THE ALL-ELECTRIC AIRCRAFT

ICAS-80-5.1

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Abstract

Combining Power-By-Wire (electrical actuation) with Fly-By-Wire (electrical signal transmission) for the all-electric aircraft would unify the secondary power system and the flight control system under one medium, electrical. The all-electric aircraft would, therefore, not only remove a troublesome hydraulic to electrical interface and all problems peculiar to hydraulic fluid systems but combine two mutually reinforcing technologies in a manner that dramatically affects the entire internal system configuration of the aircraft. The major key towards realizing the benefits of the all-electric aircraft is the successful development of electromechanical actuation as it embraces the utilization of rare earth samarium-cobalt permanent magnets in conjunction with the advancing technologies of both control and power electronics. This paper presents an overview of what is thought to be the significant events, issues, and developments that most effectively relate to the status and credibility of the all-electric aircraft concept.

Introduction

"Aircraft of the future will be all electric vehicles. Electrical generators - rather than mechanical pumps - will move primary and secondary flight control surfaces, raise and lower landing gears and steer nose wheels. That is what engineers in Air Force Flight Dynamics Laboratory (AFFDL) are predicting for 'power-by-wire' - a dramatically new idea in the design and management of electrical power in aircraft." The above is the opening two sentences of an official United States Air Force (USAF) news item released in the latter part of 1977. Since that time, the concept of an all-electric airplane (no hydraulics) has taken on far more interest and respectability than it enjoyed in 1977. A very simple and basic premise fuels this increasing interest. If the electric power system, which must be on all aircraft of the foreseeable future, can be expanded to also do actuation in a manner competitive to hydraulic actuation then the addition of hydraulic systems for the sole purpose of actuation can be avoided. The value of the all-electric aircraft concept then follows directly from an old aircraft design axiom which states, never, but never, add anything to the aircraft that doesn't pay its way. One important difference here, of course, is that we do not have the luxury of a "clean sheet" design frame of reference. We are suggesting removal of what is now accepted as a necessary technology to accomplish aircraft actuation functions, i.e., hydraulic actuation systems. We also have a problem similar to those that have stifled and prevented many otherwise desirable changes in airplane programs, i.e., the costs of incorporation can turn out to be greater than the benefits realized. It is also well to keep in mind that in too many cases, for changes actually made, the costs of incorporation were underestimated and realizable benefits were overestimated. How, then, do you best attack a problem of this nature? How do you go from an intuitive design postulation to a supportable design change decision?

Obviously, a necessary first step must be one that establishes a reasonable degree of credibility that electric powered actuators can be competitive to the time honored hydraulic actuators. By competitive, we mean that the same output requirements in terms of torque, rate, and bandpass can be satisfied with weight, space, and power usage penalties comparable to hydraulic actuators. The electromechanical actuator should not be thought of as a direct replacement for hydraulic actuators on an actuator to actuator basis because its importance derives from the overall change it can make possible, ergo, the all-electric aircraft. Nevertheless, a high degree of competitive performance must be demonstrated before investigation of the benefits of an all-electric airplane can be justified.

Once competitive performance is demonstrated, the second step is to examine the benefits that could accrue from an all-electric airplane while at the same time continuing the development of electromechanical actuation. This paper is designed to trace the development of high performance electromechanical actuation and to discuss the significant preliminary data now emerging from all-electric airplane study programs.

Background

In the late sixties and early seventies, several incidents and accidents occurred which suggested that total reliance on engine-driven hydraulic power for flight control on USAF airplanes deserved reexamination. Failure patterns had developed that had found ways of cutting across what appeared to be satisfactory independent redundancy. Programs were conceived, therefore, to enhance the independent redundancy of the power provided for flight control actuation with dissimilar power techniques. The earlier programs employed a technique that was generally labeled the Integrated Actuator Package (IAP) technique. Under this concept, electrical power would be taken from the engine and transmitted to some point near the control surface to be actuated. At this point the electrical power would then be converted to hydraulic power via an electric motor, a hydraulic pump, hydraulic reservoir, etc. to furnish hydraulic power for the actuation. The IAP concept conveyed the additional refinement of packaging the entire conversion of electrical power to hydraulic power with the actuation unit. The IAP programs have as yet had only mediocre success although the conversion of electrical power to hydraulic power at the actuator, without the integrated packaging refinement, has been employed on many aircraft. In 1972, a different approach to utilize dissimilar (electrical) power to improve independent actuation power was conceived at the Air Force Flight Dynamics Laboratory (AFFDL). In essence, this concept replaced the electrical power to hydraulic power conversion with direct electromechanical (EM) actuation. At the inception of this program, the direct EM actuation technique was visualized as only a limited supplement to conventional hydraulic actuation. There was the general feeling that EM actuation would be so inferior to hydraulic actuation performance that it could only be justified on a limited basis as a special reliability improvement feature. As the AFFDL program progressed, however, it became increasingly evident that EM actuation had far greater potential than initially visualized.

One of the significant programs that added impetus to a larger role for electromechanical (EM) actuation was the National Aeronautics and Space Administration (NASA) Space Shuttle Program. The NASA engineers were able to mount a substantial effort to investigate removal of "hydraulics" from the Space Shuttle. This effort culminated in the development of an EM actuation unit, built by the Delco Electronics Division of the General Motors Corporation that was designed to meet the performance requirements of the Space Shuttle elevon actuator.(1) The effort did not succeed in removing "hydraulics" from the present Space Shuttle, but it did demonstrate that EM actuation can no longer be dismissed as totally inadequate for high horsepower aircraft actuation requirements. Further, this program illuminated the real potential value of EM actuation, i.e., the opportunity to expand the electrical power system (that must be available in any case) to also do actuation instead of adding a hydraulic system for the sole purpose of actuation.(2) (3) The particular aspects of the Space Shuttle Orbiter Mission which differ markedly from an airplane mission make the removal of hydraulics, for the sole purpose of actuation, particularly attractive. An underlying, rapidly advancing technology that is also adding impetus to the desirability of electrically powered actuation is the rapid increase in the use of avionics and in particular fly-by-wire. Removal of mechanical signal transmission and replacement with electrical signal transmission obviously adds to the criticality of electrical power and the need for the best independent electrical power redundancy possible. The use of electrical power for actuation opens up new possibilities for improving the power redundancy of fly-by-wire that is now handicapped by the need to also provide hydraulic power redundancy. It was against this background, then, that the AFFDL (EM) actuation program was conceived and progressed from a very limited objective to one of far more portent.

AFFDL Electromechanical Actuation Program

The program was conceived in two phases: (1) a feasibility analytical study program based on appropriate ground rules, and (2) design, fabrication, and test of an actuation unit should the study results be favorable. The study results were favorable and the program schedule for the development and test program by AiResearch Manufacturing Company is shown in Figure 1.

Figure 2 shows the actuation geometry concept that was conceived from the outset. The integrated hinge concept, as it could be applied to any of the conventional trailing edge surfaces, i.e., elevators, ailerons, or rudders was considered a necessary feature to best explore the potential of EM actuation. Figure 3 shows the much better space utilization and structural efficiency that can be expected when compared to surface actuation using a conventional dual tandem hydraulic actuator. Figure 4 shows the completed actuation hardware unit and is briefly described here. Two electric motors drive through a summing differential and thence through a reduction gear box to impart rotary motion to the control surface. Each motor includes a brake that will be applied to permit operation at full torque but at one half rate, should power fail to either motor. Should complete power failure occur, the surface would be clamped at the position where complete power failure occurred. The maximum allowable diameter of the actuator was set at four inches (102 mm.). Figure 5 shows the dual channel functional concept. The remainder of the significant study ground rules and performance objectives are listed:

(a) 3-phase 115/200 volt - 400 cycle AC power assumed available

(b) 3 H.P. available at the control surface

(c) Stall hinge moment = 37,575 in. lb. (43.289 cm. kg.)

