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Simulation and Analysis of Electro-Mechanical Actuator with Position Control

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ABSTRACT

In recent times, Electro-Mechanical Actuator (EMA) is widely employed in various aerospace applications because of its compactness, ease of maintenance, and cost efficiency. It attracts most of the researcher for simulation and performance analysis. It is very much important to study its control system behaviour. In general, EMA requires, three loop cascade control, but for aerospace application two loop cascade control is used for speed and position controls due to dynamic load changing requirement. Most research efforts on EMA system has used a transfer function model of all its subsystems. Nevertheless, this technique does not yield complete outcomes for analysing its performance. To analyse its performance and characteristics in dynamic condition, an experimental model is essential. In addition, this model needs to cater for analysing performance of different capacity EMA. The primary goal of this work is to simulate unique EMA model with position control using a practical data and analyse its performance. In this design, EMA is modelled by three-phase Brushless Direct Current (BLDC) motor, six-step commutation logic, a speed sensor (Tacho) and a position sensor using Linear Variable Differential Transformer (LVDT). Position and speed controls are handled by Proportional (P) and Proportional plus Integral (PI) controllers respectively. The process reaction curve method is used to tune the controllers. This tuning approach is adequate to enable accurate and robust speed and position control. This paper focus on the simulation and performance analysis of a practical EMA system with position and speed controls in matlab-simulink. The performance analysis results shows that simulated model characteristic is close to physical system and reliable.

Keywords: EMA; Modelling; Control; Simulation; BLDC; Tacho; LVDT; Simulink

1. INTRODUCTION

In modern aerospace application, Electro-Mechanical Actuator (EMA) is used as a key component for control and manoeuvring of article position against the trajectory. Hence modelling and performance analysis of EMA is very essential to evaluate its characteristic.

In general, the characteristics of an EMA is studied using transfer function model with first or second order system approximation. This kind of approach may not yield complete information on system performance. To analyse its performance in efficient way, a practical model is required. It can be a unique model to evaluate its performance by varying physical parameters.

Considering its wide range of application, modelling, simulation and analysis are important in current scenario. The requirement of digital servo control actuator modelling and simulation analysis was discussed[1]. Modelling and simulation methods for cargo door actuator was presented[2]. The mathematical model, simulation and analysis of control system used in unmanned aerial vehicle was referred[3]. The model simulation and execution for embedded system was surveyed in[4]. The important of virtual model simulation for performance analysis of any process or system and implementation of Digital Twin is referred[5]. This gives the platform to simulate the unique EMA model for performance analysis.

EMA system consists of two parts, electrical and mechanical. The electrical part consists of three phase Brushless Direct Current (3Ø BLDC) motor, commutation logic, controllers and sensors (speed, position and current sensors). The mechanical part consists of rotor shaft, ball screw and output shaft.

Simulation of EMA system with position control using Simulink was discussed in[6-8]. The simulation of BLDC motor with speed control in Matlab was presented[9] by using transfer function model. The modelling and simulation analysis of BLDC motor and its drives was implemented[10–11] by using transfer function model.

The state phase method using Auto-regressive model with Exogenous input (ARX) model with least square criterion was used to model an EMA system using system identification and parameter estimation method in[12]. The speed sensor (tacho) model[13-14] was used and implemented for measurement of motor speed. The position sensor (LVDT) model along with signal conditioner was implemented and its performance is analysed in[15-16]. The LVDT model using geometrical parameters, with and without signal conditioner, implemented in simulink, was discussed in[17] and[18] respectively. The LVDT

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sensor compensation for non-linearity was implemented in[19] and extension of its measurement range using artificial neural network was presented in[20]. The LVDT sensor along with self-compensation was presented in[21]. The ball screw model was simulated and implemented in EMA[22] for conversion of motor rotational motion into linear motion.

The EMA system designed for aerospace application has to respond quickly as per the control and guidance requirement. The various control methods are envisaged for implementation. The analog controller is most suitable for aerospace application in view of simple in operation, easy of tunning and highly reliable. The tunning methods of PID controllers are referred in[23–26]. The Proportional (P) and Proportional plus Integration (PI) controllers are chosen for position and speed control respectively. It is simple and adequate to meet the control requirement of EMA system. The controllers are tuned by using Process Reaction Curve (PRC) method to achieve robust and fast control response and implemented in the matlab-simulink. The requirement and important of simulated model based analysis and validation for distributed system was discussed in[27].

In the simulation, practical models of three phase star connected BLDC Motor with drivers, six step commutation logic, speed and position controls are implemented for EMA system. Thus, a practical EMA system model has been simulated and its performance is analysed in time domain, subjected with step and ramp position inputs.

Further the model is analysed with repeated time varying input (sawtooth). The performance analysis results shows that the simulated model characteristic is close to physical system performance. This model can be used to study its behaviour by varying its physical parameters. In future, this model can be enhanced to other rating EMA to study its performance.

In section 2, the EMA system model has been explained with mathematical equation. The simulation of position control of EMA along with its subsystems in matlab-simulink is presented in section 3. In section 4, the performance analysis along with test results is elaborated. The conclusion for the present research work is presented in section 5, followed by direction for future work.

1.1 Highlights

- Practical EMA system model is implemented and analysed in time domain by using matlab-simulink.
- Its an unique model can be used for other rating EMA, to carryout performance analysis by simply varying its physical parameter.
- This model can also be used to study the system behaviour by introducing failure in sub systems.

2. SYSTEM MODEL

EMA system consists of BLDC motor, Pulse Width Modulation (PWM) inverter, commutation logic with gate drives, Hall position sensor, speed sensor (tacho), position sensor (LVDT) and ball screw. The EMA system can be represented in schematic diagram as shown in Fig. 1.

2.1 BLDC Motor

The BLDC motor is a permanent magnet synchronous motor having Hall position sensor embedded in the stator and PWM inverter for controlling the current in stator winding. The commutation logic through gate drives, control the PWM inverter supply based on the Hall sensor signal. The schematic diagram of BLDC motor and its control circuit is shown in Fig. 2(a).

where V_{DC} is motor DC supply, L_u, L_v & L_w are 3Ø motor coil inductance and symmetry, (i.e $L_u = L_v = L_w = L$), Q_1 to Q_6 are commutation logic drive switch commands

In general, the mathematical representation of the 3Ø BLDC motor in terms of phase voltage V, phase current i and back emf e, for three phases a, b and c is expressed in Eqn. 1[12]. The coil resistance R and inductance L are as per phase values, T_L is the load torque, J is the motor inertia, K_f is a friction constant and ω_m is the rotor speed. The line voltages (V_{ab}, V_{bc}

