Modeling of Electro Mechanical Actuator with Inner Loop controller

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Abstract: *Electromechanical actuators are used in place of conventional hydraulic actuators extensively in the control of flight surfaces in aerospace applications. the control design of these EMA's is challenging due to the non-linearity's like dead zone making the system less stable and more vulnerable to disturbances and noise thereby affecting the maneuverability and performance of system. So to deal with these uncertainties this paper presents the design of EMA system and a high gain inner loop velocity control of driving motor and inner loop compensation for the differential velocity between the motor and the aileron. The proposed methods have been proven by use of simulation and the results indicate considerable increase in bandwidth and improvement in time response of system.*

Key words: **Electromechanical actuator, Surface actuation system , Backlash, Dead zone, Inner loop control.**

INTRODUCTION

Over the recent years aerospace industry has been determined to use high efficient electrical motors in aircraft design. For flight surface control PBW (power by wire) could be implemented by using electro hydrostatic actuation(EHA) or electromechanical actuation(EMA) systems[1,2]. As the name suggests electromechanical systems are devices that convert electrical energy into mechanical movement and sometimes vice versa. An important consideration in flight surface control is the frequency response of the actuator, high bandwidth which gives faster response. Backlash and static friction play a major role in the gain and phase margin characteristics of EMA systems[3].

Backlash is an non linearity that limits the speed performance and impediment to position control as well. Backlash results in free play in gearing mechanisms together with static friction lead to dead zone[4]. Even a small magnitude of dead zone is an important limiting factor in position control zone introduces a phase lag that reduces the band width, gain and phase margins. The objective of the paper is to improve band width by using inner loop controller and the results are compared with conventional control strategies.

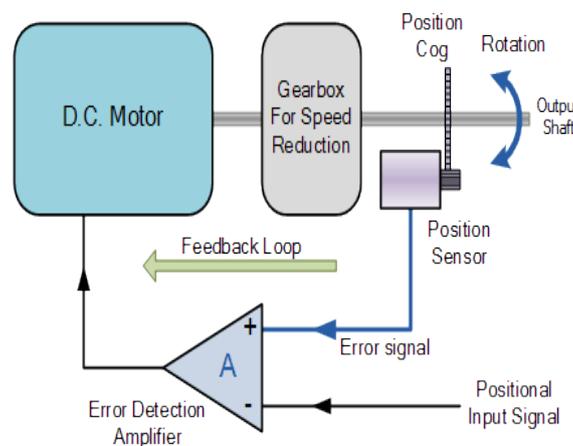## ELECTRO MECHANICAL ACTUATION SYSTEM

Fig.1 EMA block diagram

EMA actuation system would consist of control system, brushless electric motor using permanent earth magnets, velocity sensor of the motor, ball screw gear and mechanical linkage and a load.

The input to the control system is desired positional signal that is required for aero actuator shown in fig 1. The output of error detection control system is input voltage to the electric motor. Position and velocity and are the feedback signals from the motor as opposed to load that is the flight surface.

The electric motor used in the EMA is high performance brushless electric motor using permanent earth magnets. The advantages of brushless motor over brushed motor are high power to weight ratio high speed and electronic control.

Back lash is an important non linearity that can significantly affect the performance of geared electro mechanical systems. The load considered in the case study is aero surface.

MATHEMATICAL MODELLING
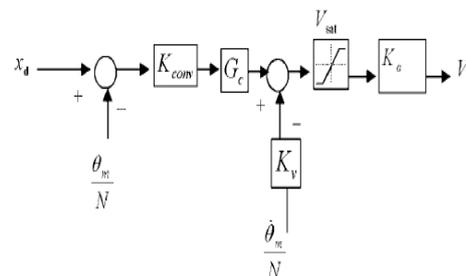
CONTROLLER

Fig . 2 controller Block diagram

The conversion factor K_{conv} used for relating the demanded position of the aileron to the input voltage

$$K_{conv} = \frac{V_{sat}}{x_{lim}} \qquad (1)$$

The amplifier K_a is assumed in order to have linear characteristic and modeled as pure gain.

