SUBSYSTEM DESIGN AND INTEGRATION FOR THE MORE ELECTRIC AIRCRAFT

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Keywords: *More Electric, Actuator, Thermal, Fatigue, Aircraft*

Abstract

Military and commercial aircraft designers are leading a quiet revolution in the aviation industry. Their goal is an all-electric aircraft that will be controlled by small high speed motors instead of heavy maintenance intensive hydraulic, pneumatic and mechanical systems. This revolutionary usage of electrical power technologies promise military and commercial airframers greater aircraft reliability and a significantly smaller logistical tail to support tomorrow's air and space force. Hence, the More Electric Aircraft (MEA) is becoming a reality.

The MEA approach provides for greater integration of subsystem functions. It also provides smarter subsystems without added weight penalties. The MEA approach has created common threads that link most or all subsystems. These threads are:

- ***Electrical power and distribution system***
- ***Thermal management system***
- **Integrated health management**

The focus of this talk will address the integration issues associated with the linkage between electric actuation and the common threads mentioned above. This paper will focus specifically on issues associated with the electromechanical actuator, address the progress of the MEA, while at the same time, discusses the growing popularity of advanced materials that are enabling the MEA.

1.0 General Introduction)

Aircraft designers have already reached a milestone – installing MEA technologies in airplanes like the Boeing 787 and various military platforms. These systems represent the first major leap in casting the MEA revolution. They involve the revolutionary application of electrical power systems, electronics, and distributed architectures to simplify much of the existing immensity bulk and complexity inherent in traditional hydraulic and pneumatic aircraft systems.

Emphasis now is on giving aircraft designers more optional opportunity of using electrical power over traditional methods. New technology concepts like electric actuation, electric environmental control and electric fuel pumps, along with magnetic bearings for generators and eventually more electric turbine engines, are in the works. These technologies promise dramatic simplifications in aircraft system design, while improving reliability and maintainability in the years to come.

Boeing Commercial Airplane (BCA) has chosen to exploit the use of MEA technologies to provide cost-efficient next generation airplanes. The 787 is Boeing's first "More Electric Airplane". Elimination of pneumatic system led to "No-Bleed" architecture for overall airplane weight savings and efficiency improvement. Many airplane systems to are become electrically powered for the first time. Some examples are the 787 wing de-icing, large hydraulic pumps (used to raise landing gear), flight control actuators (secondary systems), cabin pressurization system, braking system, and engine starting system. Advancement of efficient and reliable power electronics technology has enabled more electric architecture [1].

The MEA approach offers an increase in design flexibility, a reduction in operation and maintenance cost, and overall reduction in system weight. A more notable benefit of the MEA approach is the reduction in power conversion, where you no longer have to convert engine shaft power to electric, hydraulic and pneumatic power (Figure 1). The extraction of single electrical power provides a cost effective way to drive actuators, environmental controls, fuel pumps, brakes and de-icing systems [2]. See Figure 2.

