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Investigation of Linear Motors as Electric Actuators for Aircraft

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**Please note that competitively sensitive proprietary information was removed from various portions of the paper before this publication.*

***Abstract* – The commercial aircraft industry has been moving towards more electric aircraft in recent decades, engineers have evaluated existing hydraulic and pneumatic powered systems for conversion to electrical power. This paper describes whether a Thrust Reverser Actuation System (TRAS) could be improved by using linear motor actuators (LMAs) instead of hydraulic or electromechanical actuators. Three different LMAs were designed using Synchronous, Induction, and Switched Reluctance motor technologies. This paper compares the performance and weight of the three systems at the worst case design load condition. Also, current aircraft systems were evaluated to determine what changes would be needed to support a linear motor TRAS (LM-TRAS) and opportunities were found. The results showed that a synchronous or induction motor could meet the required loads with various weight and integration penalties to be considered.**

***Index Terms* – Linear Motor, Direct Drive Motor, Electric Actuator, Thrust Reverser Actuation System**

I. Introduction – The Operation of The Thurs Reverser Actuation System (TRAS)

TRAS is part of the fan duct/thrust reverser assembly located on the aft portion of the nacelle (Figure 1). All current aircraft models at Boeing power the TRAS hydraulically with the aircraft's main hydraulic system. It is normally activated upon landing by the pilots to assist with

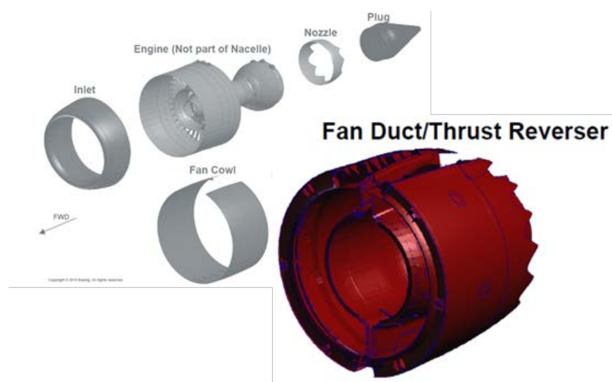


Figure 1: Typical commercial engine nacelle components and Thrust Reverser

slowing the aircraft. The thrust reverser consists of sliding cowling doors that translate aft to open the sides of the nacelle. This action also drops blocker doors into the fan duct flow path to redirect the fan flow out the side of the nacelle. The sliding cowling doors are actuated by either 4 (787 only) or 6 hydraulic actuators per engine nacelle (Figure 2). Within the actuators are acme screws that turn as the push rod extends or retracts; the screws are connected to a sync shaft through a transmission. The sync shaft mechanically connects each actuator so that they remain synchronized as a means of control. The system only actuates to fully open or fully closed, and does not require the ability to hold the stroke at an intermediate position.

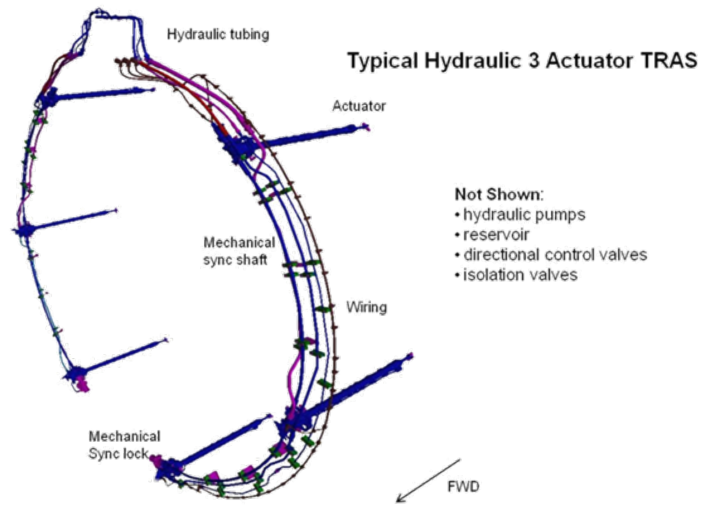


Figure 2: Typical Thrust Reverser Actuation System layout

The typical commercial aircraft thrust reverser operates as seen in the cross section view in Figure 3. At the forward end is the thrust reverser torque box structure where the actuators are mounted, it transfers the axial loads to the engine fan case. When the sliding cowling sleeve is in the closed or stowed position, fan flow travels aft ward through the duct out the nozzle providing forward thrust. When the pilot commands the thrust reverser open, the actuation system pushes the cowling sleeve aft, while a mechanical link forces a blocker door to drop into the fan flow. The fan flow is then redirected out the side of the nacelle through a series of guide vanes called cascades. The cascades steer the flow in a more forward direction, reversing the direction of engine fan thrust.

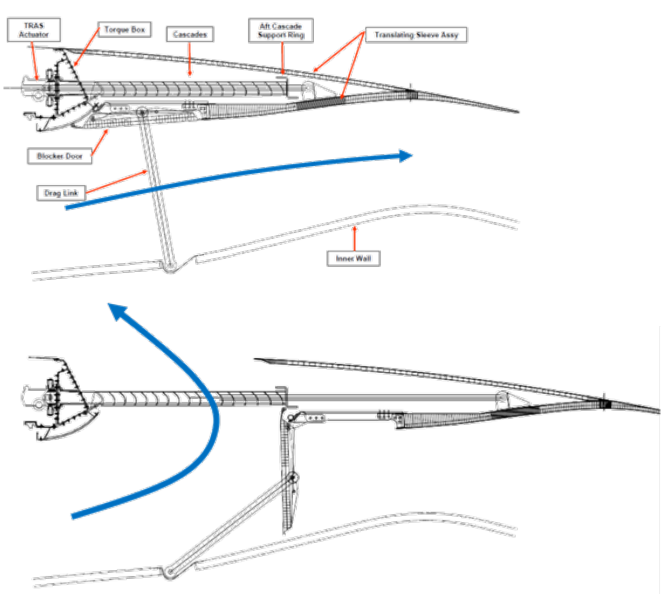


Figure 3: Cross section of thrust reverser operation in the closed (upper) and open (lower) position

Recently with the Airbus A380 and A350XWB, these aircraft use an electrically powered actuation system for the thrust reverser, commonly referred to an E-TRAS. These systems operate similarly to the Boeing hydraulic system and mostly contain the same or similar components. Table 1 compares the individual components of the electromechanical and hydraulic systems with pneumatic and linear motor systems.