(d) No load rate = 80 deg./sec.

(e) Bandwidth = 8 H_Z at ± 1 deg. amplitude

(f) Surface load inertia = 46.6 lb. in. sec.^{2} (53.7 kg. cm. sec.^{2})

Items (b) through (f) are directly comparable with the requirements for the present B-52 elevator which used a dual tandem hydraulic actuator. The actuation unit satisfied the performance objectives and weighs 35 lbs. exclusive of the signal and power electronics.

Motor Selection

The choice of basic motor designs is illustrated in Figure 6. The desire to eliminate brushes, as incompatible with the reliability requirements of primary control surface actuation for airplanes, removed consideration of the two brush type motors immediately. This left only two real choices, an AC induction motor and what is generally termed an inside-out brushless DC motor with a permanent magnet rotor. With either type of motor, the relationship with conventional 115/200 VAC, 3 phase, 400 HZ electrical power supply is significant. The necessary conversion to DC for the brushless DC motor is apparent but it can also be strongly supported that the necessary power control of an induction motor, for actuator application, will also require rectification of the AC power to DC. It was thus early determined that the motors in a high

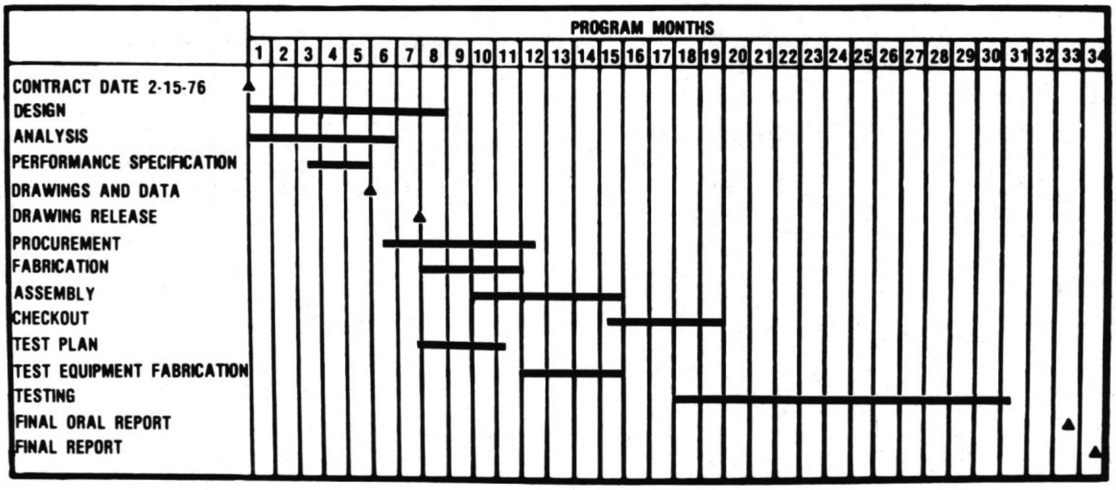

Figure 1. Electromechanical Actuation Development Program Schedule

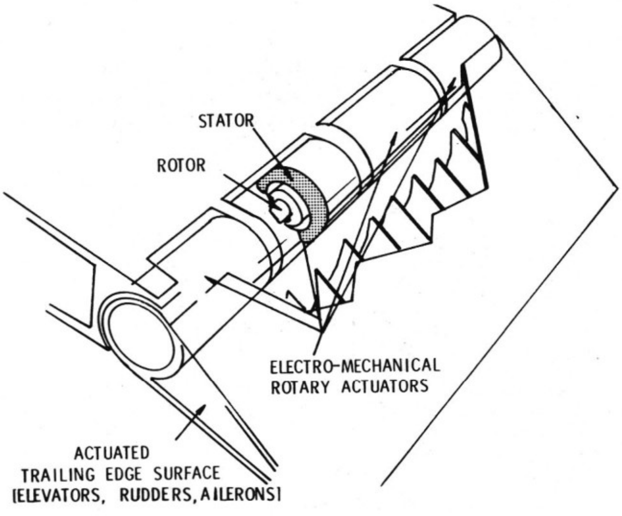

Figure 2. Typical Actuation Geometry

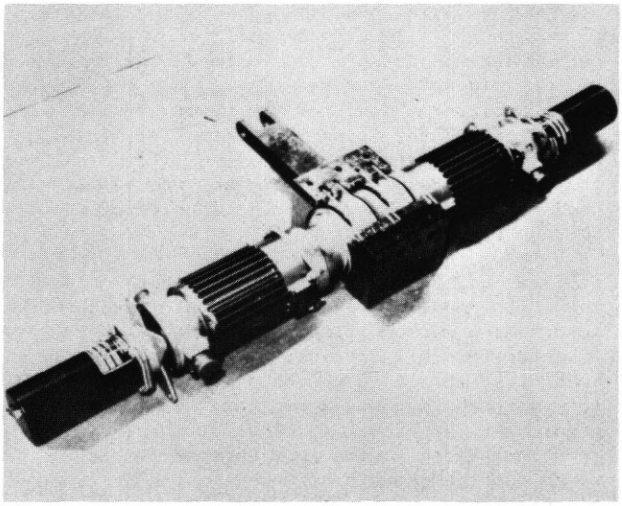

Figure 4. Actuator Hardware Configuration

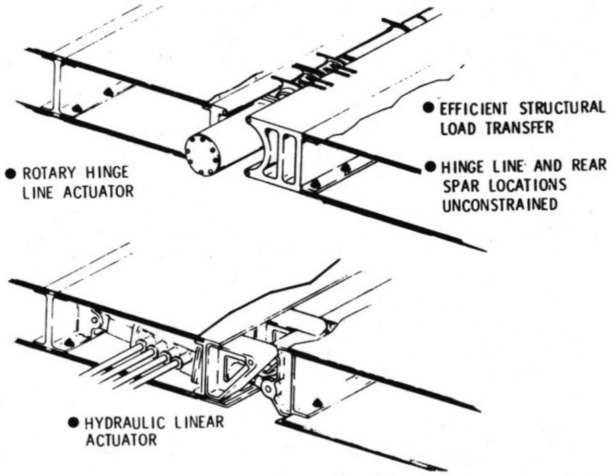

Figure 3. Comparison of Rotary Hinge Line Versus Linear Actuator

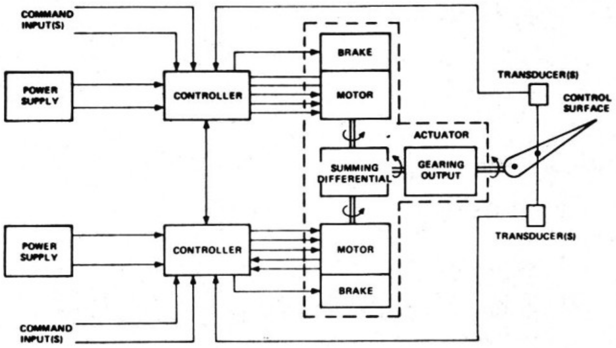

Figure 5. Actuation Functional Concept

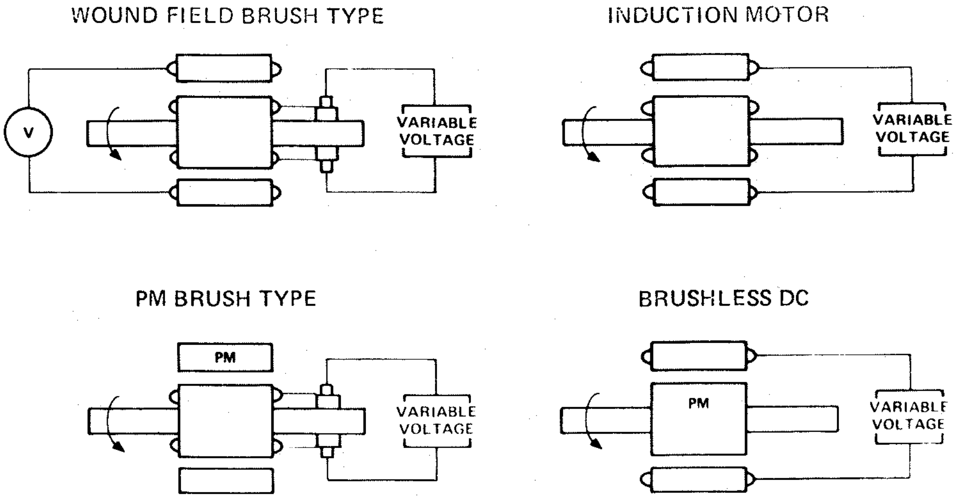

Figure 6. Motor Designs

performance EM actuation unit need high voltage DC. A value of 270 volts DC was then established as an arbitrary value for the power supplied to the motors in the actuation unit. This value is roughly equivalent to the full rectified value of the previously specified AC power and has been used by the U.S. Navy in their studies of high voltage DC power systems.

Given a 270 volt power supply, then how is the choice made between a wound rotor induction motor and a permanent magnet inside-out brushless DC motor for this application. There is little doubt that what tips the balance decisively toward the permanent magnet rotor is the single greatest breakthrough in electric motor design in recent history, the emergence of the rare earth samarium cobalt permanent magnets. The advantageous properties of these magnets have been widely extolled in the literature and have particular significance for electric motors that are to be used as servomotors, i.e., motors for EM actuation. Figure 7 helps to give insight to their value, along with a corresponding equation for the torque of an electric motor.

$T_m = K\ p\ L\ R\ F_r\ F_s \sin \delta_{sr}$ where:

T_m = motor torque

p = number of poles

L = motor length

R = rotor radius

F_r = airgap MMF from rotor

F_s = airgap MMF from stator

δ_{sr} = angle between stator and rotor airgap fields

K = proportionality constant to include other geometry factors

Now (F_r) is a direct function of the flux that

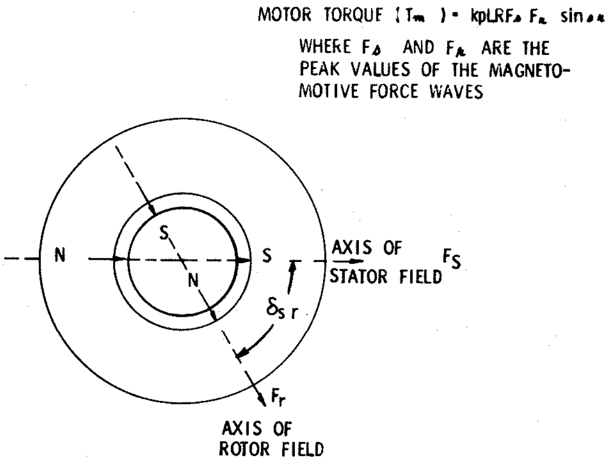

Figure 7. Motor Torque Diagram

can be stored and utilized in the permanent magnet rotor. The volume required to generate this flux and therefore the inertia of the rotor shrinks considerably, when compared to any form of a wound rotor motor, when the rare earth samarium cobalt magnets are used. The reasons for this are summarized.