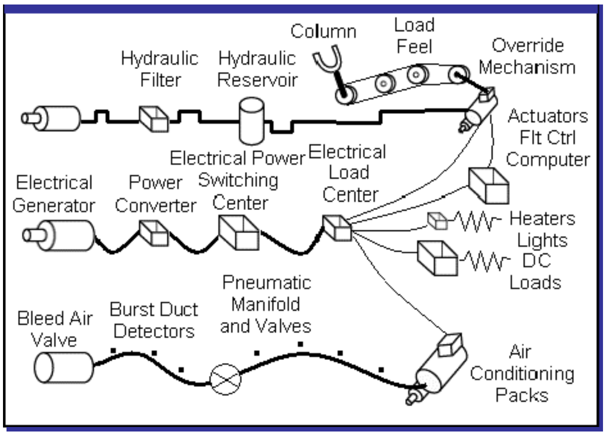

Figure 1. Conventional Aircraft Power Conversion

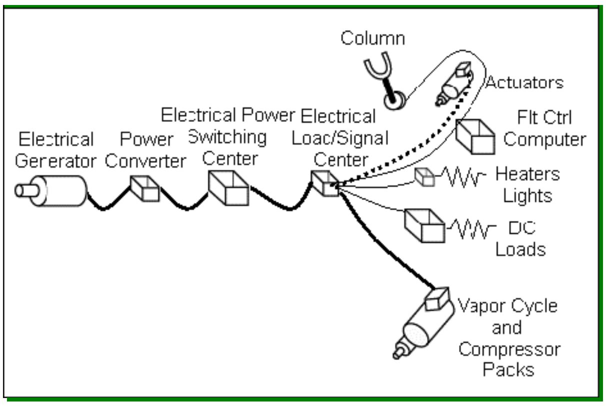

Figure 2. More-Electric/All-Electric Aircraft Power Conversion

Electric Actuation denotes a broad application of electrical power to the actuation and control of vehicle subsystems that traditionally have been controlled by hydraulic, mechanical and pneumatic power. One of the major drawbacks for using electric actuators on primary flight control surfaces has been the low power density of traditional motors and thermally efficient power electronics. There are three basic approaches to electric actuation being developed today for air vehicle flight control surfaces are electromechanical actuators (EMA), electrohydrostatic actuators (EHA), and integrated actuator packages [2]. These electric actuation systems are shown in Figure 3.

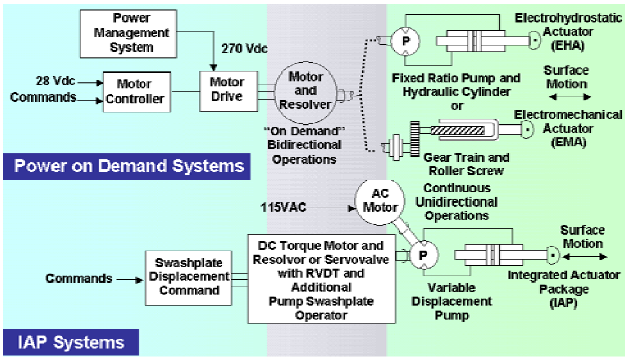

Figure 3. General Electric Actuation Technologies

For the purpose of this paper, the following definitions of an electric actuation system apply:

Electromechanical Actuator (EMA) is defined as an electric actuation system that uses an electric motor mechanically coupled to the load.

Electrohydrostatic Actuator (EHA) is defined as a self-contained electric actuation system that uses an electric motor driving a bi-directional, fixed displacement hydraulic pump that operates a typical hydraulic ram.

Integrated Actuator Package (IAP) is defined as a self-contained electric actuation system that uses an electric motor driving a servo-over center hydraulic pump that operates a typical hydraulic ram.

Flight test experiments have been performed on EMA, EHA and IAP systems to establish the credibility of electric actuation as a primary method of control for flight-critical control surfaces on tactical aircraft.

The EHA and IAP, which have been the subjects of much industry and government investments over the last decade, offer the opportunity to produce the actuation power electrically, using power-by-wire (PBW), while retaining a jam-proof connection of the actuator to the surface. The IAP has successfully completed 1,000 operational hours using an electric aileron actuation system, demonstrating the reliability and maintainability benefits with this technology. The EMA and EHA have also been flight tested on various military platforms to mature the technology.

In recent years the EMA enjoyed similar attention on several vehicle development programs. The EMA became the baseline technology on these programs largely because actuation requirements for these favored the EMA technology.

2. 0 Why Electromechanical Actuators?

EMA, EHA and IAP have their preferred applications. Program managers and system designers will continue to evaluate all three technologies; however, if all three technologies have the attributes for a particular application, the EMA may be the preferred solution (Figure 3) due to the absence of hydraulic fluid. This is especially true for spacecraft applications and vehicles with long storage requirements where hydraulic fluid leakage and freezing may be a concern. For the most part, an EHA and IAP could be considered as similar technologies because of the common use of a hydraulic ram and pump.

Electromechanical actuators are a cost-effective alternative because there is one energy conversion versus two in a hydraulic system. On some aerospace platforms, depending on the size, analyses have shown that this technology could provide weight savings averaging from a few hundreds to several thousands pounds along with annual savings of several million dollars in operating and acquisition costs. Installation time is reduced, as the system only requires the mechanical installation of the actuator and the connection of two or more electrical power cables. The requirement for periodic maintenance is greatly reduced. Additional building facilities are not required for electromechanical actuators, whereas, a hydraulic pump unit may require a separate room with fluid containment provisions.

Engineers and actuation suppliers are looking closer at the application of the roller screw as a competing technology for the ball screw based EMA. Traditionally it has been held that roller screw is superior to ball screw technology. Operational lifetime is often one of the biggest attributes of the roller screw. Roller screws have a higher dynamic load rating than ball screws. Even though roller screws are reported to be more costly than ball screws, the increased load carrying capability of the roller screw may make it an attractive technology for future EMA applications.

When considering replacement of a hydraulic actuator with an electric actuator, two basic statements are appropriate: (1) a hydraulic actuator will generally weigh less than an electric actuator designed for the same application, and (2) the hydraulic actuator will usually be capable of delivering higher power than required for its application.

