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Prognostics and Health Management Guidelines for Electro-Mechanical Actuators

RATIONALE

Electro-mechanical actuators (EMAs) are used in different aerospace applications performing functions with different degrees of criticality, and a trend exists to progressively replace hydraulic actuators with EMAs for most flight-critical applications. This carries along a growing interest in providing EMAs with a prognostics and health management (PHM) system allowing effective diagnostics, prognostics, and recovery actions. Early fault detection is needed in flight-critical applications to allow enough time for contingency management in order to avoid the occurrence of safety-critical situations.

The development of an EMA PHM system is a challenging task since EMAs are complex systems made up by electronic, electrical, and mechanical subsystems, and are typically under-instrumented. This implies that a fault in an EMA component may have effects on other parts of the actuator, which makes it difficult to successfully identify and isolate the fault, especially when only a limited number of signals is available.

The purpose of this document is to provide the guidelines of the technological approach for developing a PHM system for EMAs with particular reference to their possible use as primary flight control actuators. It provides a basic description of the physics of the most common degradation processes, a reliability assessment, and a discussion on the signals, with the associated data processing, required to build up an effective health monitoring system.

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1. SCOPE

1.1 Prognostics and Health Management for Electro-Mechanical Actuators

Reducing the power consumption—and hence, the fuel burn—is a major target for the next generation of aircraft, and electrical actuation is perceived as a technological area able to provide power saving. Electrical actuation can in fact contribute to the reduction of the non-propulsive power because electro-mechanical actuators, when compared to the conventional hydraulic actuators, rely on a form of power subjected to lower distribution losses and in general can lead to a weight savings at the aircraft level if the required power remains under a break-over point. Moreover, electro-mechanical actuators (EMAs) present higher reliability and maintainability with a lower life-cycle cost.

Two critical issues with electrically powered actuation are the temperature rise in the electric motor windings and in the power electronics, and the sensitivity to certain single point of failures that can lead to mechanical seizures, that has so far thwarted the use of EMAs for safety-critical applications. In order to address the issue of a possible actuator seizure, many research and development activities have been performed to identify ways of making an electro-mechanical actuator jam-free or jam-tolerant, since this would allow more flexibility in defining the overall architecture of the flight control system. Although interesting and ingenious design solutions have been proposed, they all have so far resulted in complex mechanical designs that on one hand allow the actuator to operate after a jam of an internal component, but on the other hand bring about increased weight, volume, and cost, and a reliability reduction due to the much larger number of parts.

With primary flight control actuators being some of the more safety-critical components of an aircraft, an undetected actuator failure can lead to serious consequences. Furthermore, failures that are not flight safety critical can still have negative consequences ranging from flight disruptions to unscheduled and costly maintenance.

The development of an effective and reliable PHM system for EMAs is thus seen as a possible way to contribute to the acceptance of EMAs as primary flight control actuators in commercial aircraft, for an effective PHM system will feature appropriate diagnostic functions to detect anomalous behavior, and prognostic capabilities indicating when an incipient fault develops and estimating how, under continuing usage, the fault will eventually become a failure. Providing EMAs with a PHM capability will entail positive results in different areas:

- Progressively improve the EMA robustness; PHM algorithms can initially provide indication of the onset of a fault, while more sophisticated reasoning functions can then assess the remaining useful life and contribute to the safety of flight.
- Minimize the unscheduled maintenance events, thereby increasing the EMA availability.
- Facilitate maintenance operations and troubleshooting.
- Simplify the supply chain.

It is important to note that a more extensive use of EMAs facilitated by PHM algorithms must be associated to all design provisions necessary to attain mandatory safety requirements.

1.2 EMA Health Monitoring Issues

A critical issue with PHM for EMAs is that faults and degradation in this part needs to be successfully detected, identified, and isolated, taking advantage of only a limited number of available signals. Adding more sensors would offer an improvement of diagnostic-ability, but at the expense of reduced reliability and greater complexity of the EMA. In fact, the possibility of sensor failures must be duly taken into account; therefore, sensor failure identification and isolation must also be performed by the PHM algorithms.

