

Challenges for Health Monitoring of Electromechanical Flight Control Actuation Systems

2011-01-2701

Published
10/18/2011

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doi:10.4271/2011-01-2701

ABSTRACT

Flight control systems of civil aircraft have undergone huge developments in the last decades. The current more/ all electric aircraft concepts lead to the replacement of the hydraulic actuators in the primary flight control systems by electromechanical systems. Integrating electromechanical systems in safety critical applications implies three main challenges: (a) the detection of all fault cases which could lead to a safety critical state, (b) finding measurement parameters capable to detect faults, and (c) the development of algorithms to detect faults under all flight conditions. Putting the scope on the health monitoring of the mechanical components of a direct drive actuator, a new technology based on piezoresistive thin film sensors (TFS) is presented and its potential shown by using defective ball bearings as an example.

INTRODUCTION

Flight control systems of civil aircraft have undergone huge developments in the last decades. The increasing size as well as speed of a civil aircraft led to higher control loads. This evolution forced the introduction of hydraulically powered flight control systems. Further developments, as the introduction of electrically signaled control surface actuation, led to the first full fly-by-wire civil aircraft with the introduction of the Airbus A320 in 1987. The primary flight control system of this aircraft generation is supplied with three independent hydraulic systems. The next step was the reduction of the number of hydraulic circuits, leading to the "More Electric Aircraft" concept, e.g. the A380 with two hydraulic and two electric power supply systems. This evolution was enabled by the introduction of hydraulic actuators with electrical backup and electro-hydrostatic

actuation systems, which are equipped with an electrically powered hydraulic circuit, locally integrated in the actuator.

These developments aimed to reduce system weight and complexity, to improve maintainability and enhance safety and availability. Current considerations regarding flight control actuation systems focus on the replacement of the entire hydraulic systems by using electromechanical actuators (EMA). Considering that flight control systems of modern aircraft have to fulfill very high safety, reliability and availability requirements, the application of EMAs still leaves several challenging topics to be worked on. A major concern is the higher probability of EMAs jamming compared to hydraulic actuators.

Ensuring the required system safety leads to three challenges that have to be overcome to pave the way to a full electrical flight control system. The first challenge is to identify all causes leading to an undesired condition, followed by the challenge to identify a measurable quantity showing faults, preferably in an early stage, and finally developing reliable algorithms that allow detecting faults in the signal trace under all operational conditions.

ELECTROMECHANICAL ACTUATORS FOR PRIMARY FLIGHT CONTROL

Recent advantages in high performance magnetic materials, miniaturized and highly efficient power electronics and gear technology make electromechanical actuators increasingly competitive compared to hydraulic actuators regarding power-to-weight ratio considering the whole flight control system. Typically, EMAs are composed of a permanent magnet electrical motor mounted on a reduction gear and/ or a linear screw and a power electronics box. Currently two

main types of EMAs with linear and rotary output, as shown in [figure 1](#), are in the focus of research and development activities. An obvious approach is the replacement of linear hydraulic actuators by EMAs using ball or roller screws. Most ball-screw-based concepts require additional reduction gears due to the low gear ratio of the screws. Roller screw driven EMAs offer the advantage of a high gear ratio usually making reduction gears unnecessary. The rotary EMA approach corresponds to conventional servo drives widely used in robotics and factory automation. However, supplying the required output torque, the gearbox diameters usually exceed the space available in the wing to incorporate an actuator at the hinge point of a control surface. Thus EMA installation in a thicker part of the wing is necessary and linkage mechanisms are required as an interface to the control surface.