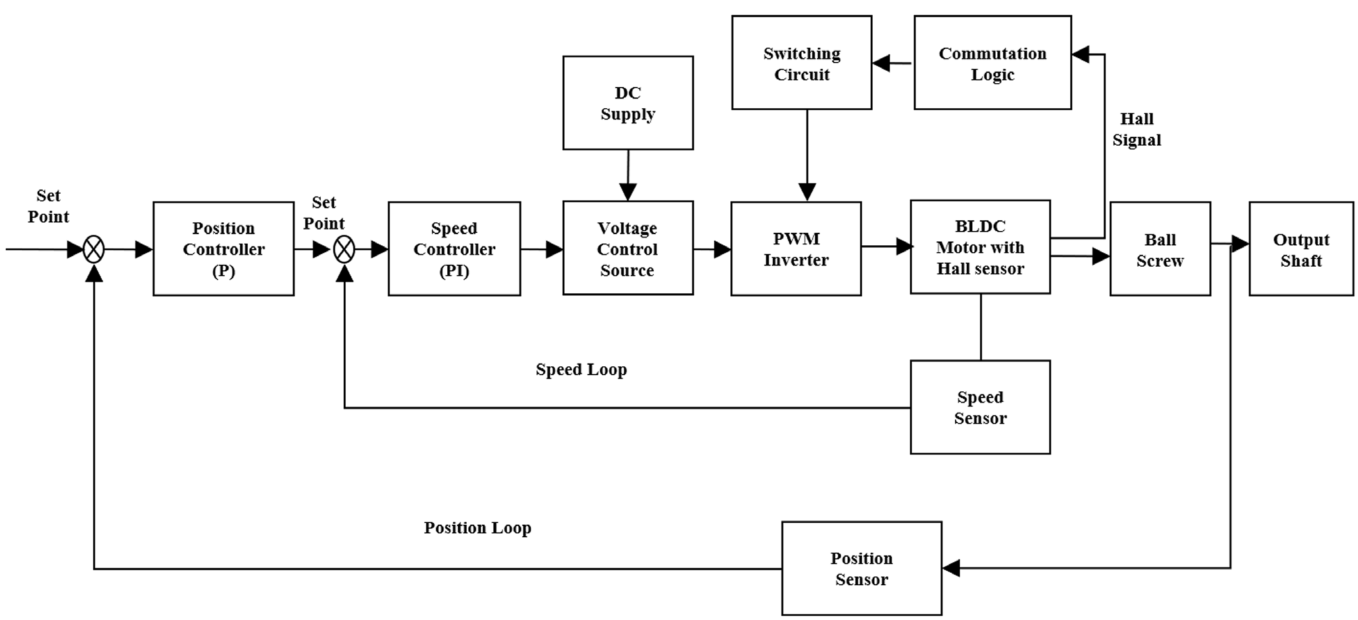

Figure 1. Schematic diagram of EMA system.

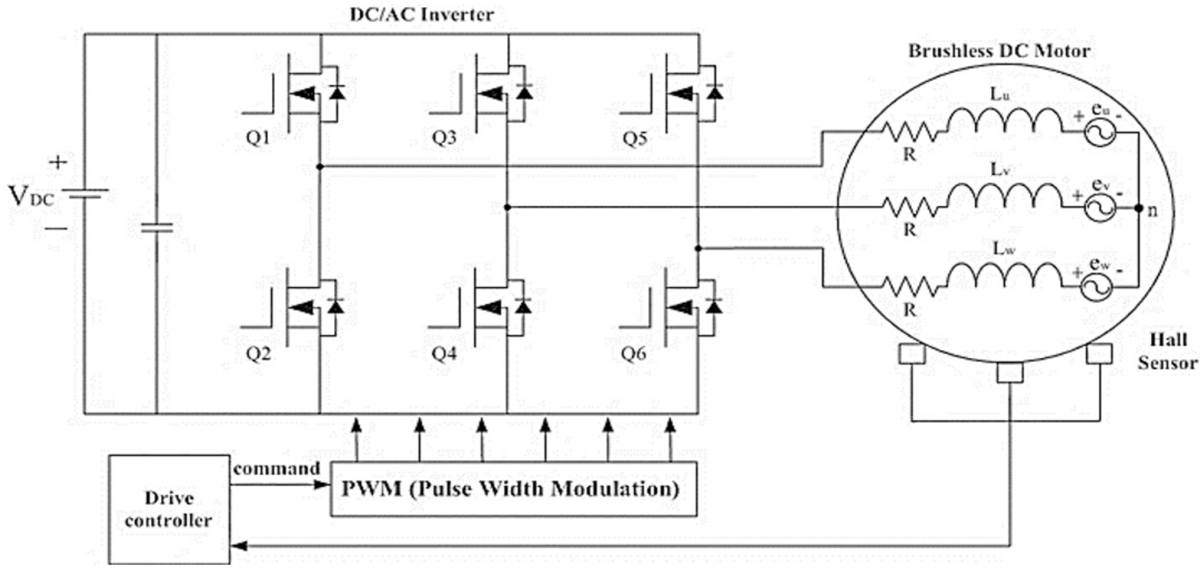

Figure 2. (a) BLDC motor schematic circuit.

and V_{ca}) are expressed in terms of phase currents (i_a, i_b and i_c) and back emf generated (e_a, e_b and e_c) as

$$\left.\begin{aligned} V_{ab} &= R(i_a - i_b) + L\frac{d}{dt}(i_a - i_b) - (e_b - e_a) \\ V_{bc} &= R(i_b - i_c) + L\frac{d}{dt}(i_b - i_c) - (e_c - e_b) \\ V_{ca} &= R(i_c - i_a) + L\frac{d}{dt}(i_c - i_a) - (e_a - e_c) \\ T_e &= k_f\omega_m + J\frac{d}{dt}\omega_m + T_L \end{aligned}\right\} \quad (1)$$

The back emf generated for the above three phases and electrical torque T_e can be expressed as Eqn. 2[12].

$$\left.\begin{aligned} e_a &= \frac{K_e}{2}\omega_m F(\theta_e) \\ e_b &= \frac{K_e}{2}\omega_m F(\theta_e - \frac{2\pi}{3}) \\ e_c &= \frac{K_e}{2}\omega_m F(\theta_e - \frac{4\pi}{3}) \\ T_e &= \frac{K_t}{2}\left[F(\theta_e)i_a + F(\theta_e - \frac{2\pi}{3})i_b + F(\theta_e - \frac{4\pi}{3})i_c\right] \end{aligned}\right\} \quad (2)$$

Where, θ_e is electrical angle, K_e and K_t are the back emf and torque constants respectively.

2.2 Speed Sensor

The speed sensor (tacho generator) is used for measurement of rotor speed and fed to the speed controller. The motor speed is measured in number of revolution per minute (rpm). The mathematical representation of sensor is expressed in Eqn. 3[13–14] the output voltage generated per phase, V_0 is

$$V_0 = 4.4f\varphi T_{ph}K_cK_d \quad (3)$$

Where f is frequency, ϕ is flux per pole, T_{ph} is number of turns per phase and K_c & K_d are constants, assumed as 1.

2.3 Position Sensor

The position sensor (LVDT) is used for measurement of output shaft position of the motor. The schematic diagram of the LVDT is shown in Fig. 2(b).

The mathematical representation of sensor is shown in Eqn. 4[18]. The core inserted in the secondary coil windings 1 and 2 respectively.

$$E_0 = \frac{E_1(N_s g(t_1^2 - t_2^2))}{4h_2N_pG} \quad (4)$$

Where, E_1 is input voltage, N_s is no. of turns in secondary winding, g is magnetic conductance, t_1 & t_2 are length of the core inserted in the secondary and primary windings respectively, h_1 & h_2 are length of the primary and secondary windings respectively, R is radius of flux in free space, N_p is no. of turns in primary windings and G is relative magnetic conductance.