(a) The tremendous useful flux of the rare earth samarium cobalt magnets. Extremely high resistance to demagnetization.

(b) All (I^2R) losses are transferred from the rotor to the stator where they can be more easily dissipated.

(c) More room is available in the stator for larger conductors to further minimize (I^2R) losses.

The net result is servomotors with much higher (T/J) (torque/inertia) and (T^2/J) (torque^2/inertia) values, and therefore acceleration capability, for a given motor diameter than is realizable with any form of a wound rotor motor.

Good discussions of the value of the T^2/J motor parameter are found in References 4 and 5. In general, the T^2/J parameter relates more effectively to the ability of the motor to accelerate a load instead of just the ability to accelerate itself as does the T/J parameter. Further, performance of the rare earth magnets becoming available, as most directly measured by their energy product in Gauss-Oersteds is steadily increasing. Full utilization of the inside-out, brushless, DC powered motors assumes electronic commutation. A good hint of what's involved here is a statement taken from Reference 6 where the author says "the inside-out construction of a rare earth motor with fixed windings offers an excellent opportunity to do away with mechanical commutation, providing certain electronic switching and timing problems are solved." First, we might consider why we would like to do away with "mechanical commutation." The rather obvious ability to do away with sliding contacts, brushes or slip-rings, because they have a poor reputation for long term reliability is certainly of value. What should be more appreciated, however, is what can be done after the constraints of mechanical switching are removed. A whole new degree of design freedom is opened up with electronic commutation. The dynamics of the motor and particularly servomotors can be controlled in a fashion that is simply not possible with fixed mechanical switching. This is the technique, i.e., "electronic commutation" that is unique to the actuation unit we are discussing along with the unit built by Delco Electronics for NASA, Houston. In both cases rotor position is sensed, and this position information utilized to energize three phase windings in the stator through six transistor power switches with the commutation logic. It is safe to say that both manufacturers, Delco Electronics for NASA and AiResearch Manufacturing for the Air Force, have become much more cognizant of what the phrase "providing certain electronic switching and timing problems are solved" really means. Usable rotor position information, at high speeds, is not all that easy to generate. Solid state transistors, now available, have limitations on how much power they can switch at relatively high frequencies. Troublesome problems generally related to (L di/dt) abound.

Nevertheless, the Delco Electronics unit and the AiResearch unit have made real progress toward demonstrating the feasibility of high performance EM actuation by exploiting the use of the new rare earth samarium cobalt magnets with inside-out motor design and electronic commutation. The design, fabrication, and test of the Delco Electronics unit and the AiResearch unit are fully documented in References 7 and 8 respectively. Only a very brief overview of some key design problems can be presented in this paper.

Current Limiting

It is hard to overemphasize the role that current limiting or current control must play to fully exploit EM actuation. The following is a brief overview of the problem as it relates to static performance, steady state performance, and dynamic performance in sequence.

