HYDRAULIC ACTUATOR REPLACEMENT USING ELECTROMECHANICAL TECHNOLOGY

SCOPE

This white paper discusses several issues encountered by Lee Air with past projects that involved the replacement of Hydraulic Actuators with Electromechanical Actuators.

HISTORIC OVERVIEW

With the development of powerful rare earth magnetics, electromechanical actuators became much lighter and more compact. This development was further spurred on with the availability of digital motor controllers, which allow DC motors to operate with extreme positional precision and speed control but without the use of commutator brushes. Removal of commutator brushes provides a substantially improved motor life. These changes have caused the Aviation industry to move away from Hydraulic Actuation and into Electromechanical Actuation.

Hydraulic actuators in their simplest form have one of the lowest parts counts of any actuator assembly. Typically, a hydraulic actuator will have a bill of materials that will have between 10 and 20 parts, while electromechanical actuators have a bill of material from 30 to 40 parts. However, in determining the functional reliability of the actuator, the total system must be considered. In this process the weakness of hydraulic actuation is exposed. Typically for hydraulic aircraft applications there will be:

- One hydraulic pump
- One accumulator
- One set of servo controls
- One set of hydraulic lines
- Hydraulic line fusing (for critical applications)

This will generate a parts count that will be 5 to 10 times that of the actuator itself. This normally results in a system with multiple single point failures. To improve the reliability of the “actuator function” a second complete set of duplicate hardware is normally required. This is usually accomplished with multiple independent hydraulic systems or by an alternate means of actuation.

Maintenance on hydraulics is also an issue as eighty percent of all hydraulic systems are removed for seal leakage. In short, while the actuator itself is extremely simple in concept, the practical delivery of the hydraulic “actuation function” normally requires multiple independent systems. This negates the simplicity of the actuator itself, since it represents only a small part of the total hydraulic system.

WEIGHT REDUCTION

The primary reason the Aircraft Industry moved away from hydraulic actuation and into electro-mechanical actuation is the reduction in overall systems weight. In a case study completed for a small business jet. The weight of a full hydraulic system for landing gear actuation was compared to an electromechanical system. The weight savings for a 28VDC system was 15 pounds over the hydraulic system with tubing and actuators. For the electromechanical system the weight was 24 pounds as compared to 39 pounds for the hydraulic system. This represents approximately a 40% weight saving for the employment of electromechanical actuators.

MAINTENANCE

The highly modular electromechanical system can be repaired with the "remove and replace" of the actuator. This is often only 2 bolts and a connector. Troubleshooting is reduced to looking for the component that is not moving. The system does not have to be checked for:

- Seal leaks
- Hydraulic contamination
- Power pack failure
- Correct pressure

The electromechanical system does not require bleeding or replacement of the fluid, and will not spill oil in the hanger when the system is opened.

Overall maintenance is performed only "on condition" for the electromechanical actuators. The landing gear actuators mentioned in the weight example were designed for an operational life of 20,000 cycles and were tested to 40,000 cycles for qualification. Demonstrations of 60,000 cycles were routine. For the example discussed in Section 2, the actuators were generating approximate 1500 pounds of force during retraction and provided a smooth and constant velocity during extension. Cycle counts of over 1 million cycles are common for actuators operating at lower loads.

For hydraulic systems periodic maintenance is a requirement. These systems require fluid replenishment as a routing service task. All tube fittings will require periodic inspection. Fluid levels usually are checked prior to each flight. Our experience has shown that the "maintenance hours" saved for conversion to electromechanical systems is better than 50%.

SYSTEM LEVEL BANDWIDTH

Electromechanical actuators normally have a higher system level bandwidth when compared to hydraulic systems. A higher bandwidth can be achieved due to the rigidity of the electromechanical design. With hydraulic systems, typically the supply line compliance will reduce the system bandwidth. However, with electromechanical systems because of the direct "metal to metal" contact of the drive train components bandwidth is limited by the motor power. Typical electromechanical systems have a bandwidth between

10 and 12 Hz. This would compare to a similarly sized hydraulic system, which would run at 8-10 Hz. Higher bandwidth means more accuracy in the servo control function can be obtained at a lower weight. These terms are subjective generalizations and highly dependent on detailed design but in general in comparing two systems of equal weight the hydraulic system will have a lower bandwidth and will tend to offer the designer less precision with respect to positional accuracy.

Boeing's 787 uses electrical actuators for its brakes. They provide higher dispatch reliability, better performance, modularized line maintenance, superior wear and "on condition" maintenance. The improved performance and superior wear characteristics point to the higher bandwidth control advantages that electrical systems offer over hydraulics.

ENERGY CONSUMPTION

Another common reason for the use of electromechanical systems is energy utilization. Electromechanical systems are more efficient and use less power than hydraulic systems for similar force gradients. This is due largely to the pump efficiency and the frictional, orifice, line losses for high-pressure hydraulic transmission. With electromechanical systems, motor efficiency is 87% to 95%. Gear drives and ball screw efficiencies are over 90%. Typically, in hydraulic servo control applications fluid must be passed around the spool valve to maintain positional stability. The requirement for fluid leakage in order to maintain a stable control function uses energy. (Motors must also use energy to generate a holding force but power consumption tends to be lower than fluid systems provided motor thermal issues are addressed.)