The magnetic conductance, g is given in Eqn. 5[18] where μ_0 is permeability of air, D is diameter of outer winding and d is diameter of core. The relative magnetic conductance (G) is

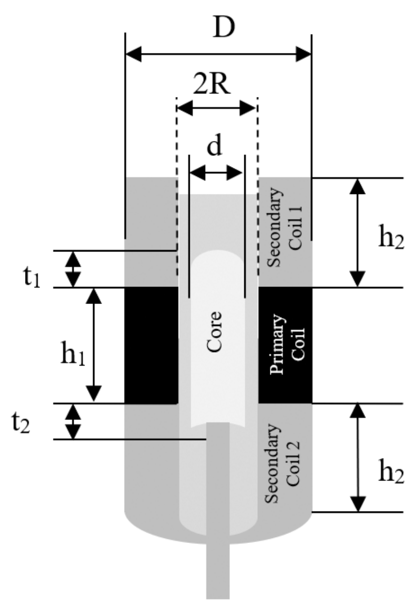

Figure 2. (b) LVDT schematic circuit.

given in Eqn. 6[18] with G_{p1} and G_{p2} being magnetic inductance due to primary flux in up and down respectively, G_{s1} and G_{s2} are magnetic inductance due to secondary flux in up and down respectively and G_{m1} and G_{m1} are mutual inductance due to inward and outward core movement respectively.

$$g = \frac{2\pi\mu_0}{\log(\frac{D}{d})} \tag{5}$$

$$G = \frac{(G_{p1} + G_{s1} + G_{m1})(G_{p2} + G_{s2} + G_{m2})}{(G_{p1} + G_{s1} + G_{m1} + G_{p2} + G_{s2} + G_{m2})} \tag{6}$$

The rotor shaft is connected to ball screw mechanism. This ball screw is used for conversion of rotor's rotary motion to linear motion. The ball screw mechanism is being used in most of the EMA due to its low energy consumption, high efficiency and minimum maintenance. Ball screw without backlash is considered in this simulation for the purpose of simplification[22].

The PI and P controllers are used for the speed and position control of the EMA system. The difference between position set point and LVDT output is fed to the position controller. The position controller output will be the set point for the speed control loop. The difference between speed set point and tacho output is fed to the speed controller. The speed controller output will set the voltage requirement to BLDC motor. Based on the applied voltage, the BLDC motor will rotate. This allows the ball screw to move in linear direction and drives the output shaft.

Table 1. Specification of BLDC motor

Parameters	Values with units
No. of poles (N_p)	16
No. of phase (Ø)	3 Ø
Rated Voltage (V)	100 V
Rated speed at No load	3000 rpm
Rated torque at No load (T)	10 Nm
Max. Peak torque (T_p)	20 Nm
Max. Peak current at load (I_p)	100 A
Rated power (P)	2000 W
Torque constant (T_c)	0.25 Nm/A
Back emf constant	0.25 V/rad/s
Line to line Resistance (R)	0.2 Ω
Line to line inductance (L)	0.2×10^{-3} H

Table 2. Specification of Tacho speed sensor

Parameters	Values with unit
Speed at No load (N)	3000 rpm
No. of Turn Per Phase (T_{ph})	114
Flux per pole (Ø)	0.025×10^{-3} Wb
No. of Phase	3Ø
Flux Density (B)	0.57 Wb/m^2
Frequency (f)	400 Hz
Back emf constant	0.02 V/rad/s

Table 3. Specification of LVDT displacement sensor

Parameters	Values with unit
Input voltage (V_{in})	3.3V
No. of turns of primary coil (N_p)	1000
No. of turns of secondary coil (N_s)	1000
Length of primary coil (h_1)	70×10^{-3} m
Length of secondary coil (h_2)	70×10^{-3} m
External diameter of coils (D)	20×10^{-3} m
Core diameter (d)	10×10^{-3} m
Length of core inserted in secondary coil at null position (t_o)	37.5×10^{-3} m
Radius of flux in free space(R)	15×10^{-3} m

3. SIMULATION OF EMA SYSTEM

The practical data for the EMA subsystems like 3Ø BLDC motor, PWM inverter, commutation logic, speed sensor (Tacho) and position sensor (LVDT) are used for system simulation. The technical specification for these subsystems is characterised based on the practical data.

3.1 Simulation of BLDC Motor

The technical specification for 3Ø BLDC motor has been taken for simulation and tabulated in Table 1. The simulation has been carried out with 6 step commutation logic, PWM inverter and gate signals based on Hall sensor feedback[12]. The simulated motor performance is analysed and presented in Sec. 4.

3.2 Simulation of Speed Sensor

The technical specification for Tacho speed sensor has been taken for simulation in matlab and highlighted in Table 2. The tacho speed sensor has been taken in view of accurate speed measurement requirement. The speed sensor model has been simulated in matlab based on the geometrical parameters[13]. The sensor performance is analysed with various speed. The analysis result is presented in Sec. 4.

3.3 Simulation of Position Sensor

The technical specification for position sensor (LVDT) used for simulation is listed in Table 3. The LVDT model has been simulated based on the geometrical parameters[17]. These geometrical parameters are used for optimum design of LVDT model[18]. The sensor with signal conditioner model has been simulated. The simulated LVDT model is analysed with various position input. The analysis result is presented in Sec. 4.

3.4 Simulation of EMA System

EMA system model has been simulated by using the sub system models of 3Ø BLDC motor along with PWM inverter, commutation logic & gate drives, speed (Tacho) sensor and position (LVDT) sensor. The simulated model of EMA system is presented in Fig. 3. The physical EMA test setup is shown in Fig. 4. This test setup is used for collection of data of EMA system performance. The simulated model performance has been compared with physical system. The performance comparison is elaborated in Sec. 4.

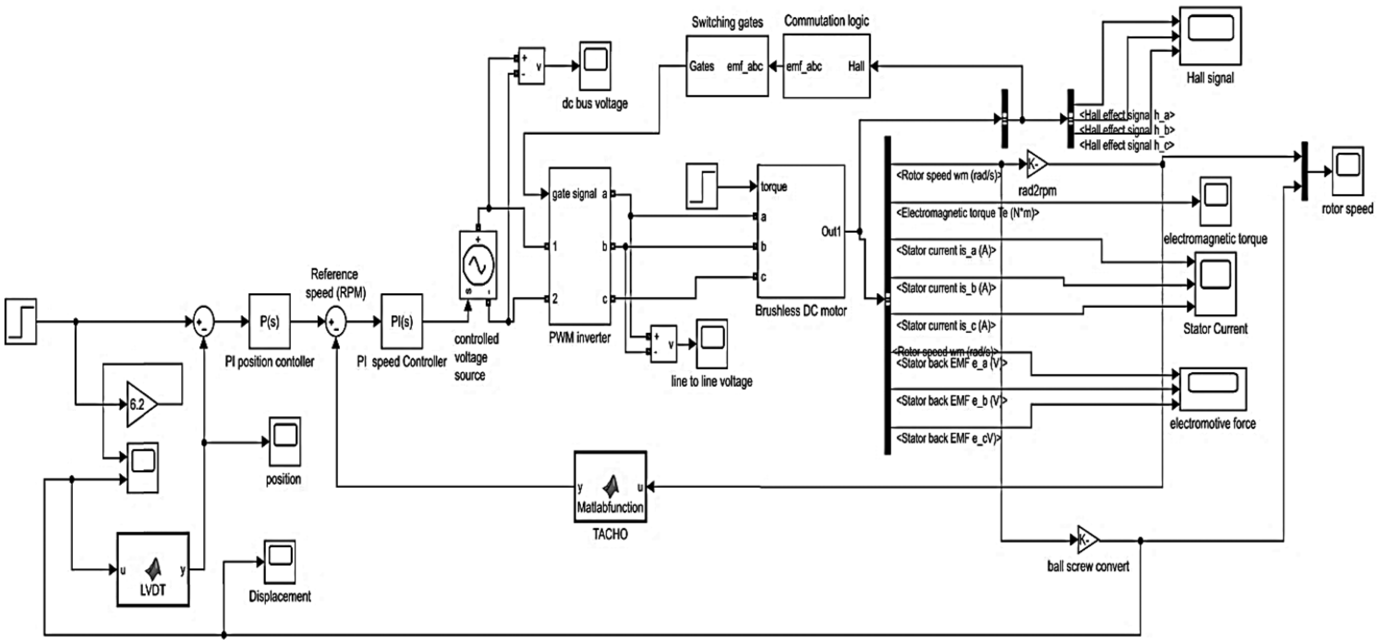

Figure 3. Simulation of EMA system in simulink.