The projected load position is then used in the compensator equation as follows

$$V_c = (G_c \left(x_{d-} \frac{\theta_m}{N} \right) K_{conv} - K_v \frac{\dot{\theta}_m}{N}) K_a \qquad (2)$$

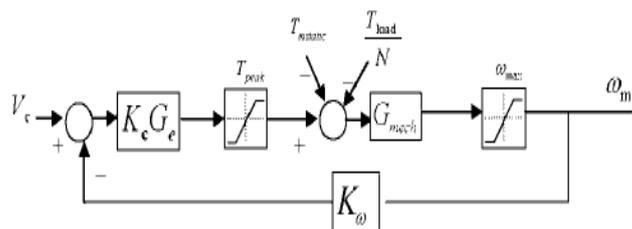Block diagram of the control system is provided in fig 2.

ELECTRIC MOTOR

Fig. 3 Block diagram of electric motor

The transfer function of the dc electric motor can be described by the first order transfer function, over all block diagram of electric motor is shown in fig 3.

$$G_e = \frac{1/R_c}{L_c/R_c s+1} = \frac{1/R_c}{\tau_e s+1} \qquad (3)$$

Where τ_e and $\frac{1}{R_c}$ are the motors electrical time constant and gain

Torque generated by the motor is given by

$$T_{peak} = K_c I_{lim} \qquad (4)$$

Torque exerted on the load is

$$T_m = J_m \dot{w}_m + K_{mv}\dot{\theta}_m + \frac{T_{load}}{N} + T_{mstatic} \qquad (5)$$

The transfer function of the mechanical part of the motor is

$$G_{mech} = \frac{1/K_{mv}}{J_m/K_{mv}s+1} = \frac{K_m}{\tau_m s+1} \qquad (6)$$

The overall transfer functions after neglecting the saturation effects

$$G_{motor} = \frac{w_m}{V_c} = \frac{K_c G_{mech} G_e}{1 + K_w K_c G_e G_{mech}} \qquad (7)$$

BACK LASH MODEL

Backlash is modeled purely as free play in gears combined with their mechanical compliances as the output shaft torque is modeled as linear function of the relative displacement between the input and output shafts $\theta_b = (\theta_m/N) - x$, preceded by a dead zone is shown in fig 4[5].

Torque is a function of both θ_b and $\dot{\theta}_b$ conventional model in this regard is specified by

$$T_{load} = \begin{cases} k_b(\theta_b - \alpha) + c_b + \dot{\theta}_b = \theta_b > \alpha \\ 0 = \theta_b \leq \alpha \\ k_b(\theta_b - \alpha) + c_b + \dot{\theta}_b = \theta_b < -\alpha \end{cases} \qquad (8)$$

The backlash model implies transfer function

$$G_T = (c_b s + k_b) \qquad (9)$$

Preceded by dead zone

An equivalent gain can be obtained by using describing function are

$$G_b(\theta_b) = \left\{ \frac{m}{\pi} \left[\pi - 2\sin^{-1}\left(\frac{\alpha}{\theta_b}\right) - 2\left(\frac{\alpha}{\theta_b}\right)\sqrt{1 - \left(\frac{\alpha}{\theta_b}\right)^2} \right] \right\} \qquad (10)$$
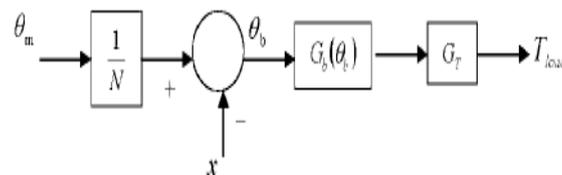
Where m is a non zero slope and is equal to 1

Fig. 4 Block diagram of black lash model
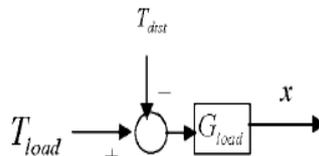
LOAD MODEL

