A METHOD FOR THE EVALUATION OF ELECTROMECHANICAL ACTUATOR SYSTEMS USING EXERGY

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Abstract

In recent years, aircraft designers have strived to reduce aircraft fuel burn and emissions through the use of more electric aircraft (MEA). In a MEA, heavy systems such as hydraulics are replaced by an electrical system. Although a significant increase in efficiency can be achieved, many design challenges must be addressed. One issue is the high amount of coupling between electrical, mechanical, and thermal management components in a MEA. In order to account for component interactions, a system level design approach is needed. The system level approach will require the evaluation of many different types of components and architectures. In order to achieve this task, a common metric and a technique for rapidly modeling different architectures are required. A modeling environment was created for the evaluation of electromechanical actuation systems which uses exergy as a common metric. Exergy was selected for a figure of merit since it can be used universally with a variety of systems and can verify feasible designs. The modeling environment consists of several modules which are linked together to create the system model. The type and arrangement of the modules can be altered to quickly evaluate different architectures. In this study, the modeling environment is used to evaluate two EMA system architectures. One system dissipates any regenerated energy and the second system stores the regenerated energy for later use. Both cases are simulated using the modeling environment and then compared using the rate of change of exergy.

1 Introduction

Due to rising concern about the environmental impact of aircraft, organizations around the world have set goals to reduce aircraft emissions and fuel burn. In order to achieve these goals, unconventional systems must be incorporated into aircraft design. One of the most notable changes in aircraft design is the push for more electric aircraft (MEA). In an MEA, heavy, inefficient systems such as hydraulics are replaced by lighter, efficient electrical systems. [1] Although the potential for a significant increase in aircraft efficiency exists, the integration of electrical systems can create a difficult optimization process. Previously aircraft have been optimized on the subsystem level. However, electrical systems create an integration challenge which requires a system level optimization approach. The primary challenges when optimizing on the system level are the variety of disciplines represented by each system present in the aircraft -- electrical, chemical, mechanical, etc. and the variety of architectures that can be selected when designing an aircraft. With the many types of systems and architectures, it can be difficult to find a way to compare different options and determine the best design. One source of difficulty is the lack of a common metric when comparing two systems which conventionally use different figures of merit. An example of this problem is trying to compare a mechanical system to an electrical system. The same problem arises when comparing two radically different architectures. Another system level modeling problem that needs to be addressed is that modeling many different types of architectures can be time consuming. A way of rapidly producing models of different architectures will also be needed to find the most fuel efficient designs.

An example of a design problem that encases all of the design issues discussed is the integration of an electromechanical actuation system into a commercial aircraft. The use of electromechanical actuators (EMAs) has the potential to significantly increase the efficiency of an aircraft. [2] Currently, aircraft use heavy hydraulic systems for actuation; these systems have multiple problems with no foreseeable solution. One major issue is maintenance. Hydraulic systems are prone to leaks that can be difficult and costly to repair. Also, the leaked fluid can be a hazard to the environment. Another problem is inefficiency. [1] The hydraulic system must always be pressurized during operation of the aircraft. The leaks in the system are another source of inefficiency. A third source of inefficiency is the weight of the pipes and fluid that have to be incorporated into the aircraft. These issues can be solved by the use of EMAs since the heavy hydraulic pipes and fluid can be replaced by electrical wiring. This should significantly reduce the weight of the distribution system and eliminates the issue of leaking hydraulic fluid. Efficiency is further increased because the EMA will only consume power when needed.

In this paper a metric will be selected and modeling methodology will be developed for the design of an EMA system. Although the methodology is specific to the design of an EMA system, the general concepts can be expanded to a variety of problems of a similar nature.

2 Methodology

The general methodology created for the modeling of EMA systems is shown in Fig. 1. It is based on the Georgia Tech Generic IPPD Methodology. [3] Each of the points in the flow chart will be explained in detail.