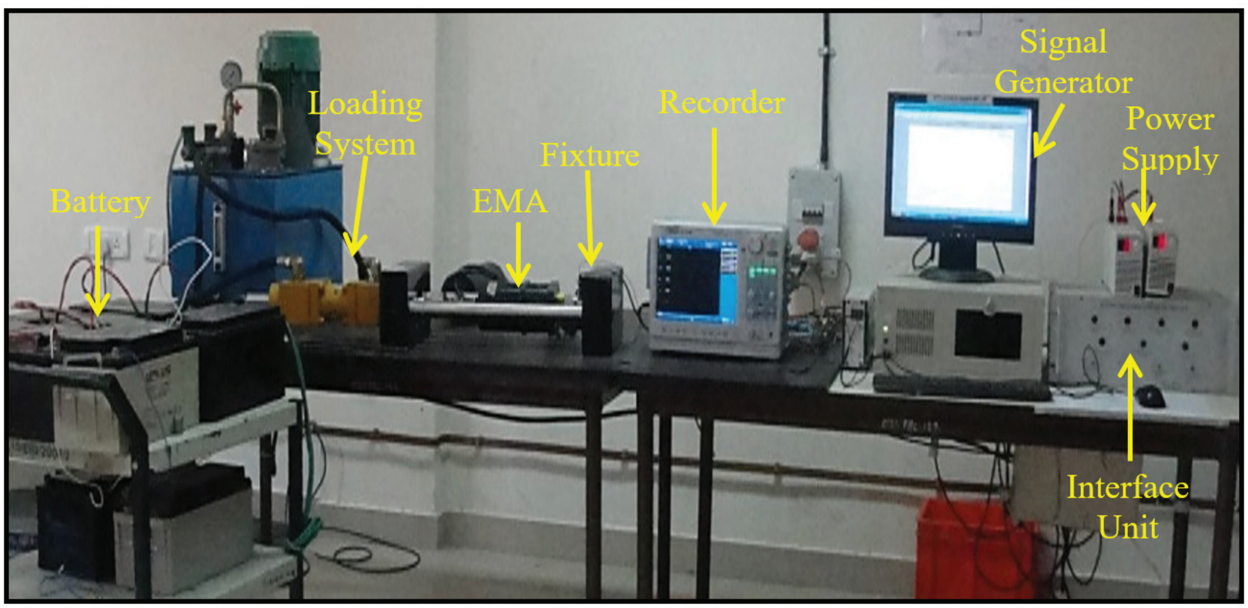

Figure 4. EMA working model test setup.

The speed and position controls are incorporated by using PI and P controller respectively. The PI and P controllers are chosen in order to minimise the speed and position error and reach the required set point quickly. This is a mandate requirement for aerospace system control and guidance application. These controllers are tuned using PRC method to achieve quick and robust control response. Also, this method was selected to tune the controller without affecting the system performance. The tuned controller parameters are provided in Table 4. The values of Proportional gain (Kp) and Integral gain (Ki) are calculated based on the PRC method.

Based on the above controller tuning, the EMA system performance at different position set point is validated and details presented in section 4.

Table 4. Speed and position controller parameters

Controller	Kp	Ki
Speed (PI)	6.75	2.75
Position (P)	9.75	-

4. PERFORMANCE ANALYSIS AND RESULTS

The performance of position control of EMA system has been analysed. The motor performance was validated at different positions. The simulation results of 3Ø BLDC motor performance such as motor torque, Hall signal response, stator phase currents, trapezoidal back emf responses are analysed with two different position set points of 0 mm and 10 mm, set at 0 and 0.25 s respectively. The motor response is shown from Fig. 5(a) to Fig. 5(d).

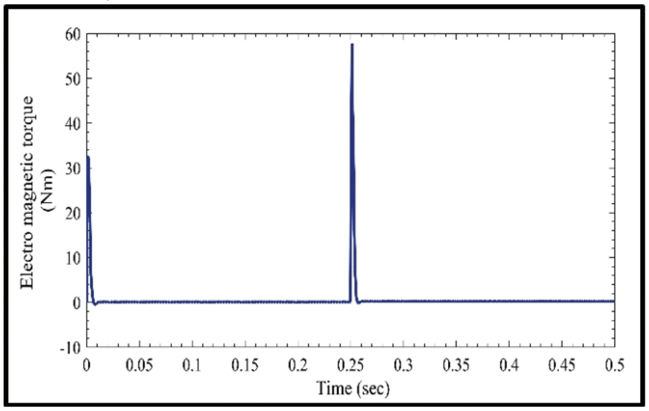

Figure 5. (a) Motor torque.

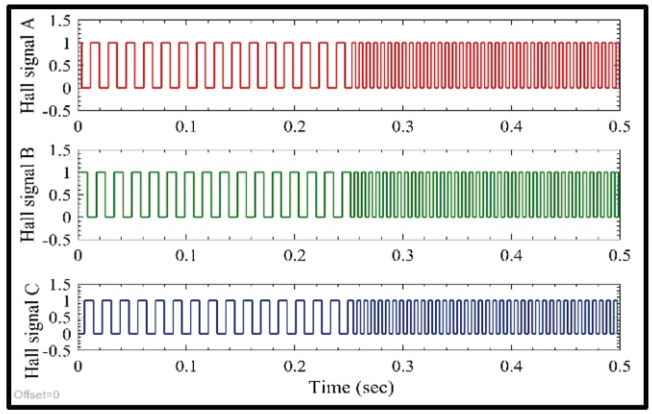

Figure 5. (b) Motor hall signal.

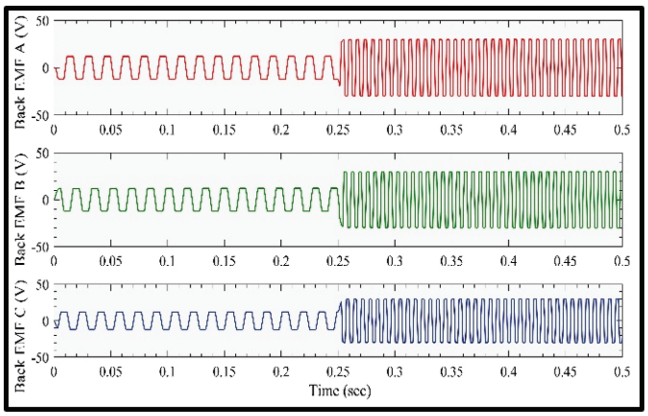

Figure 5. (c) Motor back emf.