Fig. 5Block diagram for load model

A very simplified load model is assumed for load such that

$$T_{load} = M\ddot{x} + B_l\dot{x} + K_l x + T_{dist} \qquad (11)$$

Load transfer function is

$$G_{load} = \frac{1}{Ms^2 + B_l s + K_l} \tag{12}$$

$$\frac{(\frac{\theta m(s)}{N})}{x_d(s)} = G_{ol_m} = \frac{K_{conv}G_cK_aG_eG_{motor}K_c(1+G_bG_TG_{load})}{sK_cK_aG_e(1+G_bG_TG_{load})+G_cK_{conv}G_1K_cK_aG_e(1+G_bG_TG_{load})+\frac{G_bG_TG_{motor}}{N}} \tag{13}$$

The implementation of unity feedback and closed loop transfer is given by

$$\frac{(\frac{\theta m(s)}{N})}{x_d(s)} = G_{cl_m} = \frac{K_{conv}G_cK_aG_eG_{motor}K_c(1+G_bG_TG_{load})}{sK_cK_aG_e(1+G_bG_TG_{load})+G_cK_{conv}G_1K_cK_aG_e(1+G_bG_TG_{load})+\frac{G_bG_TG_{motor}}{N}+K_{conv}G_cK_aG_eG_{motor}K_c(1+G_bG_TG_{load})} \tag{14}$$

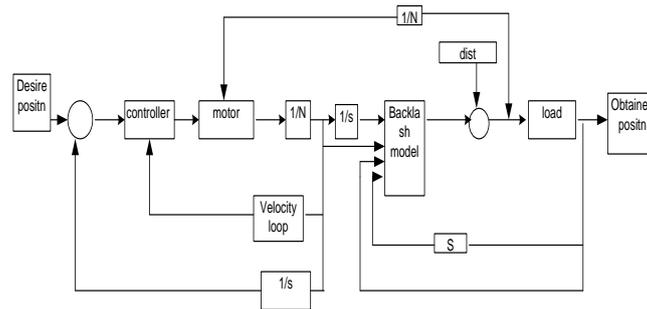**Fig.6 Block diagram for conventional controller**

The overall transfer function and EMA with conventional controller is represented below

EMA WITH CONVENTIONAL CONTROLLER

The complete block diagram with a conventional controller is illustrated neglecting the saturation effects the overall open loop transfer function of the block diagram is shown in fig. 6
Equation 13 represents the open loop transfer function from desired position to the load position and equation 14 represents the closed unity feedback of the EMA system.fig.6[6,7] represents the EMA system with conventional controller.

The overall input and output relation is

$$x = G_{MM}x_d - G_{MD1}T_{mstatic} - G_{MD2}T_{dist} \tag{15}$$

Where $G_{MM}, G_{MD!} and G_{MD2}$ is the transfer function relating the desired and actual aileron position, disturbance torques at motor and load position

$$G_{MM} = \frac{G_cK_{conv}K_cK_aG_eG_1G_bG_TG_{load}}{den(s)} \tag{16}$$

$$G_{MD1} = \frac{G_1G_bG_TG_{load}}{den(s)} \tag{17}$$

$$G_{MD2} = \frac{(s+K_{conv}G_cG_1)K_cK_aG_eG_{load}}{den(s)} \tag{18}$$

Furthermore sensitivity to dead zone is given by

$$S_{G_{MM}:G_b} = \frac{G_b}{G_{MM}}\frac{\partial G_{MM}}{\partial G_b} = \frac{G_eK_cK_a(s+K_{conv}G_cG_1)}{den(s)} \tag{19}$$

Where den(s) is

$$den(s) = sK_cK_aG_e(1+G_bG_TG_{load}) + G_cK_{conv}G_1K_cK_aG_e(1+G_bG_TG_{load}) + \frac{G_bG_TG_1}{N} \tag{20}$$

EMA CONTROL STRATEGY USING INNER LOOP FEED BACK:

The two forms of inner loop feedback that would reduce the back lash and static friction on the system performance are

1. **High gain inner loop control of motor speed:**

   Static friction occurs both at the motor and more prominently at load and with gearing system.[7,8] Static friction is associated with molecular bonding between moving surfaces and persists itself when the load is stationary or moving slowly. Due to static friction until and unless the motor exceeds the required torque to overcome friction the load would not move. So due to the addition of inner loop gain as shown in fig 8 the effect of friction is significantly reduced.