The selection of type, number, and placement of sensors is therefore a fundamental step in the definition of a health monitoring system for an EMA, and a deep knowledge of the physics underlying the degradation processes of the EMA components is needed to perform the best selection of the sensors suite. Moreover, to keep the number of sensors to the minimum necessary, physics-based modeling of failure modes and mechanisms should be developed to extract the maximum useful information from the available measurements to accomplish effective diagnostics and prognostics in real-time.

The available signals must be analyzed and classified according to their origin (EMA, aircraft), to the sensor or data function (control, health monitoring), and nature (real, virtual).

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

Garshelis, I., "New Types of Magnetoelastic Transducers for Sensing Force Related Parameters," SAE Technical Paper 910856, 1991, <https://doi.org/10.4271/910856>.

2.1.2 ANSI Accredited Publications

Copies of these documents are available online at <http://webstore.ansi.org/>.

ANSI-AGMA 1010-F14 Appearance of Gear Teeth - Terminology of Wear and Failure

2.1.3 RTCA Publications

Available from RTCA, Inc., 1150 18th Street, NW, Suite 910, Washington, DC 20036, Tel: 202-833-9339, www.rtca.org.

RTCA DO-178 Software Considerations in Airborne Systems and Equipment Certification

RTCA DO-254 Design Assurance Guidance for Airborne Electronic Hardware

2.1.4 Other Publications

MIL-HDBK-217F Military Handbook. Reliability Prediction of Electronic Equipment

MIL-STD-1629A Military Standard: Procedures for Performing a Failure Mode, Effects and Criticality Analysis

NPRD-95 Non-Electronic Parts Reliability Data

2.2 Acronyms

BLAC	Brushless-AC
BLDC	Brushless-DC
ECU	Electronic Control Unit
EMA	Electro-Mechanical Actuator
EPU	Electronic Power Unit
FCC	Flight Control Computer
HM	Health Monitoring

LVDT	Linear Variable Displacement Transducer
MTBF	Mean Time Between Failures
PHM	Prognostics and Health Management
PHMC	PHM Computer
RVDT	Rotary Variable Displacement Transducer

3. INTRODUCTION TO EMAS

3.1 EMAs General Description

EMAs are a specific class of motion control technology systems in which electrical power is used to control the speed and/or the position of the end-user by means of an electric motor and a mechanical transmission. In general, an EMA is comprised of the following major subsystems:

- An electronic control unit (ECU) receiving the commands from the flight control computer (FCC), the speed/position feedback from other EMA subsystems, closing the position control loop and generating the speed command.
- An electronic power unit (EPU), often also indicated as “motor drive module,” providing the following functions:
 - Accepting the electrical power supply from the aircraft electrical system.
 - Accepting the motor speed command from the ECU.
 - Providing the electrical supply to the rotor position sensors of the electric motor.
 - Implementing internal speed and current loops for increasing the system dynamic performance.
 - Generating the controlled currents for the electric motor to drive the motor as required by the position control loop.
 - Providing a current limiting function in order to prevent excessive temperature of the motor windings and of the power electronics.
 - Providing operational and monitoring data to the monitoring section of the ECU.
 - EMAs most often use brushless electric motors, in which case the EPU commutates the input voltage to the appropriate motor phase winding by power switches to drive the electric motor. Control of the switches is derived from the speed demand signal (generated by the position control loop) and the present rotor position.
- An electric motor (EM), usually belonging to the “brushless permanent magnets” class, performing the power conversion from electrical to mechanical. A brushless electric motor is also equipped with rotor position sensors allowing the EPU to perform currents commutation
- A mechanical drive (MD), transmitting the mechanical power from the electric motor to the actuator output. Depending on the application, the mechanical drive can perform different functions, such as speed reduction, power summing (in case the EMA contains two electric motors), and conversion from rotary to linear motion.
- A position sensor providing information of the absolute position of the actuator output, hence enabling the ECU to close the position control loop.

3.2 EMA Output

EMA output can be either rotary or linear, depending on several factors, such as the aerodynamic surface kinematics, the available room inside the actuators' bay, and the actuator load.