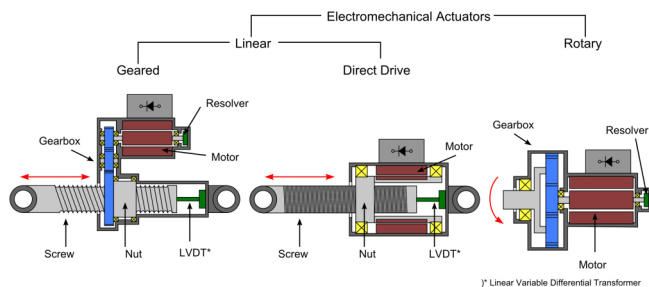


Figure 1. Classification of different flight control EMA types

The use of EMAs in primary flight control systems has been investigated for several years, e.g. [1], but still some central issues are not solved satisfactorily [2]: Currently EMAs do not reach the necessary lifetime required for primary flight control actuators. Wear of the incorporated gears may further result in an unacceptable amount of backlash, which affects flight control quality and could lead to flutter. A major concern regarding the flight control architecture is the initially mentioned probability of EMAs jamming resulting from numerous mechanical contacts of the incorporated gear teeth and ball bearings. Simply introducing redundancy by actuator duplication even increases the probability of control surface jamming, because each actuator has the ability to jam the entire control surface. Conservative solutions might be shear pins or couplers, but they are either irreversible and reduce the availability of the aircraft in combination with high maintenance costs or increase system weight making them an undesired solution for jamming concerns.

DIRECT DRIVE EMA

Keeping in mind that every component of an actuator can fail and that size and weight are critical parameters for an actuator, the direct drive concept seems to be suitable for aerospace applications. Additionally it offers the advantage of a comparably small parts count. The components of a direct

drive based actuation system can be grouped in three categories: electrics, structure and gearing. The electrics group is composed of motor control electronics, a permanent magnet electrical motor with a resolver for measuring degrees of rotation and a position measurement device like a linear variable differential transformer (LVDT). An EMA housing and rod ends build the structure group, while the gearing group is composed of bearings as well as a screw drive. Analyzing the effect of a malfunction in one of these groups in relation to the possible main failure cases of an actuator, which are actuator jam, actuator runaway, actuator disconnect and the loss of control surface efficacy [3], shows that the gearing as well as the electrics part contributes to three of the mentioned failure cases, while the structure just contributes to one case, as indicated in [table 1](#). Knowing these failure cases raises the question for appropriate counter-measures. These measures could either be active, e.g. monitoring systems or passive, e.g. redundant or fail-safe design.

Table 1. Actuator failure cases and their failure sources

	electric	structure	gearing
Actuator jam	x		x
Actuator run away	x		
Actuator disconnect / float		x	x
Efficacy loss	x		x

Structural faults could lead to disconnection of the actuator from the control surface or airfoil. The faults could be due to material fatigue, corrosion or manufacturing defects in the rod ends or the housing. Fail-safe design of these components is an alternative to reduce the likeliness of this actuator failure case to occur.

Actuator jam caused by electrical malfunctions can have several reasons. The most obvious is the loss of power supply in combination with a self-inhibiting screw drive. Another failure cause is a short circuit in the motor windings or a fault in the motor control electronics. Redundant design of the electronics with a voter or other fault detection mechanism would inhibit safety critical single point failures and offer the ability to realize an operational system even in case of a present fault.

An actuator runaway can arise as a result of a defect in the motor control or by a defective position sensor of the EMA. Redundant design of the electronics as well as plausibility checks of the measured position by the LVDT against the position calculated from the motor resolver signal can minimize the risk of this actuator failure.

Efficacy loss, similar to the performance loss of a hydraulic actuator with defective piston sealing, can arise in an EMA when demagnetization occurs caused e.g. by overheating of the permanent magnets. This leads to a reduction of the nominal output motor torque considering the same current

consumption. Temperature monitoring of the actuator provides a measure to prevent this failure to arise. Also corrosion of aged connectors could decrease efficacy, making periodic checks of the EMA mandatory.

The ability to use redundancy clearly differentiates the electric related failure cases from the ones originating from the gearing since faults in the gearing components can jam the load path. To bypass the jammed components, couplings would be required which are too large to be incorporated in an EMA with its limited installation space.