The fact that a hydraulic actuator will usually be capable of delivering higher power than required for a particular application is a consequence of hydraulic actuator area usually being sized by the maximum hinge moment yielding a corner horsepower (H_{cp}). The corner horsepower for a hydraulic actuator can be described by the following relationship.

$$Hp = 1.82 \times 10^{-3} \frac{H_m}{12} \times R \times \frac{\pi}{180}$$

Where: H_{cp} = Corner Horsepower
Hm = Hinge Moment (in-lb)
R = Rate (deg/sec)
1.82×10^{-3} = 1/550 ft-lb per sec

Maximum control surface deflection and hence actuator stroke are based on surface effectiveness characteristics at low speed, where hinge moments are low. Maximum surface rates are also set at some speed conditions. Therefore, a situation where hydraulic actuator area is set at one condition, stroke is set at another and the rate at yet a third flight condition. These results in a large-bore and long-stoke actuator that must move at high rate. This condition defines a unit with high horse power capability that is never used [3].

The premise here is that an EMA with unique capabilities need not furnish anywhere near the power of the hydraulic actuator it replaces. An EMA only needs to have sufficient torque at one point and adequate speed at another. Therefore, horsepower capability is not a valid measure for comparison.

3.0 Key Design Issues

Duty cycle is the most critical design parameter for the electric actuator. It affects the mechanical, thermal and electrical design of the electric actuator. Mechanically, duty cycle will predict the magnitude and frequency of loads. This will impact the design to ensure that the EMA meets the expected life requirements and insure that the EMA has the ability to produce the necessary force output. Duty cycle will predict the rates and cycle data and also the number of cycles per flight/maneuvers which define the fatigue characteristics of the actuator. The integration of EMA duty cycle with respect to its expected life can be analyzed to determine the total linear travel distance of the EMA. This analysis is used to size the screw for its expected L_{10} life and provides a better understanding of the EMA fatigue characteristics [4]. The expected L_{10} life of a roller screw or ball screw can easily be computed and is expressed as the linear travel distance that 90% of the screws are expected to meet before experiencing metal fatigue.

$$L^{10} = \left(\frac{C}{F_m}\right)^3 x10^6$$

L_{10} = life corresponding to a 10 percent probability of screw failure
C = dynamic load rating of the roller screw and ball screw nut assembly

This expression is then integrated with the cubic mean load (F_m) with the EMA duty cycle and the applied load (F_1) and the distance (S_1) the screw travels with a particular load with respect to time at load. The cubic load is computed using the expression:

$$F_m = \sqrt[3]{\frac{F_1^{\,3} + F_2^{\,3} \ldots F_n^{\,3}}{S_1 + S_2 \ldots S_n}}$$

F_m = mean load
$F_1 \ldots F_n$ = applied load
$S_1 \ldots S_n$ = distance of screw travel between loads

Thermally, duty cycle will help predict a thermal load profile created by the actuator as defined by the flight maneuvers/mission profiles. Important factors like load duration, load interval, rate of actuation, load, etc. generate thermal energy that must be considered. The components of the actuator will need to be designed to handle these heat loads. A thermal management system must be sized for the actuator to mitigate the risk of overheating the actuator. Duty cycle must be analyzed from the standpoint of holding load and the load with respect to expected life. For holding loads are considered to determine how hard the EMA is working. This analysis is used to size the motor torque capability and an acceptable level of operating time so that the thermal limits of the motor or actuator components are not exceeded which results in tripping the thermal overload (at best) or "burn up" the motor (at worst) [5]. The thermal duty cycle is the ratio or percentage of actuator on time to off time and is expressed as shown below.

$$D_c = \frac{T_{on}}{T_{on} + T_{off}} x100$$

D_c = duty cycle
T_{on} = time on
T_{off} = time off

Electrically, duty cycle serves as the input to an actuator model to establish the power required during flight, maneuvers, and etc. This help to size the power management and generation systems.

Jam-Resistant EMA technology needs to be developed and demonstrated to ensure widespread usage of electric actuation. If there were no jamming concerns, the EMA can be the simplest and most compact actuator. Jam-resistant EMA's can be designed, but the system may no longer be simple. Some jam-resistant EMA's add other failure modes, which increase the risk of failure. As the complexity goes up, the inertia of the EMA goes up and the response goes down. The higher the inertia, the higher the starting torque required, and the more heat generated. Generally, response goes down as the actuators get larger. Boeing is working with major suppliers and research institutions to develop EMA's that are fault tolerant and jam resistant [6].