Table 1: Typical major component comparison list for a TRAS

Hydraulic TRAS	Pneumatic TRAS	Electro-mechanical TRAS	Linear Motor TRAS
Directional valve	Directional valve	Controller	Controller
Isolation valve	Isolation valve		
Cylinder	Cylinder	Cylinder	Stator w/ Guide
Push rod	Push rod	Push rod	Mover
ACME screw	Ball screw	Ball screw	
Integrated Lock	Integrated Lock	Integrated Lock	Integrated Lock
Fluid tubes	Air tubes	(Wiring)	(Wiring)
Transmission	Transmission	Transmission	
Sync shaft	Sync shaft	Drive Shaft	
Sync lock	Air Motor w/ Brake	Electric Motor w/ Brake	Track lock
Wiring	Wiring	Wiring (More)	Wiring (More)

Note that only the linear motor system offers a dramatic difference in components, the other systems are nearly identical. The key changes Airbus made when switching from hydraulic to electromechanical power are that the actuator push rods contain ball screws instead of acme screws, and an electric motor drives the sync shaft that now becomes a drive shaft. Large electrical boxes serve as the TRAS motor controller rather than hydraulic directional and isolation valves. The switch from a hydraulic to electrical power source is the only significant difference between the two systems. This comparison is important because the reduction of components is usually a benefit to cost, maintenance, and weight of a system.

The concept of thrust reversers are not new to commercial jet aircraft and were used on the original Boeing 707 nacelles. Over the decades, they have been evolving through a variety of form factors with many patents documenting pneumatic, hydraulic, and electric thrust reverser actuation methods, architectures, and systems. As discussed in this paper, the concept of using linear electric motors to electromagnetically deploy and stow the thrust reverser is novel and patented by Boeing [1].

II. Linear Motor

A vast majority of electric actuation technologies used in the aircraft industry to create linear motion are of the electromechanical type. This is where an electric rotary motor turns a transmission that turns a screw or a rack to move a push rod (Figure 4).

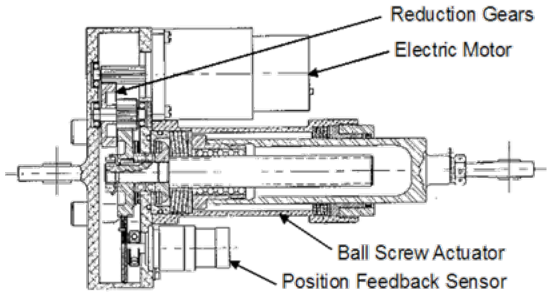


Figure 4: Typical electromechanical actuator [2]

That motor takes electrical energy and converts it to kinetic energy in the form of rotational motion which then must be mechanically converted to linear motion. There is inherent energy friction losses and wear that results from this conversion. A linear motor is often referred to as a direct drive motor because the electrical energy is converted directly to linear motion without a mechanical transmission, as shown in Figure 5.

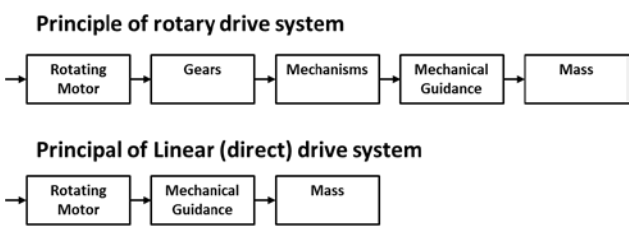


Figure 5: Comparison between an electromechanical and a linear electromagnetic (direct) drive system [2]

Visualizing a typical electric rotary motor sliced open along the drive shaft axis and rolled out flat as shown below (Figure 6) [2], provides a simple model of a linear motor. The motor still operates in the same way with the same physics, it is just reconfigured into a line instead of a circle. Since linear motors operate under the same laws and controls as rotary motors, synchronous, induction, and switched reluctance motor technologies are applicable. A key question that this study answered is: which motor technology would be preferable as a thrust reverser actuator?

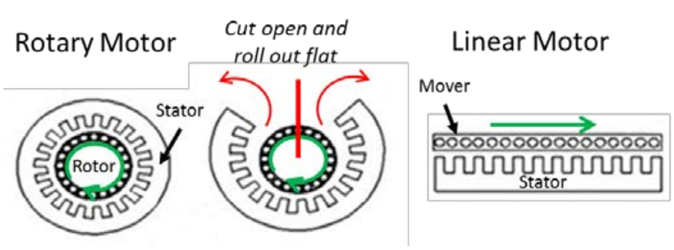


Figure 6: Simplified visualization of rotary vs linear motor

Linear motors are currently used only in limited applications. The US Navy is implementing linear motors on Gerald R. Ford-class aircraft carriers as aircraft catapults [3]. Japan is testing a high speed magnetically levitated train that relies on an implementation of a linear motor for electromagnetic propulsion [4]. Also, high speed machining companies are replacing electromechanical ball screw actuators with linear motors that are capable of higher speeds to reduce machine time that maintain the precision, but eliminate backlash and transmission wear [5]. Other applications being researched are for high speed elevators [6], robot actuators [7], and even Elon Musks' Hyperloop proposal [8] used linear induction motors as a form of continuous non-contact pod propulsion.