The output type has a significant impact on the mechanical drive responsible of the motion transformation. If the output is rotary, the last component of the kinematic chain will be a gearbox (usually a geared rotary actuator); whereas if the output is linear, it will be a power screw, most of the time featuring rolling elements (i.e., ball screw, roller screw, satellite roller screw).

In case of a linear output, the EMA can have two different configurations:

- Direct drive: The motor shaft is directly connected/integral to the screw.
- Geared actuation: A gearbox is interposed between the motor and the screw providing speed reduction.

3.3 Flight Control Surface Actuation

Actuation of a flight control surface can be performed by means of one or multiple actuators.

For the single-actuator configuration, only one actuator is driving the flight control surface. This solution is used for those cases in which the flight control surface is not prone to flutter, such as is normally the case of spoilers, since a possible fracture of the mechanical connection between actuator and flight control surface would leave the latter free floating. A free spoiler is normally pushed back against the wing by the aerodynamic loads, while a free-floating aileron, elevator, or rudder would enter into a flutter mode with a resulting flight safety-critical condition.

For the above reasons, primary flight control surfaces are normally driven by two or three (typical of rudder) parallel actuators. For the case of multiple actuators driving the flight control surface, the actuators can be controlled in active-active or active-standby modes. Active-active control adds some complexity in the overall system control, but entails advantages such as more effective redundancy, slower health degradation in time due to load distribution, possibility to operate with degraded performances after the failure of one of the actuators, and simpler design of the mechanical drive.

3.4 EMA Operation

The electric motor develops torque proportional to the current through the motor windings and drives the input shaft of the mechanical drive, thereby providing the output torque/force necessary to drive the flight control surface. During operation, heat is generated in the electric motor and in the EPU, which is a function of the electrical current and hence to the actuator load. It is thus important to note that heat generation is primarily dependent on the actuator load and not on the actuator power; temperature issues can arise while the actuator is keeping the flight control surface in a stationary position under an external load.

When the EMA drives the flight control surface under aiding loads, the positive mechanical work performed by the external loads is partly dissipated by the internal frictional and viscous losses of the EMA. The excess energy needs to be dissipated by a resistive component within the EPU, which must be activated when energy flows back from the electric motor.

Another important issue with EMAs for primary flight controls is the need for the EMA to generate a damping action in case of loss of the electrical power supply; this is fundamental in preventing a free-floating of the flight control surface that would lead to a flight safety-critical condition.

3.5 EMA Components Survey

3.5.1 Electric Motor

The electric motors typically used for EMAs belong to the "brushless permanent magnet" class. By mounting permanent magnets on the rotor and wiring the electric windings on the stator, this class of electric machines avoids the use of brushes to perform phase commutation. This operation is performed by the EPU generating the electrical currents to the motor windings based on the rotor position signals coming from sensors mounted on the rotating shaft.

Sensorless schemes can also take advantage of an indirect measure of the back-EMF, but the use of this solution is so far mostly limited to continuously operating machines working at an approximately constant speed.

Two other positive characteristics of brushless electric motors is their reduced moment of inertia of the rotating parts and the location of the windings on the stator. The lower moment of inertia allows higher accelerations with a resulting faster dynamic response; the windings on the stator entails better heat transfer to the ambient.

Other solutions, such as asynchronous machines, switched reluctance motors, torque motors, and others are possible, but of lower interest for primary flight control actuators for the less favorable power to weight ratio.

3.5.2 Electronic Power Unit

The EPU main function consists of supplying the electric motor windings with the appropriate current in order to control the motor speed in response to a speed command generated by the electronic control unit. As stated in [3.5.1](#), the vast majority of electric motors used in the EMAs for primary flight control actuators are brushless permanent magnet types, with each motor presenting in general three windings in which the currents are varied by the EPU as a function of the rotor angular position to allow the electric motor to generate the required torque. The generation of the motor current is performed by a three-phase power bridge.