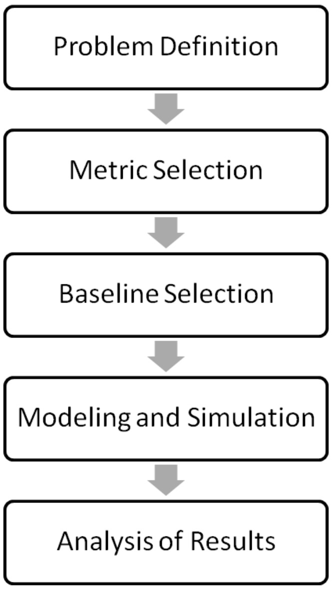


Fig. 1. EMA system modeling methodology

2.1 Problem Definition

An important issue in EMA system design is the lack of a consistent way to compare different architectures. This study aims to present a methodology that allows direct and rapid comparison of different EMA systems. Important issues that must be addressed to create this methodology are metric selection and modeling techniques. The metric must be selected so that architectures can be compared in a consistent manner. The modeling must be approached in a way that allows for different architectures to be quickly simulated.

The metric selection and modeling approach will also be a key in overcoming EMA system design challenges. One major problem is regeneration. [4] When a control surface returns under its own weight or external load to a resting position, regenerative energy is generated. This regenerated energy must be dissipated or stored for later use. Another concern is thermal management. The electronic components of the EMA will create a significant amount of heat compared to a hydraulic system. Also, in a hydraulic system, the hydraulic fluid could be used as a heat sink; in an EMA system this is no longer an option. Furthermore, if the regenerated energy is dissipated as heat, the thermal management issues increase in severity; therefore, a thermal management system (TMS) will be required. This will add weight to the system and decrease efficiency. The modeling approach used will aim to address these issues and help develop a system design that will mitigate the adverse effects of introducing an EMA system.

2.2 Metric Selection

One of the most important aspects of modeling an EMA system is selecting a proper metric. Since many different architectures need to be compared, a common metric must be used. However, this can be a difficult task since there are mechanical, electrical, and thermal components in the system. The available energy and the losses for the system must be tracked.

The first step in selecting a metric is to determine what functions the metric must fulfill. So, a list of criteria for the metric was created. The criteria selected were: measure of thermal energy; measure of electrical energy; measure of mechanical energy; quality of work; measure of energy loss; research available; general understanding; time dependence; ease of measurement; and end user interest.

Once the criteria were selected, a multi-attribute decision making process called TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) was used to determine the best metric. TOPSIS ranks each solution based on its Euclidean distance from the "ideal" solution and the worst solution [5]. To employ this method a list of alternatives, in this case metrics that could satisfy the criteria, is needed. For this study six metrics were considered. They were exergy, rate of change of exergy, entropy, rate of change of entropy, electrical power, and heat generation.

An important aspect of TOPSIS is that it uses weightings for the criteria. The weightings are on a percentage basis. Each criterion has that percentage influence on selection of the point that is the ideal solution. Once the weightings are set, each alternative is ranked on a scale from one to nine for each criterion. A rating of one shows poor performance for that criterion and a rating of 9 shows superb performance. Each of the metrics were ranked with respect to each criteria based on research and expert judgment. The ranking environment was created in Microsoft Excel. The results of the TOPSIS study are shown in Table 1.

Table 1. TOPSIS rankings

	Thermal Energy	Electrical Energy	…	Customer Interest	Rankings
Exergy	9	5	…	9	3
Rate of change of exergy	9	5	…	7	1
Rate of change of entropy	7	5	…	7	2
Electrical power	1	9	…	5	4
Heat generation	9	1	…	5	6
Entropy	7	5	…	5	5

The results show that the rate of change of exergy is the best metric for this system. Exergy is a thermodynamic concept which refers to the maximum theoretical useful (or consumable) work by all systems in interaction. [6] It can also be thought of as the "work potential" of the system. When using exergy as a metric, the focus of the design process is to minimize exergy destruction. Exergy destruction is directly proportional to the entropy generated by a system. [7] Furthermore, exergy takes the second law of thermodynamics into account. Other metrics rely only on the first law of thermodynamics. The first law is a necessary condition for a process to be feasible, but it is not sufficient. The second law ensures that a process can take place in a given direction. Another useful quality of exergy is that a single metric can be used universally with a variety of physical disciplines. Also, exergy can be used to describe the quality of work available in the system. The higher the exergy of the system, better quality of work is available. The issues that will arise from this metric are lack of general understanding and the fact that it cannot be directly measured. In order to determine the amount of exergy in a system, the system's energy must be compared to its energy at a "dead state". At the dead state the system would contain no exergy or "work potential". Therefore, in order to use exergy as a metric, a dead state must carefully be selected.

