Electro mechanical linear actuator using roller screws

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Abstract. Electro Mechanical linear Actuators as the name suggests are linear actuators operated by electric motor. The linear motion is desirable to drive a high inertia weapon system in elevation axis. In this paper, design and development aspects of an Electromechanical linear actuator using Roller screw has been attempted. Initial Comparison with ball screw drive suggests that roller screws are favorable for high dynamic load application. Selection and functional parameters of roller screw had been evaluated to optimize the linear actuator based on roller screw. This paper studies in detail the design aspects of an electromechanical linear actuator. The variation of different parameters with respect to Lead of the roller screw has been studied.

Keywords: Linear motion actuator, Roller screw, lead, Electromechanical clutch

1. Introduction

The main component of a linear actuator is the drive mechanism. Roller screw drive, which is a low-friction precision screw-type actuator, is used here for this purpose[1]. The other elements of the actuator are reduction gear box, EM failsafe clutch, No back clutch, overload slipping clutch, failsafe manual drive and mechanical structures and mountings. The electrical elements employed are Servo motor with controller and proximity switches. Proximity switches are used to sense the end positions and provide cushioning at both the extremities. P.C. Lemor and V.V. Kozyrev reports the various advantages of roller screw over ball screw [2, 3]. D.S. Blinov[4] has proposed the design and calculation methods for planetary roller screw mechanisms and D.V. Bushenin et al[5] have studied on the design aspects of screw mechanisms. D.E. Schinstock et al [6] performed the dynamic test on roller screw which proves the roller screw’s ability to withstand high dynamic loads. Efficiency analysis had been performed by S.A. Velinsky et al [7]. S. Ma et al have studied the design optimization of the Planetary roller screw [8] V.V. Morozov et al have studied the influence of the axial angle of screw profiles on the load capacity [9]. This paper studies the effect of different leads on various parameters such as Torque, efficiency, and power. The leads 6mm, 12mm and 20mm are represented by L_6, L_12, and L_20 respectively.
2. Description and Design

2.1 Roller screw mechanism

The mechanism consists of a roller screw shaft, planetary rollers and a nut. Owing to increased contact points, for the same screw diameter, roller screws have a higher load bearing capacity and lower contact stresses compared to ball screws [10]. This makes roller screws an ideal choice for actuating high inertia platforms. Higher rpm is achievable with roller screw for extended hours. High Dynamic Line Rating (DLR) and high shock load bearing capacity and ability to offer a variable lead makes the roller screw an ideal choice for high inertia system actuation. The roller screw under study has a nominal diameter of 36 mm and a free length of approximately 355 mm.

2.2 Reduction Gear box

The roller screw is connected to a drive motor through a reduction gearbox. The gearbox multiplies the torque provided by motor and also provides the axial separation of screw shaft and motor shaft so that the actuator layout is optimized to requirement. A 2 to 3x reduction gearbox with a backlash adjusting idler is employed.

2.3 Motor

Motor sizing is the most important aspect in actuator designing. The speed torque and power are the governing factors of motor selection. Duty cycle is another important aspect which selects the type and make of motor. The speed and acceleration of roller screw is lined to motor through speed reduction gearbox, which multiplies the torques and optimizes the speed. An optimized inertia matching is the goal of actuator designer by which he one can optimize the motor power requirement to meet the load operation specifications.

Inertial load speed analysis shall be carried out with different leads of roller screw and a suitable motor shall be selected.

2.4 Electro Mechanical Failsafe clutch

In case of power failure, motor loses its brake functionality. To avoid retraction of the screw and descending of the platform, an Electromagnetic clutch which transmits reversing torque to a no-back clutch is used. The static and dynamic torque capacity of the clutch shall be sufficient enough to hold the load torque.

2.5 No back clutch

It is bidirectional sprag brake which allows mechanical motion only in one direction. It is equivalent to a diode in an electrical circuit. No back mechanism allows motion to pass to roller screw during manual mode operation and acts as brake when manual handle is not used, thus preventing free movement of the load platform.

