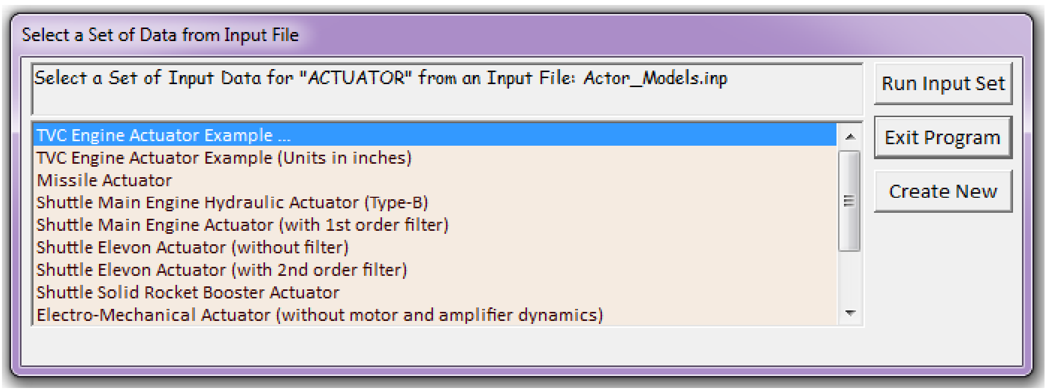
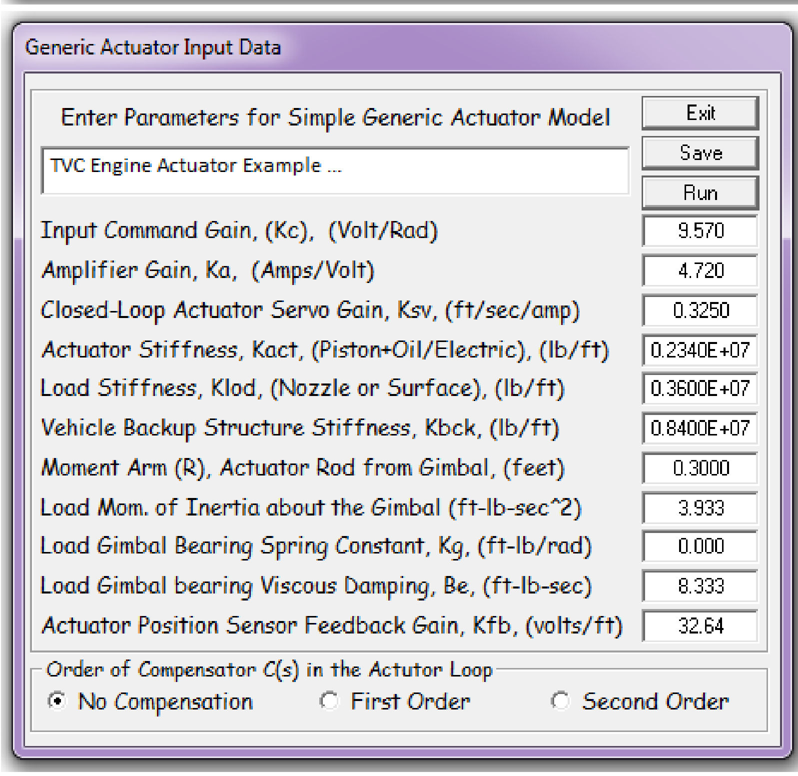
Actuator Examples

The following examples are used to further illustrate how to create different actuator model types using the actuator modeling program. The actuator input data are located in file *"Actor-Models.Inp"*. It contains actuator data for all five modeling types. There is a batch set at the top of the file that can be used to process the entire file. The state-space systems are saved in file *"Actor_Models.Qdr"*. The files are in directory *"Flixan\ Actuator\ Examples"*.

4.5.1 Simple Generic Actuator Model Example



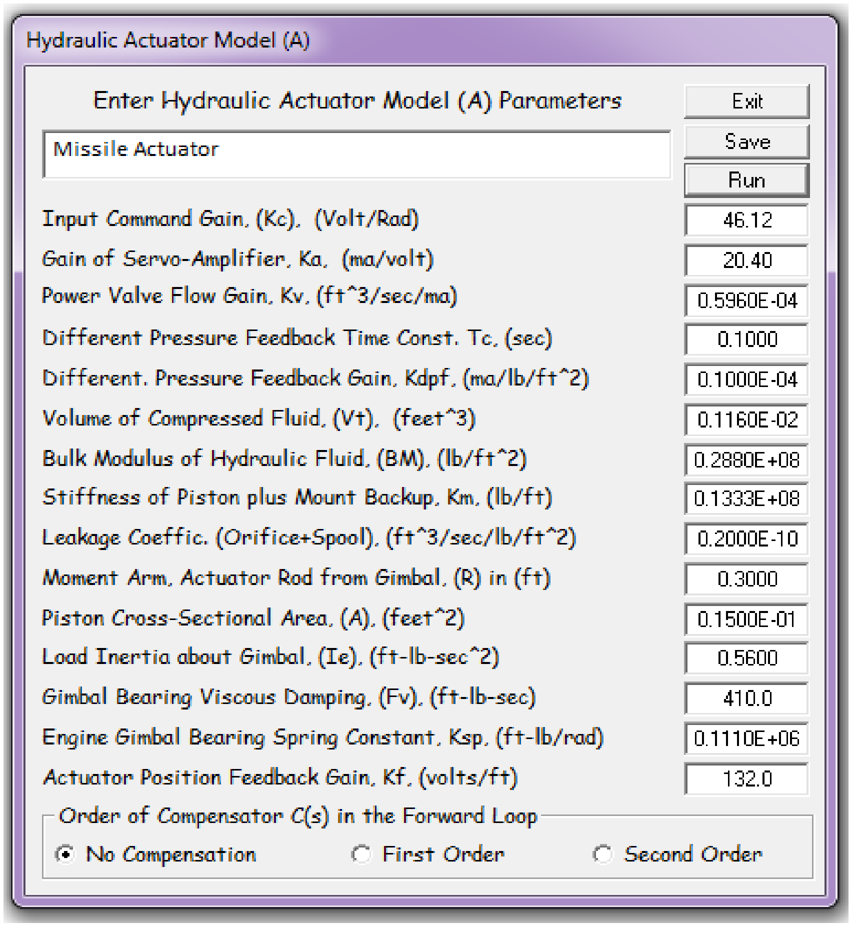


The title of the first actuator set is *"TVC Engine Actuator Example ..."* and its type is "*Simple Generic Model*". The simple actuator model was described in Section (4.3.1). To run this actuator in Flixan you must first select the project directory "*Flixan\ Actuator\ Examples*", select the filenames, and from the following menu select the first title, as shown, and click on "*Run Input Set*".

The program identifies the actuator type, reads the selected actuator data, and displays the actuator parameters in the corresponding dialog type, shown below. Click on "Run" to process the data and to create the state-space system, which has the same title: "*TVC Engine Actuator Example ...*" and it is saved in the selected systems file "*Actor-Models.Qdr*".

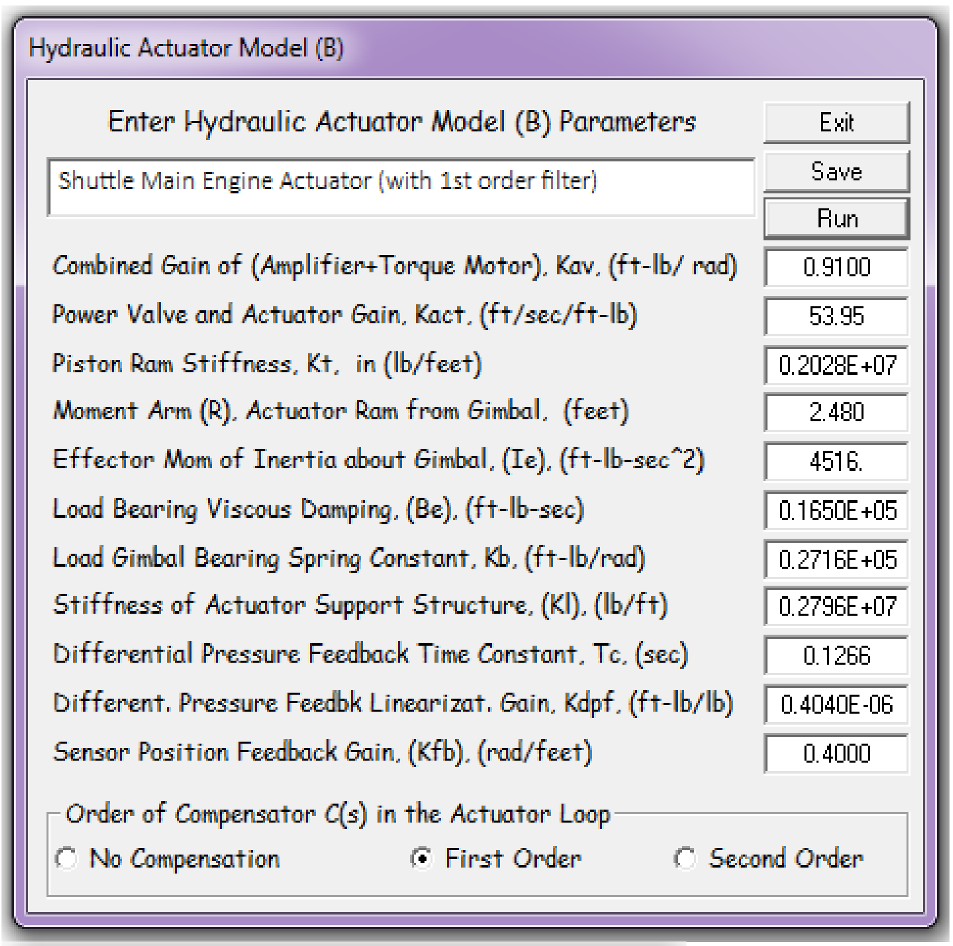
4.5.2 Electro-Hydraulic Model (A) Actuator for a Small Missile

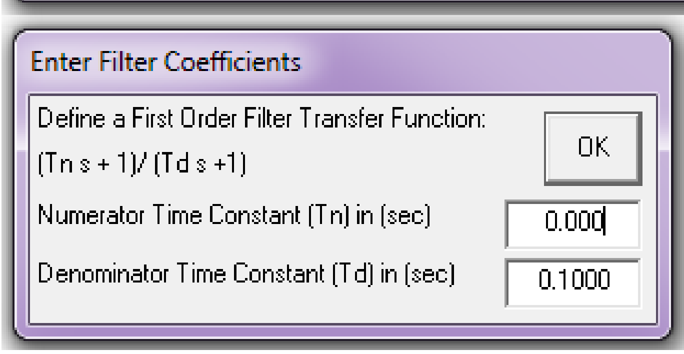
The next example is a hydraulic actuator for a small missile. It uses the Hydraulic Type (A) model that was described in Section (4.3.2). Its title is "*Missile Actuator*" and the input data is also in file "*Actor_Models.Inp*". The program reads the actuator data, recognizes that it is a hydraulic type-A model, and opens-up the corresponding Hydraulic Actuator Type (A) dialog form. Click on "Run" button and the program will process the data and create the state-space system "*Missile Actuator*" which will be saved in the systems file "*Actor_Models.Qdr*".



4.5.3 Electro-Hydraulic Model (B) Actuator for a Shuttle Main Engine

In this example we are using the Hydraulic Model (B) actuator type that was described in Section (4.3.3) to create a Shuttle main engine actuator system. The input data is also in "*Actor_Models.Inp*", and its title is *"Shuttle Main Engine Actuator (with 1st order filter)"*. We will also include a first order lag filter C(s) in the actuator control loop. We run the actuator program as before, select the actuator title from the menu, and the program will display the following actuator dialog form. Notice that in the actuator data the order of the compensator is set to (1) followed by the numerator and denominator time-constants (τ_n and τ_d) of the 1^{st} order transfer function. The presence of a first order lag 10/(s+10) in the actuator loop is also evident by the next dialog showing the filter parameters. Click on "OK", and the program calculates the state-space system and saves it in the systems file "*Actor_Models.Qdr*", using the title *"Shuttle Main Engine Actuator (with 1st order filter)"*. The plot in Figure (4.5.3.1) compares the actuator's closed loop response with (green) and without (blue) the filter.





