

Management of Regenerated Energy in Electro-Mechanical Actuators for Aerospace Application

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ABSTRACT

Electro-mechanical actuation systems are becoming more common in aerospace applications. Systems that have been traditionally based on hydraulic-mechanical (HM) actuators are now being replaced by electro-mechanical actuation systems in pursuit of the more electric airplane. The actuator's primary purpose is to convert energy (hydraulic or electrical) to mechanical energy and this operating mode occupies the primary design focus. A secondary design concern is the conversion of mechanical energy back into hydraulic or electrical energy. This energy results from potential and kinetic energy stored in the mechanical system during actuation. A portion of this energy flows back through the actuator towards the source. In the case of HM actuation, the management of this energy is well understood. In electro-mechanical actuation systems, this energy is commonly referred to as regenerated energy or regen for short. Regen can be destructive to the electro-mechanical actuator (EMA) motor drive electronics (MDE). It can also require additional circuitry that adds significant size, cost, and complexity to the product. This impact is non-value additive to the primary benefit of actuation, and therefore needs to be minimized. The optimum management of this energy to maximize value is not well understood.

This paper describes a method to characterize the actuation system and implements this characterization in a computer based model. The sources of potential energy in the mechanical system are described. Five regen operating modes are defined, two of which are EMA based, and three of which are distribution bus based. The model is applied to a test case with a representative EMA, and the two EMA based regen management modes are studied. Based on this study, the strengths and weaknesses of both approaches are presented.

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INTRODUCTION

Throughout the aircraft, there is a need to control mechanical systems that actuate flight control surfaces, landing gear, and brakes. All of these applications require high power and reliability. These have historically used hydraulic-mechanical (HM) actuators to provide this functionality. In an effort to improve reliability and reduce weight, airframe manufacturers are migrating to the use of electromechanical actuators (EMA) for these applications. The EMA's primary function is to convert electrical power to mechanical power and provide the mechanical motion at a rate and force required for the application. This functionality occupies the primary design focus of the EMA supplier. A secondary design focus is the management of regen energy. Regen energy is energy that is "regenerated" into the electrical side of the actuator by energy flowing back from the mechanical system. The source of this energy can be either forces internal or external to the mechanical system. Internal forces include elastic and inertial forces, and external

forces include gravitational and aerodynamic forces acting on the mechanical system. In either case, the management of this energy is key to optimizing the actuator value and reliability.

While the history of EMA use is limited in comparison to HM actuators, there have been several regen management approaches established as standards, particularly in the literature. One approach is to direct the energy back to the power distribution system. The energy is then routed to other loads, dissipated, stored for later use, or some combination of these. This approach is a global management approach since each actuator passes the energy back to the power distribution system to be managed at a global level. A local management approach is to manage the energy at the actuator level, and not pass the energy back to the power distribution system. The energy is stored, dissipated, or some combination of these on the electrical side of the actuator. This approach does not provide for diversion to other loads.

In general, the actuator designer would prefer that a global approach to managing regen energy be used. This

eliminates the need to include large storage capacitors and power dissipating resistors in their designs. From an aircraft architecture perspective, this would create a more optimal design since some portion of the regen energy can be diverted to other loads and the overall need for storage and dissipation would be reduced compared to the local approach. However, even with this benefit, there are some applications where the airframe manufacturer requires the EMA supplier to manage the regen energy using a local approach.

This paper focuses on managing the regen energy using a local approach. It provides a lumped parameter model implemented in Mentor Graphics® SystemVision® to model the electrical, EMA, and mechanical systems. Laboratory tests are performed to develop the model parameters for this application. The model is verified by comparing the simulation results to laboratory test results. This model is then applied to a 1hp system to study its operation. The model is then used to study different modes of regen management using the local approach in order to identify strengths and weaknesses of each mode and the optimum design approach.

SYSTEM DESCRIPTION

The actuator system is composed of electrical and mechanical components. The electrical system's function is to convert electrical power to mechanical power in the form of torque and speed. The mechanical system converts the torque and speed into the required function of force and speed. While operating in this actuation mode, power flows from the electrical system to the mechanical system as shown in Figure 1.