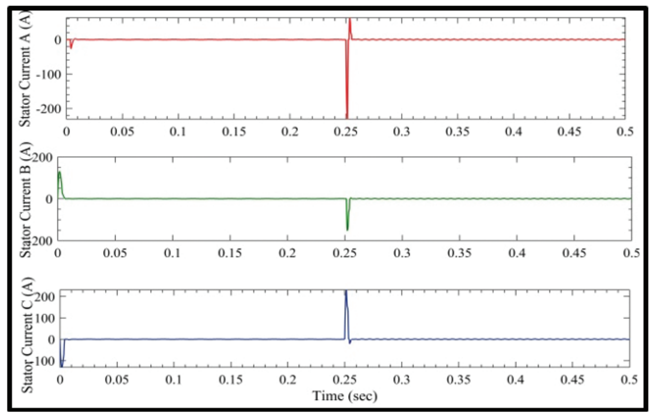

Figure 5. (d) Motor stator phase current.

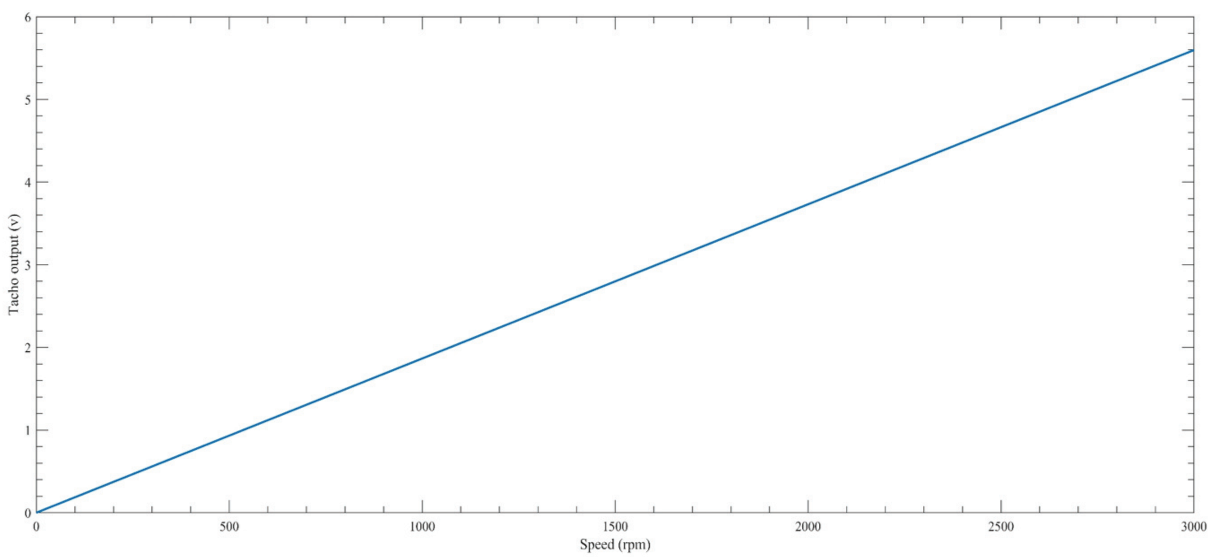

Figure 6. Tacho sensor response.

The speed sensor performance has been validated with various speed from 0 rpm to 3000 rpm. The sensor performance result is presented in Fig. 6. It shows the sensor output is linear with respect to speed.

The position sensor performance is analysed and presented in Fig 7. The sensor performance is validated with various displacement from -30 to +30 mm. The sensor output shows the linear response upto ± 21 mm and close to linear from ± 22 to ±25 mm displacement. The EMA operation requirement is ±25mm. Hence this sensor simulation is used for modelling of EMA system.

In this research work, the controller performances are studied in time domain by using step, ramp and saw tooth position inputs.

The step position input of 25 mm (maximum) is set to EMA without load at 0.1 s. The output response is shown in Fig. 8(a). The position setpoint is reached within 10 ms with overshoot of 0.08 mm. The speed controller performance is

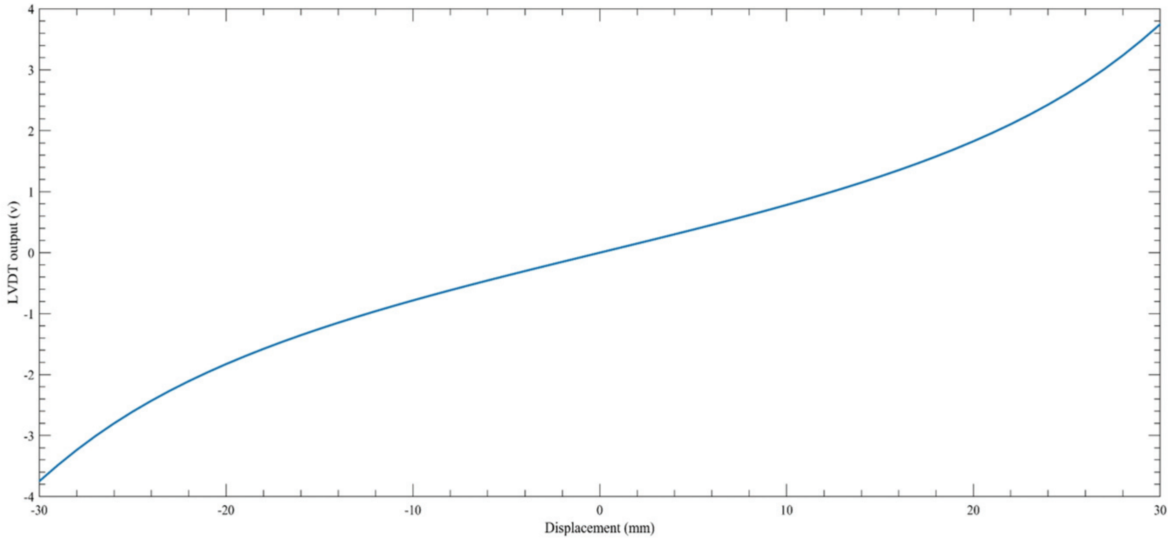

Figure 7. LVDT sensor response.

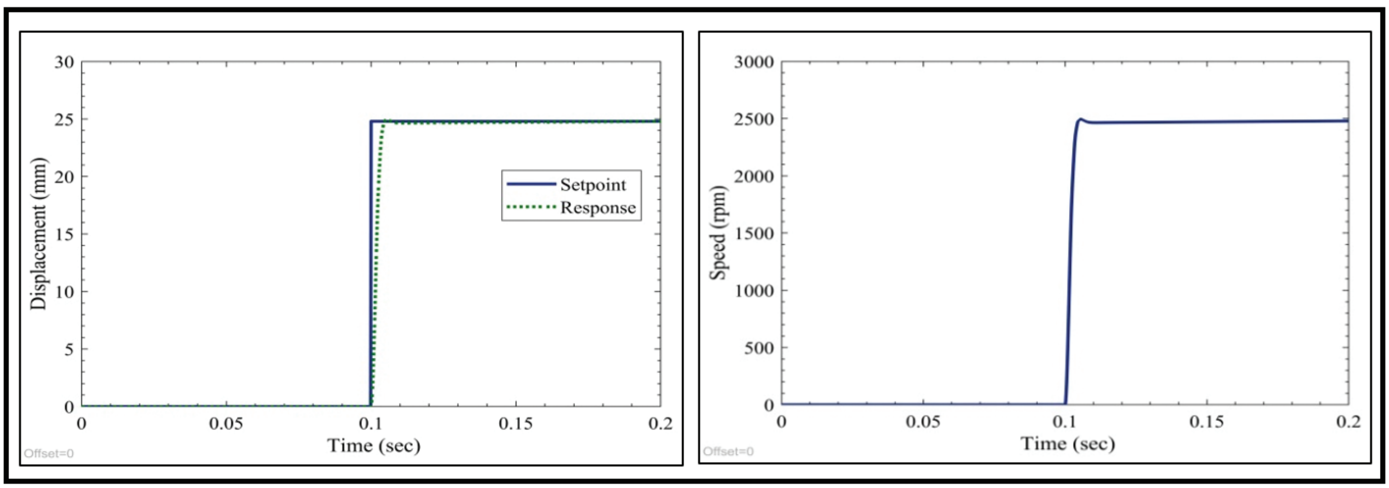

Figure 8. (a) Position and speed control response without load.