In addition to generating the current for the electric motor windings, the EPU most often includes the following components:

- EMI filter to reduce the effects of electro-magnetic interference.
- Isolator gate to provide/remove the electrical supply to the power bridge as a function of a discrete command from the ECU.
- AC/DC and DC/DC converters to supply the electric motor with the required input voltage.
- Power conditioning to generate the local low voltage electrical power supply (position sensors, etc.).
- Brake driver to engage/release a brake, if the EMA includes this component.
- Regen circuit to dissipate the regeneration energy flowing back into the EPU when the EMA operates subjected to aiding loads.

If a microprocessor is used in the EPU and some functions performed by the EPU result from the outputs of software, then the requirements of RTCA DO-178 are applicable. If programmable logic elements or complex elements are used by the EPU, then the requirements of RTCA DO-254 are applicable.

3.5.3 Sensors

EMA control requires a minimum number of sensors to measure the physical quantities needed to close position, speed, and current feedback loops. A brief list of the necessary sensors is reported hereunder.

- Current sensors: The measure of the current of each motor phase is needed to close the current control loop.
- Motor shaft position: The motor shaft position is needed to properly command the phase commutation. The choice of the sensors depends on the motor type and environmental conditions. For BLDC (brushless-DC) motors operating above -40 °C, Hall effect sensors are often used. For operation at lower temperatures, or if accurate control of low speeds is required, or if the motor is a brushless-AC, resolvers are generally preferred. The same sensor is also often used to infer the motor angular speed through numerical differentiation with time in order to allow closing the speed control loop.
- Actuator position: As the actuator controls the position of a mechanical element, a sensor is needed to measure the linear (or angular) position of the actuator output. In general, variable differential transformers (LVDTs for linear measurements, RVDTs for angular measurement) are used for their robustness.

3.5.4 Mechanical Drive

EMA mechanical drives can be of different types, depending on the concept for power transmission (direct/geared), the configuration of the output (linear/rotary), the actuation redundancy (single, multiple), and the type of flight control surface (high-lift system, primary flight controls, speedbrakes, etc.). A brief list of the most used components is reported hereunder.

- **Gearing:** Always required for rotary outputs and most often present for linear outputs. Gears are used to reduce the load torque on the electric motor shaft, allowing the use of an electric motor with the most effective combination of weight and efficiency. Speed reduction/torque amplification from the motor shaft to the actuator output can be performed with different components depending on the required speed ratio, envelope constraints, and operating conditions. Spur gears reducers, epicyclic reducers, harmonic drives, or geared rotary actuators are possible solutions for motion transmission between parallel axes, while bevel gears, worm gear drives, or hypoid gears can be used for concurrent or skewed axes.
- **Linear motion devices:** If the output is linear, devices such as ball screws, roller screws, or satellite roller screws (with no return channel) can be used. Roller screws can feature lower pitch values and are hence able to achieve higher precision and higher transmission ratio at the price of decreased efficiency and greater sensitivity to misalignments.
- **Load limiting devices:** Slipping clutches and torque limiting devices can be used in the mechanical drives to limit the maximum load transmitted to the flight control surface. These devices can provide additional protection on top of limiting the maximum current of the electric motor and hence the torque it can develop.
- **Brakes:** They are used whenever operating conditions may occur in which it is necessary to maintain the electric motor stationary without electrical power supply or control. A typical condition is that of an actuator in which the outputs of two electric motors are speed summed on a common shaft by means of a differential gearset.
- **Special devices:** EMAs for primary flight control actuators may be equipped with additional devices or modified design with respect to the standard configurations to obtain jam-tolerant (JT) or jam-free (JF) devices. JT actuators are obtained by ensuring the disengagement of the jammed actuator through a solenoid/electric motor (reversible) or through a pyrotechnic device (non-reversible). JF actuators make use of more complex design features such as telescopic screws, anti-rotation devices, and electric brakes to achieve a certain degree of mechanical redundancy.

3.5.5 Control Loop

EMA standard position control strategy features three nested control loops: inner (current loop), intermediate (speed loop), outer (position loop).