2.3 Baseline Selection

The aircraft selected for this study was the Gulfstream G550. This is a 14 to 19 passenger aircraft with a range of 6,750 nautical miles and cruise speed of Mach 0.85. [8] In this aircraft there is one aileron control surface. For each aileron there are two actuators. For safety reasons, each actuator is capable of moving the aileron under a full load.

2.4 Modeling and Simulation

The model was built in modules that are connected and pass data between them. This is so that different modules can be substituted into the model to study different architectures. In this particular study two different architectures were tested. The first is an architecture that addresses regenerated energy through dissipation. A large wire-wound ceramic resistor is placed local to each actuator to consume any excess energy that the actuator may create. The second architecture studied is a storage architecture. Each actuator has a supercapacitor that stores any excess energy from the actuator. This energy can be returned to the actuator during periods of high power demand.

An overview of the model is shown in Fig. 2. The primary input into the model is the aircraft data. This data includes the hinge moment on the actuator at various flight conditions and the size of the aileron. The hinge moment data is then fed to the EMA model. This model determines the amount of power that the actuator must consume to operate. This information is transferred to the dissipation and storage modules. The dissipation module shows that a large amount of heat is generated; so, a thermal management system must be used to keep the system temperature at an acceptable limit. From these models, the size of the storage and dissipation elements can be determined and the rate of exergy destruction can be calculated. Each of the modules will be explained in further detail in the next sections.

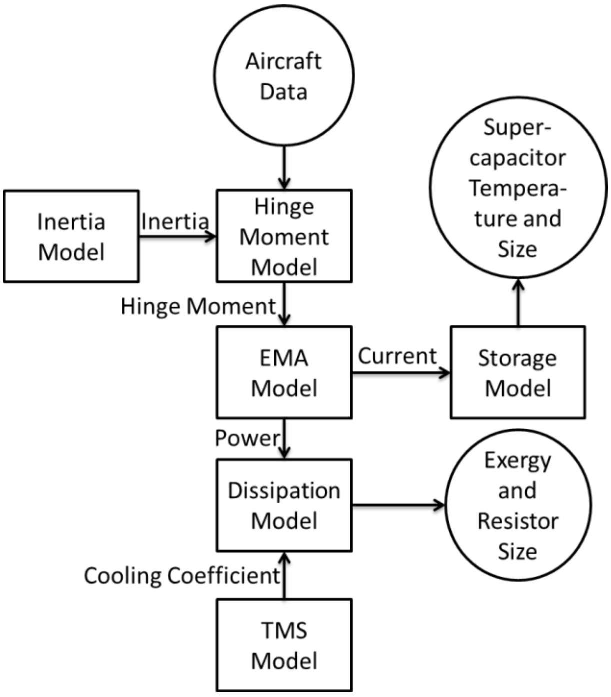


Fig. 2. Modeling overview

2.4.1 Hinge Moment Prediction Model

When calculating the aileron hinge moment, two sources must be considered: inertial loads and aerodynamic loads. The inertial loads are most important when doing ground checks of the control surfaces. During these checks, the control surfaces will be fully deflected at rapid rates. This is one of the highest loads on the actuator throughout the flight. The aerodynamic loads are the loads experienced by the actuator during flight.

The primary assumptions made in the inertia hinge moment calculation were that the mass of the aileron is uniform and the aileron is symmetric. The axis used for the calculations is shown in Fig. 3.

The equation for calculating the hinge moment due to inertia is

$$B = \iint \rho e(x^2 + y^2)dxdy = m[\frac{L^2}{6} + \frac{l^2}{24}] \qquad (1)$$

Where, ρ is the density of the aileron and m is the mass of the aileron.

The aerodynamic hinge moments were calculated using flight data for the baseline aircraft. Only a small set of data was available, so a response surface equation (RSE) was created in order to predict the loads under other flight conditions. The software program JMP was used to create the RSE [9]. The first step in creating the RSE is to perform effect screening. In this step it is determined which parameters are driving the response. The data provided showed the aileron hinge moment as a function of altitude, angle of defection, speed, and angle of attack. The error was high the first time the model was fit; therefore, trigonometric variables were added. Another option is to use the exponentiation of the angles; however, this type of transformation does not work well with large angle values. After the transformation, the effect screening was performed again. The results of the effect screening are shown as a Pareto plot in Fig. 4. An interesting find is that the angle of attack has very little contribution to the response. A possible reason for this outcome is that for a given weight and geometry, the angle of attack can be calculated with the altitude and the speed.