III. A Better Electric Thrust Reverser System

Normal operation of linear motors is in the speed range of several meters per second. A typical hydraulic TRAS actuator moves at about an average of half a meter per second, and it is a challenge for every new airplane or engine program to achieve faster system operation. A take-off field length performance analysis (Figure 7) revealed that if the thrust reverser could be deployed in 0.5 seconds, that would be equivalent to a 15% reverse thrust performance increase.

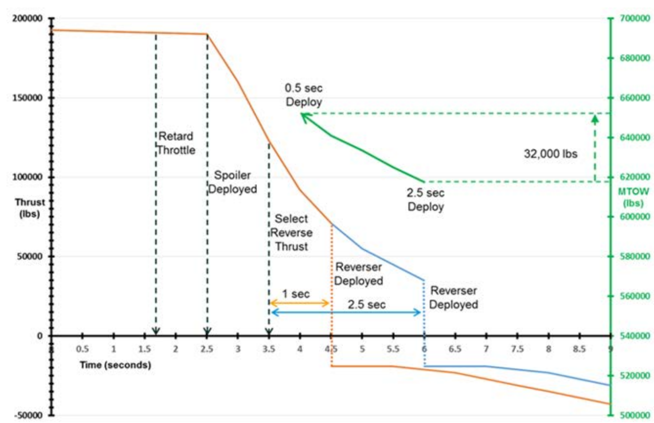


Figure 7: Thrust profile during RTO with different thrust reverser deploy times and potential MTOW benefit as deploy times decrease

For a large commercial airplane, that could mean an increase in MTOW of 32,000 pounds, or a decrease in the length of the thrust reverser. To achieve these benefits, actuators capable of averaging at least 2 meters per second over the length of the stroke would be required and linear motors are easily capable of that rate.

Linear motors are complex electrical machines, but are mechanically simple with two main parts: the translating mover and stationary stator. As shown in Figure 6, a mover translates past the stator without making physical contact. The mover can be simply supported by a slider track or guide rail. Thrust Reversers already have sliders and guide tracks, so there is potential to design an integrated motor actuator into the existing structure. This can mean fewer parts to build, install, and maintain. The simplicity of the mechanical operation and the lack of a friction drive can directly translate to less wear and tear on the structure over time.

Every electric actuator motor needs a motor controller. The controller manages the power usage and the motor phase switching. More advanced capability can be added to the TRAS by managing the actuation loads in such a way as to filter out the peak loads throughout the stroke. By reducing acceleration at high loads and increasing acceleration during lower loads, a plot of the actuation loads over the course of the stroke length could be more evenly distributed. Unlike existing hydraulic systems that have a constant speed and varying load, a linear motor TRAS is optimized for a constant load with a variable speed. That capability could enable designers to reduce the size of the actuators and the structure by reducing or removing a peak (worst case) load. Linear motors are the enabling technology for this kind of controller due to their high rate, and lack of mechanical backlash and rotational inertia, that would make rapid changes in acceleration difficult for another actuator with a mechanical drive and synchronization system. Optimized controller strategies and related design improvements have not yet been explored.

The capabilities of an electrical motor controller support improvements in system health management as well. An actuator that requires significantly more power than it typically needs could indicate a new source of friction and should be inspected. An actuator that fails to move or stops half way can trigger the controller to instantly stop moving the others to avoid damaging the structure, then send a message to the flight deck that there is a problem. The precision controllability of linear motors enables better methods of monitoring the health of the system and adapting to any failures, this helps reduce maintenance costs for the airplane.

IV. Analysis

A study was conducted to evaluate the maturity and risks inherent in practical application of linear motor actuators to a TRAS. One of the first considerations was source electrical power capability to supply the LMAs. For example, if the TRAS loads are too high such that an equivalent electrical power needed was to greatly exceed the power available, it would become the sizing requirement for the aircraft generators and a linear motor system would reduce perceived benefits. Since linear motors do not gain a mechanical advantage through gearing or pressure differentials, the output power is directly related to the input power, minus an efficiency conversion loss, until the iron stator becomes fully saturated. Thus, the power available versus power required was determined, followed by the design and performance analysis of different linear motor technologies, and qualitative application integration assessments.

The design case chosen for this study was an RTO condition. During an RTO the engine is at full takeoff power when the reverser is commanded open by the pilots, despite the engine being commanded to idle, the peak load is still higher than normal at over 8,000 pounds per thrust reverser half. The thrust reverser is deployed to help slow the aircraft along with the use of spoilers and maximum braking. Not only is available electrical power a concern, but also whether standard aircraft electrical equipment is compatible or adaptable. In other words, if a linear motor TRAS required a significant change in the aircraft's power management equipment the overall benefit to the airplane would be reduced. There would need to be minimal electrical architecture changes required to support the system for maximum value.

A power study was conducted to convert the actuation loads to Watts. The thrust reverser load vs. stroke position data was analyzed to determine a peak load and velocity assuming a constant-load/variable-speed electric system was implemented. Multiplying the actuator force by the velocity gives the Power which was converted to Watts via a 1.356 conversion factor. The analysis revealed that a thrust reverser with 4 actuators per nacelle, at a 1 second deploy rate, would require around 45 kVA per engine in electrical energy.

$$F = 3170\ \frac{ft\ lbs}{s^2} = 3{,}170\ lbf\ per\ thrust\ reverser\ (engine\ half)$$

$$V = 4.73\ \frac{ft}{s}$$

$$PF\ (power\ factor) = 0.9$$

$$P_{peak} = F \cdot V = 14{,}994\ \frac{lbf \cdot ft}{s} = 20{,}329\ W$$

$$P_{electic} = \frac{2 \cdot P_{peak}}{PF} \approx 45.2\ kVA\ per\ engine$$

The electrical load on the airplane at take-off is one of the highest demand times and there is not enough margin in the existing generators operating normally to provide that much additional power. However through electrical power management there is the potential availability for sheddable load. It is reasonable that electrical power could be redirected from non-essential systems to the TRAS to aid in stopping the aircraft faster. In addition, the electrical system is sized to be able to handle peak and shorted conditions that are over and above the steady state loading for a small amount of time. For the quick duration a linear motor TRAS would be in operation in RTO conditions, the electrical power system should have the capacity to handle an electrical TRAS load, similar to an electrical short.

