# REREARCH ON A PROGNOSTIC AND HEALTH MONITORING APPROACH FOR EMAS IN THE FLIGHT CONTROL SYSTEM

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## Abstract

For a more critical use in commercial aircraft, the Electromechanical Actuators (EMAs) technology must prove to be the same level of safety and reliability as systems based on Electrohydrostatic Actuators (EHA) and Hydraulics Actuators (HAs).The use of a Prognostic and Health Monitoring (PHM) is an additional way to secure the jamming free approach for EMA in flight control system and is becoming recognized as an efficient strategy for increasing reliability and improving maintenance of EMAs in this area.

Firstly, does a detailed analysis of the multi-EMA system, and builds the fault tree of system, considering the three aspects of the control unit, electrical equipment and mechanical equipment; secondly, monitors the real state of the EMAs, relying on already existing sensors and signals, such as motor currents, temperature sensor and position sensors, according to the presented results, the current and position signals can provide useful information for monitoring the EMAs; in the end, assesses and forecasts the health status, the failure time, remaining life of the components and system, through the fast Fourier transform algorithm and intelligent fuzzy logic model(FLM).

## Keywords:

Prognostic and Health Monitoring(PHM), Electromechanical Actuators(EMAs), maintenance, reliability, screw, wear

## Introduction

The aircraft is a complex vehicle flying on air and composed by thousands of components. In order to ensure safe flying, all the components are desired to accurately work and cooperate with each other. The aircraft is composed by three main parts: airframe, engine and onboard systems. The flight control actuation belongs to onboard systems, and is powered by the hydraulic and electric ones. It is in charge of controlling the aircraft attitude and aerodynamic configuration by moving the flight control surfaces, like rudders, elevators, ailerons, spoilers, slats and flaps.[1-2]. As a safety critical application, the primary flight control system is strictly required to have a very good performance on statics, dynamics and reliability.

As the actuator is the mechanical executive device in this flight control actuation system, its statics and dynamics behaviors have significant effects on making the upper performance to be satisfied. Therefore, sustained efforts are given on the technology innovation of actuators. The history of its innovations on commercial aerospace is summarized and future developing tendency is also forecasted [2-4].In the 2000s, the electrically powered actuators were developed and started to be introduced into the flight control actuation system to replace the hydraulically powered actuators. The actuation power was no more generated by the engine-driven pumps but by engine-driven electrical generators and transmitted by electric wires. So this kind of flight control system was called as power-by-wire (PBW) system. Eliminating the heavy and bulky hydraulic pipes saved a great weight and meanwhile removed the pipes vibration problem. In the view of power transmission and modulating, the electric is also more efficient than the hydraulic. The electrically powered actuators are the key components in the PBW system. Until now, two configurations have been developed, the electro-hydrostatic actuator (EHA) and the electromechanical actuator (EMA) [5]. Now EHAs is used for A380 slats, while the EMAs are already tested or used on the A320neo, A380 and B787 spoilers.

The PBW system is required high reliability in many countries. In fact, solely relying on a single set of electronics, electronic units and mechanical components to ensure such high reliability requirements is impossible, or wasting much more time and expenses. So redundancy technology is used to ensure the reliability of the system. Redundancy is the duplication of critical components or functions of a system with the intention of increasing reliability of the system, usually in the form of a backup or fail-safe. The two functions of redundancy are passive redundancy and active redundancy. Both functions prevent performance decline from exceeding specification limits without human intervention using extra capacity. Passive redundancy uses excess capacity to reduce the impact of component failures. Active redundancy eliminates performance decline by monitoring performance of individual device, and this monitoring is used in voting logic.

The ability of controlling the control surface determines the redundancy level of the dynamic multi-EMAs system. The general design of requirement of electrical parts are a double fault electronic work ability, with the mechanical part has fault-fault safety capability, while noncritical system redundancy grade can be lower. This has the advantages of high safety and reliability and low failure rate.