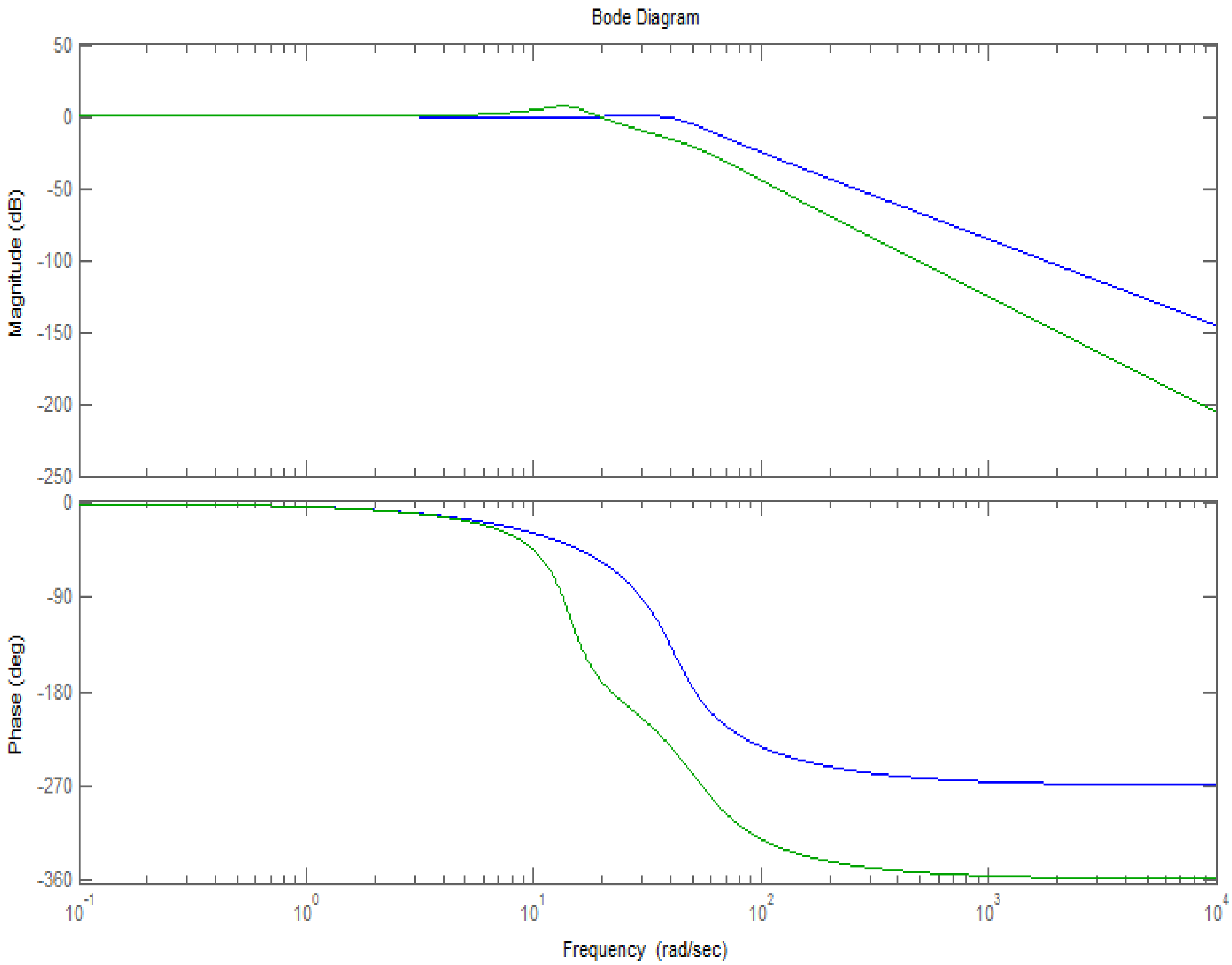
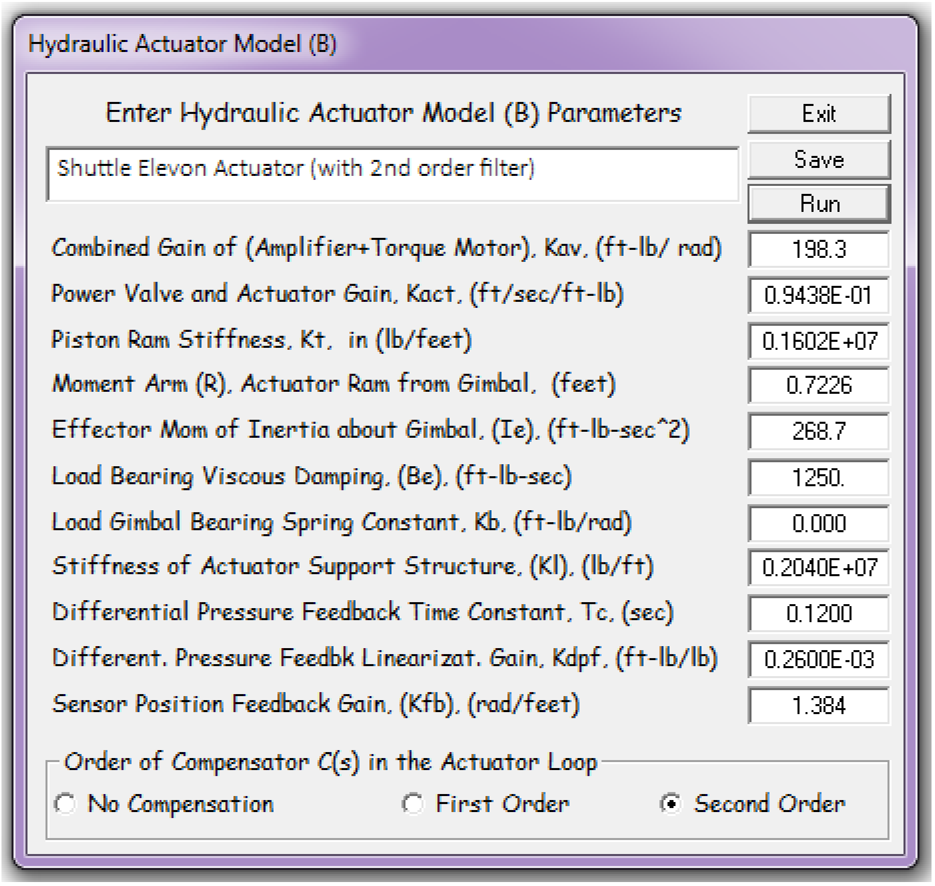


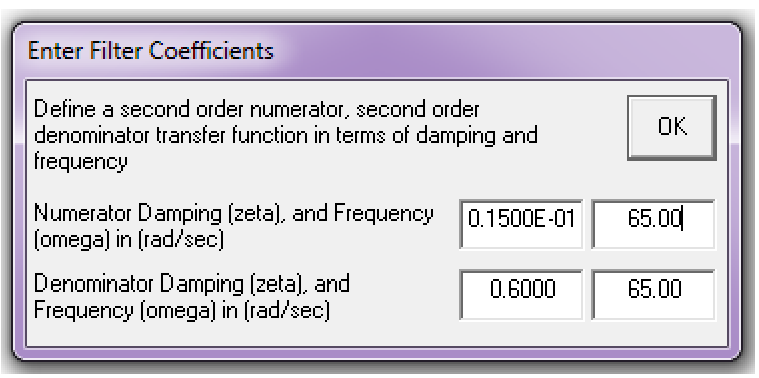
Figure (4.5.3) Shuttle Main Engine Actuator Frequency Response With (Green), and Without the First Order Lag Filter (Blue)

4.5.4 Electro-Hydraulic Model (B) Actuator for the Shuttle Elevon

In this example we will use the same "*Electro-Hydraulic Model (B)*" actuator type described in Section (4.3.3) to create a Space Shuttle Elevon actuator system that includes a second order Notch filter in the control loop. Its title is *"Shuttle Elevon Actuator (with 2nd order filter)"*. Run the Flixan actuator program and from the filename selection menu select the same input and system files "*Actor-Models.Inp*" and "*Actor_Models.Qdr*", as before, and from the actuator title selection menu choose "*Shuttle Elevon Actuator (with 2nd order filter)*". The following dialog shows the actuator parameters. Notice that a second order compensator C(s) is selected. In the actuator data the order of the compensator is set to (2) followed by the 2^{nd} order transfer function's numerator and denominator damping coefficients and frequencies. The second order compensator parameters are shown in the next dialog. The filter is a notch intended to attenuate a local structural resonance at 65 (rad/sec). Click "OK" and the program will process the data to generate the state-space model of the actuator including the notch filter. It will save it in the systems file with the same title *"Shuttle Elevon Actuator (with 2nd order filter)"*.

Notice that in the input data file includes a similar actuator data-set: "*Shuttle Elevon Actuator (without filter)*" that uses the same actuator parameters but without the notch filter. We used both systems to calculate the Elevon actuator frequency response with and without the notch filter, as shown in figure (4.5.4). They both have a control bandwidth of approximately 40 (rad/sec) and the notch is visible at 65 (rad/sec).





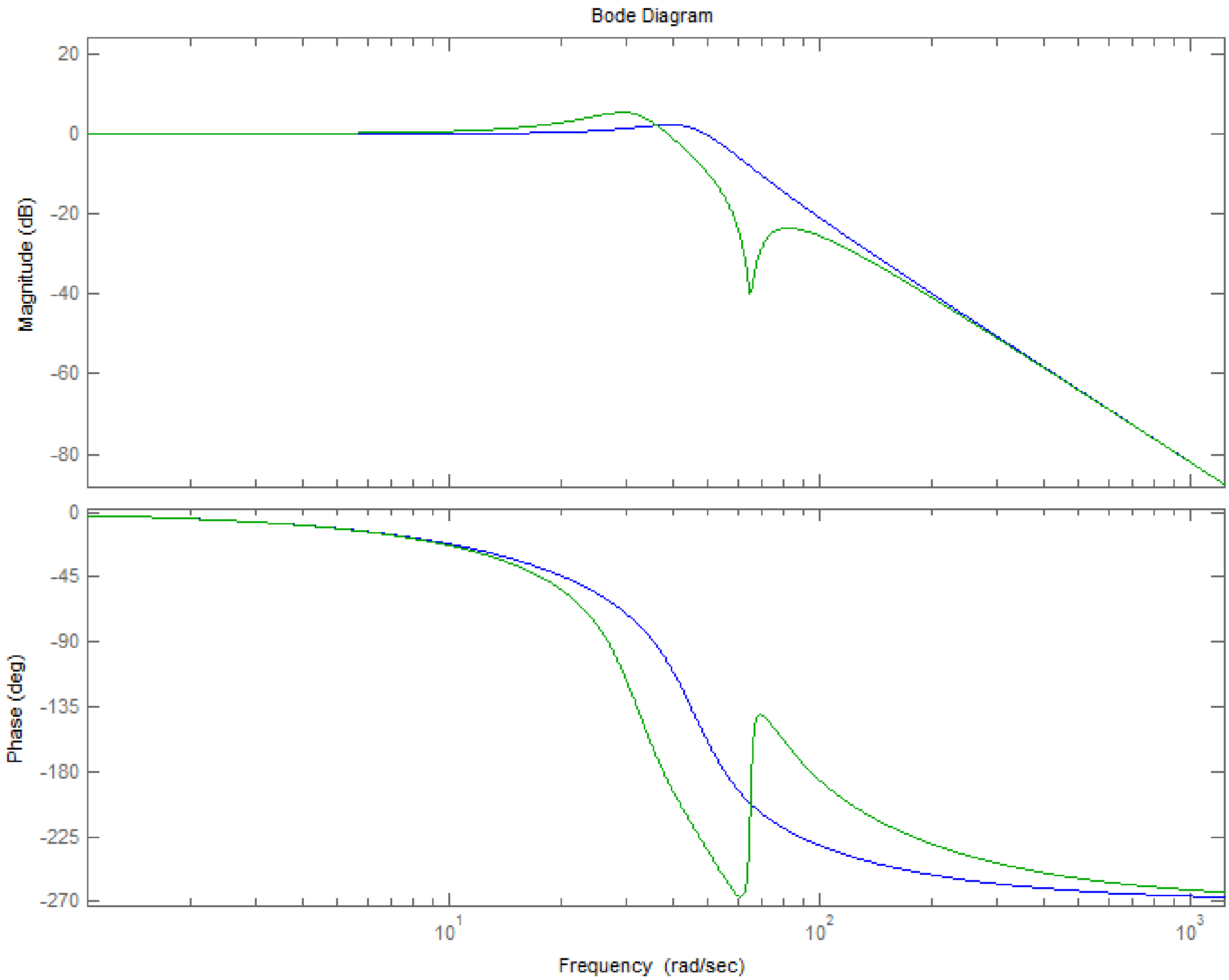


Figure 4.5.4 Frequency Response of the Shuttle Elevon Actuator With and Without a Notch Filter at 65 (rad/sec)

4.5.5 Electro-Mechanical Model (A) Actuator

In this example we are creating an "Electro-Mechanical Model (A)" type of actuator which is described in Section (4.3.4). The input data for this actuator are also in file "*Actor_Models.Inp*" and its title is *"Electro-Mechanical Actuator (without motor and amplifier dynamics)"*. The following dialog shows its parameters. Notice at the bottom of the dialog that there is no filter included. It is also provides the option to include the servo motor and amplifier dynamics which are approximated with a first order lag. However, in this example they are well above the actuator bandwidth and they are not included. In the input data line: *"Include Motor and Amplifier Dynamics, (0=no,1=yes): 0"*, the answer is "0", indicating that they are not included. This option of excluding the servo-motor and amplifier dynamics is used only in the electro-mechanical actuator models because the servo-motor and amplifier dynamics are usually at a higher bandwidth in comparison with the load dynamics and sometimes it is not necessary to include them in the model.

The program reads the actuator input parameters from file "Actor_Models.Inp", generates the state-space model of the electro-mechanical type (A) actuator, and saves it in the systems file "Actor_Models.Qdr", using the same title *"Electro-Mechanical Actuator (without motor and amplifier dynamics)"* above the matrices.