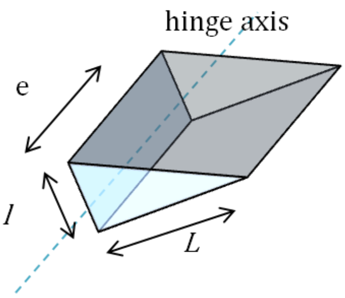
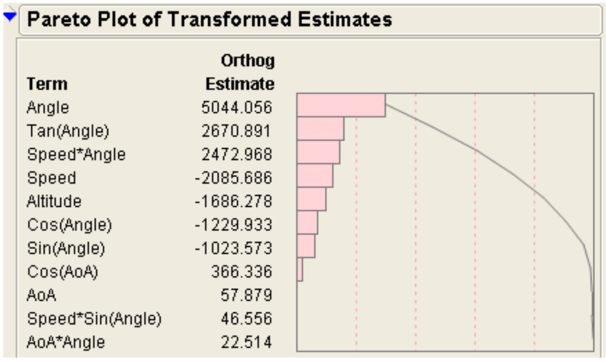


Fig. 3. Inertia calculation diagram



Pareto Plot of Transformed Estimates

Term	Orthog Estimate
Angle	5044.056
Tan(Angle)	2670.891
Speed*Angle	2472.968
Speed	-2085.686
Altitude	-1686.278
Cos(Angle)	-1229.933
Sin(Angle)	-1023.573
Cos(AoA)	366.336
AoA	57.879
Speed*Sin(Angle)	46.556
AoA*Angle	22.514

Fig. 4. Pareto plot of variables

One of the primary limitations of the RSE created was that very few points were available to fit. Since there were so few points, the RSE was able to fit the points very well. The maximum error of the RSE was 6% with a mean of zero. The only concerning point about the RSE fit was that the standard deviation is high, which could be addressed by adding additional points.

2.4.2 EMA Model

After the hinge moment of the control surface is calculated, the information is sent to the EMA model. The first step in this model is to convert the hinge moment to a load on the actuator. The geometric relationship is shown in Fig. 5. Using this schematic, a relation between the elements can be derived as Eq. 2.

$$L \cdot \cos\left(arcsin\left(\frac{D}{L}(1-cos(\alpha))\right)\right) = L + D \cdot \sin(\alpha) - \Delta \mathrm{x} \qquad (2)$$

Using conservation of work, the relation between hinge moment and the force at the piston is

$$F\Delta \mathrm{x} = \mathrm{C}\alpha \qquad (3)$$

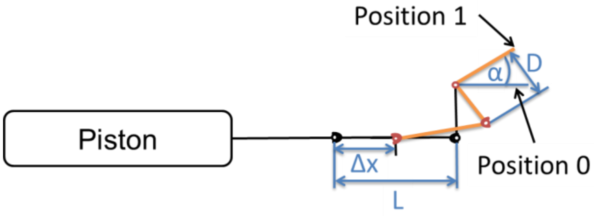


Fig. 5. Actuator interface with the aileron

Once the force on the piston is known, the next step is to determine the power draw of the EMA. To determine this, a model was built in Simulink using the SimPowerSystems toolbox. [10] In order to build this model, many assumptions were made. The assumptions are: the deflection angle input is positive; the aileron travels at a constant speed to the final angle; and there are no mechanical losses except for inertial losses in the motor.

An overview of the model is shown in Fig. 6. The hinge moment data is one of the inputs into the model. An initial guess for the angle of deflection of the control surface is also required. The model is a feedback loop which uses a PID controller to correct the angle of deflection input. This information is then converted into a form that can be used by the brush-less DC motor model, which outputs the torque generated by the motor, the power consumption of the motor, and the motor speed. The motor speed can be used to derive the angle of deflection, which is the feedback part of the loop. The power consumed by the motor is the primary output of the model. This information is fed to the dissipation and storage models.