## Analysis of the EMAs system PHM

The EMA technology has already been successfully employed in a wide range of non commercial aero-space applications, including some critical military and space uses. Nevertheless, the integration of EMAs in commercial aircrafts is still reduced to non critical applications. For a more general use of EMAs in commercial aircrafts, EMAs must prove to achieve the same level of safety and reliability as systems based on hydraulics actuators. In spite of the fact that only a few jams have been reported, jamming is one of most feared fault modes in EMAs. Jamming occurs because the load is transmitted through mechanical contacts under very high hertz stresses, thus fatiguing the materials, especially on the races where screw roll. This fatigue induces the degradation of the contact surfaces, leading to increased power consumption first and finally causing a mechanical jam. The jamming represents a catastrophic failure that makes useless any strategy based on either parallel or grouped actuators topologies. A variety of mechanical and electrical failure modes can be found in EMAs. Most of the failure modes lead to the loss of control but not to an actuator jam. Depending on the architecture of the EMA, there are several components which can potentially cause a jamming failure: primary bearings that support directly the actuation loads, secondary bearings used to support the rotor or included in the gearbox, gears, as well as screw-nut assemblies. To overcome these issues, which are inherent to the mechanical transmission of loads, two different types of strategies/approaches are nowadays being investigated. On one hand, strategies based on isolating the jam failure inside the actuator, either by adding another mechanical channel (duplex actuator) or by the integrating an unlocking device. On the other hand, strategies based on failure anticipation, based on advanced EMA Prognostic and Health Monitoring (PHM) systems.

Therefore, the application of electromechanical technology to civil aviation in critical primary flight controls raises a lot of challenges, one of them is the development of HM fault anticipating EMAs system [6-7]. It is expected that PHM systems will position EMAs closer to achieve the demanded safety requirements to be employed in commercial aircrafts for critical applications. The main benefit of PHM systems is to increase the overall system reliability. PHM systems have two main benefits; on the one hand increasing the overall system reliability and, on the other hand, allowing a more efficient maintenance task programming, thus minimizing corrective actions during the actuator service life. Nevertheless, reaching the same level of maturity as for other mechanical systems, such as bearings or gears, will still require an additional research effort in monitoring techniques for EMA assemblies. More specifically regarding linear EMAs, the development of monitoring systems for screw-nut assemblies has recently been demanded by the aerospace industry.

The efforts to reach the necessary product maturity and fulfill the reliability requirements have been oriented basically in two directions. The first direction focuses on the development of specific components for aircraft applications; including power converters, bearings, roller/ball screw assemblies, electrical motors, lubricants or sealing. The second one aims to develop PHM systems capable of anticipating system failures.

## Fault tree analysis of the system

Fault tree analysis is an analysis of the system fault graphic deductive method, through the "and", "or" the logical relationship of the causal relationship between the expression of system failure, failure of top event to the bottom events from the fault, application of Boolean operation rule for fault analysis. Fault tree analysis is a process of logical analysis, follow the logic deduction analysis principle, namely from has occurred or is assumed to occur fault results based on experience knowledge and logical relationship of fault process analysis, in order to find the main factors to cause the fault reason and fault development. Through the mathematical calculations of top-down analysis led to all the possible causes of the occurrence of the top event and mutual relationship between the fault, gradually until they find the basic reasons for the failure, which is defined as the bottom events of the fault tree. By establishing the fault tree of good through the qualitative analysis and the quantitative analysis of the implementation of the system analysis the structure importance.

As is shown in the figure 1, the EMA comprises a nonlinear description of a velocity controlled PMSM, while inner loop is a current controlled loop, and a model of mechanical transmission kinematics including a gear box and a roller-screw[8] actuator, with position and speed controlled in the outer loop.