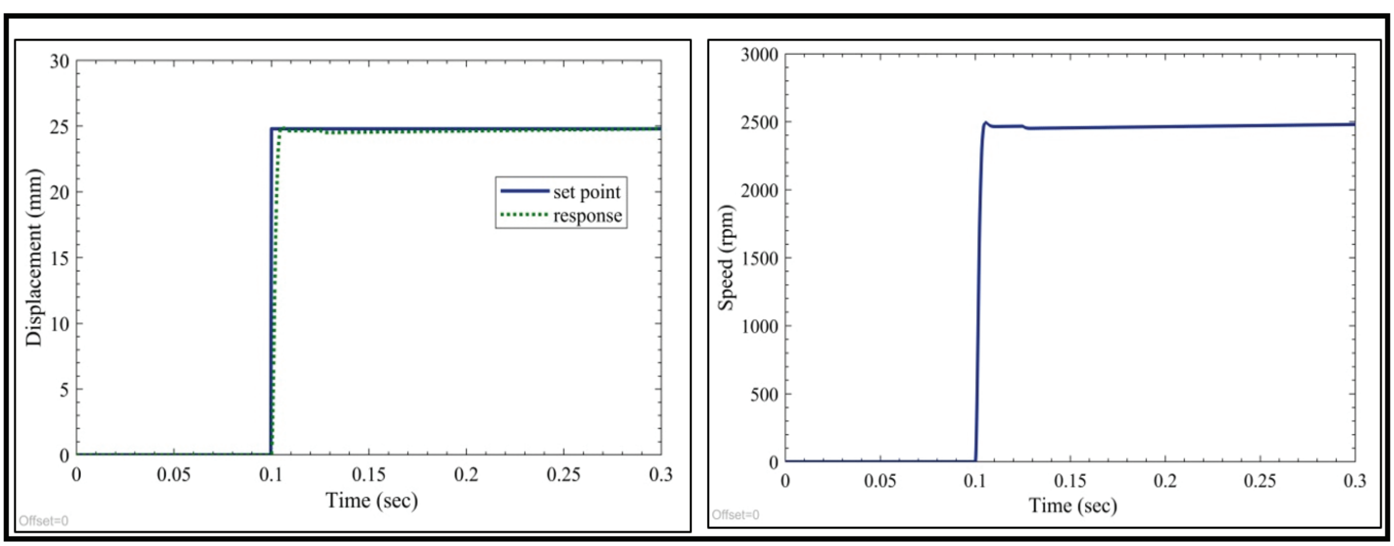

Figure 8. (b) Position and speed control response with load.

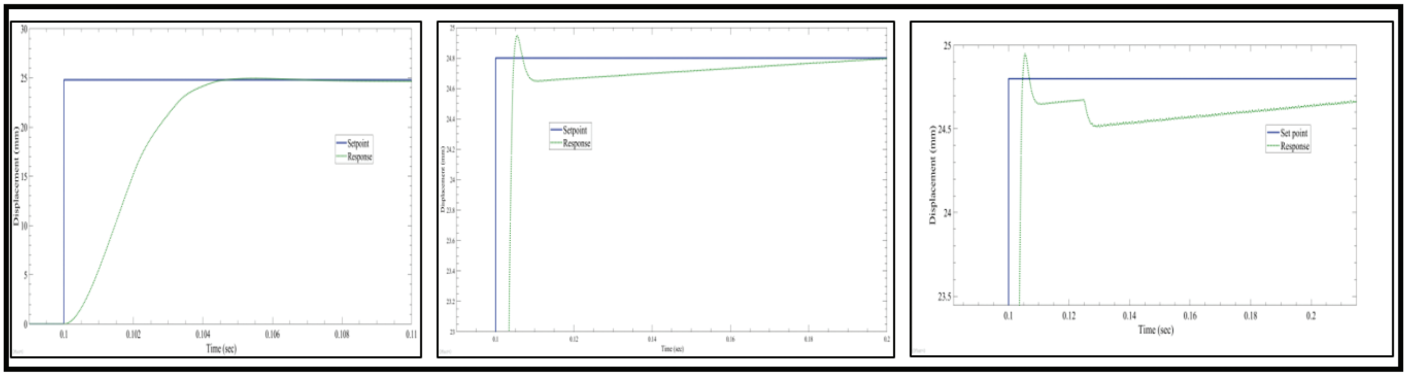

Figure 8. (c) Transient response with step input.

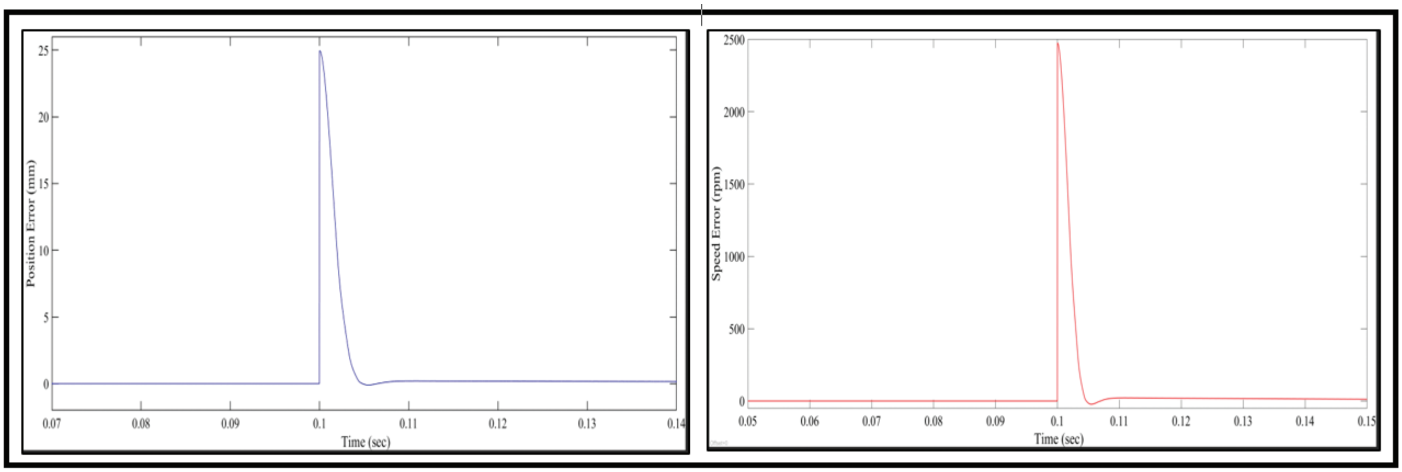

Figure 8. (d) Error plot of position and speed control with step input.