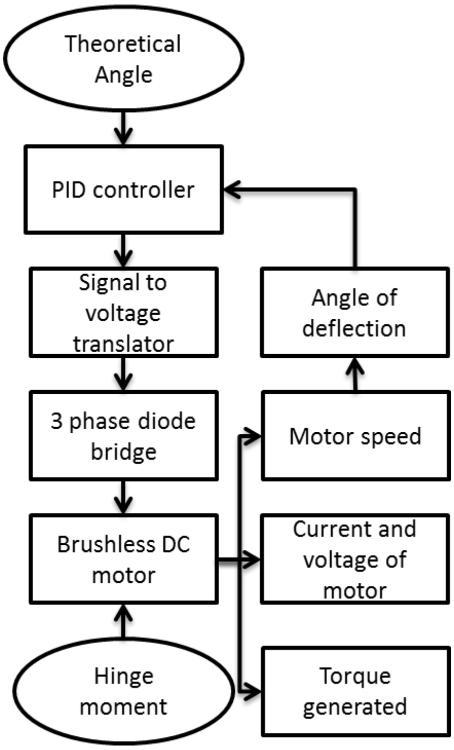


Fig. 6. EMA Model Overview

2.4.3 Dissipation Model

The primary purpose of the dissipation model is to size a resistor based on the power information from the EMA model, to determine the temperature of the resistor under the given loading conditions, and calculate exergy change over time. The primary assumptions made to create this model are: all power losses contribute to heat generation; ambient temperature is used for the exergy calculation; and the resistor type is ceramic wire-wound. The required inputs for the model are altitude, regenerated power, deflection time, and thermal management information.

The resistor size is determined using a look-up table. The look-up table includes off-the-shelf resistor sizes as a function of their maximum power dissipation capacity. This gives the dimensions of the resistor; then the resistance of the resistor can be calculated.

The models use a mix of experimental data and thermodynamic equations to predict the temperature and exergy loss of the resistor. The model first determines the temperature of the resistor using natural convection to air. If that temperature exceeds a maximum allowable temperature of the resistor, then a thermal management system (TMS) is required. The maximum allowable temperature was set at 125 degrees based on the temperature limit for the surrounding power electronics. [11] A model of the TMS was also created using Simulink. The TMS uses a ram air cooled cold plate to control the temperature of the resistor. The properties of the ram air were determined using the PCKA thermal toolset for Simulink. [12] The ram air conditions are then fed into an S-function that finds the cold plate size. Within the S-function is a genetic algorithm (GA) that finds the cold plate design with the minimum weight that meets the temperature constraint.

Using the information about power dissipation and thermal management, the rate of exergy destruction ($\dot{\boldsymbol{Ex}}_{\boldsymbol{dest}}$) by the system can be calculated. Since ram air is entering and leaving the system, the system is considered to be open. Therefore, the equation for exergy balance is

$$\dot{Ex}_{dest} = T_0\dot{S}_{gen} \qquad (4)$$

Where, T_0 is the temperature at the dead state and $\dot{\boldsymbol{S}}_{\boldsymbol{gen}}$ is the rate of entropy produced by the system. Using classical thermodynamics this value can be defined as:

$$\dot{S}_{gen} = \dot{m}(s_{out} - s_{in}) - \frac{d\dot{Q}}{T} \qquad (5)$$

Where,

$$s_{out} - s_{in} = c_p \ln\left(\frac{T_{out}}{T_{in}}\right) - R\ln\left(\frac{P_{out}}{P_{in}}\right) \qquad (6)$$

Where, $\dot{m}$ is the mass flow rate, $\dot{Q}$ is heat flux, c_p is the specific heat capacity of air, R is the gas constant, and *P* is pressure.

Using exergy destruction and thermodynamic information, an exergy balance can be performed. Satisfying the exergy balance equation ensures that the system abides by the second law of thermodynamics. This is an important check of the model and system design. The equation for exergy balance of an open system is used since ram air is flowing in and out of the system.

$$E\dot{x}_{dest} = \sum_{i=1}^{n}\left(1 - \frac{T_0}{T_i}\right)\dot{Q} + \sum_{in}\dot{m}(h^o - T_0 s) - \sum_{out}\dot{m}(h^o - T_0 s) - T_0\dot{S}_{gen} \qquad (7)$$

Where, h^o is enthalpy of formation.

2.4.4 Storage Model

Another way of taking care of regenerated energy is through a storage system. In this case, the regenerated energy is sent to a storage device local to the actuator rather than dissipated by a resistor. The storage device selected for this study was a supercapacitor. A supercapacitor was selected due to its quick charge and discharge rate, cycle life, and its performance at low temperatures. A preliminary test of the EMA model showed that the capacitor would have to be sized to store 400 Joules of energy and dissipate 2kW of power. The supercapacitor model was built using MATLAB/Simulink. The SimPowerSystems toolbox was used to model the electrical components of the system. The model's primary tasks are to size the supercapacitor based on the maximum regenerative loads from the actuator and to predict the temperature of the device.