2. **Inner loop feedback control for Backlash Compensation:**

   Due to the gap in the gearing mechanism, the driving gear motion is in limited range without causing motion in load even in rest or when direction changes [9]. so to overcome this backlash we use the differential position and velocity so as to reduce the sensitivity of EMA.

The overall block diagram of the EMA system with the inner loop control strategies is shown fig 7
The simplified block diagram [10] of EMA control is shown in the fig 7
The open loop transfer function of the EMA system can be obtained in eq.21.

$$\frac{x}{x_d} = G_{ol} = \frac{K_{conv1}G_cG_2G_{bcomp}G_TG_{load}}{sN + G_2G_{bcomp}G_TG_{load}(D_{couple}+H)} \qquad (21)$$

Where G_2 is inner loop segment transfer function

$$G_2 = \frac{K_{conv2}G_{PID}K_aK_cG_eG_{mech}}{1+(K_{conv2}G_{PID}K_a+K_w)K_cG_eG_{mech}} \qquad (22)$$

For $G_{pid} \ggg 1$ then $G_2 = 1$

And G_{bcomp} is effective dead zone gain after compensation
$$G_{bcomp} \approx \frac{sG_b}{s\left(1-\frac{K_{inner}}{N}\right)+\frac{P_{inner}}{N}} \qquad (23)$$
To improve the gain and phase characteristics of the system as well as its gain by combining the positive differential feedback with negative differential position feed back

$$G_{inner} = sK_{inner} - P_{inner} \qquad (24)$$
The coupling term combined with feedback signal after reduced by the conditions of equation(25)can be obtained by

$$D_{couple} + Hx = (sN + H)x \qquad (25)$$

Where stabilizing effect will be achieved by using derivative feedback such that

$$H_x = sk_vx \qquad (26)$$

The overall input output relationship of the EMA assuming unity feedback of the aileron position is
$$x = G_{cl}x_{d-}G_{D1}T_{mstatic} - G_{D2}T_{dist} \qquad (27)$$

Where G_{cl} is the closed loop transfer function and is obtained by

$$G_{cl} = \frac{K_{conv1}G_cG_2G_{bcomp}G_TG_{load}}{sN + G_2G_{bcomp}G_TG_{load}(D_{couple}+H+K_{conv1}G_c)} \qquad (28)$$

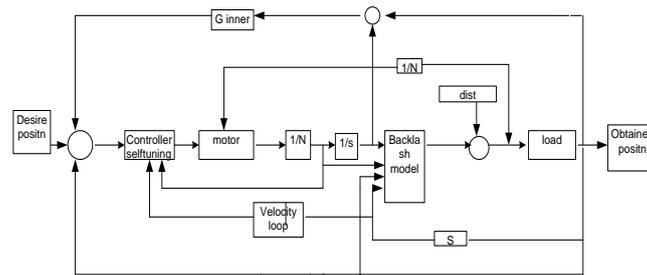Where G_{D1} and G_{D2} are the transfer functions relating the disturbance torques

Fig .7 Block diagram for inner loop control

$$G_{D1} = \frac{G_2 G_{bcomp} G_T G_{load}}{G_{PID} K_{conv2} K_a K_c G_e (sN + G_2 G_{bcomp} G_T G_{load}(D_{couple} + H + K_{conv1} G_c))} \quad (29)$$

$$G_{D2} = \frac{sN G_{load}}{(sN + G_2 G_{bcomp} G_T G_{load}(D_{couple} + H + K_{conv1} G_c)} \quad (30)$$

Furthermore sensitivity to the position to the dead zone is

$$S_{G_{cl}:G_b} = \frac{sN}{(sN + G_2 G_{bcomp} G_T G_{load}(D_{couple} + H + K_{conv1} G_c)} \quad (31)$$

The frequency response characteristics of the transfer function is a factor in design of EMA

CASE STUDY

In this section the EMA system that has been used is specified and its performance is analyzed under conventional control strategy and inner loop control strategy with following configurations

Table 1 Backlash parameters

Characteristic	Symbol	value	Unit
Backlash contact angle	A	∓ 0.003	In.
Spring constant	K_b	114,350	lb/in.
Damping factor	C_b	0	lb s/in.
Gear ratio	N	100	rad/in.

