Design of linear Electro-Mechanical Actuator for an Unmanned Air Vehicle

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ABSTRACT

LER-UAV (Long Endurance & Range Unmanned Air Vehicle) is an aircraft having an endurance of 12 to 15 hours and a ceiling of 25,000 ft operating upto a range of 250 Kms line of sight. The aircraft is of canard type with pusher configuration and is having control surfaces namely, Elevator, Ailerons and Rudders. The above controls will have to be operated through Linear Electro-Mechanical Actuators (LEMAs). LEMAs are the final elements in the control chain of flight control system. The LER-UAV demands these actuators to be highly reliable and accurate to ensure continuous, failure free flight to accomplish its missions. Operation at high altitude for long hours requires proper selection of its constituent and thorough environmental qualifications. The main thrust is on the design & development of Linear Electro-Mechanical Actuators to operate these control surfaces with required Travel, Force, Rate, Free play, Frequency response, Accuracy, Stiffness etc.

The actuator essentially consists of a frameless BLDC torque motor, which drives the ball screw. The rotor of the BLDC motor is mounted directly on one end of the ball screw, which has the nut assembly at the other end. A duplex pair of angular contact ball bearing of 25 deg. contact angle is used with preloading for greater moment rigidity. The position feed back is through an LVDT, which is connected to the output shaft. The output ends of the actuator have rod ends, which gets connected to control surface via linkages. Various design parameters like Inertia, Stiffness, Free Play, Accuracy, Friction, Life estimation, and weight have been worked out. The Thermal and reliability of the actuators have been estimated. This paper presents Mechanical engineering design, manufacturing, validation and flight integration of the Linear Electro-Mechanical actuator.

1.0 INTRODUCTION

This LER-UAV is a canard type aircraft with pusher configuration has Elevator, Ailerons and Rudders, which can be operated through Electro-Mechanical Actuators (EMAs). The LER-UAV demands these actuators to be highly reliable and accurate to ensure continuous, failure free flight to accomplish its missions. Operation at high altitude for long hours requires proper selection of its constituent and thorough environmental qualifications. Hence the main thrust is on the design & development of these Electro-Mechanical Actuators to operate the control surfaces to the required specifications.

Electro-Mechanical actuators can be of Rotary or Linear configuration. The configuration can be selected based on the specific application, and the system requirements, which is a function of efficiency, backlash and the degree of accuracy. Rotary actuators in general have a torque motor or a permanent magnet motor, which drives the gear train with a defined gear ratio for a required output speed & torque. *(Ref.vi)*. This configuration invariably offers low stiffness, higher backlash, lower efficiency, because of the number of mechanical joints and the friction between these members. But they give a fair amount of positioning accuracy. On the other hand linear actuators offer high stiffness, low backlash, high efficiency, precise positioning accuracy, and long endurance as compared to the rotary actuators. So Linear actuators are the best suitable choice for such long endurance UAV applications.

2.0 DESIGN CRITERIA:

Linear motion systems driven by rotating electric motors generally employ Acme screw, Belt drive, Roller screw, Ball screw etc, to convert rotary motion to linear motion. The majority of linear motion applications convert motor torque to linear thrust using either one of the above mechanisms. *(Ref. vii)*.

- Acme screws are the cheapest option and has the advantage of no back driving but the efficiency of the best-made screw fall short to 50%.
- Belt drives cannot be considered for such applications where precise positioning accuracies are required.
- Roller screw offers the best to meet all the system requirements with exceptionally high load carrying capacity. They are compact in size, but they are relatively expensive.
- The ball screw has the advantage to convert more than 90 % of the motor's torque to thrust. Also ball screws provide high stiffness, zero backlash with pre loaded nut, very high repeatability, smooth operation at all speeds, high duty cycle, long life and low wear etc. Due to the above advantages ball screw mechanism has been considered in this design for the conversion of rotary to linear motion.

3.0 THE SYSTEM & DESIGN APPROACH:

The linear actuator essentially consists of a frameless Brush less DC torque motor, which drives the ball screw. With direct drive motor as prime mover it eliminates the use of intermediate gearing, mechanical joints and hence minimizing the errors. The rotor of the BLDC motor is mounted directly on one end of the ball screw, with the guided nut assembly at the other end there by converting the rotary motion to linear motion effectively. A duplex pair of angular contact ball bearings of 25^0 is used with preloading for greater moment rigidity. The position feed back is through an LVDT, which is connected to the output shaft passing through the lead screw. End cushioning is provided at both the ends using Belleville springs that are kept in pre-loaded condition to withstand extreme load conditions and jamming at the ends. The output ends of the actuator have rod ends, which gets connected to control surfaces via linkages.