GM estimates that they saved 2.5% of their fuel consumption by going away from hydraulic power steering to electric power steering. The German manufacturer ZF Lenksystems estimates that 90% of the power consumed by a hydraulic steering system can be saved by converting over to electric steering.

FAILURE & HAZARD ASSESSMENT

Hydraulic systems have been used for primary flight control systems for nearly a century. They have matured in design to offer high reliability. However, this reliability is normally achieved through system redundancy and failure handling modes of operation. Modern electromechanical actuators for flight control functions have seen extensive development in the UAV segment of the market, where weight restrictions are even more critical than in manned aircraft.

Both hydraulic and electromechanical systems will be required to meet either a DAL (Developmental Assurance Level) "A" for primary flight controls or DAL A, B or sometimes C for secondary flight controls (flaps, trim actuators and often spoilers and lift dump). The DAL levels are associated with a functional reliability requirement imposed on the hardware.

DAL	Reliability Requirement	Comments
A	10^{-9} Catastrophic	This is one failure in 1 billion flight hr.
B	10^{-7} Hazardous	This is one failure in 10 million flight hr.
C	10^{-5} Major	This is one failure in 100 thousand flight hr.
D	10^{-3} Minor	This is one failure in 1000 flight hr.

Table 1: Explanation of aircraft reliability assessment

Typically, primary flight controls and weapons release hardware are deemed as being Catastrophic if they fail because they could result in loss of life or vehicle loss. As an example, loss of elevator control on fixed wing aircraft is normally considered Catastrophic.

If the failure only affects the vehicle's mission or if injury to a person could occur or if damage to the aircraft may result, then a Hazardous classification is levied on the hardware. Landing the aircraft without wheels is often ruled a Hazardous condition.

Major is applied to failures that make the crew's work load increase but do not cause either vehicle damage or loss of mission capability. An example might be the failure of a single panel in a four-panel wing spoiler system.

Minor is applied to failures that have little or no effect on the vehicle, crew or the mission. Failure of a non-essential system is normally considered a Minor failure. This might be a failure of the air conditioning system under temperate operating conditions.

The highest rating that can be handled by a "single thread" system, which is a system that does not have any alternate means for meeting the functional requirement, would be a system that has a failure rate of 10^{-5} or Major. Typically, a single simple hydraulic actuator or electromechanical actuator will be able to support this requirement. However, for primary flight controls or secondary flight controls a second means of meeting the functionality must be utilized. These types of systems usually require a DAL level of A or B. This may be a dual actuator design or it may be a dual motor and drive system. It must have some alternative means or failure mitigation must be in place to comply with a 10^{-9} or 10^{-7} reliability requirement. These requirements are true for both hydraulic systems and electromechanical systems.

One of the major advantages for the conversion to electromechanical actuators for critical applications is that much of the infrastructure for a dual redundant system is already in place. The electromechanical actuators have digital processing capability as part of its motor controller and the electrical system itself is a dual power source (battery and generators). This makes setting up a dual redundant system much simpler as compared to a hydraulic system. The hydraulic system will likely have to add some level of electrical control and is likely to be translating electrical power into hydraulic power. If engine power is used to drive the hydraulic pump a large and heavy gearbox must be used. Both of these hydraulic design approaches require the addition hardware weight and electronics, which result in higher overall costs.

In general, then we will conclude that it has been our experience that electromechanically systems are not only lighter in weight as covered in Section 3 of this white paper but also tend to have a lower cost point for the delivered function. These savings are difficult to quantify as a general statement but typically our experience has shown that costing savings for an electromechanical system will be between 15% and 20% as compared to a total hydraulic systems cost.

SYSTEM INTEGRATION

Not only is there a noticeable cost savings with the utilization of the electromechanical actuators but there is also an improvement in systems integration time. Our experience has been that this savings in design time can be attributed to 4 factors:

1. Wires are much easier to position as compared to hydraulic tubes because of the flexible nature of wires. Tubes require a precision to mate with the structural mounting provisions that wires do not need. Wires and their associated harnesses can be twisted and bent for ease of assembly and hardware mounting can be less accurate. Last, wires are not inclined to resonate in operation as do hydraulics. For example the first F-14 prototype was lost due to hydraulic line resonance.

2. Most vehicles today make use of extensive wire harnesses. The addition of a few more wires into any given harness is normally a simple task when compared to the separate routing that hydraulic lines require. Particularly, when considering that hydraulic lines are transmitting a flammable fluid, which can leak and damage other vehicle components and may present a fire hazard.

3. Hydraulic components often require the design and integration of drain system for abnormal conditions such as reservoir overflow.

4. Hydraulic components often impose orientation and access requirements for service and inspection. This often limits the location of key components to accessible bays or cutouts in the skin for sight glasses that can be seen during a walk around inspection.

CONCLUSION

Hydraulic actuation and systems design is well understood. However, it has been Lee Air’s experience that overall the benefits of using electromechanical systems particularly for lighter systems loads cannot be underestimated. Electromechanical systems offer; better weight factors, lower maintenance requirements, improved system performance, ease of design, higher reliability and an improved price point when compared to comparable hydraulics systems. These are the main reasons that vehicle designers are shifting towards this technology.