2.6 Overload slipping clutch

This clutch limits the shocks transmitted from the load side and hence prevents the system from slipping and mechanical damage. The torque limiter can be adjusted for additional overload torque greater than 100 Nm.
2.7 Manual drive

Manual drive with handle is provided as a failsafe measure in case of electrical failure. The manual drive is to provide for unbalanced and friction torques.

2.8 Linear actuator

The various modules described above are assembled and integrated to form an assembly of linear actuator (Figure 1). Displayed below is the assembly constituting roller screw mechanism, reduction gear box, clutches and driving motor. It is complete with housing and the screw shaft ends are fitted with spherical bearings for pivoting on the weapon platform. Upon arresting the rotational degree of freedom, we get linear motion from the roller screw. The model also displays a handle to aid for manual operation during cases of power failure.

![Figure 1. Virtual solid model of Electromechanical linear Actuator](image)

3. Important parameters of roller screw for design

The important parameters that define an actuator is the steady state input torque and power, efficiency of screw, nominal torque and braking torque. They are affected by the nominal diameter of the screw, screw lead, coefficient of friction of the screw, screw speed, load mass and subsystem inertias. Here

3.1 Basic formulas for the roller screw selection

Direct theoretical Efficiency,

\[ \eta = \frac{1}{1 + \frac{\pi d}{P_h \mu_{ref}}} \]  \hspace{1cm} ... (1)

Indirect Theoretical Efficiency,

\[ \eta' = 2 - \frac{1}{\eta} \]  \hspace{1cm} ... (2)

Direct Practical Efficiency,

\[ \eta_p = \frac{1}{1 + \frac{\pi d}{P_h \mu_{prac}}} \]  \hspace{1cm} ... (3)
Indirect Practical Efficiency,
\[ \eta'_p = 2 - \frac{1}{\eta_p} \] ... (4)

Steady State Input Torque,
\[ T = \frac{FP_h}{2000\pi \eta_p} \] ... (5)

Steady state Power,
\[ P = \frac{Fnp_h}{60000 \eta_p} \] ... (6)

Nominal motor Toque during Acceleration,
\[ T_t = T_f + T_{pr} + \frac{p_h(F+mLg)}{2000\pi \eta_p} + \omega \Sigma I \] ... (7)

Nominal Braking Torque during Deceleration,
\[ T'_b = \frac{p_h[F+mLg]}{2000\pi} + \omega \Sigma I - T_f - T_{pr} \] ... (8)

Where, \( d \) = nominal diameter
\( P_h \) = Lead
\( n \) = angular speed.
\( \mu_{\text{ref}} \) and \( \mu_{\text{prac}} \) - reference and practical friction coefficients
\( F \) - Design force of the screw.
\( T_f \) = Total friction torque
\( T_{pr} \) = Preload torque (if provided)
\( m_L \) = Load mass
\( \Sigma I \) = motor inertia + Screw inertia + Load inertia
\( \omega \) = angular acceleration

3.2 Governing Equations of individual subsystems [11]

The lumped system approach was used for making the inertial model of each subsystem. Based on the free body diagram of the basic mechanical interactions of the components the governing equation has been derived. The various parameters are, \( \theta \) - Angular displacement, \( J \) - Mass moment of inertia, \( R \) - Radius, \( B \) - Damping of Bearings, \( \tau \) - torque, \( M \) - Mass of the follower, \( L \) - Length of screw, \( x \) - Linear displacement of the drive. The subscripts \( g \), \( s \) represents gear and shaft respectively. The figure 2 and figure 3 depict the solid model and free body diagram of the system. The following equations govern each subsystem.
Gear train

\[
\ddot{\theta}_{g1} \left\{ J_{g1} + J_{g2} \frac{R_g^2}{R_{g2}^2} + J_{g3} \frac{R_g^2}{R_{g3}^2} \right\} + \dot{\theta}_{g1} \left\{ B_{g1} + B_{g2} \frac{R_g^2}{R_{g2}^2} + B_{g3} \frac{R_g^2}{R_{g3}^2} \right\} + \tau_{load} \frac{R_{g1}}{R_{g3}} + \tau_{ab} \frac{R_{g1}}{R_{g2}} = \tau_{in} \quad \ldots (9)
\]