Table 2 Load parameters

Characteristic	Symbol	Value	Unit
Load inertia	M	0.2588	lb m
Load viscous friction	B_l	5	lb s/in
Load spring constant	K_l	1000	lb/in

Table 3 Amplifier parameters

Characteristic	Symbol	Value	Unit
Amplifier gain	K_a	1	N/A
Conversion factor($V_{sat}/x_{\lim}$)	K_{conv}	9.1	V/in.
Conversion factor(w_{lim}/x_{lim})	K_{conv1}	139	rad/s in.

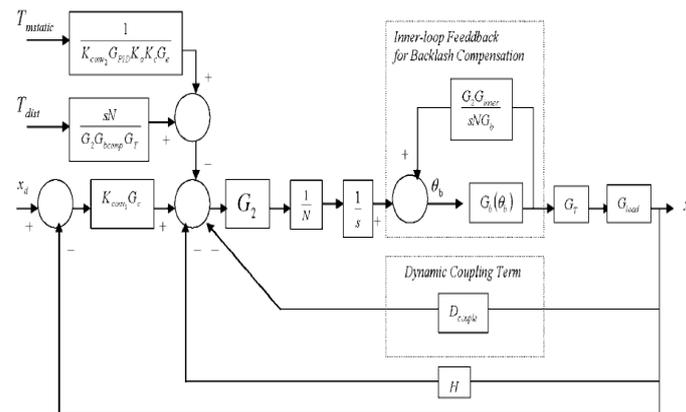| Conversion factor(V_{sat}/w_{lim})	K_{conv2}	0.0687	V-s/rad
Amplifier saturation	V_{sat}	±55	V
Maximum gear displacement	x_{lim}	±6	in.

Fig 8 simplified block diagram of inner loop controller

Table 1 shows the back lash parameters of the given EMA system, Table 2 shows the load parameter of the given EMA system Table 3 shows the amplifier parameters of the EMA system and Table 4 shows the motor parameters of the given EMA system.

Table 4 Motor parameters

Characteristic	symbol	value	unit
Rotor inertia	J_m	0.0000024	lb .in^2
Saturation current	I_{lim}	15	A
Torque constant	K_c	0.07	in.lb/A
Viscous friction	K_{mv}	0.000127	in.lb s/rad
Back emf constant	K_w	0.07	V-s/rad
Winding inductance	R_c	0.003	Ω
Electrical time constant	τ_c	0.0023	s
Mechanical time constant	τ_m	0.018	s
Torque element for static friction	$T_{mstatic}$	0	in .lb
Maximum speed	w_{max}	800	rpm

EMA SYSTEM RESULTS WITH CONVENTIONAL CONTROLLER

FREQUENCY RESPONSE ANALYSIS

A gain margin of -9db and phase margin of 44deg can be achieved with a proportional gain of $G_c = 150$ adding velocity feed back of $k_v = 0.2$ improves the time response of the system. Differential inner loop gains are specified as $K_{inner} = 40$ and $P_{inner} = N = 100$.
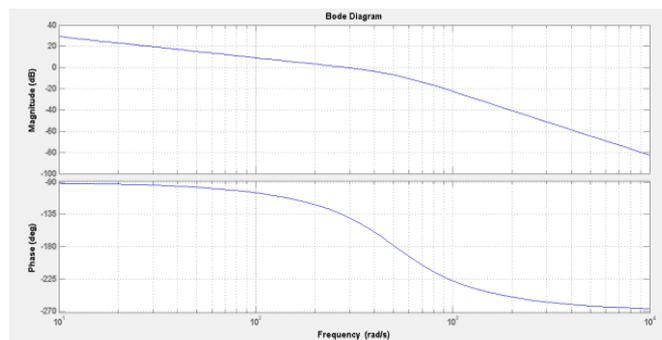