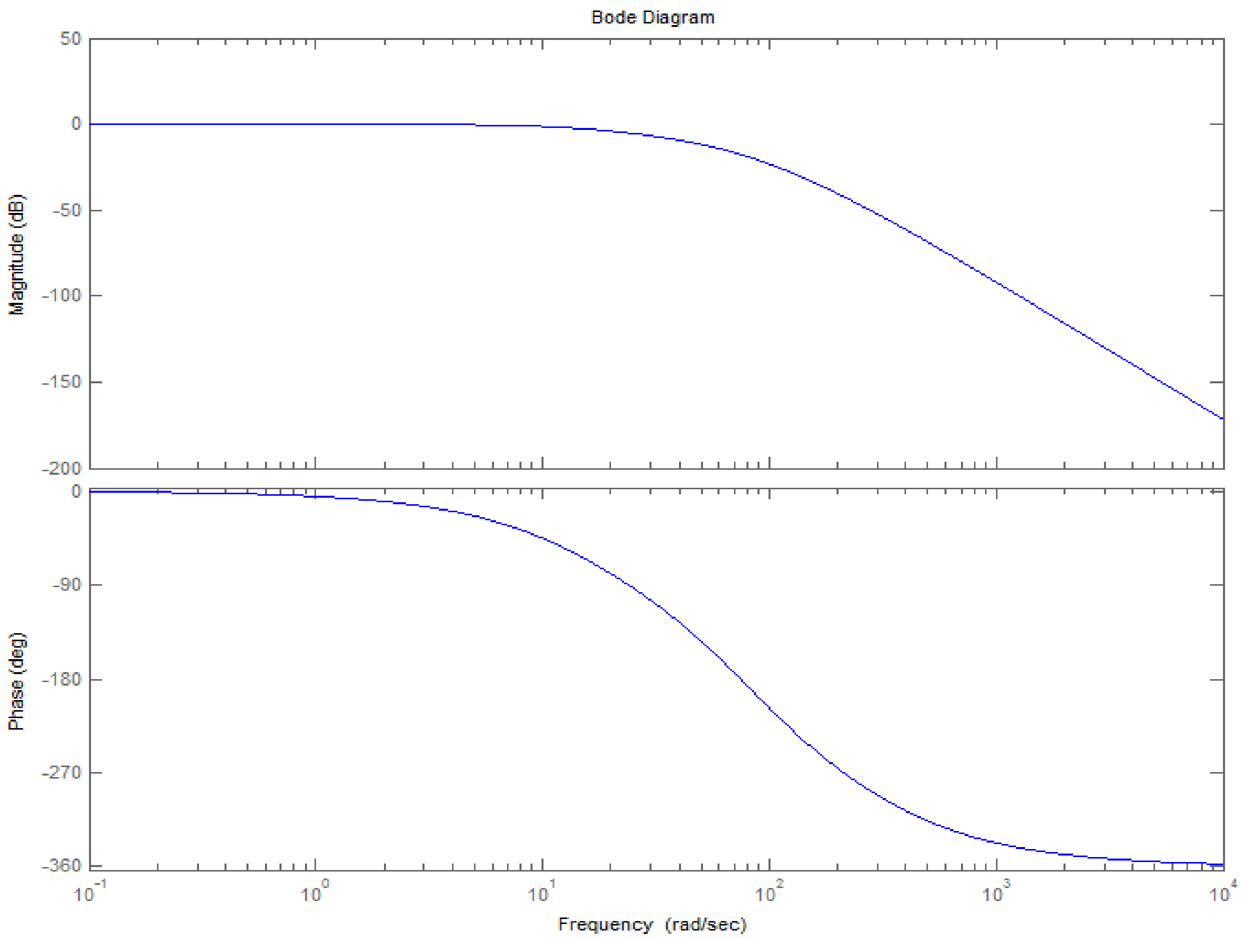
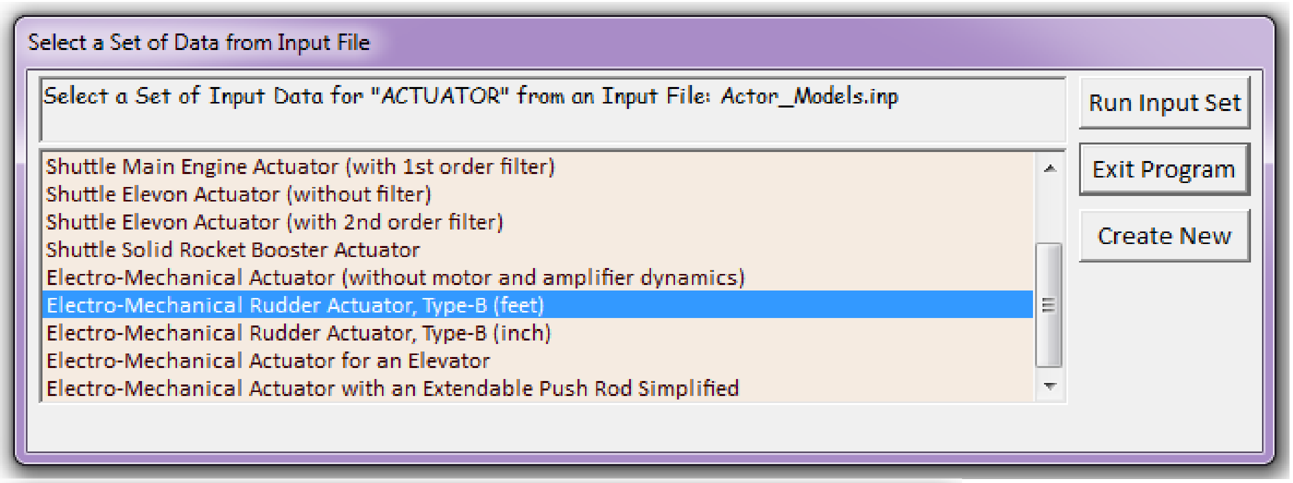


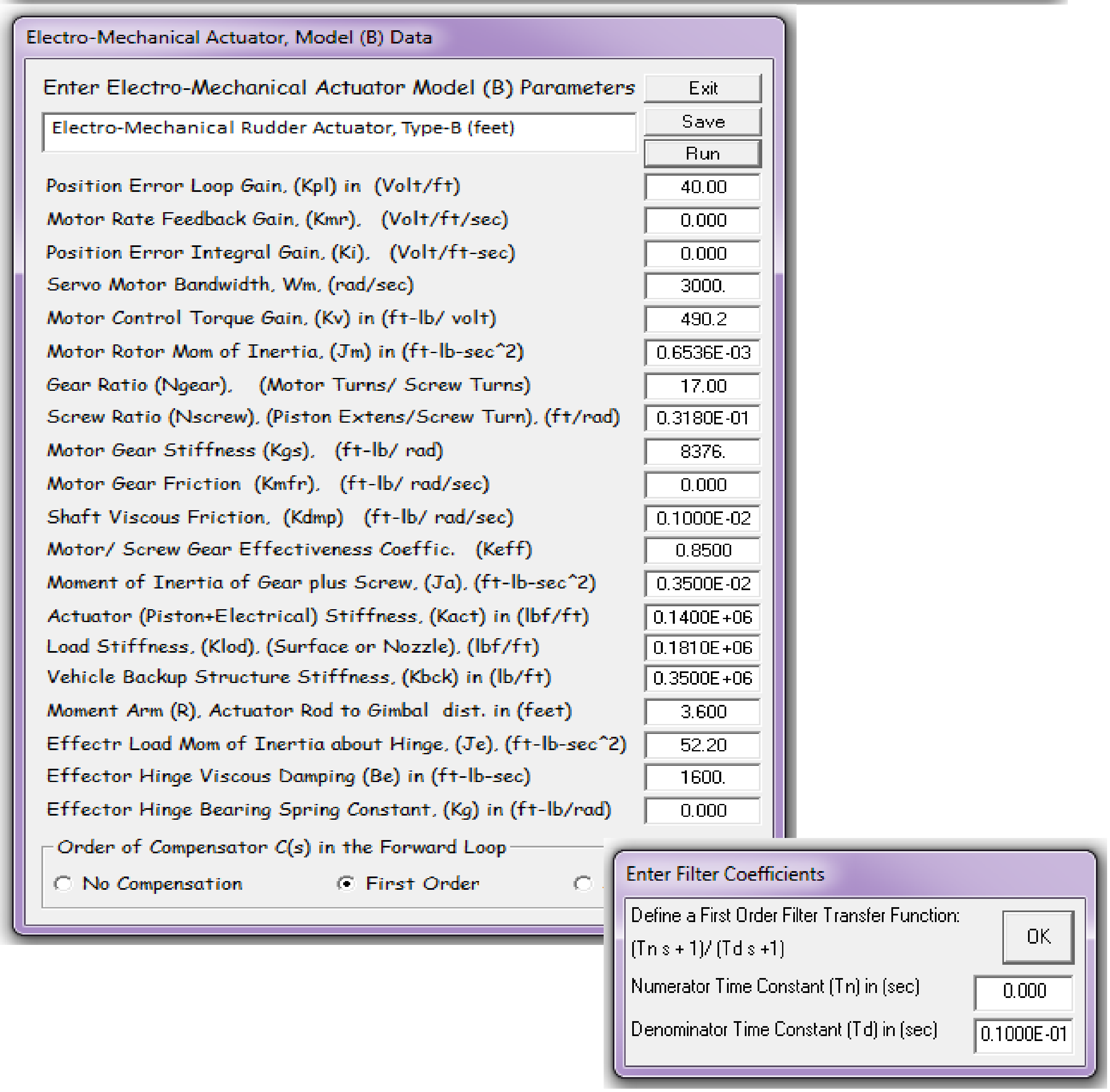
Figure (4.5.5) Frequency Response of the Electro-Mechanical Model (A) Actuator

4.5.6 Electro-Mechanical Type (B) Actuator Model

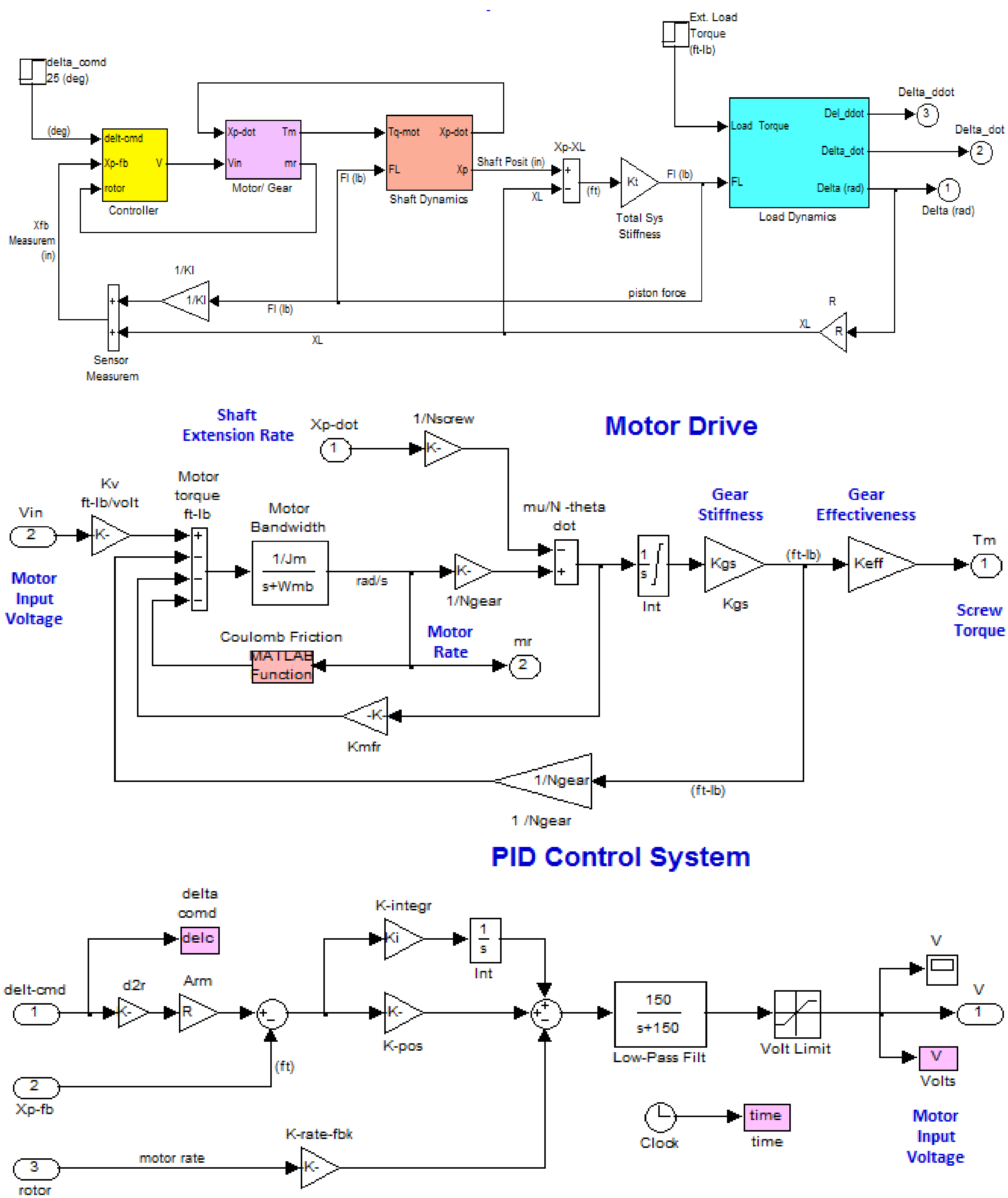
In this example we will model and analyze an electro-mechanical type (B) actuator for a rudder surface using the EMA type (B) model that was described in Section (4.3.5). We will use Flixan to create the linear model and we will also create a non-linear version of the same model in Simulink. We will simulate its non-linear response to deflection commands and also to external loads. Finally we will calculate and compare the frequency responses of the two models. The actuator parameters for this model are also in file "*Actor_Models.Inp*" and its title is "*Electro-Mechanical Rudder Actuator, Type-B (feet)*".