The design of the motor is critical to the function of a linear motor TRAS. Since there are few off the shelf units available to analyze or scale, it was necessary to design a custom motor for the study. In reading through published technical papers, no linear motors stood out as being designed with aircraft requirements in mind. An aircraft requires a large force while keeping weight and power to a minimum. In other words, which motor can provide the highest thrust to weight ratio for the least amount of power. There are three prevalent motor technologies: synchronous, induction, and switched reluctance. It was difficult to determine qualitatively which motor type would be best as described in the following paragraphs. In rotary form the different motor technologies all appear as large cylinders with a small shaft sticking out one end. In a linear configuration each motor technology takes on vastly different sizes and shapes.

Synchronous motors, also known as stepper motors, contain permanent magnets, are known to have the best power density in rotary form, and are easily precisely controllable. However permanent magnets themselves are expensive, fragile, and sensitive to heat; it is not immediately clear whether they would survive the thrust reverser operational environment. Induction motors by comparison to the others are mechanically and electronically simple and utilize no permanent magnets. Their downside is the lack of built-in precision control (which isn't exactly necessary for a thrust reverser) and the torque at stall speed (zero velocity) goes to zero. Switched reluctance motors are considered to be the cheapest to make and also mechanically simple. They contain no permanent magnets, but can suffer from low power density and torque ripple controllability issues.

Each of the three motor technologies are distinctive which required different methods of design and analysis. Multiple configurations of each motor type were analyzed to determine the optimum configuration. Then the three optimized synchronous, induction, and switched reluctance linear motor actuators were compared as described in the following paragraphs. Each motor was designed for the same sizing condition, with the objectives of full deployment in 0.5 seconds, controlled electronic snubbing at end of travel, and minimizing weight and power required. Texas A&M University was contracted to evaluate the linear synchronous and switched reluctance motors, while BDS was contracted to evaluate a linear induction motor.

The target design space was to fit the motor within the current volume of the existing hydraulic TRAS actuator. However, shortly after exploring the motor designs it was discovered that the mover (also known as a translator or rotor) push "rod" would need to be stowed over the engine fan case which violates the original target volume. Therefore, only the actuator stator was constrained to fit within the same volume as the hydraulic actuator main body on the forward side of the thrust reverser torque box structure. When activated, the mover would extend aftward to deploy in the same location as the hydraulic actuator, but in the stowed position additional integration effort would be needed to resolve any clashes with fan case mounted systems. To move forward with the study it was assumed any interferences with systems or accessories could be relocated elsewhere on the fan case or to the engine core. The power source was specified to be 3-phase AC, but voltage and amperage was not restricted. The stroke length was stated to be 1 meter with an external load forcing function similar to a TRAS Refused Take-Off load stroke curve.

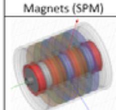
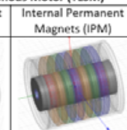
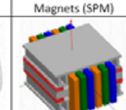
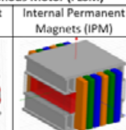
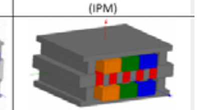
[Figure 8 and associated text have been removed from this publication for trade secret protection.]

V. Linear Motor Designs and Data

A. Linear Synchronous Motor Actuator

The Linear Synchronous Motor was designed by Texas A&M University's Dr. Won-Jong Kim and grad student Young Shin Kwon. Great effort was put into qualitatively evaluating the current state of the art in order to determine the optimum motor architectures to further analyze. Even within the linear synchronous motor design space there are many architecture configurations to choose from such as a flat or tubular shape, double or single stator, slotted or slotless, mover core with internal or surface mounted magnets, etc. The options were narrowed to five different configurations with the most potential to meet the performance and weight requirements, which were then designed, evaluated, and compared (Table 2): two tubular linear synchronous motors (TLSM) with either internal (IPM) or surface (SPM) mounted permanent magnets, two flat linear synchronous motors (FLSM) with either internal or surface mounted magnets, and one flat linear brushless motor (FLBM) with internal permanent magnets (IPM). Each configuration went through optimization of the detailed characteristics to provide the best thrust force per ampere-turn as determined by a 2D finite element analysis.

Table 2: Linear Synchronous Motor design configurations for optimization (red: magnet, grey: iron, orange/green/blue: 3 phase copper coils)

Tubular Linear Synchronous Motor (TLSM)		Flat Linear Synchronous Motor (FLSM)		Flat Linear Brushless Motor (FLBM)
Surface Permanent Magnets (SPM)	Internal Permanent Magnets (IPM)	Surface Permanent Magnets (SPM)	Internal Permanent Magnets (IPM)	Internal Permanent Magnets (IPM)
				
SPM-TLSM	IPM-TLSM	SPM-FLSM	IPM-FLSM	IPM-FLBM

Of the five synchronous motors analyzed, the configuration with the best thrust force per ampere to weight ratio was the double-sided Internal Permanent Magnet - Flat Linear Brushless Motor (IPM-FLBM) where the mover (translating rotor) was sandwiched between two fixed stators. The actuator design is depicted in Figure 9.

