Electro-Mechanical Actuator Servo Design For Launch Vehicle Application

[1] Lini M.Thomas, [2] Mrs. B. Hemalatha
[1] PG student, [2] Assistant professo,
Dept. of Instrumentation & Control Engineering
SRM University Kattankulathur
Tamil Nadu, India,
[1] linimorrinthomas@yahoo.co.in, [2] Lathab99@yahoo.com

Abstract: **—** In a launch vehicle the Electro-Mechanical Actuation (EMA) system gimbals the rocket nozzle and provides accurate steering of the vehicle. The adequate amount of force or thrust at the gimbal point is obtained by the small rotation of the gimbal. The force generated from the EMA system stabilizes and steers the launch vehicle in the required direction in to overcome the wind-gust disturbances and balance the aerodynamic movements. The mathematical model of the linear actuator is considered for the servo system design. In this paper the servo design of the actuation system is carried out for the launch vehicle application. The servo system integrates actuators, sensors and embedded intelligent systems for control, optimization and supervision which aim in improving the performance of the system. Due to high reliability demands of such systems, accurate supervision and fault diagnosis concepts are of particular importance.

Index Terms**—** Compensator design, EMA, Servo design, Step response, TVC system

I.INTRODUCTION

In reference to the literature [1, 2], for better control of the motion the control systems were designed to operate at a fixed speed. An actuator is a motor that is used for creating a movement or for controlling a mechanism or a system. They are the key component in any industrial system. It is operated by a source of energy, such as electric current, hydraulic fluid pressure, or pneumatic pressure, and converts that energy into a movement. EMA are nowadays replacing the hydraulic actuators for Thrust Vector Control (TVC). They are used in a variety of flight control systems of aircrafts, missiles and launch vehicle. They are also used as shock absorbers for the rocket liquid fuel engines at their ignition due to the initial combustion instability.

The paper discusses the position control system which is based on an electromechanical actuator. The position servo system used is a Brushless DC motor (BLDC) and it is considered as an electromechnical actuator. The servo system consists of the main drive element which is the BLDC torque motor and a ball screw mechanism with very high precision, enclosed with in closed loop position control [2] to achieve best accuracy and performance. The position measurement consists of an LVDT position sensor. The entire work involved in this paper may be outlined into actuator design, system simulation and performance evaluation.

II.SYSTEM DESCRIPTION

The engine configuration of the liquid stage EMA system is shown in Fig.1. The nozzle is gimbaled using an orthogonal electro-mechanical actuator; that control the deflection of the nozzle of the engine [1]. The actuators are used for the movement in yaw and pitch direction. One end of the actuator is attached to the trust frame of the vehicle and the other end of the shaft is attached via a linkage mechanism to the nozzle and causes it to pivot about its hinge. The actuator length can be varied by the electro mechanical force that causes the shaft to extend or retract. During the flight, the flight control system and the actuators are commanded by the autopilot to either extend or retract to achieve the desired pitch and yaw changes in engine rotation and hence achieving the required nozzle deflection.

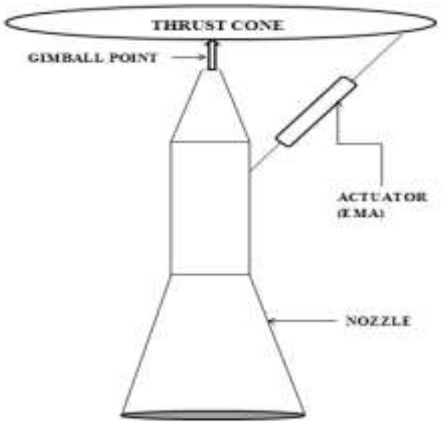

Fig.1. Schematic diagram of TVC servo actuation system

Block diagram of a TVC system based on an electro mechanical actuator is shown in Fig.2. The actuator under consideration is a linear electromechanical actuator in which the main element is a brush less DC torque motor [2]. It represents a closed loop position control of a BLDC motor excited from a DC source. The angular position of nozzle is sensed using Triple redundant LVDTs. The angular position is compared with a voltage equivalent to the desired displacement. The resulting error voltage is amplified, compensated and is fed to the BLDC torque motor, which in turn will produce the opposing moment torque in order to nullify the error signal about the nozzle pivot point. PWM amplifier provides the required power amplification for the control signal.