The title of the actuator data-set is selected from the following menu and the actuator parameters are shown in the EMA type (B) dialog below. The actuator also includes a first order compensator [100/(s+100)] in the control loop. Click on "Run", and a smaller dialog shows up for browsing or entering the 1^{st} order compensator data. Click "OK" to accept the filter, process the data, and to save the system in file "*Actor_Models.Qdr*" under the same title "*Electro-Mechanical Rudder Actuator, Type-B (inch)*". This system is also saved as a Matlab function in file "*ema_b.m*" to calculate its frequency response.


Select a Set of Data from Input File
Select a Set of Input Data for "ACTUATOR" from an Input File: Actor_Models.inp
Run Input Set
Exit Program
Create New
Shuttle Main Engine Actuator (with 1st order filter)
Shuttle Elevon Actuator (without filter)
Shuttle Elevon Actuator (with 2nd order filter)
Shuttle Solid Rocket Booster Actuator
Electro-Mechanical Actuator (without motor and amplifier dynamics)
Electro-Mechanical Rudder Actuator, Type-B (feet)
Electro-Mechanical Rudder Actuator, Type-B (inch)
Electro-Mechanical Actuator for an Elevator
Electro-Mechanical Actuator with an Extendable Push Rod Simplified


Electro-Mechanical Actuator, Model (B) Data
Enter Electro-Mechanical Actuator Model (B) Parameters
Exit
Save
Run
Electro-Mechanical Rudder Actuator, Type-B (feet)
Position Error Loop Gain, (Kpl) in (Volt/ft) 40.00
Motor Rate Feedback Gain, (Kmr), (Volt/ft/sec) 0.000
Position Error Integral Gain, (Ki), (Volt/ft-sec) 0.000
Servo Motor Bandwidth, Wm, (rad/sec) 3000.
Motor Control Torque Gain, (Kv) in (ft-lb/ volt) 490.2
Motor Rotor Mom of Inertia, (Jm) in (ft-lb-sec^2) 0.6536E-03
Gear Ratio (Ngear), (Motor Turns/ Screw Turns) 17.00
Screw Ratio (Nscrew), (Piston Extens/Screw Turn), (ft/rad) 0.3180E-01
Motor Gear Stiffness (Kgs), (ft-lb/ rad) 8376.
Motor Gear Friction (Kmfr), (ft-lb/ rad/sec) 0.000
Shaft Viscous Friction, (Kdmp) (ft-lb/ rad/sec) 0.1000E-02
Motor/ Screw Gear Effectiveness Coeffic. (Keff) 0.8500
Moment of Inertia of Gear plus Screw, (Ja), (ft-lb-sec^2) 0.3500E-02
Actuator (Piston+Electrical) Stiffness, (Kact) in (lbf/ft) 0.1400E+06
Load Stiffness, (Klod), (Surface or Nozzle), (lbf/ft) 0.1810E+06
Vehicle Backup Structure Stiffness, (Kbck) in (lb/ft) 0.3500E+06
Moment Arm (R), Actuator Rod to Gimbal dist. in (feet) 3.600
Effectr Load Mom of Inertia about Hinge, (Je), (ft-lb-sec^2) 52.20
Effector Hinge Viscous Damping (Be) in (ft-lb-sec) 1600.
Effector Hinge Bearing Spring Constant, (Kg) in (ft-lb/rad) 0.000
Order of Compensator C(s) in the Forward Loop
No Compensation
First Order
Enter Filter Coefficients
Define a First Order Filter Transfer Function:
(Tn s + 1)/ (Td s +1)
OK
Numerator Time Constant (Tn) in (sec) 0.000
Denominator Time Constant (Td) in (sec) 0.1000E-01

This actuator system is also implemented using Matlab/ Simulink in directory "*C:\Flixan\Actuator\ Examples\ EM-Actuators\Rudder*". The Simulink model is "*Rudder_EMAB.Mdl*", shown in Figure (4.5.6.1), and it includes the actuator non-linearities. The parameters are initialized from file "run.m".



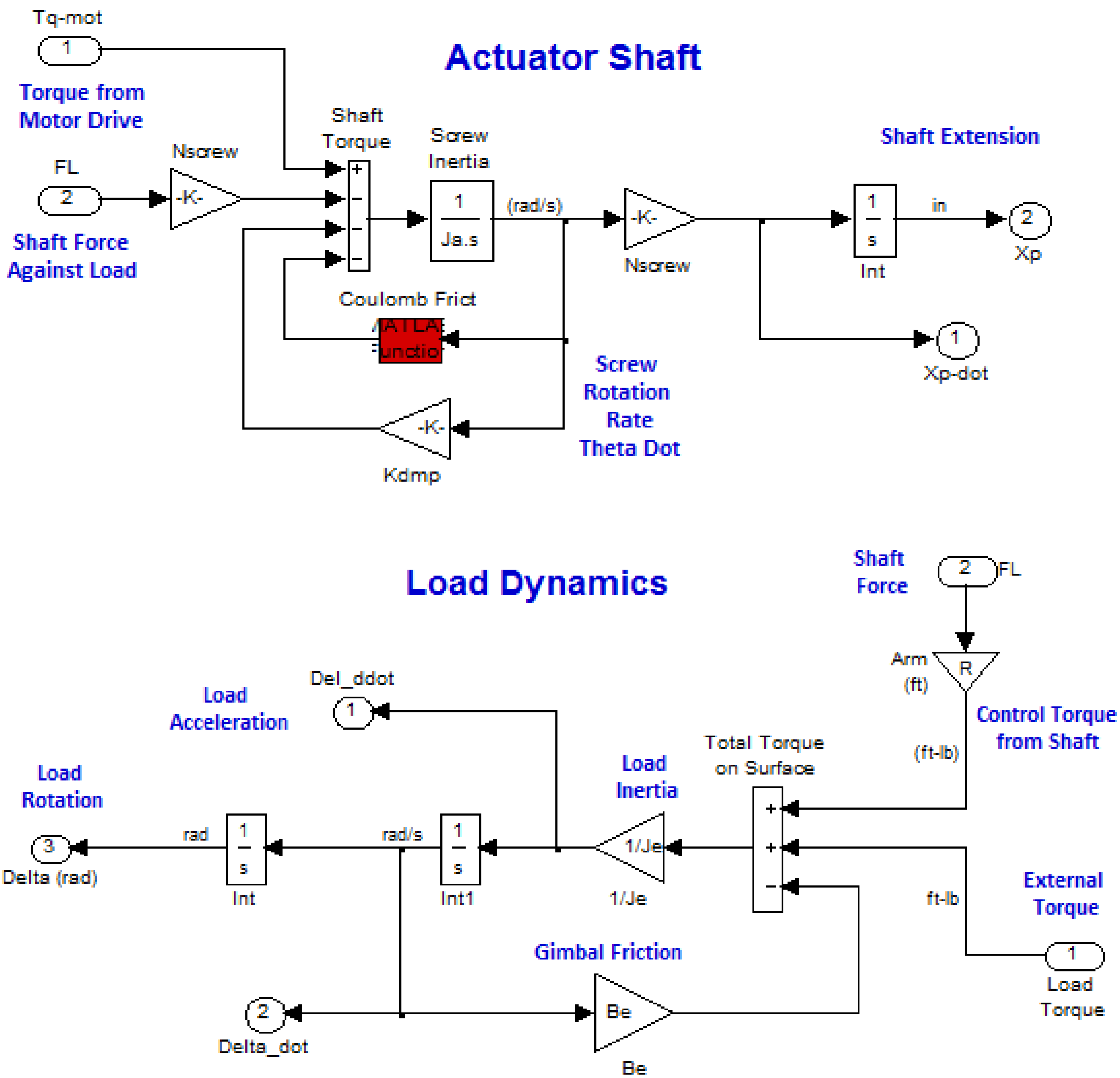
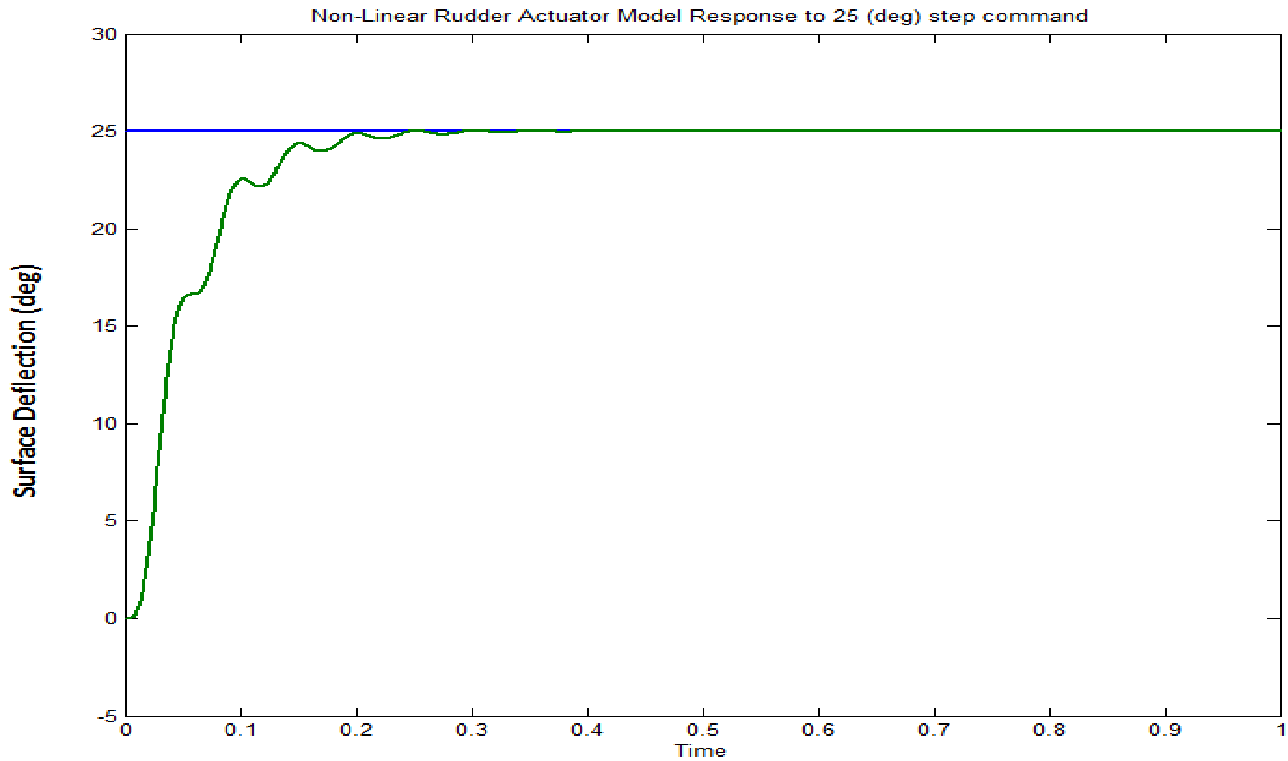
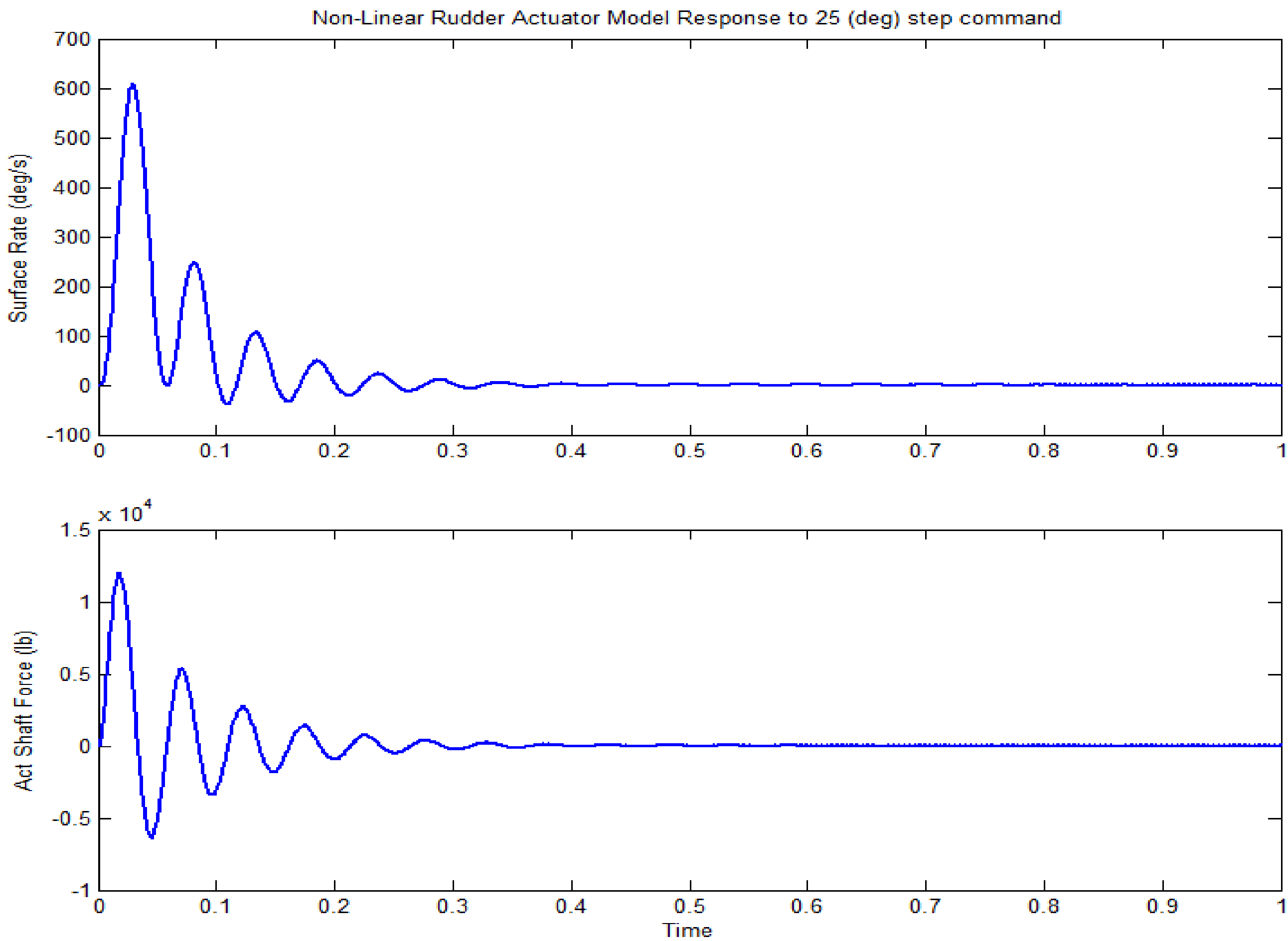


