to systematically replace the actuator at fixed time intervals.
- Maintenance inspections: a qualified maintenance technician inspects the actuator at fixed time intervals; if a failure is imminent the actuator is replaced.
- HM: the health monitoring system assesses the condition of the actuator at fixed time intervals and indicates if replacing the actuator is necessary.

In all four cases, the actuator is replaced at the end of its useful-life.

Data used for the simulation were the following:

- Reliability of an electro-mechanical actuator: Weibull scale parameter (114010 hours) was chosen based on the average useful life of an electro-mechanical actuator (10300 hours according to reliability database NPRD-95) and based on the Weibull shape parameter (1.5, typical value).
- Cost of an electro-mechanical actuator: 5000 € (estimated)
- Cost of a failure requiring corrective maintenance: 1 M€ (estimated)
- Preventive maintenance interval: 500 hours (estimated A check, once per month).
- Maintenance inspection interval: 6 hours (estimated average duration of one flight)
- Maintenance inspection cost: 20 € (estimated)
- Probability of a maintenance inspection not detecting an imminent failure of the actuator (false negative): 0.001 (estimated error probability in simple routine operation [2])
- Probability of a maintenance inspection incorrectly detecting an imminent failure of the actuator (false positive): 0.005 (estimated)
- Health monitoring test interval: 6 hours (estimated average duration of one flight)
- Cost of an actuator with health monitoring technology: estimated as 35% more than the cost of a normal actuator (~6700 €)
- Health monitoring false negative rate: 0.001 (estimated)
- Health monitoring false positive rate: 0.005 (estimated)

Simulations were done for calculating total maintenance costs (including end-of-life replacement) during one million hours (equivalent to using one hundred actuators for the whole of their average life-time). Results are presented as the average maintenance cost per usage hour:

- Corrective maintenance: 71.46 €/hour
- Preventive maintenance: 28.88 €/hour
- Maintenance inspection: 8.19 €/hour
- Health monitoring: 4.99 €/hour

The lowest maintenance costs correspond to an actuator with health monitoring technology (4.99 €/hour), despite the cost of these actuators (~6700 €) being higher than the cost of normal actuators (5000 €). As the price of an actuator with health monitoring increases, the cost for the health monitoring strategy will get closer to the cost of the maintenance inspection strategy (see figure 10). The health monitoring strategy would reach a cost similar to that of maintenance inspections when the cost of the actuator with health monitoring was as high as 40,000 €.

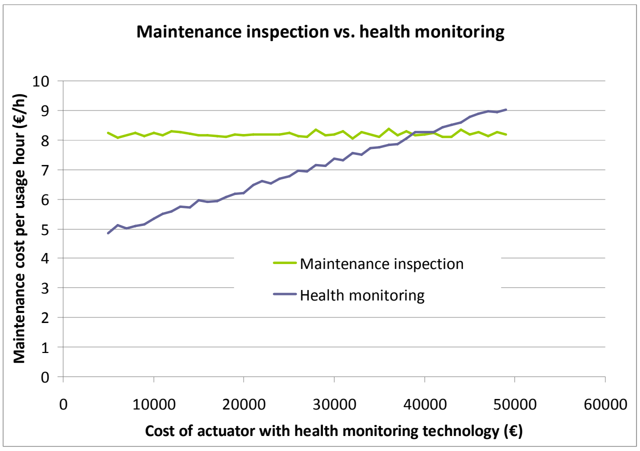

Figure 10. Cost of the HM strategy as the cost of the actuator increases. Results for the maintenance inspection strategy are presented for comparison.

Another advantage of simulating maintenance strategies is the possibility of establishing requirements for the health monitoring system in terms of acceptable false negative and false positive rates for obtaining a benefit over other maintenance strategies. It is not unusual that during the development of a decision making system a compromise has to be made between its false negative rate and its false positive rate, since a decrease of one of them typically leads to increasing the other.

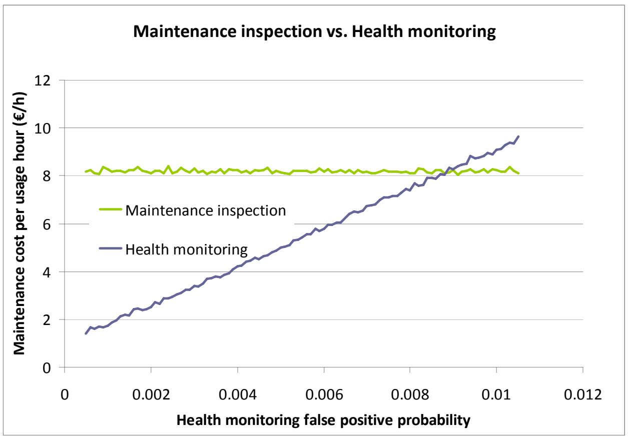

Figure 11. Cost of the HM strategy as the false positive probability of the monitoring system increases. Results for the maintenance inspection strategy are presented for comparison.

CONCLUSION

The proposed HM system is a tool that allows a predictive and intelligent maintenance protocol to be implemented in EMA systems for aircraft, helicopter and aero-engines.

Some of the expected innovations are:

- Definition of EMA Health Monitoring System Strategy
- Establish EMA Health Management
- Develop sensor and signal processing technologies
- Integrate wireless data transmission technology
- Selection of Health Assessment technologies
- Definition of the predictive maintenance strategy
- Innovative and strong EMA architecture with reliable and safe health monitoring
- Define feasible solutions for integration of sensors within a EMA, without reduction in performance or reliability of "intelligent" EMAs
- Identify solutions with associated cost-benefits during whole life cycle

One of the issues for the future is to consolidate this approach based on European projects where this topic is considered as one of the priorities for the “more electrical aircraft”, involving final users as technology evaluators.

The project is at the Mid Term period and final results will be presented in future conferences and workshops.

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NOTATIONS

EMA	*Electromechanical Actuator*
MINITED	*Mini Trailing Devices*
SHM	*Structural Health Monitoring*
HM	*Health Monitoring*
A/C	*Aircraft*
FPGA	*Field Programmable Gate Array*
BPFO	*Ball Pass Frequency of the Outer*
BPFI	*Ball Pass Frequency of the Inner*

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