STATIC - A discussion of current limiting in a static "load holding" sense is initiated by quoting two statements that are relevant. The first is taken from an article which appeared in the February 1975 issue of the Proceedings of the IEEE authored by Eric R. Laithwaite. Mr. Laithwaite says "Force machines, more commonly known as actuators, are generally called upon to perform tasks at very low speeds, in electro-magnetic terms. Often they may be required merely to produce pressure with virtually no linear movement whatever. In such circumstances it is clear that criteria different from those used in assessing conventional rotary motors will have to be applied. For example, at zero speed a motor has zero mechanical output and therefore both its power to weight ratio and its efficiency are zero, but this by no means implies that it is not performing a useful job."

The second is taken from a feature article that appeared in Control Engineering, October 1974 entitled "Vantagepoint - 20 Years of Control Engineering." In comparing electric motors to do actuation jobs with hydraulic actuators the authors say "The choice for the system designer revolves around the fact that, while electric motors can and do compete with hydraulics for instantaneous acceleration, they lose hands down in applications where high continuous holding force is also required in the same drive."

The first statement calls attention to some very hard-to-uproot myths that power can be effectively related to weight and that power efficiency is an "end-all" performance parameter of significance where electric motors are used for actuation. He ends with describing one of the main jobs an EM actuator is going to have to do for a primary control surface actuation, i.e., hold a static load. The second statement suggests strongly that past experience with electric motors to do this type of job has not been encouraging. Clearly some new techniques are required. The first real aid in reducing the current required to hold a static load can be visualized from Figure 8. The current required to hold static load torque (T_1) is (I_1). The voltage required to produce this current (V_1) is then obtained by controlling (reducing) the line voltage available to (V_1). The manner of controlling the voltage to the motors is also important but will be set aside for now. Thus, the amount of current flowing through the motors is limited to only that required to hold the static load. Further, the friction in the gearing, that acts to reduce the efficiency when the load must be driven, now acts in our favor. The load torque that the motors "see" when they are only required to hold the load is diminished by the same friction they must overcome when they are driving the load. This is not an argument, necessarily, for reducing the efficiency of the motor gear-train actuator on a power-out vs power-in basis but it certainly is an argument that conventional power efficiency has limited relevance to an actuation job. Depending on a particular application, the techniques described above may still be inadequate if the combination of load and time to hold that load gets too high. At least one additional "current limiting"

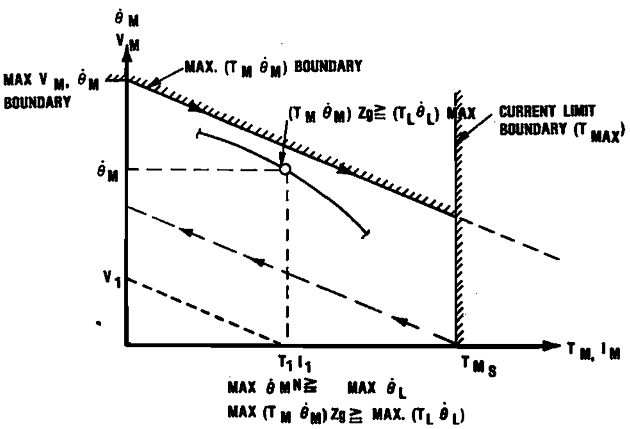

Figure 8. Motor Torque-Speed and Voltage-Ampere Considerations

technique has potential. The brakes provided on the AiResearch unit are termed "parking brakes" because they are not designed to dissipate kinetic energy. They are only designed to hold a motor locked should power fail and provide a "ground" so the remaining motor can be used. But we are not talking about kinetic energy when we consider holding a static load. Thus, both motor brakes have the potential to hold static loads that become too high and last too long and thus limit the current required. The sensor-logic circuits to do this are implementable. At least two cautions must be exercised: (1) to use the brakes in this manner will introduce time constants associated with the brake engagement and release which can be troublesome, and (2) the current required to release the brakes is not negligible. After all "there is no such thing as a free lunch."

Now the manner of controlling the voltage and thus limiting the current will be discussed. One way this could be done is shown in Figure 9a. Voltage to the motors would be simply controlled by utilizing the voltage drop across a variable resistor. The motors wouldn't really care but the people responsible for furnishing the electrical power wouldn't consider this a very effective form of current limiting. The technique used by the AiResearch unit is pulse width modulation control at constant frequency to regulate "average voltage" for current limiting. The manner in which average voltage is controlled by pulse width modulation is illustrated in the geometric representation shown in Figure 9b. The means of actually implementing this capability is not simple but achievable and demonstrable.

STEADY STATE - The next step in current limiting considerations concerns the steady state torque-speed regime. An initial insight into this area can be seen by again viewing the geometric presentation of Figure 8. It can be assumed first that there is some maximum allowable current to prevent undue temperature rise in the actuator assembly which established the current limit boundary shown in Figure 8. For a given hardware configuration this also establishes the maximum available static torque at point (T_{m_s}). Proceeding left from this point (T_{m_s}), along a line that represents the torque-speed slope of the motor, the no-load axis is intercepted at some voltage level. With more voltage available, however, the no-load speed can be raised along the no-load axis to the maximum no-load speed. Proceeding right from this point, along the same torque-speed slope as before, and until the current limit boundary is intercepted establishes the steady state, (torque-speed) operating envelope of the motor. As long as the horsepower requirements of the motor fall within the envelope established these horsepower requirements can be satisfied. Without worrying about how the current limiting is actually implemented we can see the advantages. In effect, the use of current limiting has expanded the steady state operating envelope of the motor (horsepower) by allowing the use of overvoltage techniques. It is also argued that the motor is operating in the high efficiency portion of its power-out vs power-in spectrum. This argument has limitations, however, because the discussion to date has not included "acceleration"torque, a vital consideration for a servomotor. Figure 10, a simplified schematic of the control loop that must be closed, serves to emphasize the part that acceleration torque must play for satisfactory EM actuation.

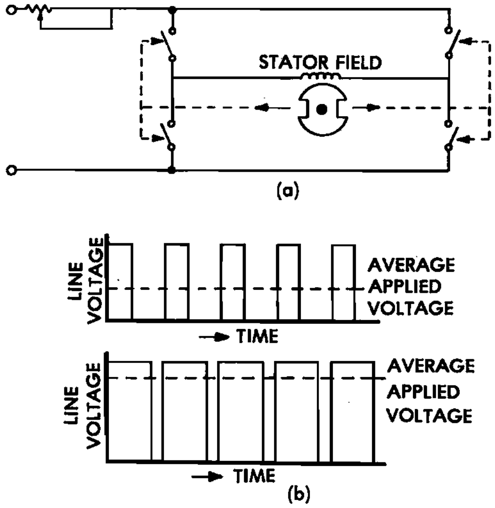

Figure 9. Voltage Control Techniques

DYNAMIC - Again referring to Figure 8, we can see that large increases in torque are available to the right of the steady state current boundary, if the large currents are restricted to short time usage. (I^2R) losses are somewhat immaterial if their time duration is short enough. This increase in torque is particularly useful to avoid acceleration saturation for high bandpass capability. One of the problems in utilizing this increased current, high torque area, however, concerns the manner in which the motors must respond to a position command change at the control surface. For a step position change, the motor(s) must accelerate to maximum speed and then decelerate rapidly to avoid excessive

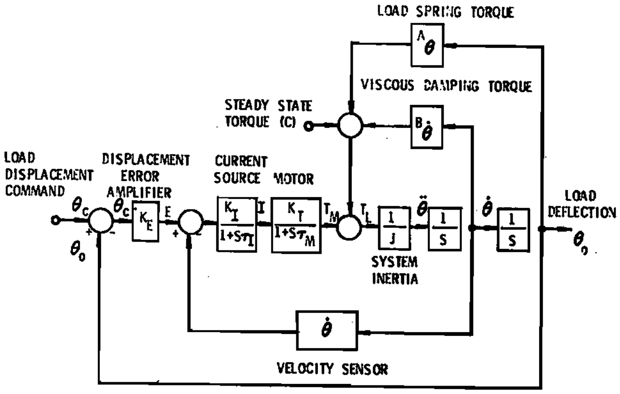

Figure 10. Actuation Closed-Loop Block Diagram

overshoot. Without going into a complete explanation, the motor power circuitry, during deceleration, now "sees" currents that are due to the sum of the line voltage and the back EMF produced by the motors. The techniques for current limiting must, therefore, be stepped up in sophistication. Further, we are no longer talking about a gradual deterioration due to temperature rise, we are talking about possible imminent failure of the power transistor switches used for electronic commutation. Finally, current limiting as it applies to the dynamic case must also be extended to include the transient (L di/dt) problems mentioned earlier.