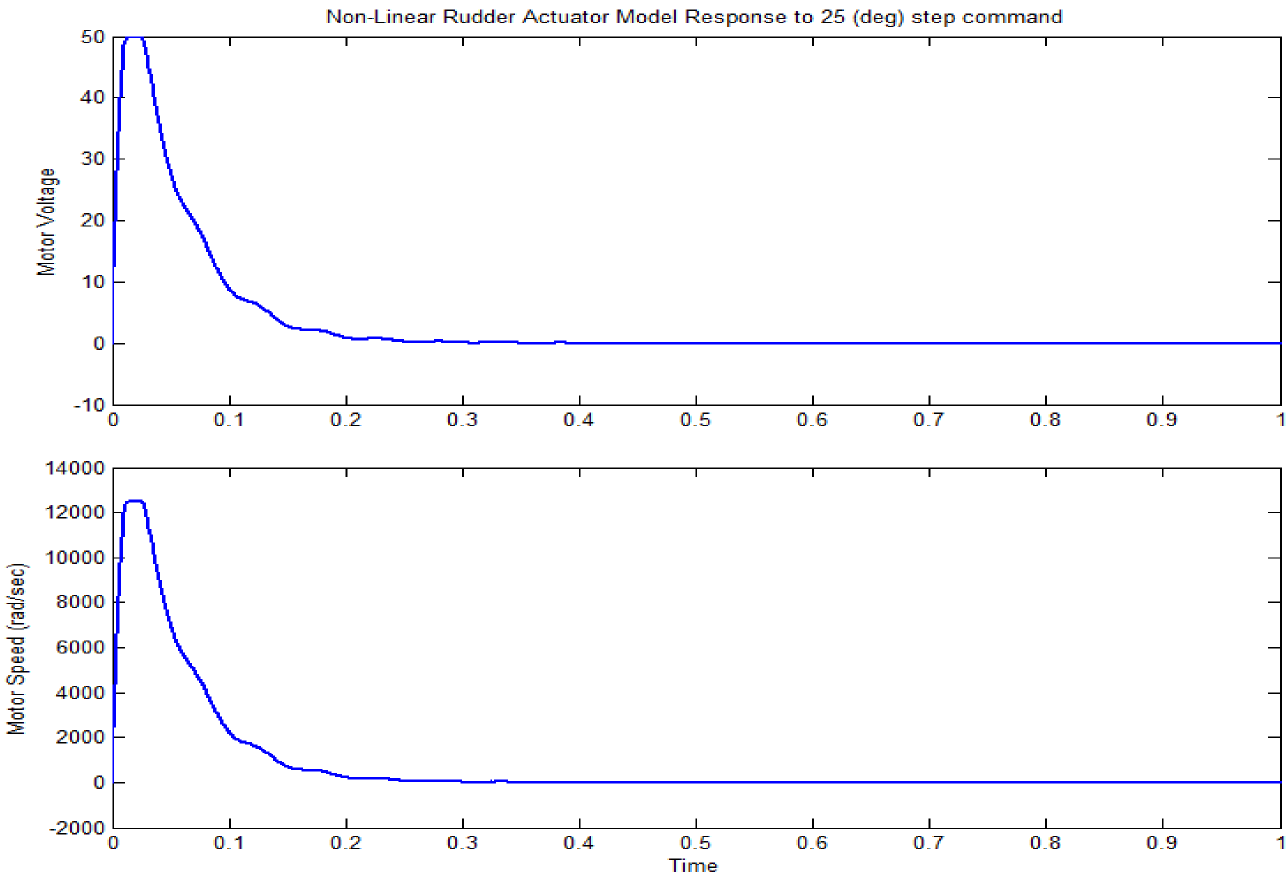
Figure (4.5.6.1) Non-Linear Simulink Model "*Rudder_EMAB.Mdl*" for simulating the Electro-Mechanical actuator system response to external loads and rudder deflection commands

Simulations

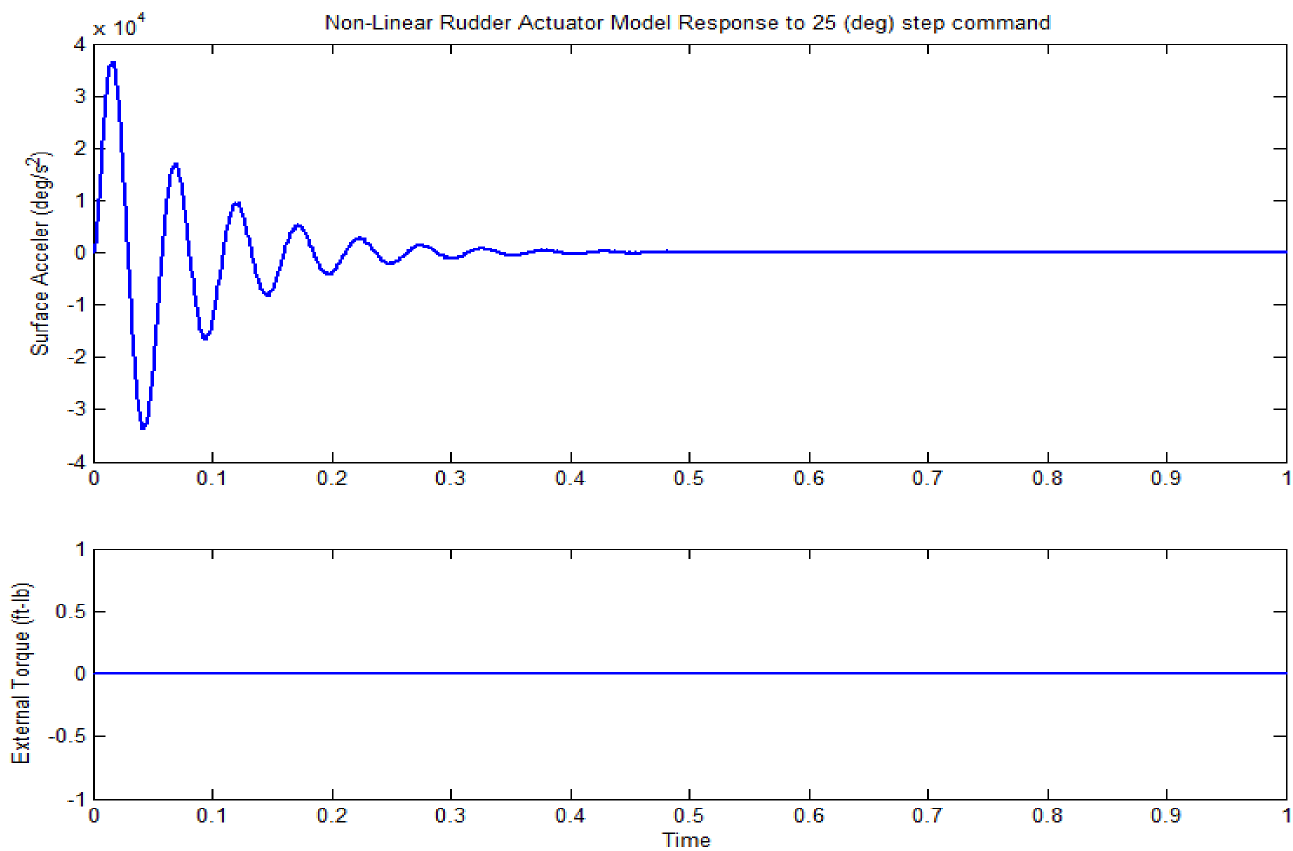
Figure (4.5.6.2) shows the actuator's response to a 25° deflection command. The system's response time is 0.15 (sec) and there is no steady-state error. The motor voltage momentarily peaks to the 50 volts saturation level and the motor speed is proportional to the voltage. The combined stiffnesses due to the support structure, shaft, and rudder stiffness create a resonance at approx 22 Hz which damps out reasonably fast. The actuator shaft displacement is about 1.5 (in). The screw torque from the motor is noisy because of the non-linearities and the gear stiffness.


Non-Linear Rudder Actuator Model Response to 25 (deg) step command
Surface Deflection (deg)
30
25
20
15
10
5
0
-5
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Time


Non-Linear Rudder Actuator Model Response to 25 (deg) step command
Surface Rate (deg/s)
700
600
500
400
300
200
100
0
-100
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
x 10^4
Act Shaft Force (lb)
1.5
1
0.5
0
-0.5
-1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Time



Non-Linear Rudder Actuator Model Response to 25 (deg) step command
Motor Voltage
Motor Speed (rad/sec)
Time



Non-Linear Rudder Actuator Model Response to 25 (deg) step command
× 10⁴
Surface Acceler (deg/s²)
External Torque (ft-lb)
Time