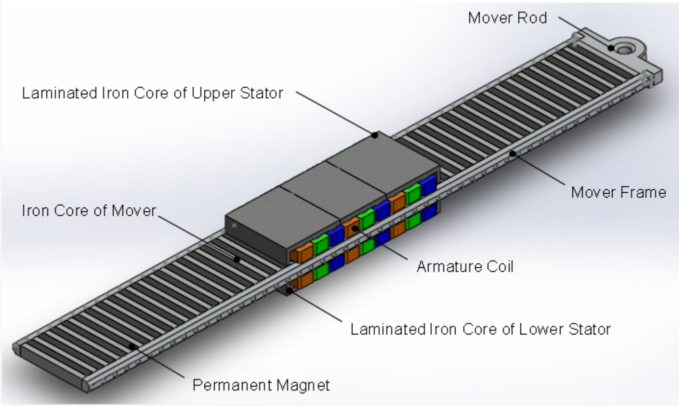


Figure 9: Design for an Internal Permanent Magnet Flat Linear Brushless Motor (IPM-FLBM) actuator

The two stators consisted of the typical back iron and teeth (poles) wrapped in copper coils. Each stator contained 3 unit modules, where a unit module consisted of a single 3 phase AC motor making 9 coils per stator. The mover was made of alternating blocks of laminated iron core and neodymium iron boron NdFeB magnets. The mover was supported by a guide rail to hold it together and maintain proper air gap clearance with the stator. The weight of a single actuator was estimated to be about 90 pounds (52% of which is the mover) with a maximum thrust force of 3400 pounds. Therefore the TRAS would need four actuators per nacelle.

The IPM-FLBM actuator controller contained a position and speed controller with independent feedback loops. A simulation was built to input the TRAS load stroke curve as the external disturbance force and measure the response as the motor deployed. These responses can be seen in Figure 10.

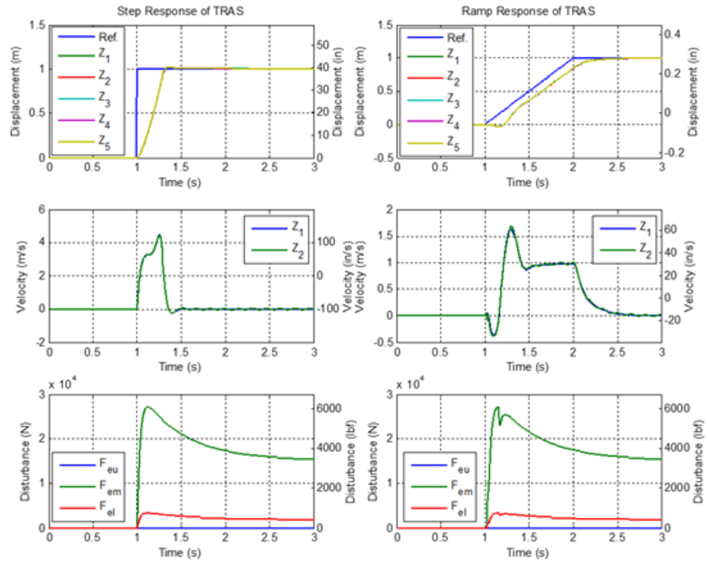


Figure 10: Controller simulation with step or ramp input command and RTO external loading function

It was observed that the motor could stably meet the deploy time requirement of 0.5 seconds with a step function input, achieving a peak velocity of 4.5 m/s. A 1 second ramp function could deploy in 1.5 seconds with a peak velocity of 1.6 m/s. Triangular and Trapezoidal velocity profile responses were also measured with profiles similar to the ramp deploy function. A power analysis showed all four response types peaking at 57 kW and maintaining it for about 0.2 seconds, and the RMS power ranging from 22.6 kW (ramp) to 24 kW (step) per actuator.

In addition to the design of the motor and controller, a MATLAB program with a graphical user interface (GUI) was built as a linear motor design tool. The tool shown in Figure 11 allows the user to adjust multiple characteristics of the IPM-FLBM and output the various performance plots.

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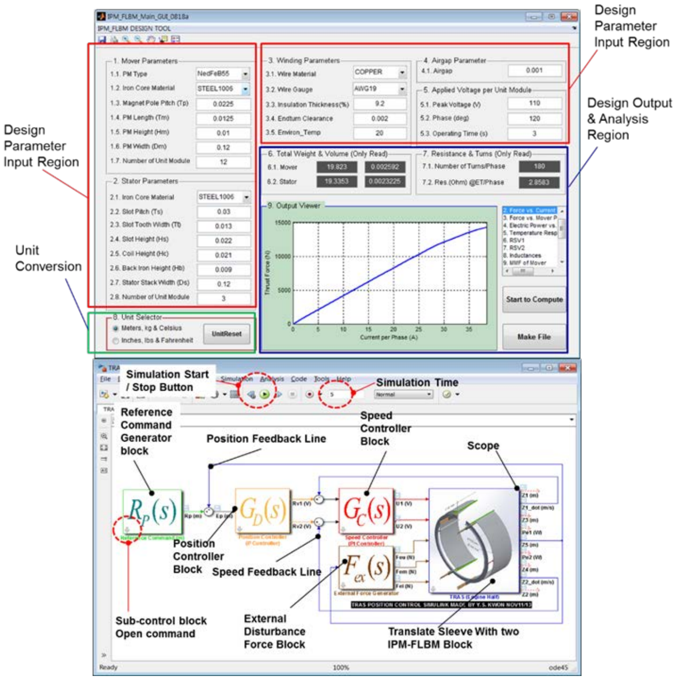

Figure 11: MATLAB IPM-FLBM design tool and controller user interfaces

The program uses linear equations to predict the performance of the motor in order to save computational time, and those equations are supported by finite element models. With the program, the motor can be redesigned and resized to fit different applications that a user might require. In addition, a parameterized controller simulation was built using Simulink to take a motor design and predict its response with a custom external forcing function such as a TRAS load stroke curve. The external forcing function can also be changed to test the response in different applications.

There is some apprehension regarding whether a permanent magnet actuator would survive in a nacelle environment. The biggest challenges for this motor technology and design would be the reliability, operability, and manufacturability. For the permanent magnets specifically, the key reliability concerns are temperature and vibration. An initial thermal analysis showed a 37 degree Celsius rise after 3 seconds at 2.4 kW, but to reduce risk of inadequate reliability a full thermal profile would be needed and validated by test with the motor in a housing run at full power. Another concern is that as the permanent magnets get heat cycled their magnetic field will deteriorate over time. Powerful magnets are likely to collect ferrous dust within a factory environment which could be difficult for maintenance personnel to keep clean. If not clean, the actuator performance will degrade and the small air gap between the mover and stator could close to create contact and wear. The engine nacelle environment has a lot of vibration, so there is additional concern that the magnets (being made of sintered powder) may be too fragile and crack or fall apart. Electro-Magnetic Inference (EMI) due to the exposed permanent magnets could play a role by affecting other system wires routed near the movers on the fan case. Faraday's Law of Induction describes how a moving magnetic field can induce an electrical current in a nearby wire; therefore, it would be important to perform a detailed look at electrical systems routing around the fan case relative to this actuator to avoid any interference.