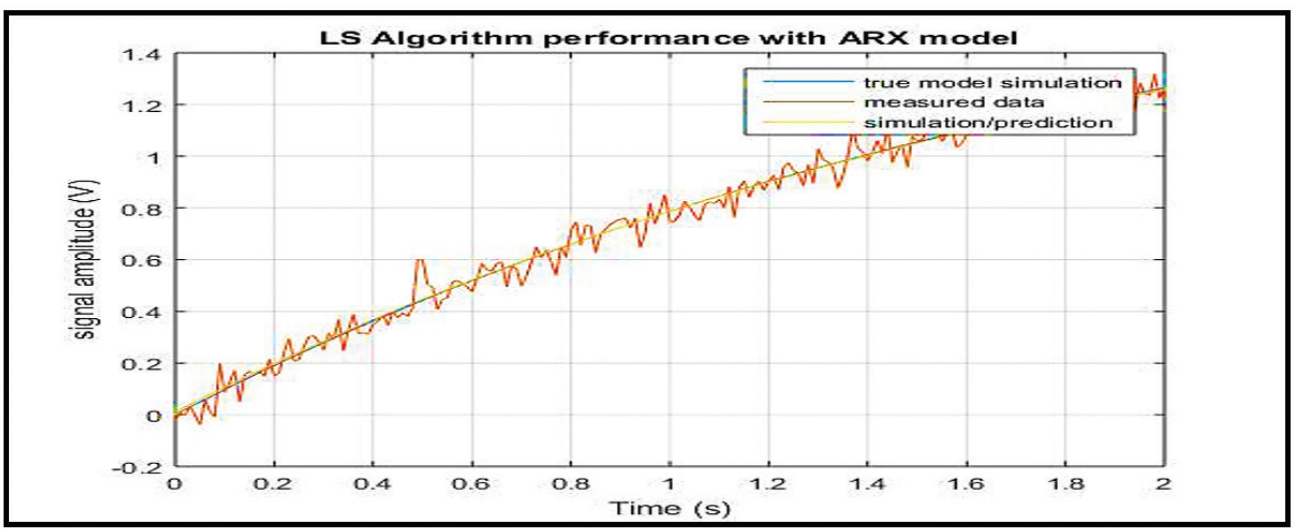

Figure 9. Comparison of simulated model.

shown in Fig. 8(a). This is meeting the acceptable limit of ≤ 50 ms response time and ≤ 1 % overshoot.

The load of 10 Nm torque is applied to motor at time 0.125 sec. The position and speed controller responses against the load are shown in the Fig. 8(b). This result shows that even load is applied on the motor, the controllers are able to maintain the required setpoint within 20 ms. The transient response of the position control in zoom view is shown in Fig. 8(c). The error plots for the position and speed control are shown in Fig. 8(d).

The simulated model performance has been verified with physical system in terms of signal amplitude and presented in Fig. 9. The performance matching of 98.6 % has been achieved.

The EMA system performance is further analysed with time varying position input. The system response is verified

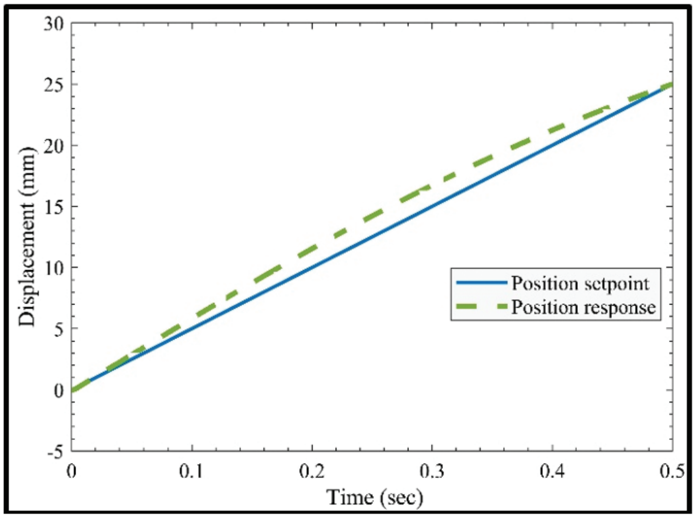

Figure 10. (a) Position control with ramp input.

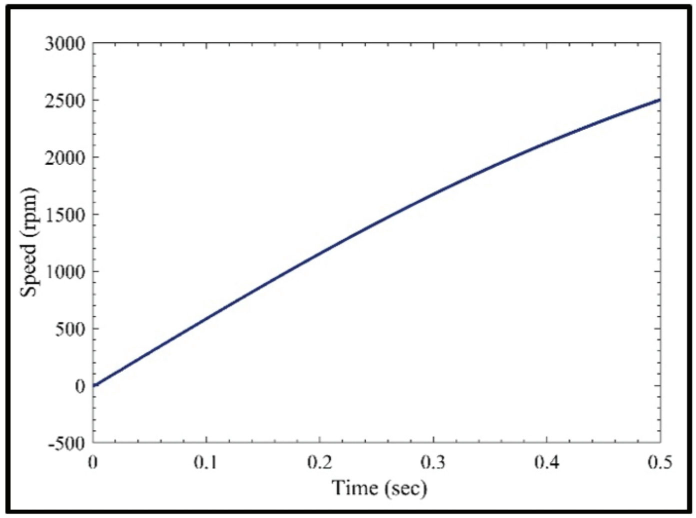

Figure 10. (b) Speed control with ramp input.

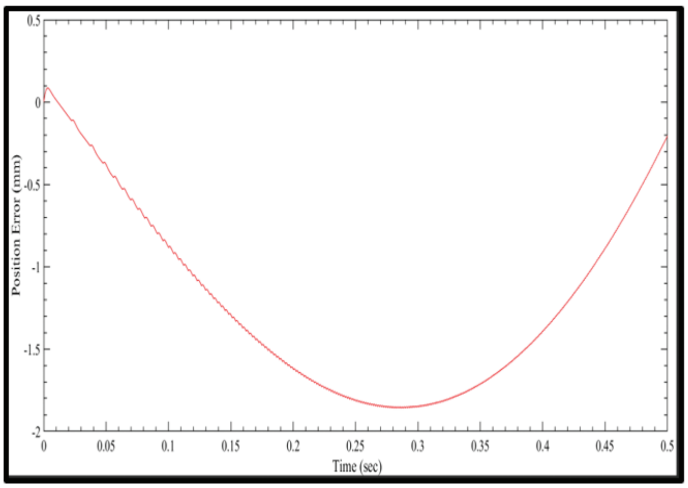

Figure 10. (c) Position error with ramp input .

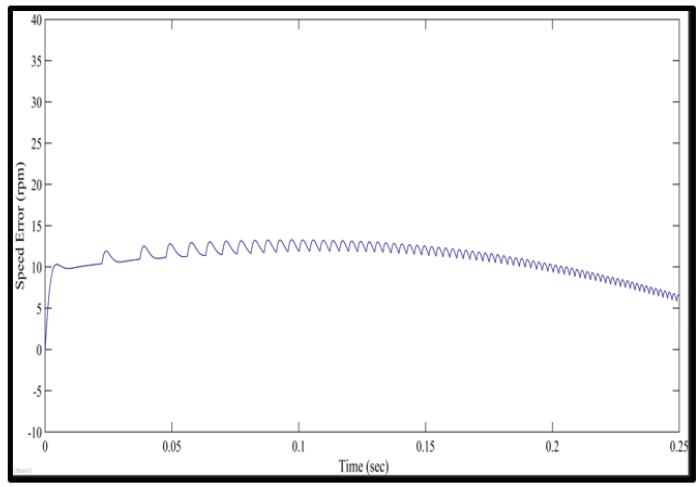

Figure 10. (d) Speed error with ramp input.