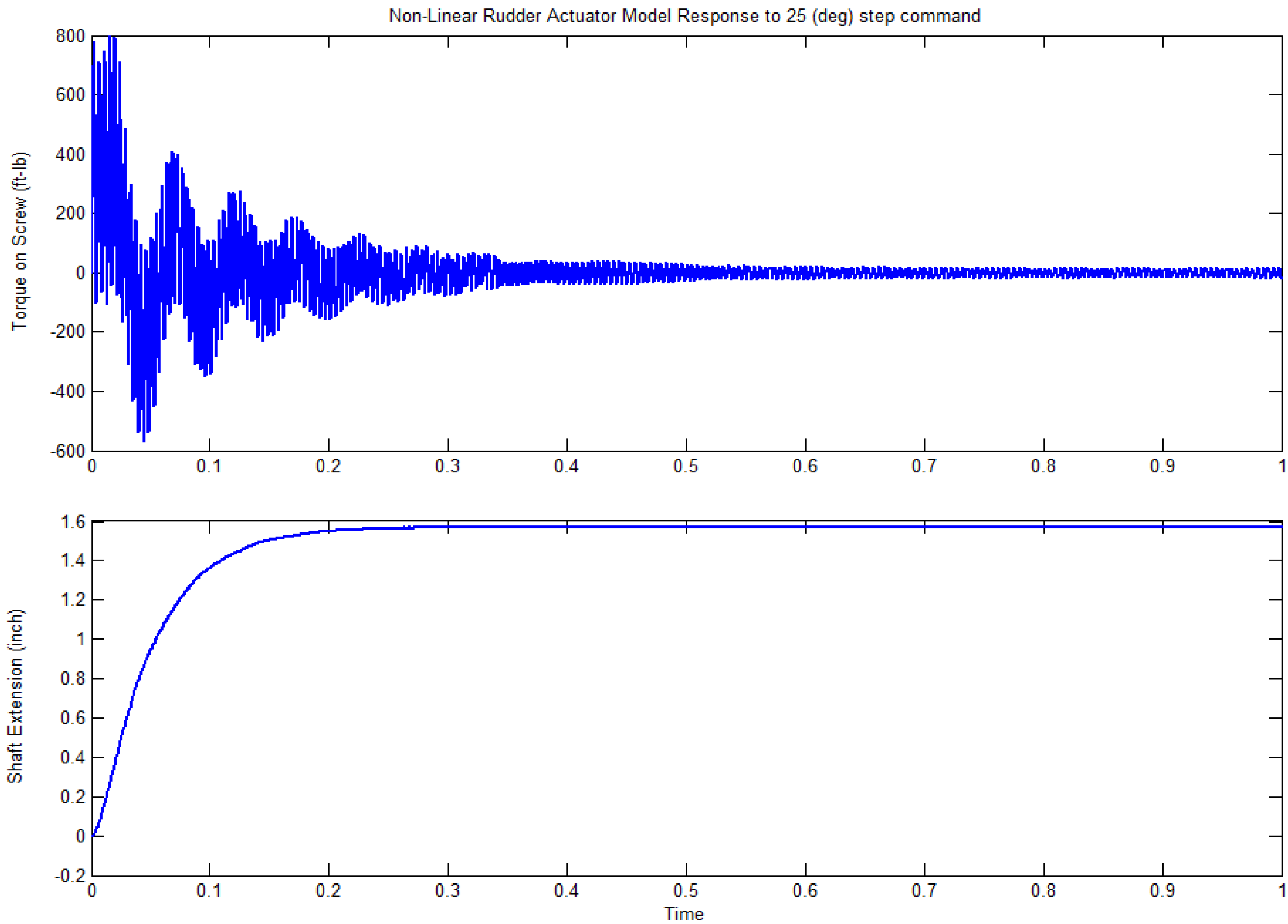
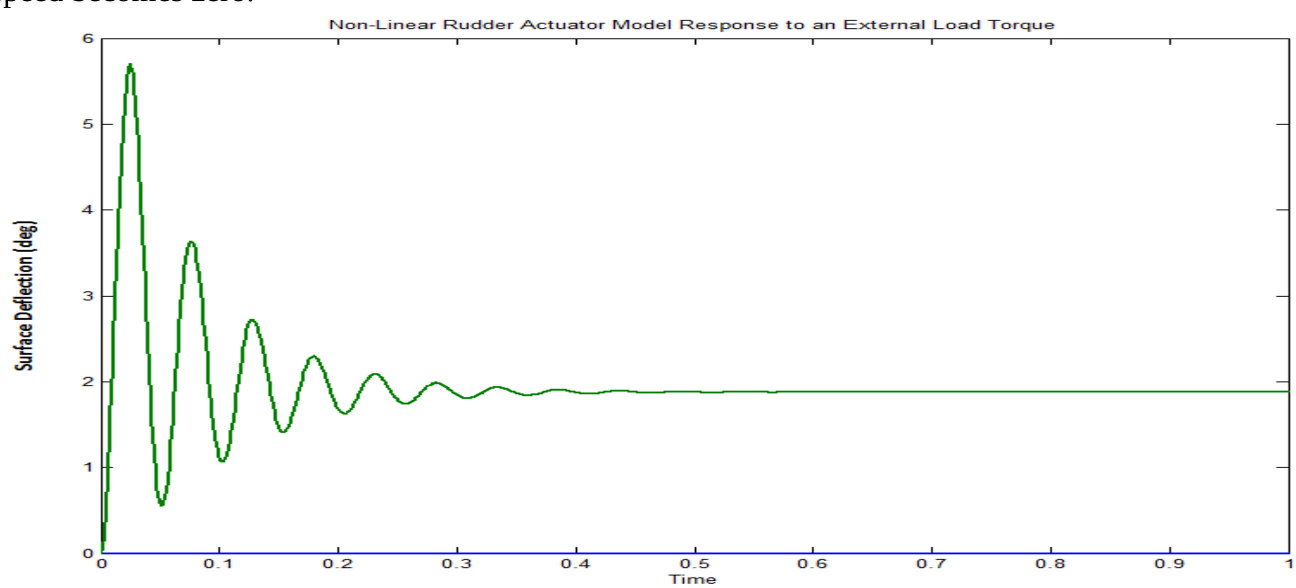
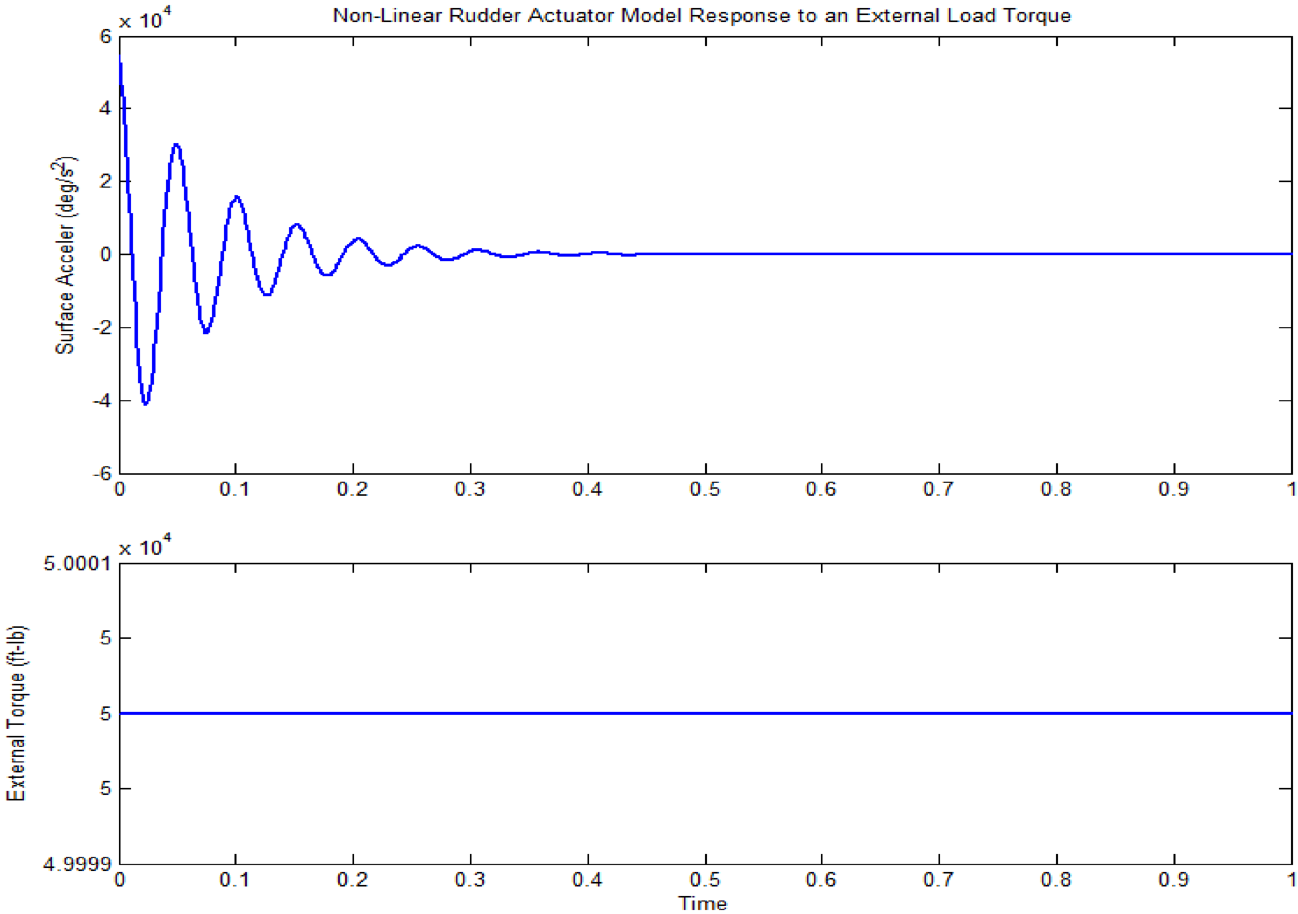
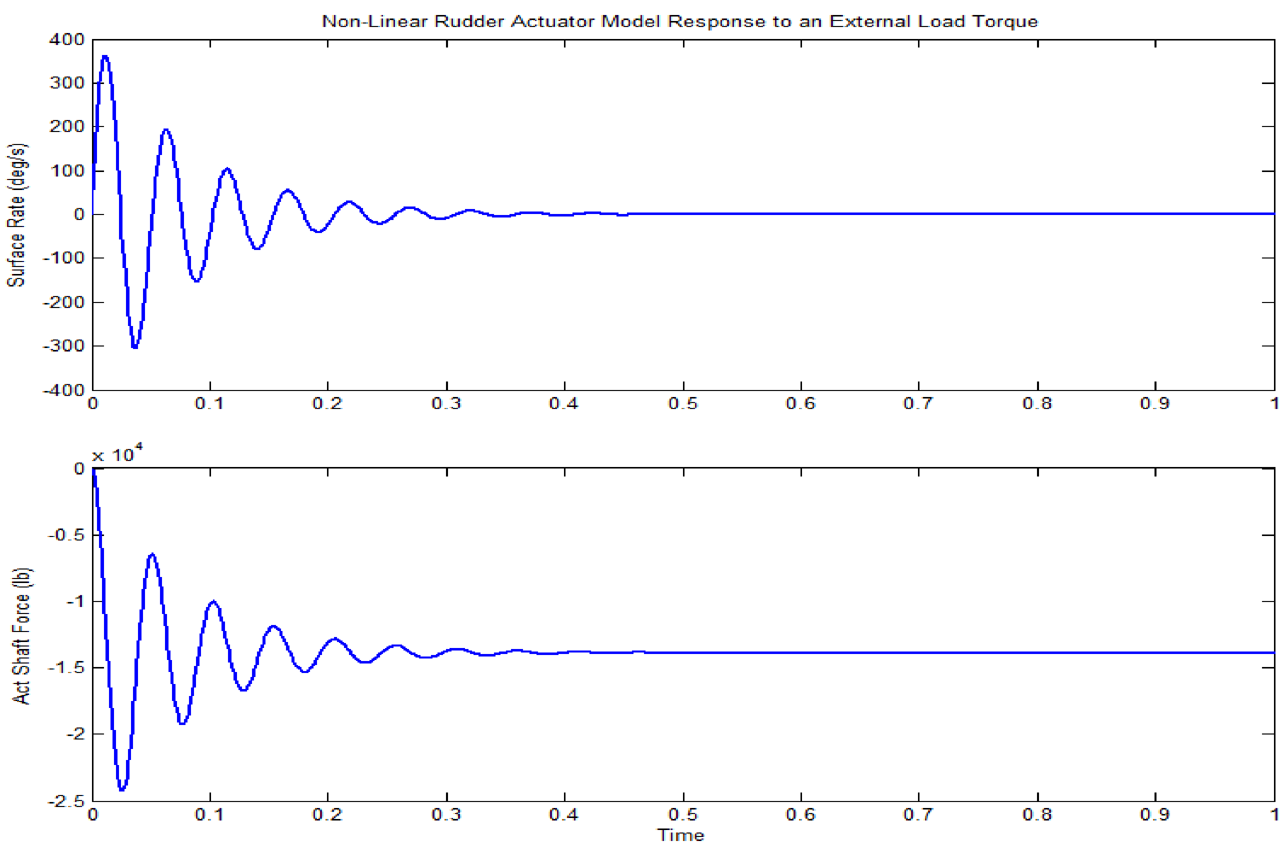


Figure (4.5.6.2) Non-Linear Actuator System's response to a 25° deflection command

The next set of plots in Figure (4.5.6.3) shows the actuator system response to a steady 5,000 (lb) external load-torque with zero deflection command. The load causes a steady shaft displacement of 0.1 (in) and 2° of surface deflection due to structural stiffness. The voltage goes negative to counteract the disturbance but it only takes a very small voltage at steady-state to supply 400 (ft-lb) of torque to the screw when the motor speed becomes zero.




Non-Linear Rudder Actuator Model Response to an External Load Torque
x 10^4
Surface Acceler (deg/s^2)
External Torque (ft-lb)
Time


Non-Linear Rudder Actuator Model Response to an External Load Torque
Surface Rate (deg/s)
x 10^4
Act Shaft Force (lb)
Time

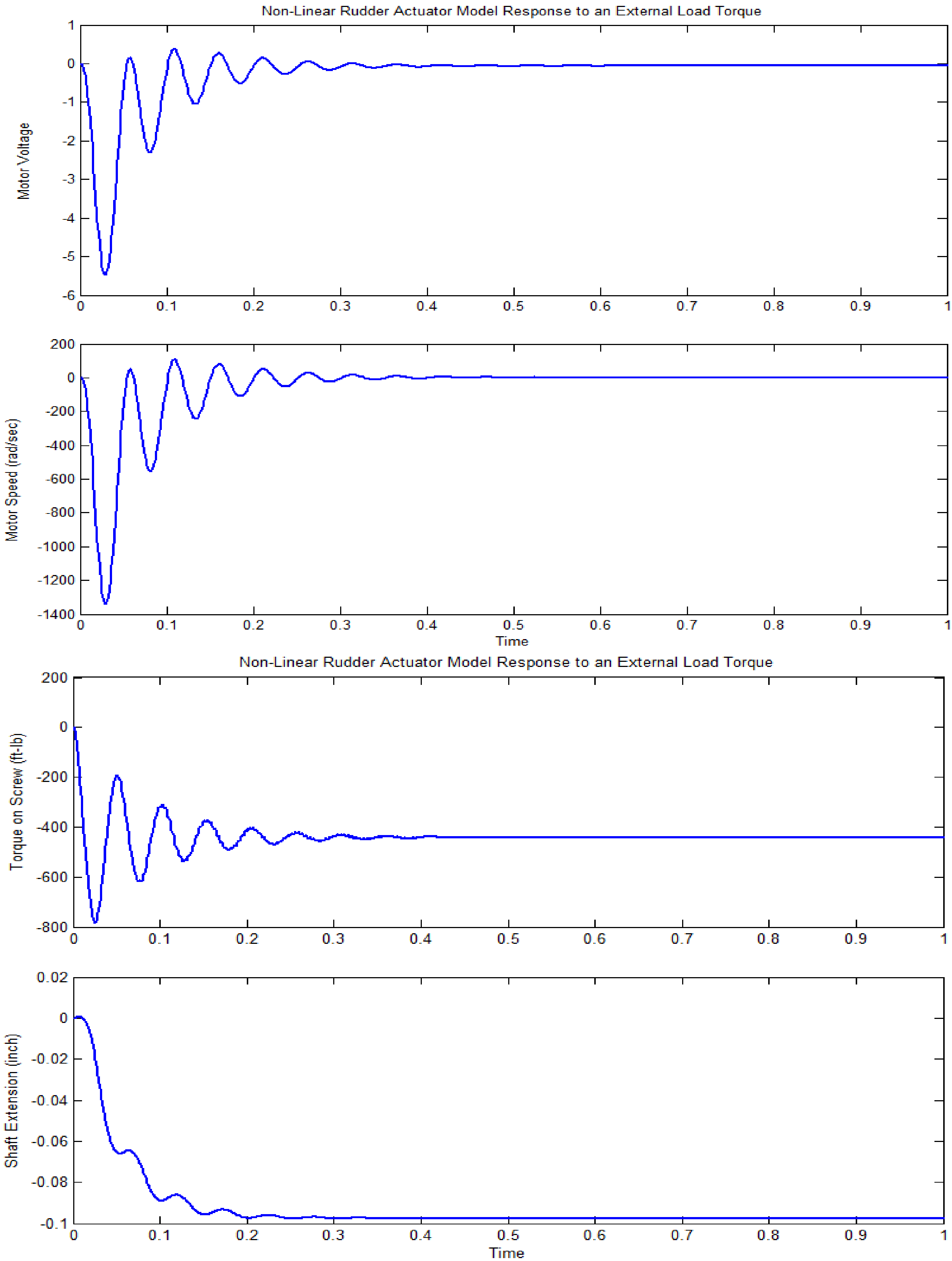


Figure (4.5.6.3) Non-Linear Actuator System's response to an External Load-Torque