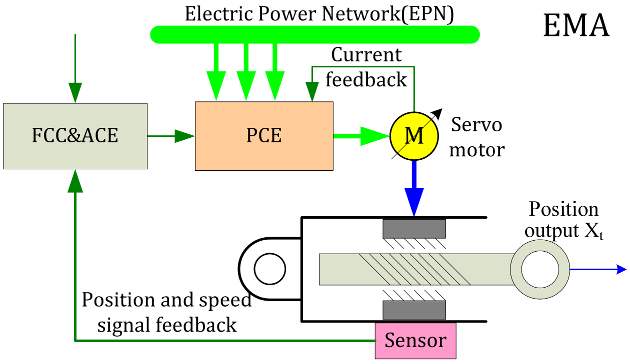

Figure 1 Schematic and some application of EMA

EMAs are the power execution and output mechanism of the servo actuation subsystem. The failures of the EMAs are usually have the big relationship with the working condition of the system and intrinsic factors. The mainly failures from EMAs are characterized by control unit failure, actuation failure, power without output, cable breakage and potentiometer failure. These lead EMAs to out of performance.

Through the fault tree analysis method, the EMA components are analyzed in detail. And the fault tree is established as follow shown in figure 2.

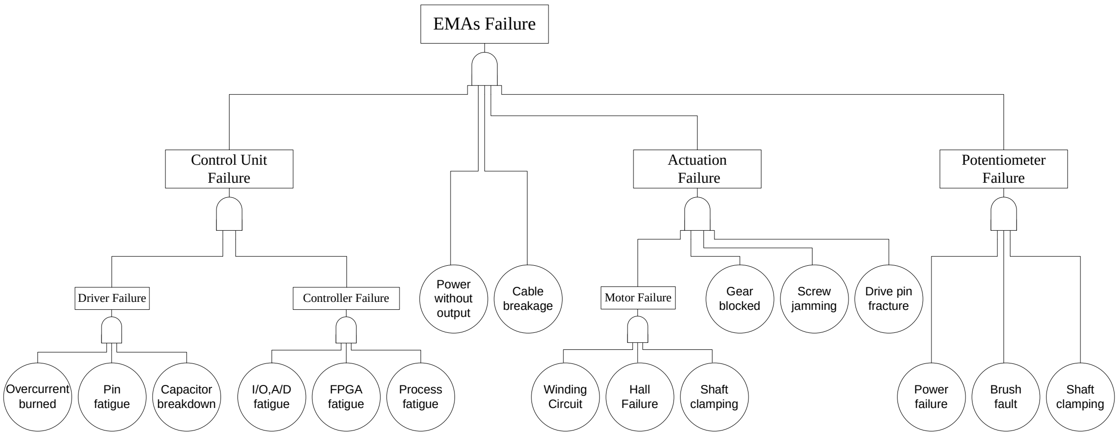

Figure 2 EMAs Failure Tree

Control unit failure result from driver failure and controller failure. Because of the over current in the driver circuit, the driver may be burned. At the same time, because of the overvoltage, the breakdown of the capacitor can easily be occurred. And pin fatigue can also result in control unit failure. As for the controller failure, the failure occurs after some time service. The I/O, A/D, FPGA and process fatigue lead to controller out of service. In the practical application, the redundant design should be done for the control unit.

Actuation failure is composed of motor failure, gear blocked, screw jamming, drive pin fracture. What’s more, motor failure is brought about by winding circuit, hall failure and shaft clamping. Most of failures are mechanism failure. To prevent these failures to happening, as is analyzed above, the best method is introduce the PHM. Depending on the sensors, such as current sensor, position sensor and force sensor, failure and health message can be obtained.

Potentiometer failure, as an electrical fault, is most result from power supply failure, brush failure and shaft clamping. This failure may cause the position and speed loop to be out of performance, even to the extent that the system is out of control. As the same to the control unit, the redundant design should also be introduced to the system.

Through the detailed research, the failure mode and solution of EMAs are shown in the table below.