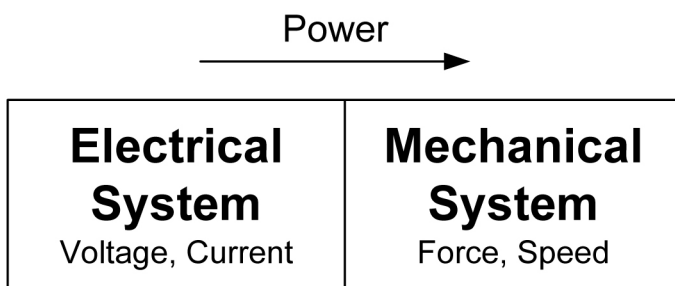


Figure 1. Actuation Mode Power Flow

When the actuator is not actively controlled, it is possible for power to reverse direction and flow from the mechanical system to the electrical system. In this case, elastic and/or inertial forces in the mechanical system, and aerodynamic and gravitational forces acting on the system can drive the actuator to act as a generator and provide power to the electrical system as shown in Figure 2. In this mode, the mechanical system is regenerating energy, and this phenomenon is commonly referred to as the regenerative operating mode, or regen for short.

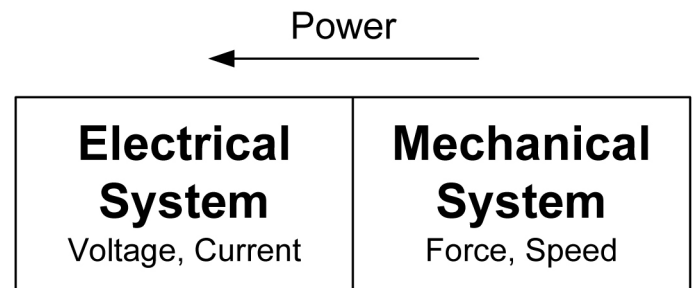


Figure 2. Regen Mode Power Flow

The forces which cause the regen energy can be split into internal and external forces with respect to the mechanical system. Elastic and inertial forces within the mechanical system are internal forces. The external forces acting on the mechanical system are gravitational and aerodynamic. Figure 3 shows the forces that cause regen energy.

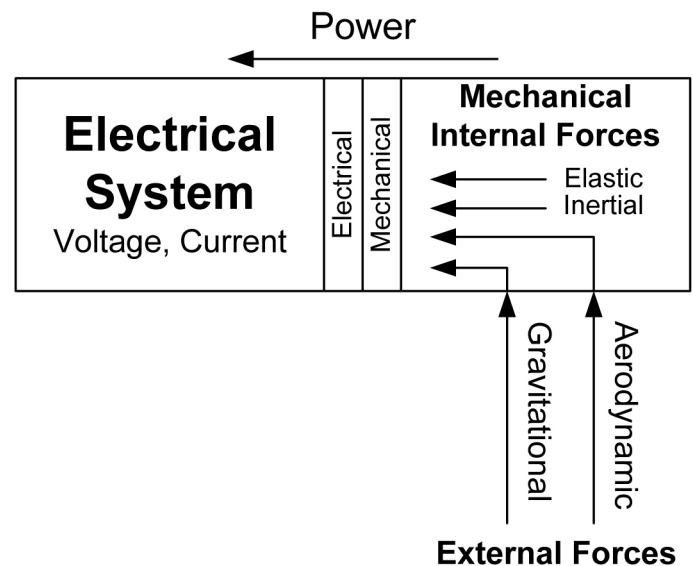


Figure 3. Regen Forces

The regen energy in the electrical system must be managed in order to assure that the resulting voltage and current is within acceptable levels. There are two broad management possibilities from a system design perspective. A global management approach can be used where each EMA passes the regen energy back to the power distribution system. A global management system can then be used to coordinate the power source, regen energy and actuator power from each of the EMA's along with a global storage and dissipation capability to control the power distribution system effectively. A second regen management approach is to manage the energy locally at the EMA level. Using this approach, the EMA must incorporate the means to store or dissipate the energy locally. This prevents the regen energy from disturbing the power distribution bus. However, it also eliminates the possibility of sharing the regen energy with other global loads, and causes the EMA to incorporate bulky

storage and dissipative components and circuits. Figure 4 shows the regen management approaches.