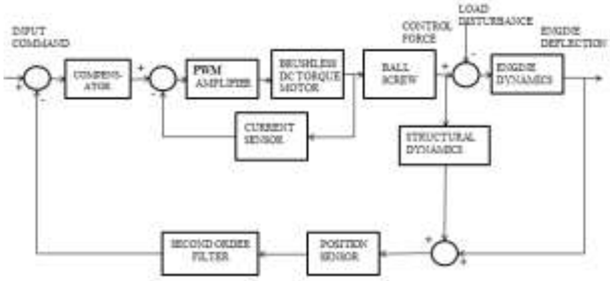

Fig.2. Block diagram of an actuator used in launch vehicle application

III.ELECTROMECHANICAL SYSTEM MODEL

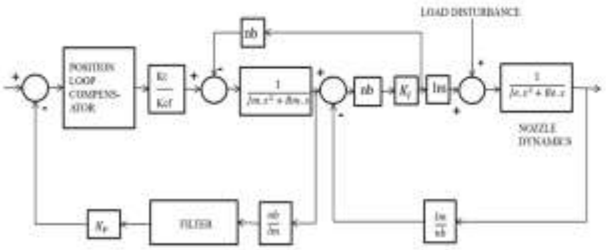

Fig.3. linear model of the EMA OF launch vehicle

The linear model of the EMA [2] considered for the thrust vector control is as in Fig.3. The mathematical model of the torque motor employed in the actuation system for servo development and analysis is expressed in (1).

$$G_M = \frac{1}{J_m S^2 + B_m S} \qquad (1)$$

The net driving torque available to accelerate the motor rotating moment of inertia is derived from the linear model of the EMA system and is given in equation (2).

$$T_m = T_{gm} - T_{lm} \qquad (2)$$

Where $T_{gm} = K_T \times i_m$; is the rotary motor torque and $T_{lm} = F_L \times nb$; is the load torque transmitted to the motor side. The Load force (F_L) transmitted to motor side is given by (3).

$$F_L = \theta_m - \left(\delta_e \times \frac{lm}{nb}\right) nb \times K \qquad \textbf{(3)}$$

Where θ_m and δ_e denotes the Motor angular position and the nozzle deflection respectively. Driving torque of the nozzle dynamics is expressed in the equation (4).

$$T_L = F_L \times lm - T_D \qquad (4)$$

Where T_D is the load disturbance and the effect of T_D is such a way that A positive T_D will produce a positive actuator force. Demodulator filter with dynamics equivalent to that of a second order Butterworth filter is used to extract the signal from LVDT output. LVDT output is related to motor output as follows, in equation (5).

$$V_{LVDT} = \theta_m \times \frac{nb}{lm} \times K_p \qquad (5)$$

Table.1. System parameters and description

SYMBOL	DESCRIPTION
B_e	Viscous damping coefficient of engine gimbal
B_m	Viscous damping of torque motor
J_e	Engine moment of inertia
J_m	Moment of inertia of torque motor rotating assembly
K_b	Torque motor back emf constant
K_{cf}	Current loop feedback gain
K_l	Equivalent stiffness of actuator mounting
K_p	LVDT scale factor
K_t	Torque sensitivity of motor (for $i_m = 0$)
l_m	Actuator lever arm length
n_b	Ball screw gear ratio
N_{ch}	Number of operating channels of torque motor

IV.DESIGN OF COMPENSATOR

Based on plant dynamics and the requirements the compensation scheme for the TVC actuation system has been designed for improving the dynamic performance of the system. The compensator design consists of a pseudo rate loop and a position loop. The position loop compensator consists of a notch filter, lag filter and a gain. The pseudo rate loop is derived from position sensor (LVDT) output. It improves the rigid body servo mode through sufficient damping to the resonant mode.

For launch vehicle application the frequency specificationsare:

1. -3Db Bandwidth=4.5+/-0.5 Hz
2. -90 degree Bandwidth=4.0+/-0.4Hz

The lag compensator and notch compensator in order to meet the above frequency specifications.

A. *Lag compensator:*

Lag compensators are essentially low-pass filters. They permits a high gain at low frequencies in order to improve the steady state performance of the system and thus improves the phase margin.it also reduces large steady state error in the system.