Exergy destruction can also be calculated for this system. The approach is similar to the dissipation system, but the equations are simplified since the system is closed. Since there is no ram air flow, the mass flow rate term drops out of the rate of the entropy production equation. This equation simply becomes

$$s_2 - s_1 = nc_v \ln\left(\frac{T}{T_0}\right) \qquad (8)$$

The subscripts 1 and 2 correspond the beginning and end states of the system. The equation for exergy balance for the closed system is

$$E\dot{x}_{dest} = \sum_{in}\dot{Q}\left(1 - \frac{T_0}{T_k}\right) + \sum_{in}\dot{m}\Psi - \sum_{out}\dot{Q}\left(1 - \frac{T_0}{T_k}\right) - \sum_{out}\dot{m}\Psi \qquad (9)$$

Where, **Ψ** is the flow exergy, and T_k is the temperature of the system at the time of measurement.

3 Results

Both the dissipation architecture and the storage architecture were studied using exergy as the primary metric. Furthermore, the weight and volume of each system were also calculated.

3.1 Dissipation Model Results

When calculating the exergy destruction of the dissipation system, two sources of entropy must be considered. The first source of entropy is the heat created by the resistor. The second source is the ram air. The change in air temperature and pressure contributes to entropy production.

In order to determine the amount of heat created by the resistor, the amount of regenerated power must be calculated. The amount of regenerated power is calculated by the EMA model. However, in order to run the EMA model, the hinge moment must be calculated first.

3.1.2 EMA Model Results

When determining the hinge moment on the aileron, two factors have to be taken into consideration. The first factor is the inertia of the control surface during the deflection. This is critical when doing ground checks of the control surface. The hinge moment generated by the inertia of the aileron is shown in Fig. 7.

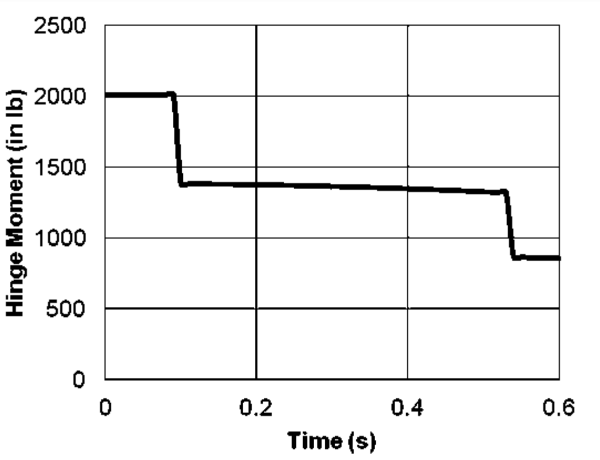


Fig. 7. Hinge moment due to inertia

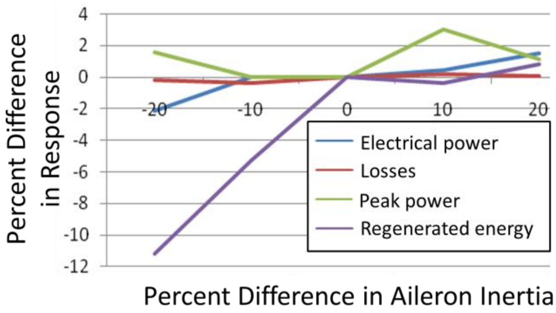


Fig. 8. Sensitivity of the response to aileron inertia

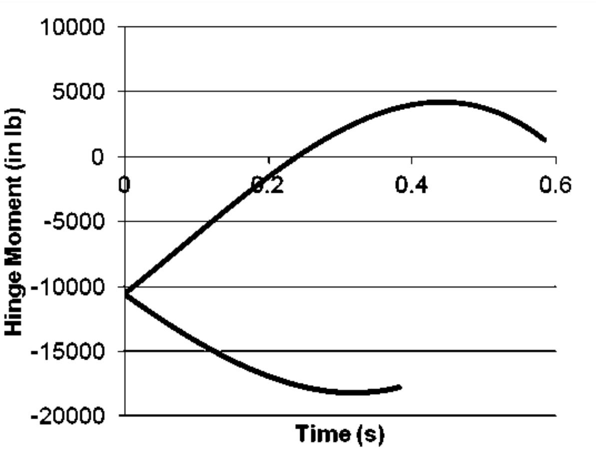


Fig. 9. Hinge moment due to aerodynamic loading

A study was conducted to show how the results differed with a change in aileron inertia. The inertia would change if a different geometry was selected or the aileron was not uniform. The results are shown in Fig. 8. The largest change is the calculation of regenerated energy.