Power Densities of current motor-drive technologies need to exceed 1 kW/lb to meet the need of future military, space and commercial platforms. Studies have been conducted to evaluate the electric motor power densities that exceed 1kW/lb as well as a fault tolerant architecture. A specific research focus has been to evaluate the suitability of switched reluctance (SR) motor technology for EMAs. SR motor drives are considered to be robust and fault tolerant. These are important attributes given the hostile environment of an aircraft in flight and the safety-critical nature of the application [7].

Motor Selection like duty cycle can sometimes be the most challenging aspect of designing and sizing and electric actuation system. A priority list must be made as to which properties of the motor system will be optimized. These properties may include motor efficiency, motor torque, motor power, reliability, and of course, cost. Generally, torque is the driving factor in motor weight, size, and consequently, cost. Therefore, knowing the torque requirements is paramount.

The torque for an SRM machine can be described by the following relationship:

$$T_e = \frac{1}{2} i^2 \frac{dL(\theta, i)}{dt}$$

Where: T_e = Air gap Torque
i = current
$\frac{dL(\theta, i)}{dt}$, Variation of inductance

Social Change, though not a technology issue, is one of the major hurdles for widespread acceptance of EMA technology. Over the years, there has been a reluctance to make a major leap toward a widespread use of electric actuation, especially EMA's. Actuator designers and air framers have a well-documented database for conventional hydraulic system technology. This database is supported by well-developed specifications, ground rules, and even rules of thumb that have been developed over the past 50 years. A similar database does not exist for electric actuators, especially EMA's. To achieve the desired weight benefits, hydraulic system designers addressed the issue of reduced weight by going to higher pressure hydraulic systems and developing lighter weight plumbing and fitting systems.

4.0 Electrical Power and Distribution System

The electrical power and distribution system distributes the electrical power from various power sources to aircraft loads. The increased electrical power required for the MEA may only economically be achieved through utilization of reasonable high voltages AC and DC distribution systems. 270 Vdc appears to be the current choice for current electrical actuation systems. In some cases traditional 115 Vac and 28 Vdc has been used for compatibility reasons with present aircraft electrical systems infrastructure. In these cases power conversion units (PCUs) can be installed to rectify the 3-phase, 115 V ac aircraft supply into the 270 V dc power required by the actuator [8].

High power, electric actuation systems are being proposed on many new aircraft with ratings up to 50 kW. The electrical loads presented by these actuators are dynamic in nature and appear highly nonlinear, drawing non-sinusoidal current waveforms. This has a significant effect on the quality of the power system voltage as it introduces harmonic noise that is seen by other connected loads [8]. These requirements are placing a demand for more stringent power quality, and this means increasing the number of solid-state components. Many of these electric actuators and power control units operate at high powers during only certain portions (take-off, flight maneuvers and landing) of the mission. The temperatures associated with these systems must be maintained at threshold values that will not have a negative effect on the electronic and electrical component reliability.

5.0 Integrated Thermal Management

Thermal Management is quickly becoming a limiting design factor for electric actuation systems for future military aircraft and commercial airplanes. The design of the thermal management system for the EMA is a function of the heat rejection of the drive and the operational duty cycle. Future cooling demands will require an integrated thermal management strategy at the aircraft, subsystem, and component levels for MEA to become a reality. A new approach of dealing with the individual component heat loads at a local level was perceived to best achieve the goals of the MEA Initiative. There are a number of thermal management approaches and technologies including: thermal energy storage, advanced liquid cooling provides greater integration between power generation and thermal management systems. Advanced materials such as nano technology and high thermal conductivity graphite foams are being developed that offer potential near and far term thermal management advantages. Oak Ridge National Laboratory (ORNL) has developed graphite foam (Figure 4) that has a specific thermal conductivity six times more than copper and five times more than aluminum [9].

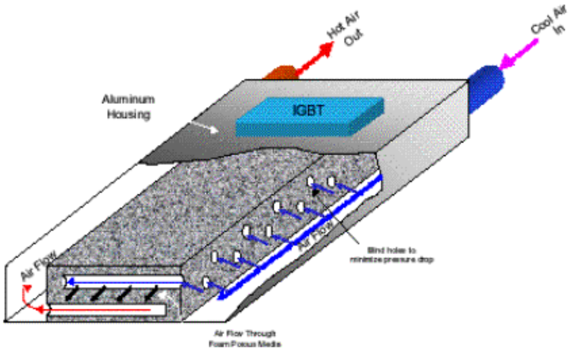

Figure 4. Graphite Foam Heat Sink

These new technologies allow engineers to evaluate concepts that will thermally integrate and structurally embed the electric actuator and its associated electronics into the vehicle structure. This integration approach concept allows the heat generated by the actuator to be managed by a passive system that could use existing airframe structure and other advanced thermal management technology to transfer the heat to a nearby heat sink. This passive cooling system has the potential of offering the best near term solution in terms of reduced weight, reduced maintenance and reduced operation cost.