Based on the essential system performance requirements *(Ref. i)*, like Hinge moments, Response, Accuracy, Power, Size, Weight, and Natural & induced environmental requirements, the Linear Electro-Mechanical Actuators (LEMA's) for the control surfaces has been designed. To achieve these system requirements, some of the mandatory design drivers like free play, inertia, stiffness, and accuracy are considered. Other limitations like weight, size, operating environment under high and low temperature range, shock, vibration etc has been considered.

Since a servo system has to provide best positioning accuracy, with required acceleration without undergoing deflection, the above parameters has been strictly controlled in the design as well as at fabrication stage by iterative computation of various combinations of component & material selection, manufacturing, assembly, sealing and maintenance. This section of the paper presents the mechanical design details of the Linear Electro Mechanical actuator. The assembly model of the actuator is as shown in the Appendix 'A', *figure-1 & figure-2.*

4.0 SYSTEM REQUIREMENTS:

The Actuation System requirements defined *(Ref. i)*, for the designs of LEMA's are:

- Travel (Electrical & Mechanical)
- Continuous Force
- Rate (Load & No Load)
- Free play
- Accuracy
- Bandwidth (Load & No load)
- Stiffness
- Threshold
- Physical dimensions and weight

4.1 SELECTION OF COMPONENTS:

Standard components of linear actuator are:

- Motor
- Ball lead screw
- Rod ends
- Bearings & Linear bush

4.1.1 MOTOR:

Based on the maximum power and speed requirements *(Ref. i)*, Brush less DC motor has been selected. The system operates at 28V DC with a current limit of 15Amps. The controller & the control electronics and its specifications are beyond the scope of this paper.

4.1.2 BALL SCREW:

Selection of the ball screw is primarily based on the speed, force and accuracy requirements. The advantages of ball screws over conventional screws include higher efficiency (>90% with coefficient of friction $\mu = 0.01$), speed capability, load capacity and duty cycle. It also has lesser free play (~0.005mm) and longer life for the selected class of accuracy. Based on the Speed and availability, the requirements are worked out as given below: *(Ref: ii)*

- Max. Force at the output is given by $\mathbf{F_{max} = (1- \mu * Tan\ \alpha) / (Tan\ \alpha + \mu) * Ts * 2 / dm}$ *(4.1)*
- Stiffness of the ball lead screw $\mathbf{k_{bs} = AE/L}$
- Permissible Buckling load, $\mathbf{P_b = \pi^2 * E * I / (n * \eta * L^2)}$ *(4.2)*
- Permissible Tensile Compressive load, $\mathbf{P_{tc} = \sigma * \pi * (d_1^2 - d_2^2) /4}$ *(4.3)*
- Permissible rotational Speed based on critical speed : *(Ref: iv)*

$$\mathbf{N_1 = 60 * \lambda^2 / (2 * \pi * L^2) * \{ E * 10^3 * I /(\gamma * A)\}^{\wedge 1/2} * n} \qquad (4.4)$$

- Speed based on DN value for precision ground ball screw, *(Ref: iv)*

$$\mathbf{N_2 = 70000/ D} \qquad (4.5)$$

From N_1 and N_2, whichever is lower has been taken as the permissible speed of the ball screw.

4.1.3 ROD ENDS:

Output end of the actuator is having a rod end, which gets connected to control surface via linkages. Rod end has advantage of having stiffness ~ 30 % more than that of a deep groove ball bearing of almost similar size. Radial play of rod end is also 4 times less than that of ball bearing.

- The Stiffness of the rod end was estimated assuming that the full load is experienced by one ball. Combined deformation along the axis of the load is given by: *(Ref. iii)*

$$\mathbf{\delta = 1.04 * [F^2 * \{(1- \nu_1^2/E_1) + (1- \nu_2^2/E_2)\}^{\wedge 2} / \{(d_1 * d_2) / (d_2 - d_1)\}]^{\wedge 1/3}} \qquad (4.6)$$

$$\mathbf{k_{re} = F / \delta} \ \textit{(Ref. ii)} \qquad (4.7)$$

4.1.4 BEARINGS & LINEAR BUSH:

A duplex angular contact ball bearing (25° contact angle) is selected with medium preloading *(Ref. v)*. Preloading is done on a back-to-back mounted duplex pair for greater moment rigidity. Linear bush is provided to guide the output rod and minimize friction between sliding surfaces. The stiffness of the bearing is estimated using the following relations: *(Ref. ii)*, *(Ref. iii)*

- Axial load, **Q** $= F_{ao} / Z \sin\alpha$ (4.8)
- Axial deflection, δ_{ao} $= 0.45 / \sin\alpha * (Q^2 / D_a)^{1/3}\ \mu m$ (4.9)
- Axial Stiffness, k_{ab} $= 3 * F_{ao} / \delta_{ao}\ N/\mu m$ (4.10)

5.0 DESIGN PARAMETERS:

5.1INERTIA:

The load inertia of the drive system reflected at the motor is to be controlled in order to get the required response at the out put *(Ref. vi)*.