The second consideration when determining the hinge moment is the moment on the control surface due to aerodynamic forces. Fig. 9 shows the aerodynamic moment on the aileron at 15,000 feet while traveling at 300 knots. The results are shown for both directions of deflection. Using these hinge moment results, the amount of power regenerated could be calculated using the EMA model.

3.1.2 EMA Model Results

The motor model was tested for a deflection of 19 degrees of the aileron during flight. The amount of power drawn by the actuator motor is shown in Fig. 10. There is a large power spike in the beginning of the simulation. This represents the aileron overcoming the initial moment of inertia. Fig. 11 shows the regenerated energy by returning the aileron back to a zero degree angle. The amount of power regenerated is about 2,000 Watts. This is the number that is used to size the resistor and supercapacitor and perform the exergy calculation.

The model sensitivity relative to the inertia of the motor was studied. The results of this study are shown in Fig. 12. The amount of electrical power drawn is the most sensitive to a change in motor inertia. A change in motor inertia also affects the losses, peak power draw, and regenerative energy created; however, the changes are small and mostly insignificant.

3.1.3 Thermal Management System Sizing

Once the amount of regenerated power was known, the resistor could be sized. From the EMA model, it was determined that the peak heat load to be dissipated by the resistor is 2,000 Watts. Based upon this information, a ceramic wire-wound resistor was chosen. Using the look-up table in the model, it was determined that the resistor would have a length of 0.51 meters, a diameter of 0.07 meters, and mass of 7.5 kg. Using the dimensions of the resistor and ambient conditions, the amount of heat transfer available using natural convection was calculated. At sea-level conditions, the amount of heat transfer via natural convection is only 38 Watts. This falls well short of the required 2,000 Watts; therefore, a TMS is required for the dissipation system.

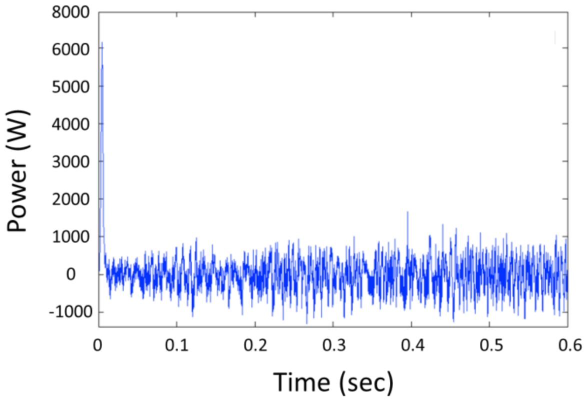


Fig. 10. EMA power draw to deflect aileron by 19 degrees

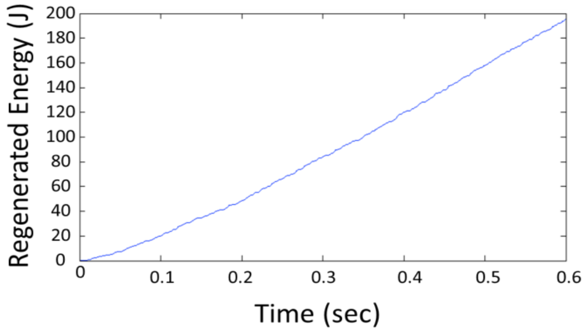


Fig. 11. Regenerated. energy for a 19^o aileron deflection

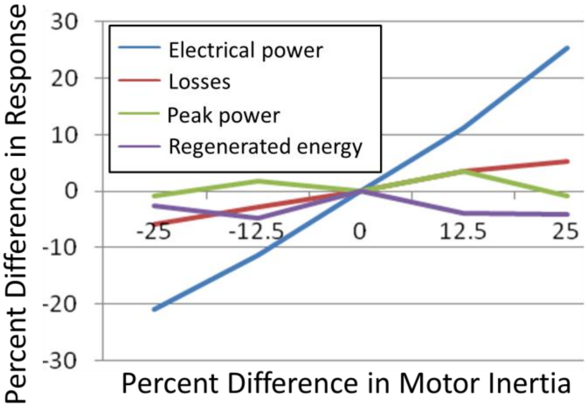


Fig. 12. Motor sensitivity to a change in inertia

Table 2. Cold plate sizing results

Parameters	Result
Fin height	2.2 cm
Number of fins	89
Fin Spacing	0.5 cm
Plate thickness	1.27 cm
Peak temperature	116.15 Celsius
Mass	4.28 kg