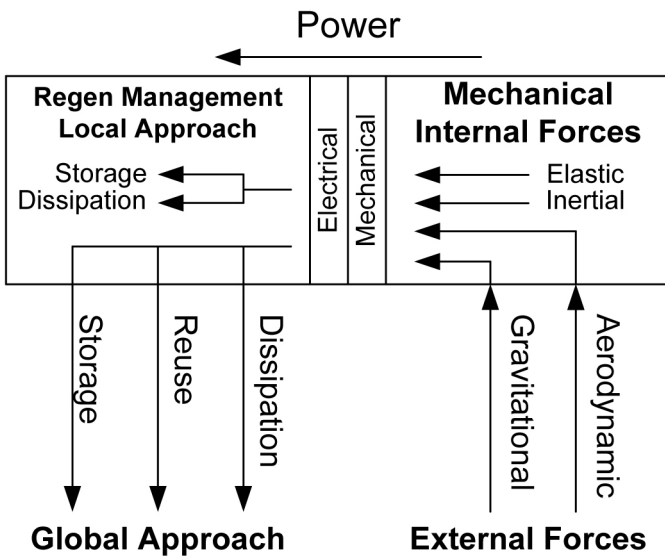


Figure 4. Regen Management Approaches

ELECTRICAL SYSTEM DESCRIPTION

The electrical system for an EMA is made up of three primary components as shown in Figure 5. These are the power source, the motor drive electronics (MDE), and the electrical-magnetic portion of the motor (stator, rotor, and position feedback device). At a high level, the power source provides the electrical power to the MDE required for actuation. The MDE converts this power to an electrical form that is suitable for the motor. The motor converts the power from electrical (voltage and current) to mechanical (torque and speed).

The analysis in this paper is focused on a brushless DC motor based EMA. This type of motor requires a 3 phase asynchronous AC voltage source. The frequency, voltage, and current are controlled based on speed, torque, position requirements of the actuator, and the rotor position of the motor. The MDE uses a 3 phase power electronic bridge circuit to convert a DC input voltage into the 3 phase source required for the motor. The power source available to the MDE is based on the airframe manufacturer's architecture. It may be AC or DC with various voltage levels (28VDC, 130VAC, 130VDC, 270VDC, etc.). In the case where this voltage does not match the requirement for the MDE, a front end will be added to the MDE to convert the available power source into the DC level required by the MDE. For this paper a 130VDC source is used and there is no front end on the MDE.

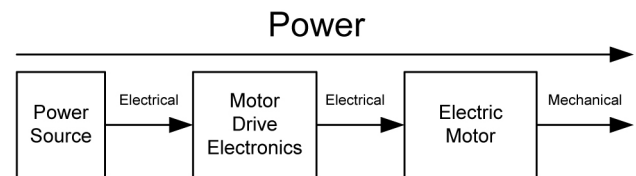


Figure 5. Electrical System Diagram

MECHANICAL SYSTEM DESCRIPTION

Components

The mechanical system of a linear EMA system consists of a load, lead screw, gear element, and the mechanical portion of an electric motor (shaft, bearings, and housing) as shown in Figure 6. The EMA can be either rotary or linear in design. For this analysis a linear actuator powered by a rotary electric motor will be assumed.

The gear element of the EMA consists of a rotary gear system typically used to reduce angular velocity of the electric motor while increasing the system output torque. Rotational to linear transmission within the EMA is assumed to be created with the use of a lead screw which translates the electric motor's rotation into linear motion.

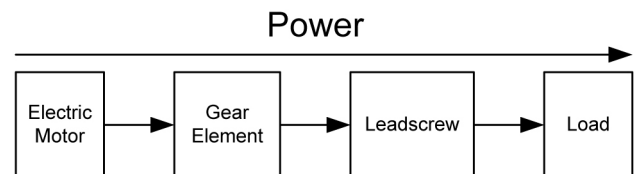


Figure 6. Mechanical System Diagram

Forces Description

The input force to the mechanical side of the EMA is motor torque. The motor torque is translated through a lead screw to create linear actuation force. The conserved internal forces for a bounded system can be represented by a linear or torsional spring (if material yields are not achieved), inertia and mass. External loads such as gravitational and aerodynamic can add to the internal forces of the EMA and increase the system's energy. Forces that dissipate energy include friction, fluid dynamic forces such as drag on the internal mechanism, and pumping loads created by displacing/compressing air within the system. These forces create mechanical loss energy which translates into heat within the mechanical system.

Energy Description

Potential energy (U) is the energy due to forces that act on the system. These forces can be either internal or external. Internal potential energy is the energy stored in the torsional elastic forces within the system. Torsional elastic forces are

the forces created by compressing material within the system. The compression forces will remain within the limits of non-permanent deformation and be assumed and verified to be linear in nature and represented by a torsional coefficient (κ) and be considered as an internal component of potential energy. External forces such as aerodynamic forces and gravitational forces are returned to the EMA via a mechanical linkage and are a function of the position of the system. They can be considered as an external component of potential energy.