B. *Notch filter:*

A notch filter is provided in the forward path of the position loop to suppress the excitation of this mode [2]. The function of the notch filter is to attenuate the gain of the system at the required frequency value.

Consider the transfer function of the notch filter:

$$\frac{S^2 + 2\zeta_1\omega_n + \omega_n^2}{S^2 + 2\zeta_2\omega_n + \omega_n^2}$$

The parameters ζ_1, ζ_2 and ω_n are adjustable and the ratio $\frac{\zeta_1}{\zeta_2}$ sets the depth of the notch. The frequency ω_n is the natural frequency of the notch. The coefficient of the numerator is 0.1 and that of the denominator is 0.5.

V.SIMULATION RESULT

The open loop frequency response of the uncompensated system is as in Fig.4. The open loop response gives the phase margin as,

Open loop gain margin of uncompensated system,

$$\gamma_n = 7.3661^0$$

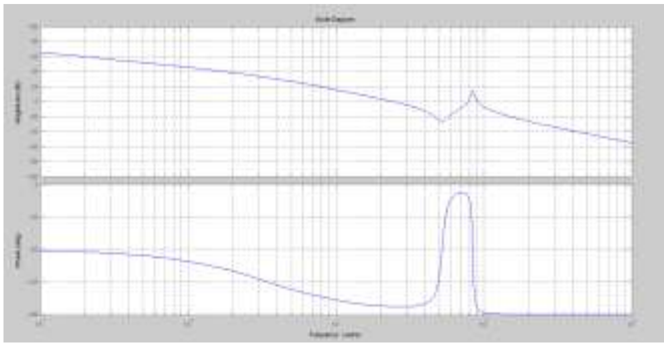

Fig.4. Open loop bode plot of the uncompensated system

The compensator is designed and the frequency response of the compensated system is obtained as in Fig.5. From the closed loop frequency response the -3db frequency and -90 degree frequency is obtained as required for a launch vehicle application by trial and error method as in table 2.

Table 2. Frequency specification for desired gain margin

Desired gain margin	-3db frequency	-90^0 Frequency
30^0	11.5 Hz	8.323 Hz
12^0	4.1 Hz	4.5Hz

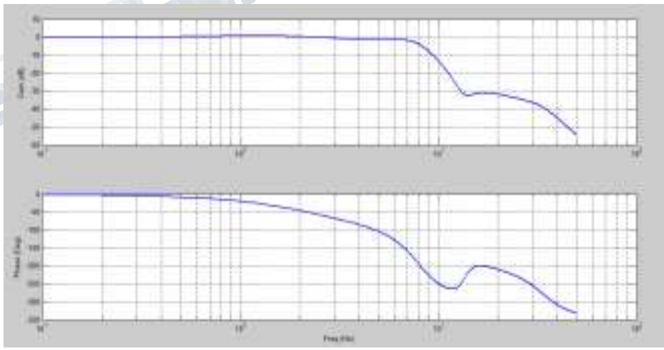

Fig.5. Bode plot of the compensated system

The step response of compensated system is given in Fig. 6, which shows that the servo system is tracking the command

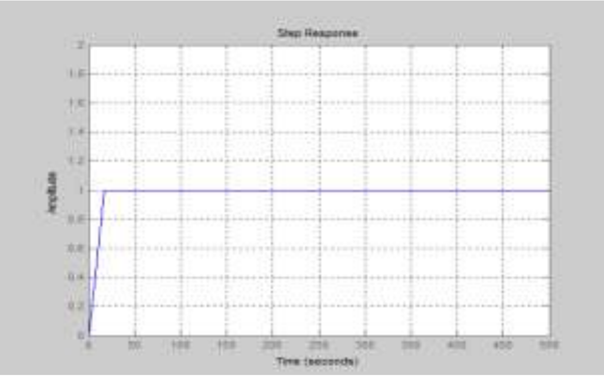

Fig.6. Step response of the compensated sytem

VI.CONCLUSION

The servo design was carried out by choosing BLDC motor as the actuation system. The frequency and the step response of the compensated system were obtained with the -3db frequency and 90 degree frequency within the required range for the launch vehicle application.

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