Gear Ratio Selection

The selection of a gear ratio to best match the motors to the actuation loads is also a critical aspect of EM actuation design. A good vantage point to better understand the role of the gear ratio selection is obtained by writing the equations which relate the motor torque and speed to the surface actuation requirements through the gear ratio (N) as:

$$T_m = J_m \ddot{\theta}_L N + \frac{J_L \ddot{\theta}_L}{NZ_g} + \frac{T_L}{NZ_g} \qquad (2)$$

$$\dot{\theta}_m = \frac{\dot{\theta}_L}{N} \qquad (3)$$

where:

T_m = motor torque required

J_m = motor inertia

$\ddot{\theta}_L$ = load acceleration

J_L = load inertia

T_L = load torque

Z_g = gearbox efficiency

$\dot{\theta}_m$ = motor speed

$\dot{\theta}_L$ = surface rate

In equation (2), the first term on the right represents the motor dynamic torque to overcome its own inertia and reflect the needed acceleration at the load ($\ddot{\theta}_L$). Note that increasing gear reduction is unfavorable for this term. The second term represents the inertia of the load reflected to the motor and the third term the external aerodynamic load reflected to the motor. Note that it is favorable to increase gear reduction for these last two terms. Finally, in equation (3), increasing gear ratio is unfavorable in that it directly reduces the velocity obtained at this load. It should be evident that any fixed gear reduction must be a design compromise. Since, maximum torque for the maximum static load does not generally occur at the same time as a requirement for maximum rate or acceleration at the load, a desire for a variable gear reduction is evident. Before setting this desire aside as impractical, there are at least two possibilities that have merit for future design. One could use a variable-gearing traction drive where considerable improvements in torque transmission have been effected by using special fluids.(2) (9) The other would build the variable gearing, i.e., variable torque-speed capability, directly into the motors by further exploiting electronic commutation. With a fixed gear reduction, however, the general idea is to balance the most critical requirements in terms of an increasing or decreasing gear ratio such that maximum torque at the motor is minimized and satisfactory no-load speed is attained. One need for minimizing motor torque is self evident from viewing equation (1). In effect, selection of the best compromise for the gear ratio is another form of current limiting beyond that discussed previously, i.e., minimizing maximum motor torque minimizes maximum current. One way of establishing a gear ratio to be used is to equate the first and third terms of equation (2) for a given application and solve for the balancing gear ratio. This assumes that the second term is negligible as it tends to be for high hinge moment application. In addition to minimizing torque and current, there is also an overall desire to minimize gear ratio in the interests of reducing complexity and weight and improving efficiency. There are also limiting factors here that stem from the second term in equation (2). The "stiffness" that a geared unit presents to external forces that would excite the control surface in an undesirable oscillatory fashion is primarily a function of the gearing. If the second term is negligible, it indicates that the motor(s) is "decoupled" from the load and less sensitive to external load disturbances. The reader is referred to Reference 10 for a greater discussion of gear ratio and its criticality than possible here.

Electromechanical Actuation Design Summary

Considerable effort has been expended to emphasize the importance of current limiting and current control as they relate to the successful development of EM actuation. The use of the inside-out design with permanent magnet motors is really the first big step forward in current limiting and current control. Current is controlled by the basic design such that it is limited to flowing in the stator and, therefore, greatly enhances the thermal characteristics for actuation application. See Reference 11 for an interesting basic discussion of inside-out design. The importance of current limiting and current control as it relates to satisfactory static, steady state, and dynamic actuation application was emphasized. Finally, the point was made that selection of a gear ratio to minimize maximum torque is really an exercise to minimize maximum current. From here it should be a short step to say that we really can't isolate current limiting and current control from voltage control and that we are really emphasizing power control. Power control such that the thermal tolerance of EM actuation can be expanded while still providing satisfactory signal response capability. Power control such that the demands on the aircraft power supply can be limited to the minimum necessary. In his book "Cybernetics", Norbert Wiener made a succinct observation that is relevant to the further development of EM actuation. He says, "There is in electrical engineering a split which is known in Germany as the split between the technique of strong currents and the technique of weak currents, and which we know as the distinction between power and communication engineering. Actually, communication engineering can deal with currents of any size whatever and with the movement of engines powerful enough to swing massive gun turrets; What distinguishes it from power engineering is that its main interest is not economy of energy but the accurate reproduction of a signal."

The relevance of the Wiener quotation, perhaps in a backhanded manner, is that the development of high performance EM actuation cannot allow divorcement of "economy of energy" from "accurate reproduction of a signal." Power control must be integrated with signal control. The first big step forward has been taken with the inside-out motor design through the use of the samarium cobalt permanent magnets. Further improvements are awaiting the full exploitation of electronic commutation as it involves solid state power switches, microprocessor control logic, sensing for that logic, and almost surely new motor pole structures. The "brushless" motor is in approximately the same stage of development as the "horseless" carriage was fifty years ago.

EM Actuation Program Generation

The above summarizes the progress and problems of EM actuation development as they were viewed in early 1979. It had become increasingly evident that although real progress had been made in establishing basic credibility on an individual, typical flight control actuation basis, far stronger motivational forces were required if development into actual operational capability was going to occur. In particular, the intuitive concept that removal of hydraulics could lead to many benefits, needed to be tested on the most factual basis possible. Accordingly, two U.S. government sponsored programs were launched, one by USAF and one by NASA to evaluate total system impact if all actuation is done electrically instead of hydraulically. Both programs could be characterized as emphasizing a premise which would state, given electromechanical actuation is feasible, what happens to the total aircraft secondary power system and what are the benefits that could be expected if hydraulics are removed. A secondary portion of these programs would necessarily extend examination of electromechanical actuation for functions other than flight control. Removal of hydraulics from aircraft involves the extrapolation of EM actuation into many functions other than flight control such as landing gears, extension and retraction, nose wheel steering, guns, brakes, etc. The ground rules for the USAF funded study were (1) Conduct a trade study between a power-by-wire (electrical) actuation airplane and one that retains an engine driven hydraulic system for actuation (2) Use an advanced fighter concept as the point of reference airplane on which the trade study is conducted (3) Consider an airplane to be proposed in 1990 as the time frame of reference (4) Include other systems such as environmental control systems as they become relevant to the basic trade and (5) Assess the trade on the basis of performance, reliability, maintainability, weight, life cycle costs, growth potential, survivability, and environmental constraints (6) Assume a fly-by-wire control system as common to both trade study airplanes. The NASA study is similar but concentrates on the commercial-civil aircraft sector. Both programs have been underway since mid 1979 and some preliminary data is reported here.