Kinetic energy (E_k) is the mechanical energy of the EMA system due to the motion of its constituents. It is the amount of energy needed to accelerate a given mass to a certain velocity. The body will retain this kinetic energy unless a force acts upon it to remove the kinetic energy. For this body of work, mass and inertia will remain constants. Therefore the change in kinetic energy can be calculated by the change in EMA system velocity.

Mechanical loss energy (E_{ml}) is the energy loss due to mechanical forces that are not recovered within the system. The energy escapes the system through heat and sound energy. For this body of work the mechanical losses will be represented by a corresponding frictional torque (T_f) which will be empirically measured and defined by two terms, one fixed and the other dependent on angular velocity. Coulomb frictional forces will be considered to be represented within this lumped parameter.

Electrical energy is the energy that flows into the motor during actuation or out of the motor during regen (E_{regen}). This paper is focused on modeling regen and a detailed description of this energy flow is provided under the Regen Energy Description section.

REGEN ENERGY DESCRIPTION

The sources of regen energy are entirely in the mechanical system as described in the Energy Description section. These sources can transfer energy back into the electrical system via the generator action of the motor. The brushless DC motor generates a voltage when its shaft is driven by the mechanical system. The magnitude and frequency of this voltage is proportional to the speed of the motor. The speed of the motor increases as more potential energy is converted into kinetic energy. If no current is allowed to flow in the actuator windings, then no electrical power is generated, and no power is removed from the mechanical system by the motor. The transition of the mechanical system to a new position will be completely based on its kinetic and potential energy, and frictional losses. The electrical system will have absolutely no impact on this transient cycle. However, if current is allowed to flow out of the motor in phase with the generated voltage, then power will flow from the mechanical system into the electrical system. By removing energy from the mechanical system, the motor reduces the acceleration of the mechanical system.

The circuit model shown in [Figure 7](#) can be used to explain the flow of regen energy from the motor. A single phase of a brushless DC motor can be modeled with an inductance, resistance, and back emf (voltage source). The back emf is an AC voltage source whose magnitude and frequency is proportional to the rotor speed of the motor. This is represented by $K_b \omega_m \cos(\omega_m t)$ where K_b is the back emf constant for the motor and ω_m is the shaft speed. The flow of energy can be modeled by the current flow in the winding and its phase relationship with the back emf. If current flows out of the back emf voltage source when the voltage is positive as shown in [Figure 8](#), then the back emf acts like a power source and energy flows from the mechanical system into the electrical system. This corresponds to the regen mode. If current flows into the voltage source when the voltage is positive, then energy flows from the electrical system into the mechanical system. This corresponds to the actuation mode. If no current flows, then regardless of the speed of the motor and the magnitude of the back emf, no energy is being transferred between the mechanical and electrical system.

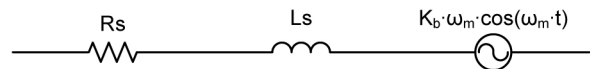


Figure 7. Motor Winding Model

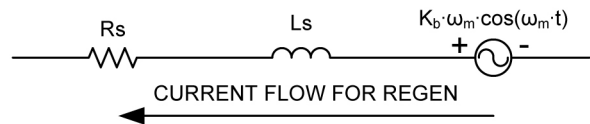


Figure 8. Motor Winding Model - Regen Mode

From this model, several key conclusions can be drawn. First, the flow of power from the mechanical to the electrical system can be controlled by controlling the current from the actuator. Second, if current is allowed to flow, this will add energy to the electrical system and it's important to understand the implications of this energy flow. Third, the back emf voltage is determined by the mechanical system and the speed at which it drives the motor. This may result in a voltage that exceeds the normal bus voltage of the MDE.

In the regen mode, the motor winding appears as a 3-phase voltage source. The 3-phase FET based circuit shown in [Figure 9](#) is typical for the power section of the MDE. The FET's are switched to provide actuation power to the motor. In the regen mode, the FET's will be switched off, but the body diodes will act to form a 3 phase passive rectifier. The bridge will act to rectify the back emf sources whenever their line-to-line voltage exceeds the DC bus voltage. In the typical application, the bus voltage will be held to a DC level by the DC input voltage to the MDE. Thus, the actuator will have to accelerate to a high speed before the rectified back emf exceeds the bus voltage and regen current begins to flow. Below this speed, no current will flow and no energy will be