- **Current control loop:** Used to indirectly regulate the electro-magnetic torque generated inside the motor. This loop is affected by the disturbance of the back-EMF. It is the fastest control loop whose bandwidth is typically on the order of 1 kHz or greater. Depending on the motor type, it may feature from one to n-control loops, working on the n-phase currents or on their combination.
- **Speed control loop:** Used to regulate the angular speed of the electric motor shaft. External disturbances for this control loop are load and/or friction. Order of magnitude of the speed control loop bandwidth is 100 Hz.
- **Position control loop:** In the position control system, the position control loop is the outer loop and is the dominant one. Its bandwidth depends on the type of application. For primary flight control actuators, a bandwidth of 5 to 10 Hz is normally required, though some special applications such as in-blade control of helicopters rotors or missile fin controls may require a higher bandwidth.

A general schematic of an EMA control loop, featuring a brushless motor controlled in d-q axis, is shown in [Figure 1](#).

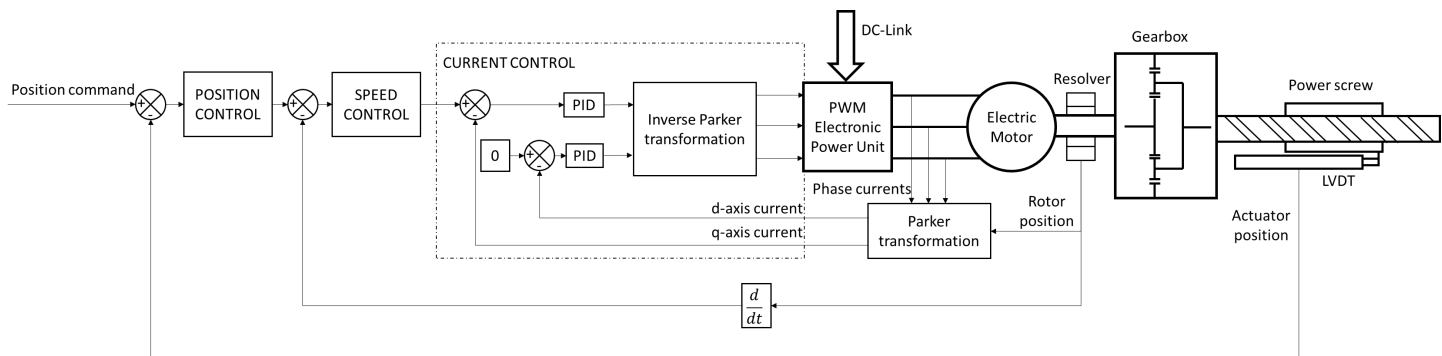


Figure 1 - General block diagram of an EMA control loop

3.6 Reliability, Maintainability, and Safety Considerations

Reliability, maintainability, and safety are issues that need to be properly addressed for an EMA to ensure that, at the conclusion of the development and qualification phases, the EMA can enter into service with the necessary confidence of safe and reliable operation. To achieve this objective, appropriate management, methods, and procedures need to be adopted to achieve and demonstrate the compliance versus the reliability, maintainability, and safety requirements that are established for the specific EMA application, and the preparation of a reliability, maintainability, and safety program plan is recommended for defining the activities to be performed. The plan should also take into account the interaction between reliability, maintainability, safety, and system design engineering to ensure that a coordinated and integrated approach is pursued and achieved.

Reliability requirements for the EMA should be apportioned down to major component level as follows:

- Failure rate prediction of the electric/electronic parts of the equipment according to MIL-HDBK-217F.
- Failure rate prediction of mechanical components derived from field data of comparable equipment already in-service or, where no such data exists, the prediction can be derived from standard reliability reference documents such as NPRD-95.

This apportionment can be used to establish the baseline requirements during the preliminary design phase of the EMA. The data should then be continuously updated and amended as necessary as more information becomes available, including the operating stresses and the environment that will be experienced by each component in service.

Reliability and safety analyses require a failure modes and effects analysis (FMEA) to be performed (that can be based on the guidelines defined in MIL-STD-1629A) in order to identify all possible failures and their effects impacting aircraft operation and performance.