B. Linear Induction Motor Actuator

The linear induction motor was designed by Boeing's Senior Tech Fellow Robert Atmur and his team. Mr. Atmur has extensive experience in designing induction motors and has programed sizing tools for optimization. The architecture of this motor design in Figure 12 consists of a 3 phase AC double-sided linear induction motor, commonly known as DLIM, where the mover is also sandwiched by two fixed stators.

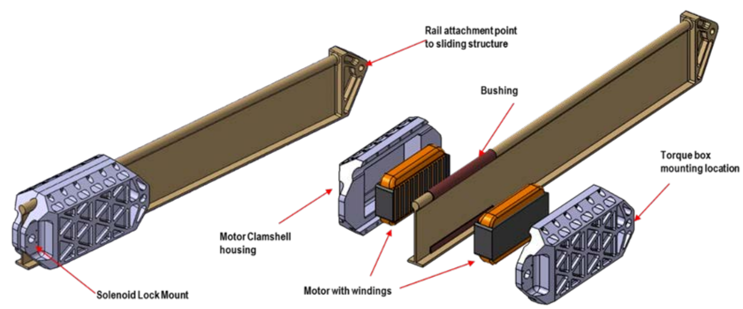

Figure 12: Design for a Double-sided Linear Induction Motor (DLIM) actuator

Similar to the synchronous motor, the stators are the typical back iron with teeth wrapped in copper coils, however, the way the coils are laid out around the poles is different from the other motor technologies. The mover is a simple single piece aluminum beam resembling an I-beam with guides on either end. It was determined that the DLIM would be 62 pounds with a thrust load capability of 8200 pounds. An early cost estimate for a prototype was about $12k per actuator. Theoretically, a TRAS system would only need two of these actuators per nacelle, but a real system would cut the actuator size and add more of them.

A noted side effect of driving a mover with 4000 pounds thrust per stator is that the stator pushes away from the mover with equal force. Therefore it was necessary to examine a design for a stator housing that could prevent displacement in order to maintain the designed air gap to the mover. The gap is a critical performance parameter for electric motors where a small increase in the air gap can significantly reduce the thrust force generated. The housing in this case consisted of two aluminum hog out clam shells with a row of fasteners along two opposing edges. Even without optimization, a FEM analysis of an 8000 pound separation load shown in Figure 13 resulted in only 0.005 inches deformation.

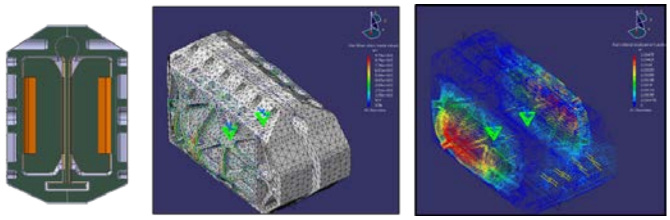

Figure 13: DLIM actuator housing with 8000 pound separation load applied

That deformation was without factoring in the stiffness of the iron stators and provided confidence that it would not be a problem. The 62 pound weight stated previously was the total weight that included the housing. No housing had been designed for the 90 pound IPM-FLBM permanent magnet motor, however it would require something similar which was not a significant effort. The key difference however would be that instead of the housing taking a separation (tensile) load, the permanent magnet motor would generate an attractive (compressive) load on the housing.

To control the linear induction motor actuator, a novel controller was devised. Ashwani Chaudhary was responsible for building the controller simulation. The initial electrical simulations showed a stable controllable system was feasible regardless of whether a large or small magnitude step command was input. The resulting simulated actuator was able to deploy in 0.5 seconds, hitting a peak velocity of 7 m/s in about 0.1 seconds and spending the remaining 0.4 seconds coming to a controlled stop. In this case however due to time constraints a more accurate motor model was unable to be included in the simulation to substantiate the calculated peak electrical loads. During standard operation it was determined that the peak electrical load would be 47 kW; however, a problem was discovered that when the actuator is at stall speeds (zero velocity) the power required would be greater than 141 kW per actuator. This would be a higher load than the aircraft electrical power system can accommodate. A means to provide initial motion would significantly reduce that load.

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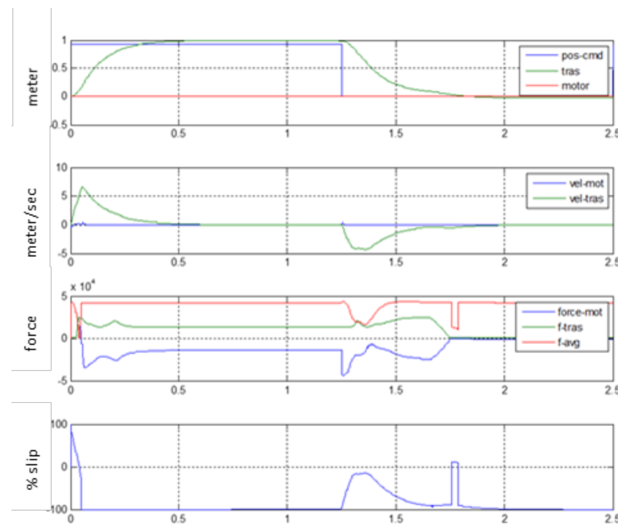

Figure 14: Model and response of three thyristor controller for a linear induction motor

What makes the DLIM attractive is the actuator simplicity and its thrust to weight capability. This actuator design would be fairly easy to integrate with the thrust reverser because it contains no permanent magnets, and the triple thyristor controller is simpler. In a thrust reverser actuation application, the motor is not in operation for a long enough period of time for heat rejection to be an issue, the temperature rise was calculated to be very small at less than 10 degrees Celsius. The biggest challenge to integration would be the added mechanism needed to provide motion when stalled so as to prevent the unmanageable electrical load. A solenoid or spring could be integrated into the actuator design in order to provide some small impulse when the mover velocity is at zero. Or that the sudden high demand could be managed by a bank of capacitors, though initially that solution appears to be heavy which is not appealing for aircraft applications.