Table 1 Failure mode and solution of EMAs

| Number | Failure | Solution | Redundancy |
|---|---|---|---|
| 1 | Screw jamming | Ensure the machining accuracy/Ensure that the assembly process/Use effective lubrication | No |
| 2 | Shaft clamping | Select high precision and load bearing/Ensure that the assembly process/Use effective lubrication | No |
| 3 | Drive pin fracture | Ensure the design strength/Ensure the machining accuracy/Ensure that the assembly process | No |
| 4 | Gear blocked and fracture | Ensure the design strength/Ensure the machining accuracy/Ensure that the assembly process | No |
| 5 | Potentiometer shaft clamping | Ensure the design strength/Ensure the machining accuracy/Ensure that the assembly process | No |
| 6 | Motor shaft clamping | Improve the bearing load/Use effective lubrication/Redundant configuration | Yes |
| 7 | Cable breakage | Ensure the cable manufacturing process/ Double points double lines | Yes |
| 8 | Motor failure | Motor redundancy allocation/Each independent power supply | Yes |
| 9 | Overcurrent burned | Redundant configuration /Each independent power supply | Yes |
| 10 | Hull failure | Redundant configuration /Each independent power supply | Yes |
| 11 | Winding circuit | Redundant configuration /Each independent power supply | Yes |
| 12 | Driver failure | Driver redundant configuration/ Each independent power supply, indendent output | Yes |
| 13 | Controller failure | Controller redundant configuration/ Capacitor redundant configuration/ Each independent power supply, indendent output | Yes |

It is shown in the table above that redundant configuration is introduced to the control unit and potentiometer.

If the sensor fault rate is $\lambda_s = 70 \times 10^{-6}/h$, and the control unit failure is $\lambda_c = 570 \times 10^{-6}/h$.

So the one channel fault rate $\lambda$ for electrical part is

$$\lambda = \lambda_s + \lambda_c = 640 \times 10^{-6}/h$$

The single channel safety reliability in one hour is:

$$R(t) = e^{-\lambda t}$$

So the three redundancy system safety reliability in one hour is:

$$R_r(t) = R^3 + 3R(1-R)R^2 + 3(1-R)^2R = 3e^{-\lambda t} - 3e^{-2\lambda t} + e^{-3\lambda t} \approx 1$$

And the fault rate is:

$$\lambda_r = \frac{-R_r'(t)}{R_r(t)} = \frac{3\lambda e^{-\lambda t} - 6\lambda e^{-2\lambda t} + 3\lambda e^{-3\lambda t}}{3e^{-\lambda t} - 3e^{-2\lambda t} + e^{-3\lambda t}} = 7.9 \times 10^{-10}/h$$

And the mean time to failure (MTTF) is:

$$MTTF = \int_0^\infty R(t)dt = \frac{3}{\lambda} - \frac{3}{2\lambda} + \frac{1}{3\lambda} = 2864\text{□}$$

While the safety reliability and MTTF under the single channel is:

$$R(t) = e^{-\lambda t} = 0.993$$

$$MTTF = \int_0^\infty R(t)dt = \frac{1}{\lambda} = 1562\text{□}$$

Three redundant configurations make the electrical part have a high reliability.

## Monitor of the EMAs

Reliability aspects should also be taken into account when adding new components for PHM in EMAs. Safety cannot be affected due to the introduction of new elements in EMA systems. In fact, additional sensors integrated into the actuator are also prone to failure. Integrating new sensors and electronics, also increases manufacturing costs and EMA complexity, thus reliability of the actuator can be affected. Moreover, the cost of PHM systems, increased by adding new elements, should not be as high as to exceed maintenance cost savings. Signals such as consumed currents, encoders and position sensors are already integrated in the EMA. Regarding position sensor, these are generally used for two different purposes; both as absolute position feedback for the control and to commutate the motor windings both in case of PMSM or switched reluctance motors. The most used position sensors in EMAs are linear variable differential transformers (LVDT), resolvers, magnetic encoders and hall sensors. The measurement of the currents injected into the motor is easily realizable based on the voltage drop across a sensing resistor. The analogue voltage signal is proportional to the current and can be sampled by a microcontroller/DSP/FPGA based system. A set of advanced sensor system of EMA is composed of these sensors. This system shows robustness, simplicity and cost effectiveness, reducing the cost of the monitoring functionality and minimizing the overall EMA reliability.

The monitor is completed by this sensor system. Based on the fault analyzed above, one or two sensor is used to monitor the health state of the EMAs, shown as follow.