Fig. 8 Frequency response analysis for conventional controller

The simulated load position of the EMA system using conventional controller is show in fig 9.
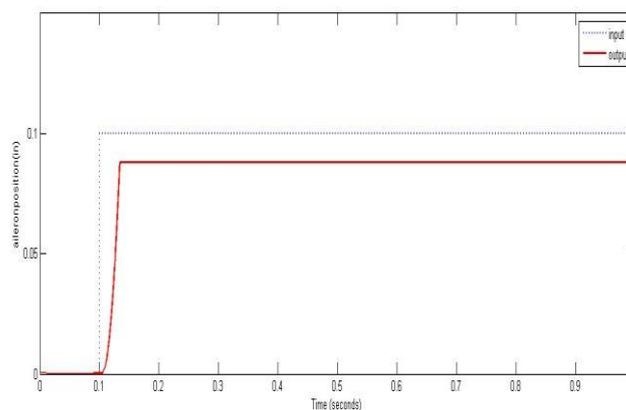
Fig . 9 step response to load position for conventional controller

The gain and phase plots of the transfer function with the disturbance input and the sensitivity with respect to the free play are shown in fig 10 and fig 11.
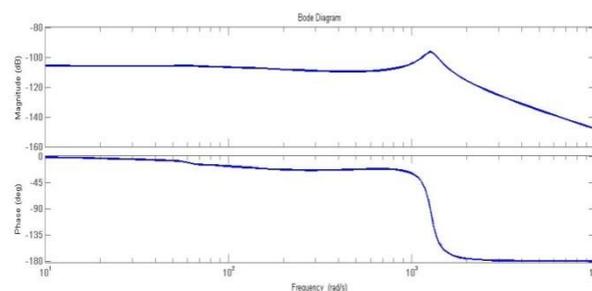

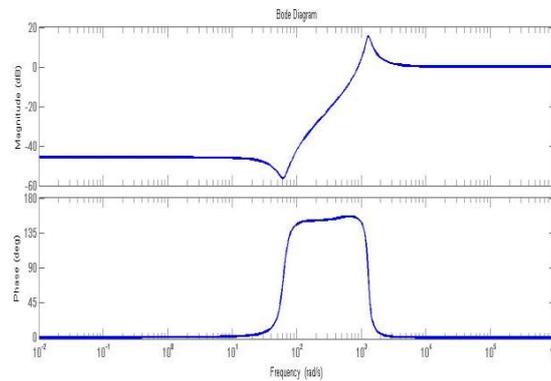**Fig . 10 Frequency response analysis for disturbances**

Fig .11 sensitivity of the conventional controller

EMA SYSTEM RESULTS WITH INNER LOOP CONTROLLER

FREQUENCY RESPONSE ANALYSIS

Self-tuning PID controller is used in the inner loop controller[10] .differential inner loop feedback gains are specified as K_{inner} =120 and $P_{inner} = 100 N = 10000$.The gain and phase margin of the closed loop transfer function are 5db and 90deg for $G_c = 200$ and $K_v = 0.15$ plot shown in fig 12.
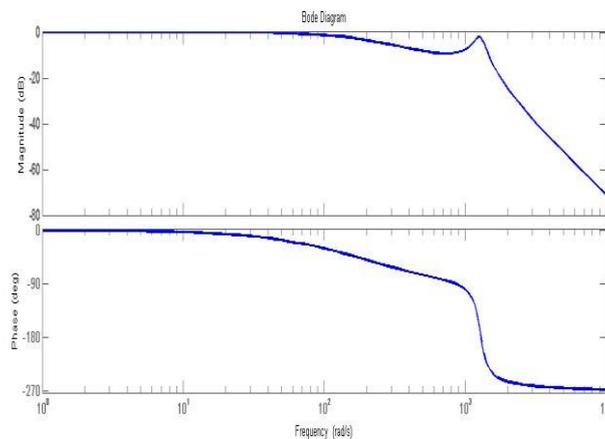

Fig .12 Frequency response analysis for inner loop control

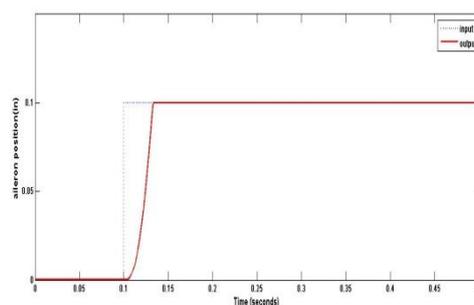The simulated load position of the EMA system using inner loop controller is shown in fig 13