Linear Analysis

The following Matlab script "frequ.m" calculates and plots the frequency responses of the two EMA type (B) models. That is, the Flixan generated model from file "*ema_b.m*" and the Simulink model "*Rudder-EMAB-Anal.Mdl*" shown in Figure (4.5.6.1). Figure (4.5.6.4) compares the responses and they are identical. The structural resonance is clearly visible at 22 Hz.

```
run
[a1,b1,c1,d1]= ema_b;
[a2,b2,c2,d2]= linmod('Rudder_EMAB_Anal');
w=logspace(0,4,10000);

sys1=ss(a1, b1(:,1), c1(1,:), d1(1,1));
sys2=ss(a2, b2(:,1), c2(1,:), d2(1,1));
w=logspace(0,4,8000);
figure(1); Bode(sys1,sys2,w)
```

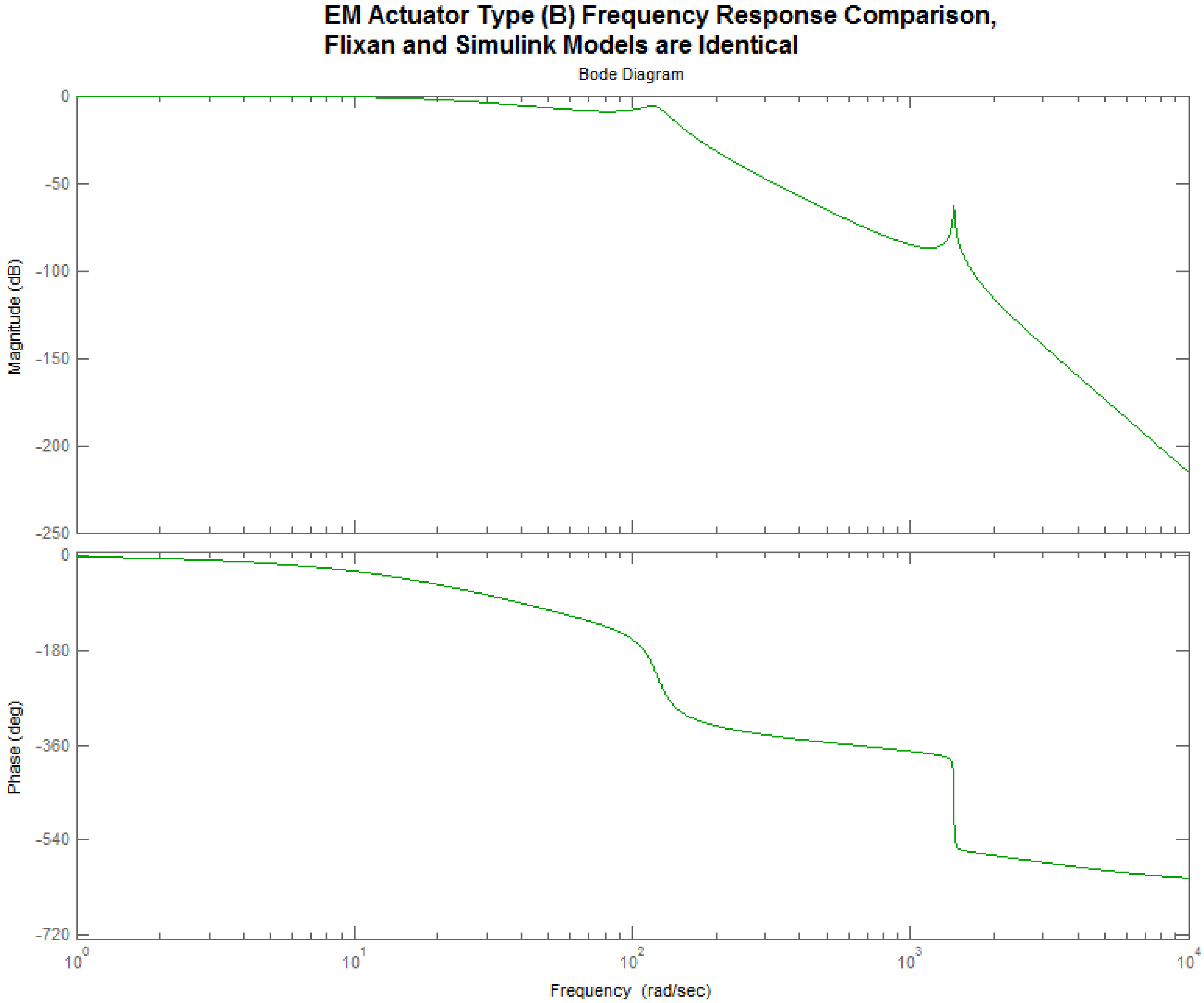


Figure (4.5.6.4) Frequency response comparison between the Flixan and Simulink implementations of the closed-loop EM actuator model. The responses are identical.

The same script file also generates the Nichols plot using a similar open-loop Simulink model to show the actuator loop gain and phase margins.

```
[a3,b3,c3,d3]= linmod('Rudder_EMAB_OpenLp');
sys3=ss(a3, b3(:,1), c3(1,:), d3(1,1));
figure(3); Nichols(sys3,w)
```

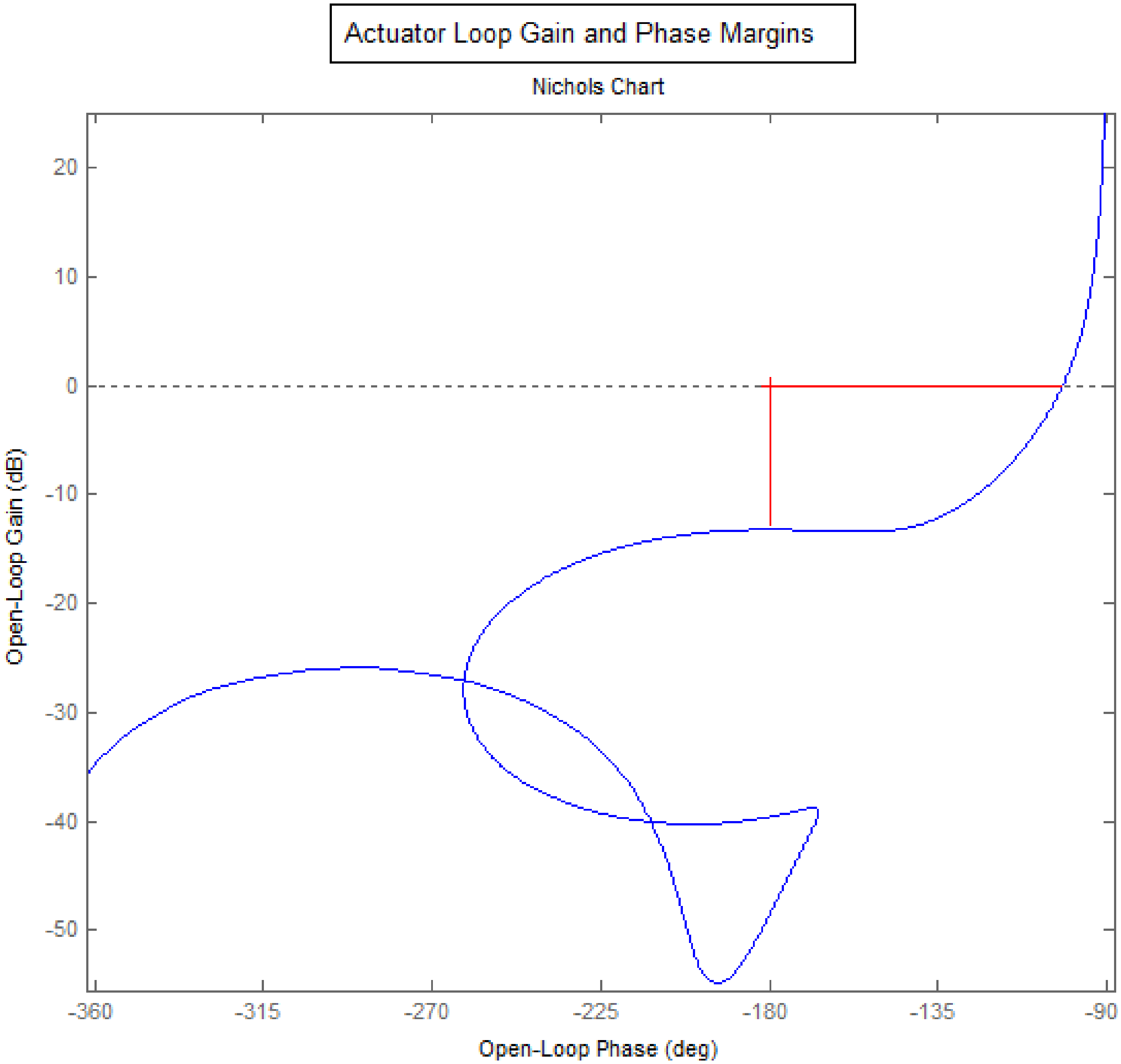


Figure (4.5.6.5) Nichols Plot showing the Gain and Phase margins of the Rudder EMA type (B) system

There are more actuator models included in files "Actor_Models.Inp" and "Actor_Models.Qdr" which are shown below.

4.5.7 Electro-Mechanical Type (B) Actuator Model for an Elevon

The input file "*Actor_Models.Inp*" includes also the EMA parameters for an Elevator actuator. Its title is "*Electro-Mechanical Actuator for an Elevator*" and its Matlab system function is "*elev_ema_b.m*". This EMA system is also implemented in a Simulink model "*Elevator_EMAB.mdl*" in folder "*C:\Flixan\Actuator\Examples\ EM-Actuators\Elevator*" that includes all actuator non-linearities. Its block diagram is similar to Figure (4.5.6.1), but it includes a 2nd order low-pass filter and a lead-lag in the feedback path. Figure (4.5.7.1) shows its response to a 5° deflection command.