C. Linear Switched Reluctance Motor Actuator

Like the linear synchronous motor, the linear switched reluctance motor (LSRM) was designed by Texas A&M University's Dr. Won-Jong Kim and grad student Young Shin Kwon. This part of the study analyzed four different architectures of switched reluctance motors. There was a longitudinal-flux tubular (LF-T) LSRM, two longitudinal-flux flat (LF-F) LSRMs with either iron or a mix of iron and non-ferrous materials, and a transverse-flux flat (TF-F) LSRM, each qualitatively assessed to have the highest force output compared to other architecture options. Figure 15 shows that the longitudinal-flux term is reflective of the traditional flux path through the stator poles and back iron that is parallel to the force output direction; the transverse-flux term defines the flux path as being perpendicular to the motor force output direction. Due to the non-linear nature of LSRMs it was impossible to solve for the thrust force analytically, and therefore was necessary to do the analysis optimization entirely using software FEA tools.

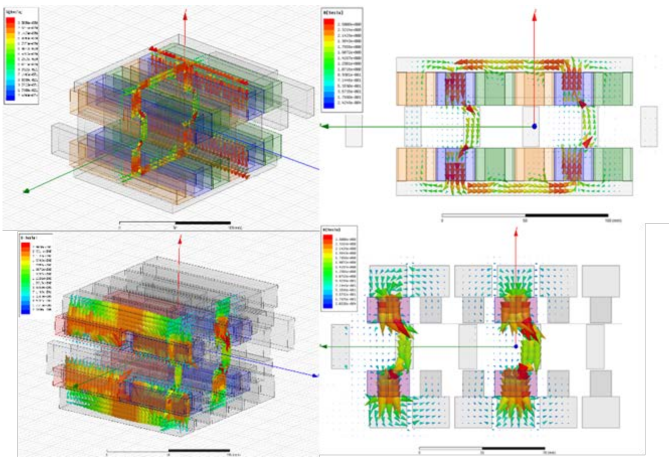

Figure 15: 3D FEA analysis of Longitudinal (top) and Transverse (bottom) flux LSRM

The four architectures were analyzed, and the highest thrust force switched reluctance design was of a double-sided Longitudinal-Flux Flat Linear Switched Reluctance Motor (LF-FLSRM) configuration, using 3 phase AC. Each of the two iron stators for this motor contained 24 poles wrapped in copper coils, and the mover consisted of iron bars spaced out connected to a guide. The spacing allows for reduced weight of the mover, but this also increased its length so it would be more difficult to integrate over the engine fan case. The LF-FLSRM motor depicted in Figure 16 weighs in at 83 pounds with a maximum thrust force of only 2140 pounds at 25.5 kW.

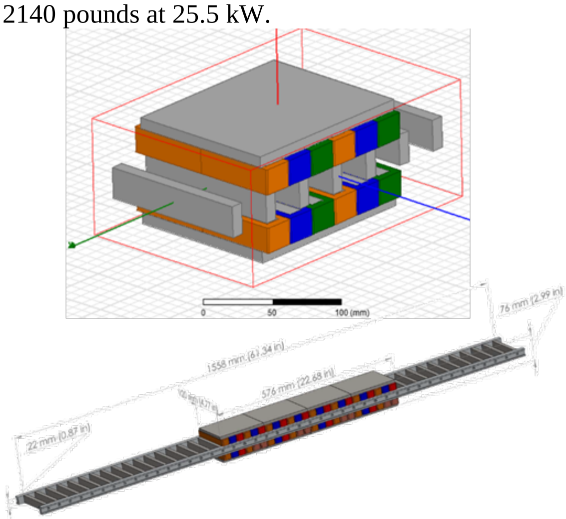

Figure 16: LF-FLSRM Actuator Design

Therefore, to output the required load the TRAS would need 6 actuators per nacelle which results in an unacceptable weight. Figure 17 shows the performance gap of the LSRMs relative to the synchronous IPM-FLBM. No further development work, such as a control method, was performed for this motor technology.

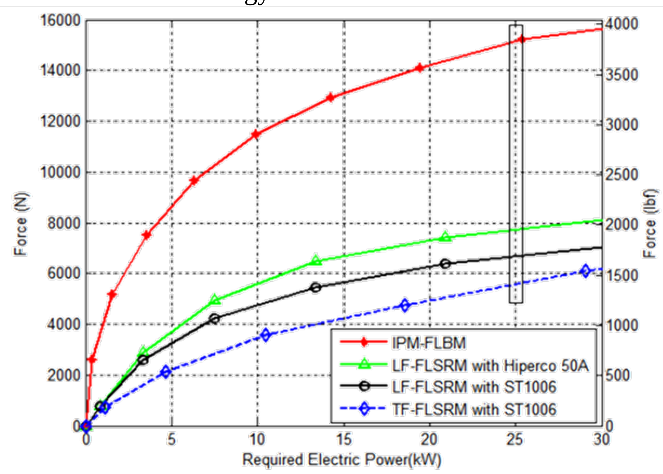

Figure 17: Comparison of Force to Power of the IPM-FLBM with three LSRM configurations

In terms of integration with a thrust reverser on a nacelle, the LSRM configuration, similar to the DLIM, benefits from not containing permanent magnets. Manufacturing of the LSRM would be more costly than the DLIM since there will be more poles to machine and coils to wind, but still likely cost less than the IPM-FLBM. The LSRM length of both the mover at 61 inches and stator at 22 inches is longer than the other linear motors. Because the mover must be the required length of stoke plus the length of the motor stator, the LSRM violated the study’s volume guidance. The amount of unsupported length stowed over the fan case would be a problem in a nacelle environment where high vibration loads are common. The extra length would require additional hardware supports and guides bolted to the fan case which would further increase the weight of an LSRM thrust reverser actuation system.