Equivalent reflected inertia, $I_{eq} = (I_{bs} + I_{cb} + I_{fb}) * \{L/(2*\pi)\}^{2} + I_m$ (5.1)

Where, Inertia of the ball screw, I_{bs}

Inertia of the coupling bush at feedback, I_{cb}

Inertia of feedback shaft, I_{fb}

Inertia of other moving components, I_m

Lead of the ball screw, **L**

5.2 AXIAL STIFFNESS:

The overall mechanical stiffness of the actuator depends on the stiffness of all other elements. The equivalent axial stiffness of the system is given by the relation: *(Ref. i)*.

Equivalent axial stiffness, $k_{eq} = 1 / [\, (1 / k_{bs}) + (1 / k_n) + (1 / k_{or}) + (1 / k_{ab}) + 2 * (1 / k_{re})\,]$ (5.2)

Where, Ball screw stiffness, k_{bs}

Nut stiffness, k_n

Output rod stiffness, k_{or}

Bearing stiffness, k_{ab}

Rod end stiffness, k_{re}

5.3 FREE PLAY:

The crucial parameter that controls the positioning accuracy of a servo system is free play. The important step in estimating the free play is the selection of the class of ball screw, nut configuration and other machining accuracies of the housing and components. Hence these are worked out more precisely. The total free play at the output is the summation of all the individual free plays given as: *(Ref. i)*.

Total free play, $f_{eq} = f_{bs} + f_{cl} + 2 * f_{re}$ (5.3)

Where, Free play of ball screw, f_{bs}

Free play due to clearance in the slot to arrest nut rotation, f_{cl}

Radial play of rod ends, f_{re}

5.4 ACCURACY:

The accuracy of the actuator is the factor, which provides the required positioning of the control surfaces at loaded condition. The factors that affect the accuracy are lead error, and clearances of the components in the axial direction. Other factors like thermal displacement due to heat generation also can contribute to the total error. By selection of proper materials, close tolerances, precise machining and assembly the required accuracies are met.

5.5 THERMAL ASPECTS:

Components are supposed to withstand temperature variations from - 40° to +70° C from normal ambient conditions (25° C). In case of ball screw, change in length due to environment temperature variations will not affect the positional accuracy because this variation is absorbed at floating end of the ball screw. *(Ref. iv)* The design takes care of the effect of variations under low and high temperature environment.

6.0 MANUFACTURING & TESTING:

During the manufacturing strict control was exercised on geometrical tolerances, concentricity's of bores in the motor housing, air gap between the rotor and the stator. Boring of ball screw for the required length accurately to accommodate the LVDT inside the ball screw was a challenging task. Special fixtures were made to get a uniform concentric bore. The whole assembly is to be carried out in a clean environment. Inspection at each stage of the manufacturing and assembly is mandatory to achieve the required accuracies and finish.*(Ref. vi).*

Since the actuator is under the process of final assembly various tests are proposed to be carried out using a hydraulic loading test setup. The final assembly is required to be tested for excursions, break of torque, free play, and stiffness before the control integration as functional checks. Also the actuator is proposed to be tested for EMI/EMC, ESS, SOF and other qualification tests. *(Ref. i)*

A typical linear electro mechanical actuator for engine control of an UAV application has been designed, based on the above stated approach. The actuator is manufactured and tested. The compliance chart to system specification is as given below:

PARAMETER	REQUIRED	TEST RESULTS
Continuous Torque by Motor	0.0265 Nm	0.0494Nm
Rate @ 100N	8mm/sec	8mm/sec
Free Play @ 5N	0.05mm	0.02mm
Accuracy @ (30N load)	0.2mm	0.02mm
Stiffness	500 N/mm	600 N/mm
Frequency Response	-3dB /< 90° Ph lag	> -3dB/ 3.6 ° Ph lag
Threshold	50mv	30mv
MTBF	2100 Hrs	10365 Hrs (cal value)
Weight	1 kg	1.05 kg.

CONCLUSIONS:

Electro-Mechanical Actuators are the ideal choice to actuate the control surfaces of unmanned air vehicles because of low cost, low weight and least logistics. This design is based on the competence developed by the successful use of rotary electro-mechanical actuators for various UAVs like Lakshya, Nishant etc. Here an attempt has been made to design and develop a linear actuator for Long Endurance UAV for the first time. The design and the simulated tests results show that all the specified requirements are met in general.