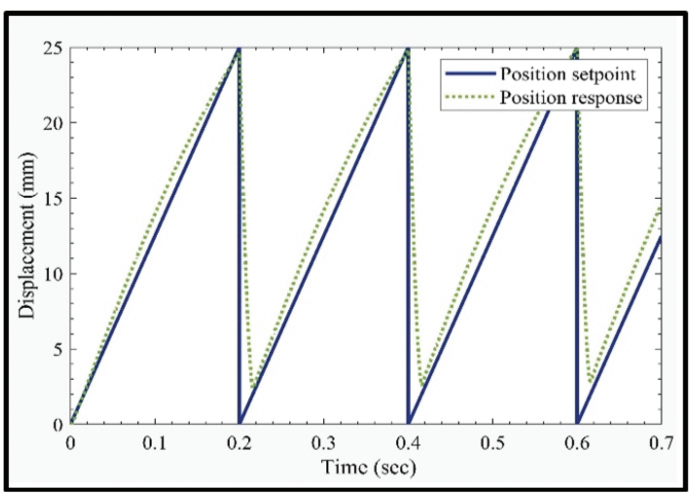

Figure 11. (a) Position control with repeat input.

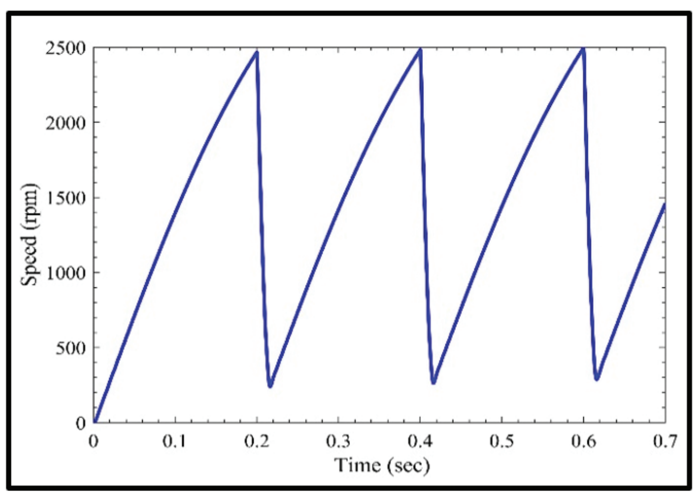

Figure 11. (b) Speed control with repeat input.

with time varying input (ramp signal). The position input of 50 mm per second is set. The delay of 20 ms is observed to reach the desired set point in the position response. The responses of position and speed controls are presented in Fig. 10(a) and Fig. 10(b) respectively. The error plots for the position and speed control are shown in Fig. 10(c) and Fig. 10(d)

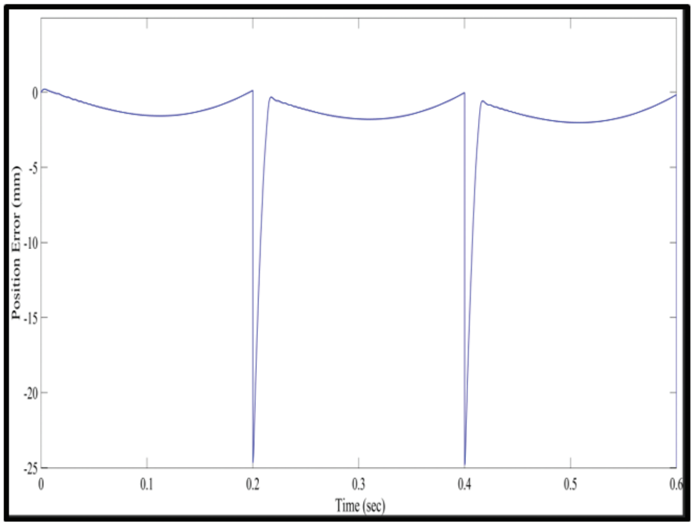

Figure 11. (c) Position error with repeat input.

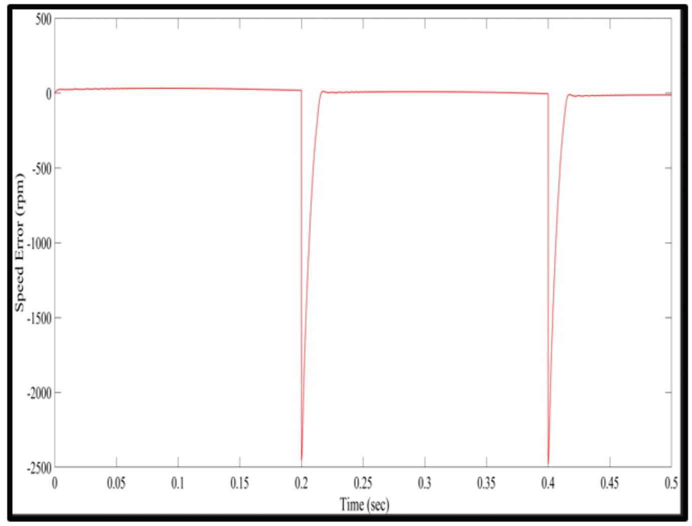

Figure 11. (d) Speed error with repeat input.

The position and speed control performance with repeated time varying input (saw tooth signal) is analysed. The sawtooth position input of 25 mm amplitude, 0.2 s time period for three cycle is set as input. Both the control responses are studied and presented in Fig. 11(a) and Fig. 11(b). The position and speed errors are shown in Fig. 11(c) and Fig. 11(d).

The above position control response indicated that the simulated model follows the required setpoint closely. The time delay of 20 ms is needed to respond to the repeated time varying position input. This time delay is an inherent characteristic of physical system due to its mechanical property. This simulation result shows that the practical model-based simulation has yielded results close to physical system performance.

5. CONCLUSION

The practical with geometrical model-based simulation and analysis of electro mechanical actuator system with position control was envisaged. Till date, not much research work on the practical model based simulation study for EMA was reported. The geometrical parameter for subsystems of EMA was used precisely for implementation in matlab-simulink platform. The simulated EMA model has been analysed in time domain and the responses were presented in the form of performance analysis results. The EMA performance has been checked with various step position set point with and without load. The analysis shows that controller reach the required position of 25 mm within 10 ms with overshoot of 0.08 mm. This met the acceptable limit of $\leq$ 50 ms response time and $\leq$ 1% overshoot. The EMA performance has been further analysed with time varying position input (ramp and saw tooth signals) and the results were presented. This analysis shows that model performance is close to physical system behaviour. The precise position control for EMA was achieved to meet the control requirement. This shows that the simulated model is unique in nature and being used for analysis of other variant EMA by changing its physical parameters.

6. FUTURE WORK

The EMA system has been simulated based on the practical data with geometrical parameters of subsystems. This model can be enhanced to other type of actuator (Electro hydraulic or Electro pneumatic) to study its performance. This research work gives the scope for further study of Digital Twin operation by introducing dynamic models for load and environmental condition. In present research work, analog controller is used for position and speed controls. It can be enhanced to digital controller for ease of communication with other processor in aerospace application.

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