Fig .13 Step response to load position for inner loop controller

The gain and phase plots of the transfer function with the disturbance input and the sensitivity with respect to the free play are shown in fig 14 and fig 15.
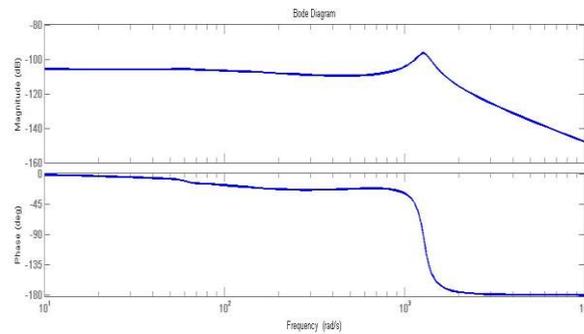

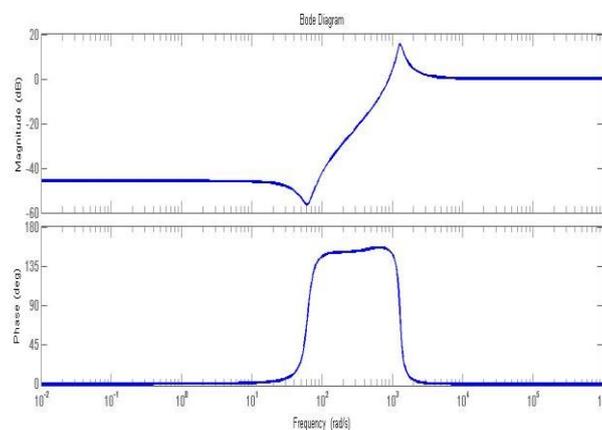**Fig . 14 Frequency response analysis for disturbances.**

Fig.15 Sensitivity of the inner loop transfer function

CONCLUSION

In this paper the design of electromechanical actuation system is discussed and the limitation of performance due to dead zone non linearity has been reduced due to proposed inner loop controller design and has been implemented in various case studies and simulated in MATLAB/SIMULINK environment. From the results the system has shown considerable improvement both in time domain and frequency domain in terms of rising time, bandwidth, and crossover frequency of the modular actuator system.

REFRENCES

[1] Saeid Habibi, Jeff Roach, Greg Luecke..,2008, "Inner loop control for Electro mechanical(EMA) flight surface Actuation systems" J. Dynamic systems, Measurement and control sep 2008 vol.130

[2] Nordin, M., and Gutman, p., 2002, "controlling mechanical system with Back a Survey,"Automatica,38,pp.1633-1649.

[3] Habibi S R.., and singh G.2000 "Derivation of design requirements for optimization of high performance Hydrostatic actuation systems" Int. J. Fluid power 1(2) pp 11-29.

[4] Nordin , M.., Galic, J.., Gutman, p.., 1997, "New Models for Back lash and gear play" Int . J . Adapt control signal process..,11,pp 49-63.

[5] Kolk W.R.., and Lerman, R., 1992, Nonlinear System Dynamics, Van Nostrand Reinhold, New York.

[6] Andreas Wilde.., Peter schiender.., Wellinton Presot.., p.2006 "Modeling of Electro Mechanical Actuators" IEEE conference on computer aided control system design oct 2006.

[7] Joshi,S.. and Kelkar, A..,1998, "Inner loop control of supersonic Aircraft in the presence of Aeroelastic Modes" IEEE trans. control system technology..,6(6),pp. 345-354.

[8] M.Mozzoleni.., Y.Maccarana.., F.Prevedi.., G.pispola.., M.Nardi.., F.Perni and S.Tori P.2017 "Development of a reliable electro mechanical actuator for primary control surfaces in small aircrafts" IEEE conference on advanced intelligent Mechatronics 2017.

[9] Fu Jian..,Jean Charles Mare.., Fu Yongling p.2017.., "Modelling and simulation of flight control electro mechanical actuators with special focus on model architecting, multidisciplinary effects and power flows" Chinese journal of aeronautics 2017:47-65

[10] Gang Tao..,Peter V kokotovic..,p.1993 "Adaptive control system with Backlash" Automatica Vol.29 pp.323-335..