6.0 Integrated Health Management

Integrated Health Management for electric actuation systems includes failure analysis of the system and the components. It requires a thorough understanding of the underlying root causes of device failures—failure physics—as a basis for credible and reliable predictions on remaining life of the device, component, or equipment.

It has long been a sound engineering practice to utilize S-N (stress-number of cycles) curve as a mean to determine the expected life of a component while operating at a level where the stress, strain, or similar metric can be measured and the cycles counted until the lower bound was exceeded and the component would be retired from further service. These components were evaluated based on high-cycle fatigue (HCF) >10,000 cycles and low cycle fatigue (LCF) <10,000 cycles (Figure 5). Looking at fatigue as the root cause of most mechanical failures, then the fatigue characteristics such as thermal, surface, rolling contact, pitting, impact, corrosion and fretting [10] must be considered.

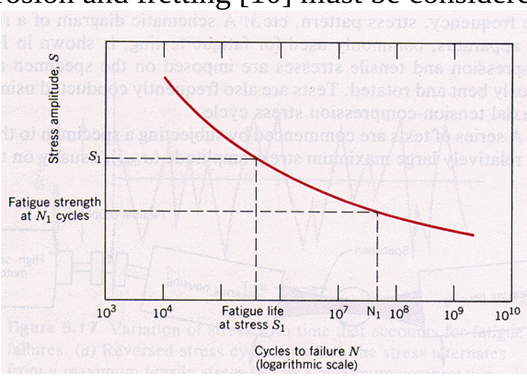

Figure 5. A Typical S-N Curves

Health management approaches using S-N type curves can takes advantage of the robustness characteristics of the EMA and the application environment can generate a fatigue life prediction curve (Figure 6). This S-N approach will allow EMA designers to monitor health indicators of the unit and detect actuator faults before the occurrence of a catastrophic failure.

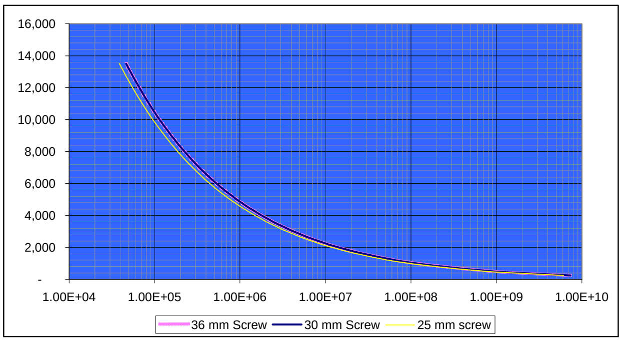

Figure 6. Representative EMA Life Performance Curve

This health management approach provides for the monitoring of the EMA life performance curve by using existing sensors to develop a method that integrates the actuator average total life available with the actual life based on usage.

$L_{Avg} = \int s \, dn$ (Average total life available)

$L_{Act} = \int s(usage) \, dn$ (actual life based on usage)

Remaining Life = $L_{Avg} - L_{Act}$

This method will monitor the motor torque generated by the mechanical gear train. Thus at any point during the EMA operation a projected remaining life can be computed.

7.0 Summary

Electric actuation is an evolving technology with high payoffs in terms of vehicle safety, reduced cost, reduced maintenance, and reduction in overall vehicle weight.

Electromechanical actuators are a cost-effective alternative because there is one energy conversion versus two in a hydraulic system. Because of absence of hydraulic fluid, electromechanical actuators will be the preferred solution for most MEA aerospace platforms.

Advances in electric motor and power electronics are making the technology both affordable and cost effective as well as providing a greater opportunity for expanded subsystem integration.

Thermal management is a critical technology need and more integrated solutions are required to minimize the adding of additional weight to cool the electric motor and power electronics. Concepts for integrated thermal management approaches are being evaluated within the aerospace community.

Though not a technology hurdle, social change is one of the major hurdles for widespread acceptance of EMA technology.

8.0 Acknowledgement

The author wishes to acknowledge that the content and many of the thoughts advanced herein have evolved from papers, presentation and discussions with many individuals. This paper has been influenced by previous work done by the author while employed at The Boeing Company and by others in the aerospace industry

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