Table 2 Sensor use in the monitor

| Number | Failure | Sensor cobination | Isolation/redundancy |
|---|---|---|---|
| 1 | Screw-nut failure | Current sensor | No/No |
| 2 | Gear failure | Current sensor | No/No |
| 3 | Potentiometer failure | Position sensor | Yes/Yes |
| 4 | Motor failure | Current sensor and position sensor | Yes/Yes |
| 5 | Driver failure | Current sensor and position sensor | Yes/Yes |
| 6 | Controller failure | Position and current sensor | Yes/Yes |

The screw-nut and gear failure belong to mechanism failure, and both failure are because of fatigue and wear. The failure process need a relative long time, failure is gradually showed. With the increase of fatigue and wear, the driving torque need more. That means bigger current need to be given to the driver. The current sensor can easily discover this process. When the current exceeds the threshold value, the control unit must give the alarm information to the fly control computer(FCC). This will reduce the complex maintenance work. Because the alarm information signal is before failure, when the signal is come about, there is no need to isolate the EMA.

As for other failures, the artificial intelligent voting mechanism should be introduced. Based on this mechanism, the failure channel is found and isolated. At the same time, the alarm message is also sent to the FCC. When the signal is come about, the channel is out of service, and must be isolated. Under this condition, the EMAs is degraded as safe state.

## Life Forecast of EMAs

In order to get statistical analysis of lifetime distribution, accelerated relationship as well as stress-life model, the following assumptions should be made prior.

Assumption A. The lifetime of products belongs to Weibull distribution Firstly.

Assumption B. Statistically independent covariates sizes of headings.

Assumption C. Common shape parameter. They have the same mode of failure.

Assumption D. There is a relation between the characteristic life parameter and stress.

If the function $f(\Phi)$ is introduced to express degradation product life process, the degradation model of product and with the passage of time life consumption process is expressed as:

$$\frac{df(\Phi)}{dt} = K$$

where, $\Phi$ is characteristic degradation values, $K$ is degradation speed, $f(\cdot)$ is a function associated with the characteristic and the failure process of state of matter. $f(\cdot)$ has a relationship with material and failure mechanism, while K is determined by the stress (the use environment). The degradation curve is shown in the figure 3. The higher the stress is, the faster the failure occurs.

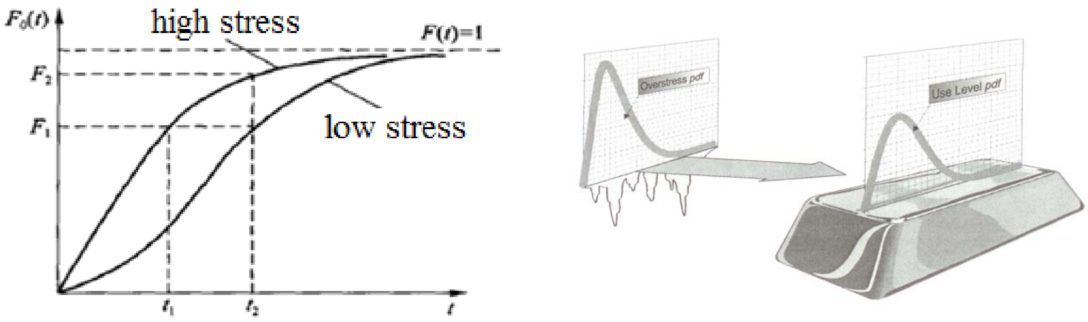

Figure 3 Degradation curves and probability density function under stress

If $\Phi$ reached to the threshold value $a$, the EMAs are regarded as out of service. The life of the EMA is:

$$L = f(a)/K$$

$f(\cdot)$ can be obtained from the accelerated life testing (ALT), based on the GLL accelerated model and Weibull life distribution under the high stress. The use level pdf can be extrapolated from the overstress pdf, shown as follow:

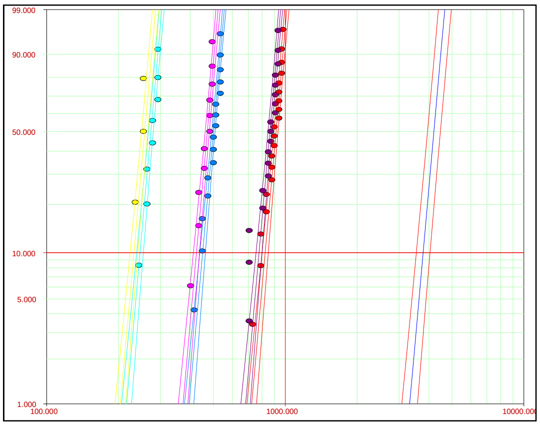

Figure 4 Non-reliability function under different over stresses

Based on the overstress stress, the non-reliability functions (left six curves) are obtained, then the user level non-reliability function (right curve) is extrapolated. From the user level non-reliability, the life can be forcasted.