USAF Airplane Actuation Trade Study Program

This program has over a year to go and is under parallel contracts to Rockwell International and the Boeing Company. These programs are jointly funded by the Flight Dynamics Laboratory (FDL) and the Aero Propulsion Laboratory (APL).* No type of direct comparison data has yet been developed between the conventional hydraulic powered airplane and the all-electric airplane because the program is geared to emphasize the best design basis possible before the comparison is made. At least one significant data point has been generated, however, that is summarized in Figure 11. Figure 11 clearly illustrates the impact that can occur on both the amount and type of electrical power required if the secondary power system is unified under one type of power (electrical) as compared to conventional design. Conventional design in this case includes both hydraulic actuation and engine bleed

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*On 15 January 1980, the four major laboratories at Wright-Patterson Air Force Base were consolidated under one organization which is now titled the Air Force Wright Aeronautical Laboratories (AFWAL). The designation of each laboratory was then changed to remove the Air Force prefix. For example, the Air Force Flight Dynamics Laboratory (AFFDL) became the Flight Dynamics Laboratory (FDL).

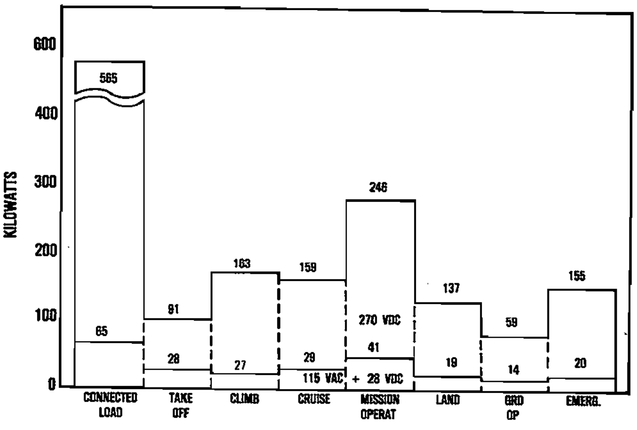


Figure 11. Electrical Load Profile

air for environmental control systems. Reference 12 includes some good discussions of the reasons for considering other than bleed air for environmental control. The electrical power required for a conventional secondary power system during the mission for this type of airplane is shown in the lower vertical boundary as either 400 cycle 110/208 AC or 28VDC power. The maximum amount of power required during the mission is projected as 41 KW. Now, the assumption is made that all actuation will be done with electrical power and further engine bleed air will be minimized by using electrical power for environmental control. The maximum amount of power required for the mission now jumps to 246 KW or roughly six times as great. Further, the additional power from 41KW to 246 KW is shown as 270 VDC. The reason for this is that it can be shown that the power control techniques required for efficient EM actuation better utilize high voltage DC power. The impact on the electrical power generation and distribution system can now be summarized. The amount of electrical power generated for the all-electric concept is greatly increased with subsequent increase in the size of the generators. The long standing sizing mismatch between the generator and its potential use as a starter-motor for the engine has been greatly reduced if not eliminated. The need for high voltage DC at the actuators suggests that it might be better to convert the electrical power to DC at the generators and distribute it as DC than to require each actuator to convert the conventionally supplied AC to DC. Certainly, it would seem that if 270 volt generation and distribution systems have merit within the context of airplanes using conventional hydraulic actuation, then an all-electric aircraft greatly amplifies this merit. The step increase in generator size would also seem to stimulate the development of the samarium cobalt permanent magnet rotor generator designs to minimize weight and space of these larger generators. Generally speaking, the technology of what is good for the motors in EM actuation is also good for generators.

Further stimulation of the permanent magnet solid rotor starter-generator capability occurs from the increased locational freedom with respect to the engine when combined with the all-electric airplane concept. Divorcement from the conventional assessory section module with hydraulic pumps, separate starter, ECS bleed, etc. allows consideration of a mounting as shown in Figure 12. Another possibility that is heavily tied to the above technology would mount the generator-starter rotor directly on the engine shaft as shown in Figure 13.(13) Reference 14 concerning this internal mounting is an interesting paper to review in light of the all-electric aircraft concept and the advances in technology since it was presented in 1972. A further item of significance is the growing embracement of electronic fuel controls by the propulsion people and their need for ultra-reliable power supplies. It would appear that this could offer a high degree of motivation to develop an ultra reliable engine shaft electrical generator.

NASA - Houston Program

This program is funded through the NASA-JOHNSON SPACE CENTER and is officially titled, "Application of Advanced Electric/Electronic

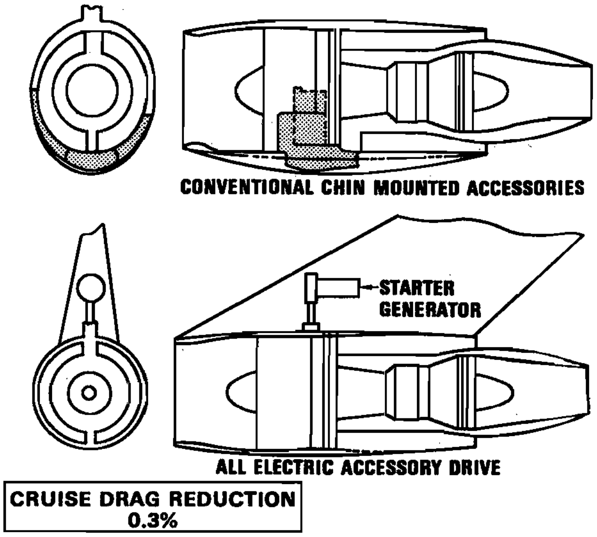


Figure 12. Remote Starter-Generator Location

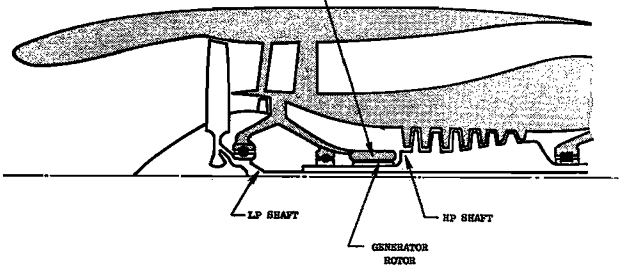


Figure 13. Engine Shaft Starter-Generator

Technologies to Conventional Aircraft." The prime contractor for the study effort is the Lockheed-California Company with support from the Lockheed-Georgia Company, AiResearch Manufacturing Company and Honeywell Incorporated. A separate company-funded investigation of an all-electric transport had been completed earlier by the Lockheed-Georgia Company.(15) The NASA study concerns application of the various electric/electronic technologies to three different classes of airplanes as indicated by Figure 14. The greatest emphasis during the study has been given to the Advanced Transport Airplane (ATA) or roughly an advanced version of the L-1011 airplane. Figure 15 then represents the equipment weight reduction increments that are considered achievable by employing technology items 1 through 6 on an L-1011 type aircraft. The eye-catching weight reduction item is the projected weight reduction of 4580 pounds accruing from converting to an all-electric airplane. An insight into how this weight reduction is achieved is illustrated in Figures 16 and 17. The most significant effect of utilizing electromechanical actuation on airplanes, however, is the message conveyed by comparing Figure 18 with Figure 15. Few comparisons could better convey the futility of considering EM actuators vs hydraulic actuators on an actuator by actuator basis. EM actuation, if good, is good because of the changes it permits in the total aircraft secondary power system, not because it is a better actuator in the conventional comparison sense.