GEARING FAULTS

Gearing faults leading to one of the above mentioned actuator failure cases can be divided in two groups depending on their root cause. The first group comprises faults originating from design, production or maintenance faults. Typical examples are inadequate fit of a bearing seat, insufficient surface hardening or usage of a wrong or contaminated lubricant. Looking at bearings in an industrial environment, these root causes are directly related to 35 % of the cases, where a bearing does not reach its expected lifetime [4, 5]. Paying tribute to the fact that the aerospace industry works on a very high level when it comes to quality and design assurance as well as personnel skill, it can be assumed that the percentage of this fault cause is much lower, allowing disregarding these faults for monitoring.

The second group includes the unavoidable faults originating from the usage of an EMA in its rough environment. Even though some of these faults tend to grow gradually, it is not unlikely that they grow to safety critical faults making it necessary to take a closer look at these effects. Within the scope of this paper it is assumed, that the actuator is built on direct drive design with four-point contact bearings supporting the roller screw.

Bearing Faults

Assuming a correct bearing handling and design, five root causes for an early unserviceability of a bearing exist [4, 6]. These are: overloading, vibration, foreign particles, inadequate lubrication and passage of electric current. In the case that overloading occurs while the actuator is not running, the rolling elements generate indentations in the raceways accompanied by the building of rolled-up edges. The indentations induce fractures leading to flaking of the raceways. Flaking has to be considered as very critical since the flakes could migrate in the actuator inducing further faults. Overloading of the running bearing leads to metal to metal contact causing cracks on the surface, known as surface distress. Although the growth of these cracks is slow, they promote the building of subsurface cracks leading to flaking. Faults induced to the bearing by vibration need special attention since they occur in the paramount operational condition of the actuator, which is a not running actuator

during level flight. In this condition there is no lubricant between the balls and the raceways. The vibrations induce small movements to the rollers, entailing small particles breaking away from the surfaces and thus leading to pits in the raceways. These pits have the same consequences as the indentations by overloading.

Foreign particles have an effect on all bearing components and could either be a result of wear of other components of the actuator or they could have entered the actuator via a damaged sealing. Depending on the material of a particle the life of a bearing decreases 1 to 10% of its normal life. Particles on the raceways overrun by the rolling elements create indentations with rolled-up edges in the raceways consequentially leading to flaking. Abrasive particles could also lead to wear of the cage and therefore to an increased cage pocket size weakening the cage and rising the risk of cage fracture, and thus potentially leading to a blockage of the bearing. Cage fracture could also be the result of increased friction between the roller and the cage as a result of insufficient lubrication.

Insufficient lubrication could have several reasons. These are the loss of lubricant via a defective sealing, aging lubricant losing its lubricating properties or dilution of the lubricant by fluids entering the actuator. As a result of poor lubrication small fractures arise everywhere on the raceways leading to cracks and flaking. In the worst case of a complete loss of the lubricant in the bearing, the temperature in the bearing rises rapidly with the risk of a bearing seizure. Water or saltwater entering the actuator induces the onset of corrosion leading to pitting and flaking of the raceways. With the installation position of the bearings being inside the motor of the EMA, the risk of current flowing through the bearing also has to be considered. In the worst case the passage of current leads to a local increase of the temperature such that the metal melts resulting in craters on the raceway. Finally, faults in the bearing arise when the bearing reaches its end of life as a result of material fatigue. In this case cracks emerge underneath the raceway surfaces and propagate until they reach the surface resulting as well in flaking.

Roller Screw Faults

As shown in [figure 2](#), the roller screw consists of a nut (1), a screw (2) and rollers (3). The rollers are supported in the end-rings (4) mounted on the nut. The end-rings are equipped with a tooth wheel. The tooth wheel engages the gearing of the rollers assuring axial parallel and equally spaced guidance. Looking at this system, it is obvious that it shares many of the fault root causes with these of a bearing.