VI. Summary of Results

Table 3 compares the thrust-to-weight and thrust-to-power ratios of the three linear motor actuators, where the double-sided linear induction motor (DLIM) design stands out as the highest performer.

Table 3: Comparison of the three linear motor actuator designs

Actuator	Thrust (lbf)	Weight (lbm)	T/W Ratio (lbf/lbm)	Power (kW)	T/P Ratio (lbf/kW)
IPM-FLBM	3400	90	37.8	22.6	150.4
DLIM	8200	62	132.3	47	174.5
LF-FLSRM	2140	83	25.8	25.5	82.9

It is important to note that the internal permanent magnet flat linear brushless motor (IPM-FLBM) and the DLIM were both able to meet the thrust force needed within the design volume restrictions. Even allowing the longitudinal flux flat linear switched reluctance motor (LF-FLSRM) to violate the design volume, its performance was still not competitive with the other types.

When considering the nacelle integration aspects the DLIM is preferable, because it is much simpler to integrate and would cost less to manufacture than either of the two alternatives. The cost reductions come from not needing to purchase large quantities of expensive rare earth magnets, the part count is lower, overall size is smaller, and the simplicity of assembly would lower manufacturing flow time. The only disqualifying characteristic of the DLIM is the large power required to initiate movement when the mover is stalled at the end of travel. This could be solved by an additional bolt on mechanism, or bank of capacitors, that could be used to overcome that challenge; however, the added complexity begins to work against the preferred integration and manufacturing benefits. If an additional device was unable to be incorporated into the design of the DLIM actuator for it to function as a thrust reverser actuator, then the only remaining feasible design would be the IPM-FLBM. While it is unattractive from both a weight and integration standpoint, it could provide performance value to the airplane with a 0.5 second thrust reverser deploy. Additional study and testing is needed to validate the performance analysis and determine the overall net present value.

The Thrust Reverser is typically operated only once per flight cycle. Since it is not a continuous operation application, like a flight controls aileron or rudder actuator, a synchronous permanent magnet linear motor likely could utilize high electrical power for short durations without thermal degradation of performance. Linear motor actuators could supplement or replace other aircraft actuation systems that value fast response times and precise control. Their unique flat configuration could be an enabler for alternative architectures where the overall integration benefit is higher versus a traditional hydraulic or electromechanical actuator configuration. Landing gear actuators or door actuators also have a similar two position operation where faster actuation would reduce airframe drag. However, for an IPM-FLBM to be applied as an electric flight control actuator with continuous operation, the power and thrust force would either need to be reduced to prevent overheating or require added passive or active cooling features. In that case the DLIM could have an advantage without the permanent magnets, but it is the permanent magnets of the IPM-FLBM that give it greater precision and controllability. BCA now has a MATLAB design tool to size and predict the performance of an IPM-FLBM, where BDS has shown to have similar capability for a DLIM.

This article recommends further model based analysis, prototyping, and lab validation testing of the IPM-FLBM and DLIM actuators. Prototypes and tests would validate the design, analysis, control, manufacturability, and operability of the actuators to advance their technology readiness level. This activity is essential for reducing the risk to existing or future programs that always surrounds a novel technology and system architecture. An actuator test rig was briefly studied to gauge material and cost requirements for a LMA prototype test in the Seattle labs, one conclusion was that a typical hydraulic actuator force-fight system would be insufficient to provide the simulated TRAS load. The key problem was the hydraulic actuator response time was too slow to test the full performance of an electric linear motor actuator. The only way to adequately test a linear motor actuator at full rate in a lab against a TRAS force function would be to build additional linear motor actuators to provide the realistic load condition.

In terms of future design work, the IPM-FLBM requires a housing design to mount the stators and guide rail to a thrust reverser. It would be similar to what was designed for the DLIM, but potentially with integrated heat rejection devices for passive or active cooling. The DLIM actuator requires a design for a bolt-on mechanism that would initiate movement when the mover is stalled; it would have to function regardless of the actuator position or commanded direction of motion. The DLIM also requires a more accurate software simulation motor model to analytically test the controller before it is manufactured and prototype tested. All the challenges associated with completing detailed design, prototype manufacturing, and laboratory validation testing could be overcome with additional resources.

VI. Conclusion

Aircraft actuators are either hydraulic, pneumatic, or electromechanical in most applications. A novel electric linear motor is proposed as a thrust reverser actuator. Three different types of linear motor actuators were designed using synchronous, induction, and switched reluctance technologies. The designs have been analyzed for performance and controllability, and assessed for manufacture and nacelle integration impacts. The study shows that the double sided linear induction motor (DLIM) is an attractive technology. However, with the zero torque at stall issue, an IPM-FLBM may be a viable alternative for a thrust reverser actuation system. The LSRM technology was ruled out during the study. Next steps include developing detailed software models, manufacturing a prototype, and lab testing to validate the predicted performance.

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Biographies

Eric Bol joined the Boeing Company in 2006 with Flight Test Engineering after graduating from the University of

Washington with a B.S. in Aeronautical and Astronautical Engineering. From 2006-2011 he primarily flight tested and certified the 747-LCF DreamLifter and the 787-8 DreamLiner. In 2011, he moved to Propulsion Product Development as a design engineer and continues to explore new technologies and evaluate how they could be incorporated to improve the performance of the nacelle and airplane. Eric plans to stay with Boeing to work towards becoming a member of the Technical Fellowship and is pursuing a PhD in metal additive manufacturing through the University of Washington Mechanical Engineering department.

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