3.1.4 Exergy Calculation

In order to determine exergy, a dead state must first be chosen. In this study ambient conditions were selected for the dead state. The second piece of information needed to determine the rate of exergy destruction is the rate of entropy production. The rate of entropy production is calculated using information from the thermal management model. The entropy production rate for this case study was 4.6126 Joules per Kelvin per second. The entropy production rate is used to determine the exergy destruction rate and proves that the system does not violate the second law of thermodynamics. Using the dead state as the ambient environment, the exergy destruction rate was determined to be 1,457.4 Joules per second.

3.2 Storage Model Results

The second architecture studied uses a storage system rather than a dissipation system. In order to determine the exergy destruction rate of this system, the same hinge moment and EMA data were used to determine the regenerative load. Simulink was used to create a model of a supercapacitor. Based upon the 2,000 Watt load, the capacitor size was set at 2,000 F. A capacitor of this size would weigh approximately 0.36 kg. [13] A thermal analysis of the system was also required to calculate exergy. The results of the thermal analysis are shown in Fig. 13. The figure shows the temperature of the capacitor as a function of actuation rate. Under all conditions, the capacitor's temperature never exceeds the 125 degree Celsius limit; therefore, a ram air cooled cold plate is not required in this architecture.

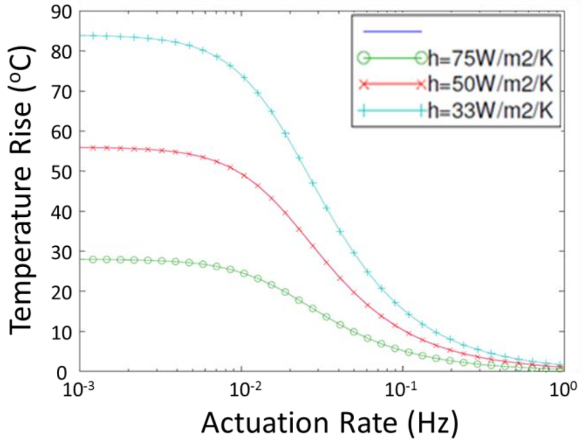


Fig. 13. Capacitor temperature

Since a thermal management system is not required, the mass flow portion of the exergy destruction equation drops out and only leaves the entropy due to heat production. The heat production calculation is different than the calculation used for the dissipation system since not all of the regenerated power goes directly into heat production. The amount of heat produced by the capacitor is equal to the power losses in the capacitor. The power losses can be deduced using the thermal resistance of the capacitor. Based upon manufacturer's specifications for a 2,000 F capacitor, the thermal resistance would be about 3.8 degrees Celsius per Watt. Given this information, the power loss in the capacitor is 22.37 Watts. Therefore, by applying the exergy destruction equation, the rate of exergy destruction is 4.74 Joules per second.

4 Conclusion

In this study a modeling approach was developed to study two types of EMA systems. The modeling uses exergy as a metric to compare the systems. The exergy metric takes into account inefficiencies of the systems and the impact of thermal management. The dissipation system had an exergy destruction rate of 1,457.4 Joules per second, and the storage system had an exergy destruction rate of 4.74 Joules per second. The exergy destruction rates show that the dissipation system is much more inefficient than the storage option. Two things cause this large contrast. The first is that the dissipation system loses all regenerated power as heat, while the capacitor only loses about 1% of the power as heat. The second difference is the thermal management. The entropy increase in the ram air flow is another significant source of exergy destruction. Another outcome of the study is the size of each system. Again, the dissipation system is inferior to the storage system. This is because the dissipation element, the resistor, is much larger than the storage element, the capacitor. Furthermore, the thermal management system required for the dissipation system further increases weight and volume.

Although the modeling approach was used to design an EMA system in this paper, this approach can be used for a variety of system level design problems. The exergy metric is especially valuable in the system level design process due to the second law approach and its versatility. Through the use of exergy based design, rapid comparison of architectures can be performed and the most efficient design can be found.

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