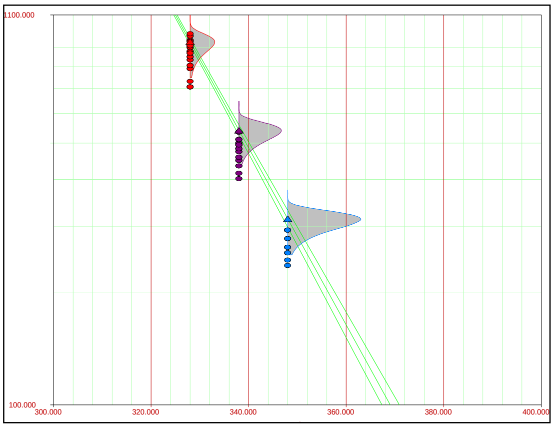

Figure 5 Relationship of life and temperature

It is shown in the figure above that the life of EMA have a big relationship with temperature. In fact, the temperature has a large influence on the fatigue and wear of the EMAs.

## Conlusion

For a more critical use, the Prognostic and Health Monitoring (PHM), based on artificial intelligence, is adopted to secure the jamming free approach for EMAs in main flight control system. The fault tree analysis is done to describe the fault mechanism and fault mode, and the solution is also given. The redundancy can well improve the reliability of the EMAs. Based on the existing sensors (current and position sensor), the advanced sensor system is built to monitor the operate state of the EMAs. Meanwhile, the alarm and isolation mechanism are described. Monitor, as the core of the PHM, changes the traditional inspection and maintenance (day or hour) to only the hardware failure truly. In the end, the life forecast is done depending on ALT. Though many testing have to be done before the forecast, the remaining life message extrapolated from the testing can obtained. This means a lot to the PHM of EMAs. The PHM approach is recommended as an efficient strategy for increasing reliability and reducing the maintenance cost of EMAs in this area.

## Reference

[1] Wikipedia.org. Aircraft flight control system.

[2] William H. Philips, P. Douglas Arbuckle. Flight controls. Accessscience website, http://accessscience.com/content/Flight-controls/260900. Jul.2012.

[3]Ian Moir, Allan Seabridge. Flight Control Systems, one chapter of “Aircraft System: Mechanical, electrical, and avionics subsystems integration”. John Wiley & Sons Ltd.2008.

[4]Amit Kulshreshtha, Jean-Jacques Charrier. Electric Actuation for Flight & Engine Control Evolution & Challenges. Presentation on boulder meeting. Feb.2007.

[5]Stephen L. Botten, Chris R. Whitley and Andrew D. King. Flight Control Actuation Technology for Next Generation All-Electric Aircraft. Technology Review Journal, Fall/Winter 2000.

[6]Legrand, B., Loyer, J. Manon, G.Perrochat, J-M., Ruprecht, T. and Wagner, H. EMA technology development. Proceedings of The More Electric Aircraft Forum, 8-11 September Barcelona, Spain, 2009.

[7] Edward Balaban, E., Saxena, A., Narasimhan, S. Roychoudhury, I. and Goebel, K. Experimental Validation of a Prognostic Health Management System for Electro-Mechanical Actuators. AIAA Infotech@Aerospace Conference and Exhibit. St. Louis, Missouri, USA, 29-31 March 2011.

[8] Karam, W. and Mare, J.-C. . Force control of a rollerscrew electromechanical actuator for dynamic loading of aerospace actuators, paper presented at International Conference on Fluid Power and Motion Control, 2008.