Screw-drive

\[
\ddot{\theta}_{s} \left\{ J_{s} + M \frac{l^2}{4\pi^2} \right\} + \dot{\theta}_{s} \left\{ B_{s} + B \frac{l^2}{4\pi^2} \right\} + k_s \theta_{s} + \frac{l}{2\pi} F_{ext} = k_2 \frac{R_{g1}}{R_{g3}} \theta_{g1}
\quad \ldots (10)
\]

Inertial Platform

\[
F_{ext} = k_3 (x - x_1)
\quad \ldots (11)
\]

Where, \(F\) - Force; \(k\) - linear stiffness

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{gear_train_diagram}
\caption{Mechanical Connections of the Electromechanical Linear Actuator}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{screw_diagram}
\caption{Rotation to Linear Travel}
\end{figure}

3.3 Evaluation of operational speed and torque for varying lead of roller screw

The speed and torque of the roller screw varies with the lead. Lead is the linear distance moved by the roller screw upon one revolution. So as the lead increases, the speed of the screw increases and hence the motor speed requirement also increases. The speed-torque variation with lead should be studied so as to select the right lead based on load requirement.
4. Results and Discussion

4.1 Input and Braking Torque

In the Figure 4, at steady state, L_6 has the least input torque of 58 Nm and the L_20 has the highest input torque of 160.5 Nm. The L_6 screw requires the minimum back driving and braking torque of 33 Nm and the L_20 screw requires the maximum torque of 136 Nm. If back driving is not desired, a braking mechanism must be provided.

![Figure 4. Effect of lead size on Input and braking torque](image)

4.2 Nominal Motor Torque

This is the amount of torque needed from the motor. From the figure 5, the L_20 requires the highest motor torque of 595.2 Nm during an acceleration of 3 rad/s^2. During retardation, L_6 requires the highest braking torque of 445.6 Nm and that of L_20 is 277.64 Nm. The results above do not include the preload torque. Preload torque, which is given to eliminate backlash, would increase the above obtained results.
4.3 Steady State Power

Figure 6 represents the power requirement for L_6, L_12, L_20 are 12.9 kW, 11.4 kW, and 10.7 kW respectively. With reference to L_6, the percentage reductions in power are 12.13% and 5.9%.

4.4 Efficiency

There are 4 efficiencies measured for the screw viz., theoretical direct, theoretical indirect, practical direct and practical indirect efficiency. Direct efficiency measures the input torque required to transform the rotary motion to a translatory motion. Indirect efficiency measures the reverse of this
and is a defining factor for the braking torque needed to prevent that rotation. Figure 7 shows that the screw with 20 mm lead has the highest theoretical efficiency of 93.15%. Comparing with L_6, L_12 has a significant increase in the efficiencies whereas increasing to L_20, a marginal increase in efficiencies is seen.

![Efficiency Graph](image)

**Figure 7.** Effect of Lead size on Efficiency

### 5. Conclusion

Comparing the three leads, L_12 has the following advantageous aspects

- The steady state power requirement of L_12 is 12.7% reduced compared to L_6. For comparison L_20 provides a reduction of only 5.5%
- L_12 shows about 11% increase in theoretical efficiency over L_6 but L_20 gives only a 4.5% improvement over L_12.
- L_12 has an input torque of 102 Nm which is sufficient for our required load

So, the screw of 12mm lead satisfies our need and so has been selected for the actuator.

The motor selected has a rated speed of 3400 rpm. The rated torque of the motor is 11.42 Nm and the peak torque being 61.06 Nm. Figure 8 shows the speed- Torque characteristics of the motor.
The static and dynamic torque capacity of the clutch to be used is 60 Nm and 40 Nm respectively. The engagement and disengagement times are 200 ms and 80 ms respectively.

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