The EMAs for primary flight control actuators must be designed to maximize the equipment safety characteristics. In particular, special attention must be given to ensure that any possible safety-critical condition arises with an acceptable low probability of occurrence. In particular, the EMA robustness must be preserved and must be designed in a way that those safety-critical events identified as catastrophic/hazardous for the aircraft and its crew can occur only as a combination of multiple failures.

In general, it is recommended that EMAs be designed according to the “on-condition” maintenance concept with scheduled intervention reduced to a minimum. In particular, the only scheduled tasks to be performed should be limited to the ball screw/roller screw actuator greasing and direct backlash measurement to be carried out with a fixed frequency based on experience gained on similar components already in service. It is also recommended that EMAs be replaceable at first maintenance level by semi-skilled maintenance personnel without the need for further operation after replacement (adjustments, shimming, and calibration).

4. EMA FAILURES ANALYSIS

4.1 Failure Modes

The following sub-sections present a description of the most common types of faults occurring in EMAs.

4.1.1 EPU

The electronic power unit and its control circuits are an extremely complex subsystem of their own. As for every other electronic device, failure modes are many and of different nature. Excessive mechanical stresses due to impact or vibration may lead to board, connection, or switch rupture, while local temperature peaks may lead to MOSFET degradation and/or burnout, partial fusion of the pins with ensuing electrical shortage, or circuit opening. Deposition of metallic debris, electrical overstresses, and electrostatic discharge may cause significant performance loss as well. Each component—be it active like the power MOSFET, or passive like capacitors, inductors, and resistors—features its own failure modes. Many of these failure modes eventually lead to overheating of at least one of the power switches which tend to fail almost instantly due to their extremely low thermal capacity.

It is possible to classify the failure modes for EPUs into two main categories. Catastrophic failures are those that cause the breakdown of the devices; they may occur suddenly or as the product of a progressive degradation of one or more components. Parametric failures are instead those issues that cause performance loss without completely compromising the EPU behavior; these are usually the result of several minor failures and can be thought as progressive degradations. Examples of this type of failure are insulator damage or metallization damage due to conductor weakening, which may lead to the catastrophic junction (short) and metallization (open circuit) burnouts.

4.1.2 Electric Motor

The electric motor is a subsystem of its own, hence featuring a certain number of mechanical, electrical, and magnetic failure modes. The mechanical degradations are mainly related to issues in the motor shaft bearings which are addressed in [4.1.4](#). The following sub-sections briefly outline the most common degradations in the electrical and magnetic parts of the electric motor.

4.1.2.1 Windings Turn-to-Turn Short

Turn-to-turn short (TTS) is the most common failure mode directly addressing the motor windings. It occurs when two (or more) turns of the same phase get in contact and it is usually associated with the degradation of the windings insulants. Several issues can cause the inception of this fault. The most common one is the natural, thermal-driven aging of the insulation materials. Others causes are excessive mechanical strains and corrosion.

TTS causes a progressive increase of current unbalance, leading to motor overheating, output torque reduction, and local burning of the windings themselves. TTS may evolve into other failure modes, such as phase-to-phase short and phase-to-ground short.

4.1.2.2 Windings Phase-to-Phase Short

The phase-to-phase short (PPS) is a secondary failure mode for electric motors that occurs whenever the windings of two adjacent phases get in contact. The causes are similar to those of the TTS; however, since the number of adjacent windings that may be impacted by this failure mode is lower than the one related to the TTS, its probability of occurrence is lower. PPS is typically a byproduct of the TTS itself, once it has propagated enough in the tangential direction.

The inception of PPS usually causes a more severe degradation than TTS. Since two phases are affected, the resulting output torque is significantly decreased and an increase of its ripple is noticeable.

4.1.2.3 Windings Phase-to-Ground Short

The phase-to-ground short (PGS) is the last failure mode for electric motors windings and is related to the direct contact between one or more turns with the external case. This is by far the most problematic of the windings failure modes. Firstly, an increasing percentage of one (or more) phase(s) is lost, hence limiting the output torque; secondly, the electrical circuit may be partly closed through the motor bearing(s). The passage of current through the bearings and the associated local overheating and electric-arc generation, may lead to a failure of the bearings even before the motor windings themselves.