Other Significant Developments

The Air Force and NASA-Houston study programs, when completed, should give a far greater insight into the pay-off potential of an all electric airplane than is now available. Final report documentation of the NASA-Houston study will be available in the latter portion of 1980 and final report documentation of the Air Force funded study will be available in early 1982. In the meantime other efforts to investigate the feasibility and potential of an all electric airplane are worthy of mention. The Boeing Commercial Airplane Company has mounted a substantial effort over the last two years within their own IR&D funding to examine the potential cost savings of an all electric airplane and to initiate the development required to achieve it. The development effort they have conducted towards utilizing a 270V dc electrical power generation and distribution system as a basic feature of an all-electric airplane is thought particularly significant.(16) (17) They also plan to flight test EM actuators on the NASA Quiet Short-Haul Research Airplane (QSRA) in 1980. This Quiet flight test program will replace two of the four hydraulic actuators now being used to actuate the spoilers on the QSRA airplane and will, therefore, give a direct comparison with the existing hydraulic actuators. Another development is important. For reasons beyond detailed discussion here the Space Shuttle program is again taking a hard look at eventually replacing their present hydraulic actuation system with either a different hydraulic actuation system concept or removal of hydraulics entirely and replacement with electromechanical actuation. The latter

		ATA	SHORT HAUL 50	SHORT HAUL 30
①	CONVENTIONAL TECHNOLOGY	✓	✓	✓
②	DIGITAL FBW	✓	TBD	NA
③	MUX + ②	✓	✓	✓
④	RLG INTEGRATED SENSORS + ③	✓	NA	NA
⑤	INTEGRATED DISPLAYS, FMS, ACS, ADC + ④	✓	✓	✓
⑥	ALL ELECTRIC AIRCRAFT + ⑤	✓	✓	✓
⑦	ALL ELECTRIC AIRCRAFT + LOAD MANAGEMENT + ⑥	✓	✓	✓
⑧	FIBER OPTICS	✓	✓	✓

Figure 14. Technology Application

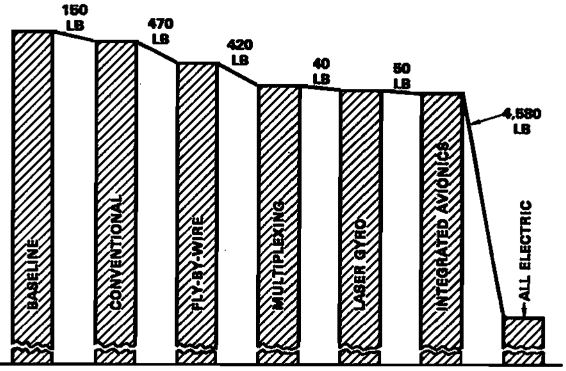


Figure 15. Equipment Weight Trade-Offs

FEATURES

- **ELIMINATES**
  - ✓HYDRAULICS
  - ✓ENGINE BLEED
  - ✓PNEUMATICS
  - ✓SEPARATE START SYSTEM
  - ✓COMPLEX MECHANICAL CONTROLS } FCS
  - ✓HYDRAULIC SYSTEM } FCS
  - ✓HOT BLEED DUCTS } IN ENGINES, PYLONS AND WINGS
  - ✓H. P. HYDRAULIC LINES } IN ENGINES, PYLONS AND WINGS
- **REDUCES**
  - ✓ACCESSORY POWER PROVISIONS
  - ✓THRUST LOSSES } IN ENGINES
  - ✓SFC PENALTIES } IN ENGINES
  - ✓ENGINE WEIGHT
  - ✓OEW
  - ✓COMPLEXITY OF SPS INSTALLATION

Figure 16. All-Electric Airplane

		L-1011	ALL ELECTRIC
HYDRAULIC PUMPS	ENGINE	4	0
	AIR TURBINE	2	0
	ELECTRIC	2	0
	RAM AIR TURBINE	1	0
	POWER XFER UNITS	2	0
ELECTRIC GENERATORS	ENGINE	3	3*
	APU	1	1
	BATTERIES/INVERTERS	2	2
BLEED	ENGINE-ECS PACKS	3	3
	APU COMPRESSOR	1	0
	ENGINE STARTERS	3	0

*GEN/STARTER

Figure 17. Components of Conventional vs. All-Electric Airplane

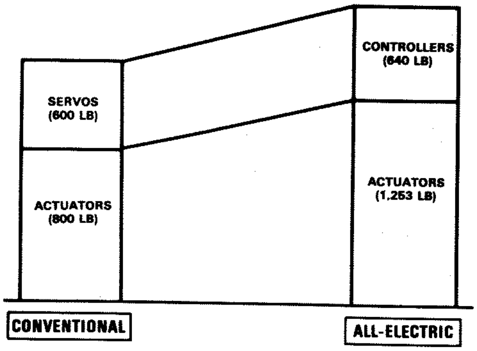
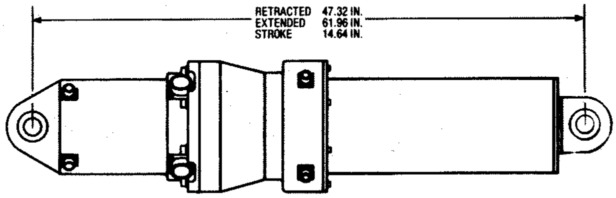


Figure 18. FCS: Actuators and Power Servo Weights - Conventional vs. All-Electric



CHARACTERISTICS

- Quad redundant motor; brushless PM, rare Earth magnets
- Quad redundant rotary position sensors
- Quad redundant linear position sensors
- Force: 50,100 pound minimum at stall with two faults
- Rate: 7.84 inch/second minimum at 19,000 pound force with two faults
- Power: 270 vdc
- Cooling: passive mass heatsink