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Appendix-'A'

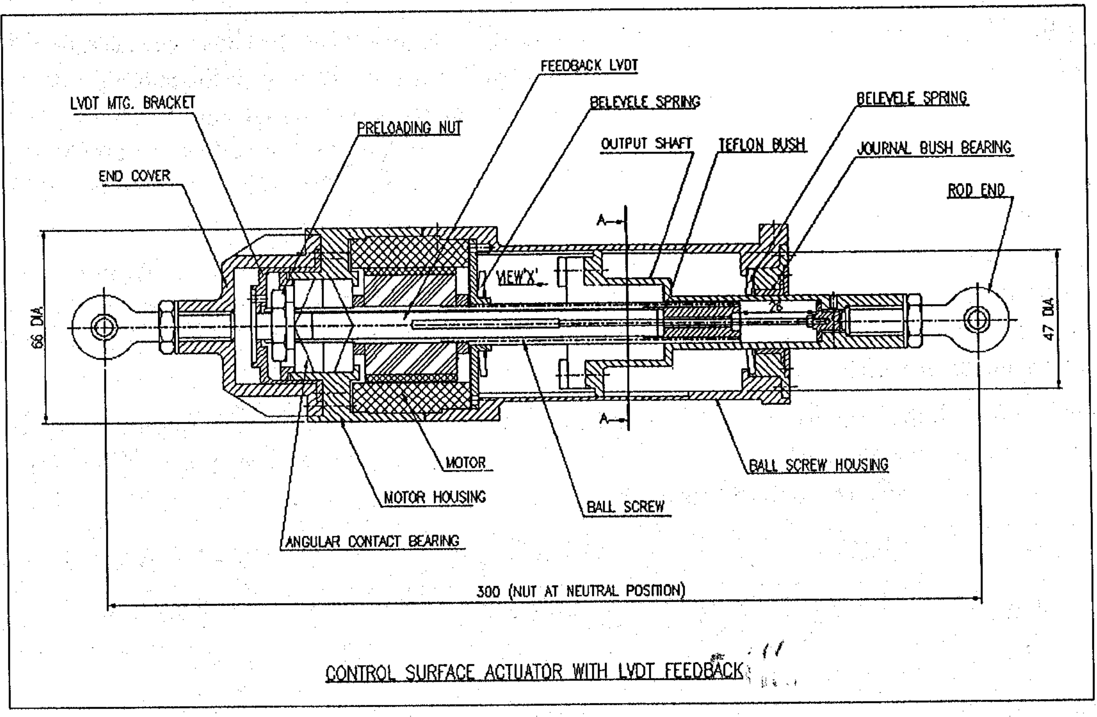

Figure-1, 2D Model of the Linear Electro Mechanical Actuator

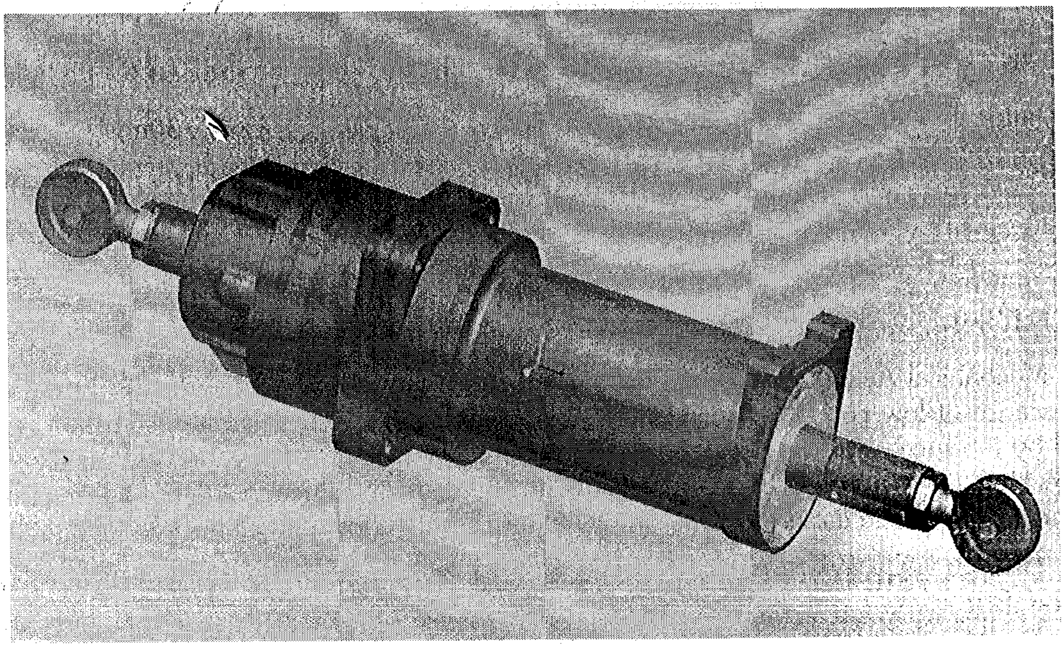

Figure-2, 3D Model of the Linear Electro Mechanical Actuator.

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