Figure 19. Honeywell-Inland Actuator

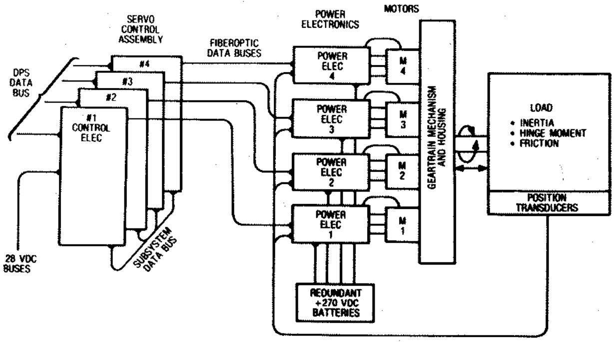


Figure 20. Actuation Unit Functional Concept

possibility has encouraged the development of a new electromechanical actuation hardware unit that can be at least as significant as the AiResearch and Delco Electronics units discussed earlier. This actuation unit is designed as a drop-in replacement for the present Space Shuttle elevon hydraulic actuator, is therefore a linear actuator, and is being designed, fabricated, and tested as a joint effort by Honeywell Inc. and the Inland Motor Division of the Kallmorgen Co. Figure 19 illustrates the physical actuator and its main requirements as they relate to the elevon actuation. Commonality with the AiResearch and Delco Electronic actuators discussed earlier include use of samarium-cobalt inside-out electric motors, electrically commutated, and powered from a 270 volt DC power supplies. The unit will feature 4 separate power channels as well as 4 separate signal channels and introduces a new redundancy summing concept for the power channels. See Figure 20. Unlike the AiResearch and Delco Electronics actuation units which sum the mechanical output of each motor in a differential velocity summing manner, the Honeywell-Inland actuation unit uses a four channel force summing concept. Perhaps even more important is the manner of force summing. Instead of force summing the mechanical outputs of each of the four motors with a common mechanical carrier, the magnetic torque produced by each of the four motor windings will be directly summed on a common mechanical drive member. An immediate advantage is the elimination of the clutches or brakes that are normally associated with mechanical summing in either the "force" or "series" techniques. Another feature of the Honeywell-Inland Motor actuator which will be watched with interest and is a direct result of the new degree of design freedom opened up with electronic commutation concerns energizing the motor(s) windings in either a series or parallel fashion. In effect, this allows a change in the motor(s) characteristics (variable gearing) from a high speed-low torque machine to low speed-high torque machine for better adaptation to the varying mission requirements. See Figure 21. Preliminary negotiations are underway to test this actuation unit at the Flight Dynamics Actuation Test Laboratory in mid 1981. The primary test fixture that would be used for this testing is shown in Figure 22 and has been used extensively to test hydraulic actuators of similar size and capability to the Honeywell-Inland actuator.

Continuing FDL EM Actuation Programs

The AiResearch EM actuation unit discussed earlier is being utilized for further development and testing. Major improvements have been made with higher power handling transistor switches and more refined current limiting techniques to more than double the original motor(s) torque. Thermal tests for representative duty cycles along with tests designed to explore the sensitivity to variations in the DC power supply were conducted on the improved unit. Results from both types of tests were favorable with a particularly good demonstration of insensitivity to variations in the DC power supply. The performance period for this follow-on effort was from early 1979 to early 1980 and is reported on in Reference 18.

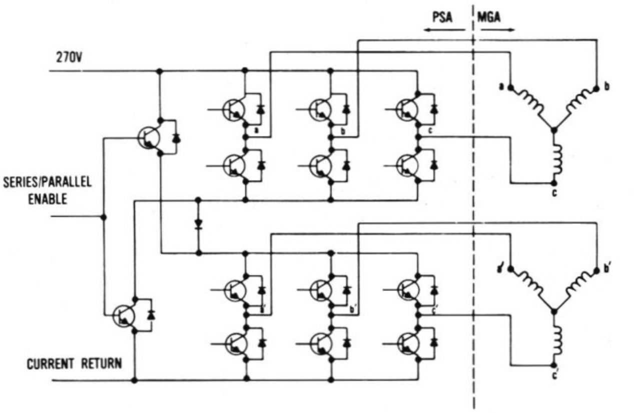


Figure 21. Series-Parallel (Variable Gearing) Provisions

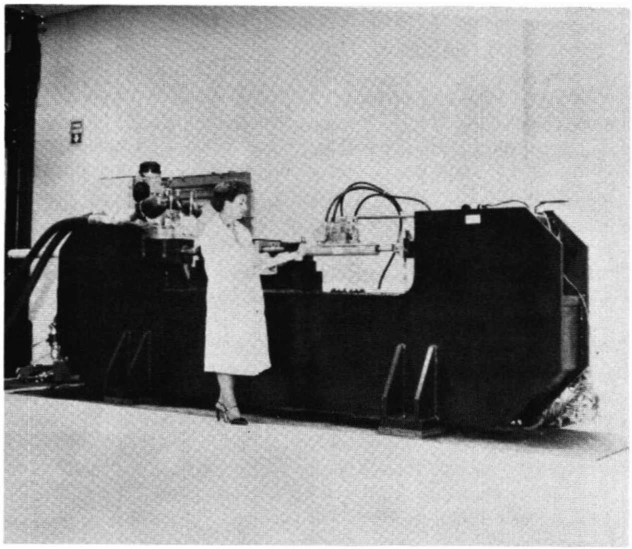


Figure 22. Flight Dynamics Laboratory Actuator Test Fixture

A further developmental effort is planned to start in July 1980. The main emphasis for this effort is improved stability at higher closed-loop gains and better failure mode characteristics. The increases in motor(s) torque obtained from the 1979 effort tended to aggravate the actuator positioning stability and rigorous design to reconcile the dual channel normal operation with satisfactory failure mode characteristics has hitherto been set aside in favor of other developments. Satisfactory demonstration of solution to these two problems should go a long way towards establishing the confidence required for flight testing an EM actuator on a critical high performance control surface.

In addition to the FDL EM actuation programs aimed directly for application to manned aircraft, an FDL program is underway to further develop EM actuation for missiles. EM actuation has had great success in removing the need for hydraulic systems on missiles with the use of rare earth samarium cobalt permanent magnets. Hitherto, however, the motors used in these missile actuators have placed the permanent magnets in the stator and employed conventional brush commutation with wound rotors. The FDL program, now under contract to Lear-Siegler, Maple Heights, Ohio, will develop a missile EM actuator that features motors with a permanent magnet rotor and electrical commutation for better thermal properties. Testing of the Lear-Siegler actuator is scheduled to start in mid 1981.

Concluding Remarks

Combining Power-By-Wire (electrical actuation) with Fly-By-Wire (electrical signal transmission) in the all-electric aircraft has tremendous synergistic implications that can only be satisfactorily understood by instituting the complete top-down unified all-electric systems design approach that it represents.

As we try to consider all factors relating to the future credibility of the all-electric aircraft, technology developments exterior to the aircraft domain must not be overlooked. At long last, there seems to be increasing commercial interest in the development of better solid state power switches, i.e., higher performance - lower cost which are so vital to the power conditioning and handling that would be required on an all-electric aircraft.(19) The electric car appears to be a future necessity that is on the way and which can exert tremendous economic pressure to improve the cost/performance ratings of present electronic/electrical components. Even before or without the electrical car, a recent article states, "The state of automotive engine control sensor art is the pacing factor in the introduction of micro-computer-based engine controls. During the 1980 model year, some 25% of the world's automobiles will include at least one electronic engine control loop. By 1983 that figure will surpass 50%, and the sensors which provide signals to those electronic controls will be produced in multi-million-per year quantities."(20) The article goes on to point out that the most important sensor required is crankshaft position. These developments become important when you consider that rotor position for commutation of an inside-out permanent magnet motor is one of its most troublesome components. Both the performance and the environment of an engine crankshaft position sensor are comparable to the use on the motors now being used for electromechanical actuation. As an aside, a recent inside-out electronically commutated motor has been developed which controls motor speed-torque characteristics effectively without a discrete rotor position sensor.(21) All of these items relate effectively to what, in the author's opinion, is the biggest driver by far to bring the all-electric airplane into existence, reduction of costs. A primary output of both the NASA studies and USAF studies that is yet to be completed will be projection of cost benefits and particularly life cycle cost projections. By the time the NASA and USAF studies are completed, a much better potential benefit/feasibility picture will emerge, not only because of those studies, but because of many other related activities. At the moment the hard evidence required for the "supportable design change decision" mentioned in the introduction is not yet here. Let there be no mistake, however, there is a rapidly rising interest in the development of the all-electric airplane and all the technologies it represents including EM actuation.

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