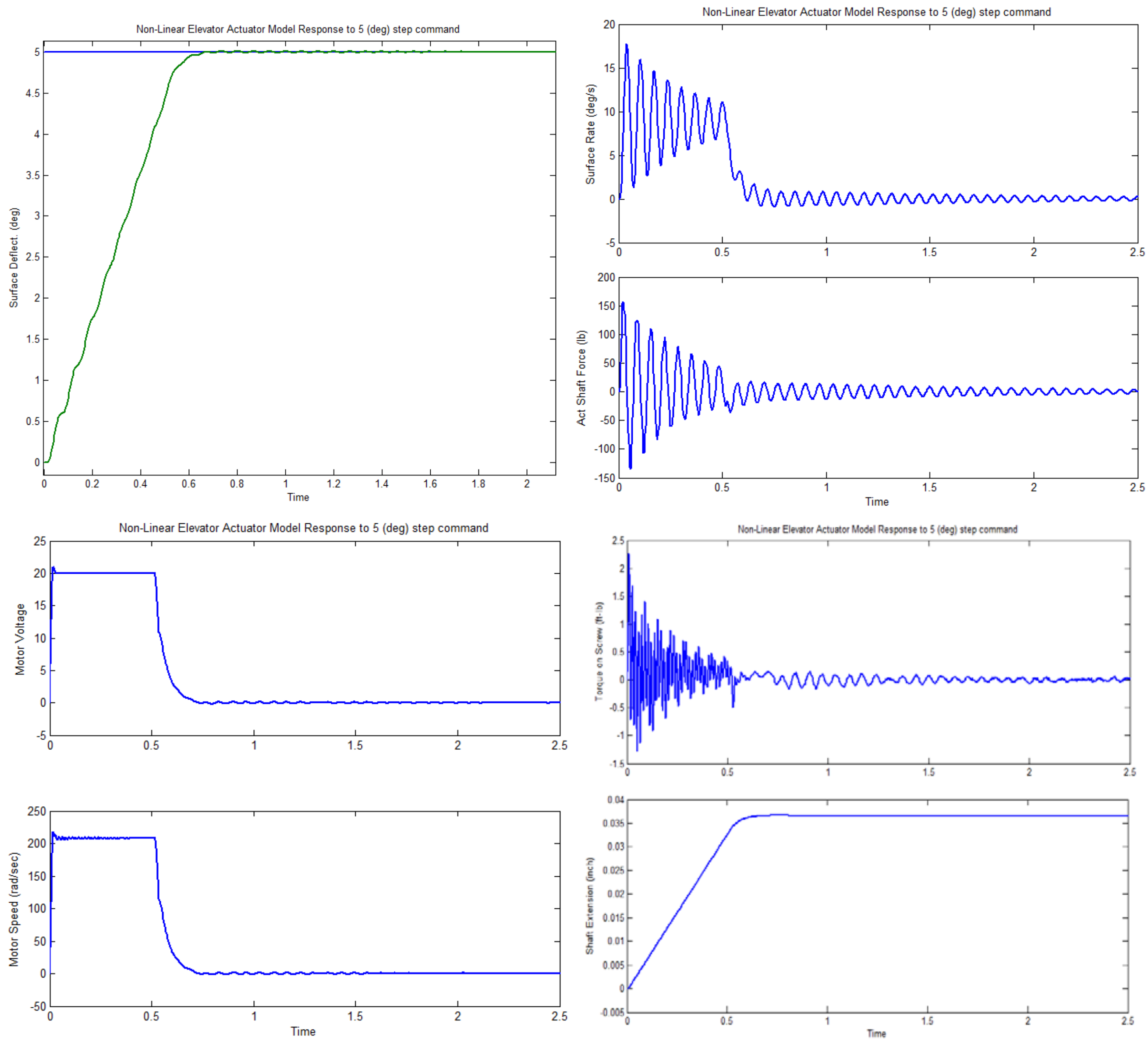
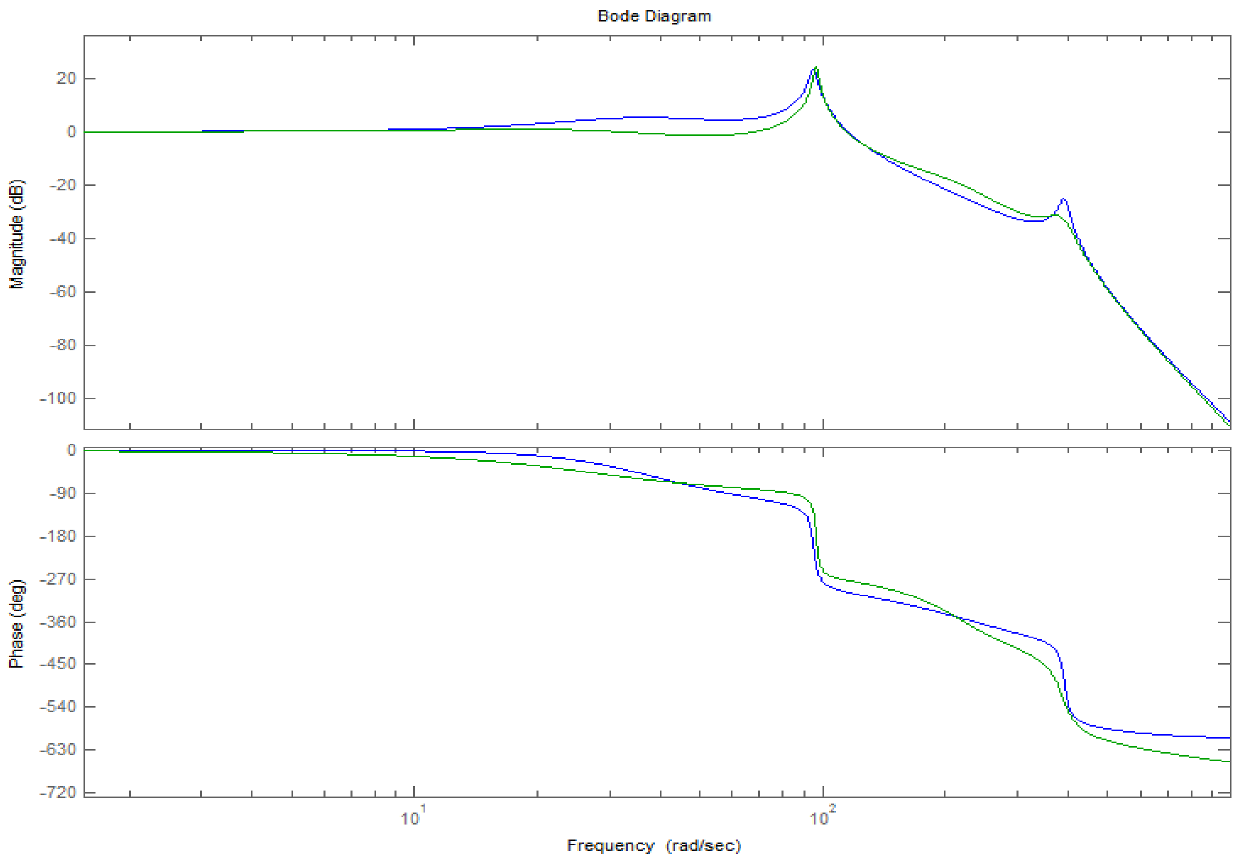


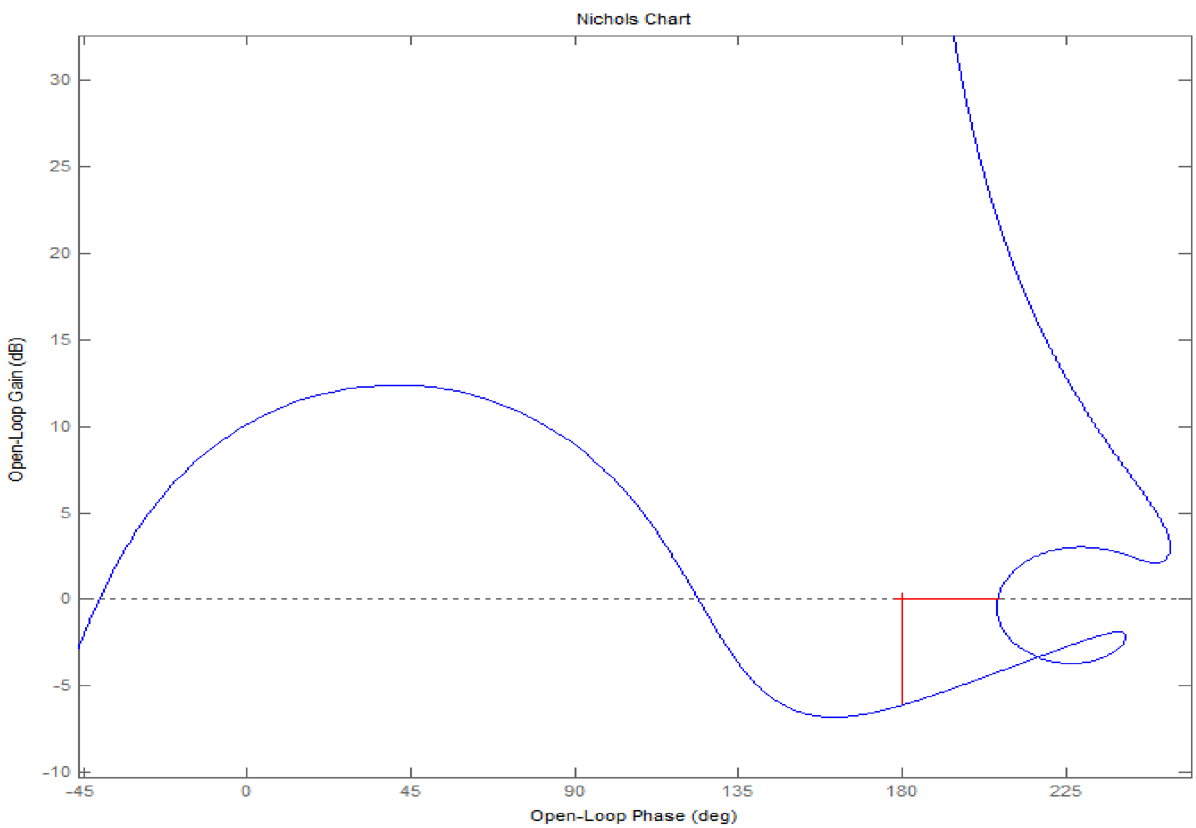
Figure (4.5.7.1) Elevon Actuator Response to a 5 (deg) step deflection command

Figure (4.5.7.2) shows the actuator frequency response calculated from the two models: the Flixan model and the Simulink model. They are a little different because the Simulink model includes a lead-lag filter in the position measurement feedback. The responses show two resonances due to backup and gear stiffnesses. Figure (4.5.7.3) is a Nichols plot that shows the actuator loop phase and gain margins.

Elevator EMA Actuator Frequency Response Using Different Compensators



Stability Margins for the Elevator Actuator



4.6 The Input Data File "Actor_Models.Inp"

```
BATCH MODE INSTRUCTIONS ..............
Batch set for creating a bunch of actuator models
! This Batch generates several types of actuator models. It also saves them as Matlab
! functions for further analysis
!
Actuator Model   : TVC Engine Actuator Example ...
Actuator Model   : TVC Engine Actuator Example (Units in inches)
Actuator Model   : Missile Actuator
Actuator Model   : Shuttle Main Engine Hydraulic Actuator (Type-B)
Actuator Model   : Shuttle Main Engine Actuator (with 1st order filter)
Actuator Model   : Shuttle Elevon Actuator (without filter)
Actuator Model   : Shuttle Elevon Actuator (with 2nd order filter)
Actuator Model   : Shuttle Solid Rocket Booster Actuator
Actuator Model   : Electro-Mechanical Actuator (without motor and amplifier dynamics)
Actuator Model   : Electro-Mechanical Rudder Actuator, Type-B (feet)
Actuator Model   : Electro-Mechanical Rudder Actuator, Type-B (inch)
Actuator Model   : Electro-Mechanical Actuator for an Elevator
Actuator Model   : Electro-Mechanical Actuator with an Extendable Push Rod Simplified
!
!  Matlab Models ...
To Matlab Format : TVC Engine Actuator Example ...
To Matlab Format : Missile Actuator
To Matlab Format : Shuttle Main Engine Hydraulic Actuator (Type-B)
To Matlab Format : Shuttle Main Engine Actuator (with 1st order filter)
To Matlab Format : Shuttle Elevon Actuator (without filter)
To Matlab Format : Shuttle Elevon Actuator (with 2nd order filter)
To Matlab Format : Electro-Mechanical Actuator (without motor and amplifier dynamics)
To Matlab Format : Electro-Mechanical Rudder Actuator, Type-B (feet)
To Matlab Format : Electro-Mechanical Rudder Actuator, Type-B (inch)
To Matlab Format : Electro-Mechanical Actuator with an Extendable Push Rod Simplified
--------------------------------------------------------------------------------

ACTUATOR INPUT DATA ............ SIMPLE GENERIC MODEL
TVC Engine Actuator Example ...
Symbol Parameter Description                    (Units)      Value
C(s)   Order of Compensat:(0,1,2), Coefficients   (---)       0
Kc     Input Command Gain ..................... (volt/rad)    9.5700
Ka     Gain of Amplifier ...................... (amps/volt)   4.7200
Ksv    Closed-Loop Actuator Servo Gain ....... (ft/sec/amp)   0.325
Kact   Actuator Stiffness (Piston+Oil+Electric) (lb/ft)       2340000.0
Klod   Load Stiffness,(Con. Surface or Nozzle)  (lb/ft)       3600000.0
Kbck   Vehicle Backup Structure Stiffness ....  (lb/ft)       8400000.0
R      Moment Arm of Actuator Rod from Gimbal..  (feet)       0.3
Jl     Load Inertia about the Gimbal .......... (ft-lb-s^2)   3.9333
Kg     Load Gimbal Bearing Spring Constant      (ft-lb/rad)   0.0000
Bg     Load Gimbal Bearing Viscous Damping .... (ft-lb-sec)   8.3333
Kfb    Actuator Position Feedback Gain ........ (volts/ft)    32.64
--------------------------------------------------------------------------------

ACTUATOR INPUT DATA ............ HYDRAULIC TYPE A
Missile Actuator
Symbol       Parameter Description               (Units)     Value
C(s)   Order of Compensat:(0,1,2), Coefficients   (---)      0
Kc     Input Command Gain ..................... (volt/rad)   46.12
Ka     Gain of Servo-Amplifier ................ (ma/volt)    20.4
Kv     Power Valve Flow Gain .................(ft^3/sec/ma)  0.596E-04
Kdpf   Differential Pressure Feedbk Gain ..... (ma/lb/ft^2)  0.1E-4
Tc     Differential Pressure Feedback Time Constant (sec)    0.1
Cl     Leakage Coeffic. (Orifice+Spool), (ft^3/sec/lb/ft^2)  0.2E-10
Vt     Volume of Compressed Fluid ............   (ft^3)      0.11600E-02
BM     Bulk Modulus of Hydraulic Fluid ........  (lb/ft^2)   0.28800E+08
Km     Stiffness of Piston Rod plus Mount Backup (lb/ft)     0.13333E+08
R      Moment Arm of Actuator Rod from Gimbal..   (feet)     0.30000
A      Piston Cross-Sectional Area ............  (feet^2)    0.015
Ie     Engine Inertia about Gimbal ............(ft-lb-s^2)   0.56
Fv     Engine Viscous Damping .................(ft-lb-sec)   410.00
Ksp    Engine Gimbal Bearing Spring Constant   (ft-lb/rad)   0.11100e+06
Kf     Position Transducer Feedback Gain ...... (volts/ft)   132.0
-----------------------------------------------------------------------------
```

ACTUATOR INPUT DATA .... HYDRAULIC TYPE B
Shuttle Main Engine Hydraulic Actuator (Type-B)
! Shuttle Main Engine Actuator Without Compensator
! Using the Hydraulic Actuator Model Type (B)

```
Symbol       Parameter Description                (Units)      Value
C(s)   Order of Compensat:(0,1,2), Coefficients   (---)       0
Kav    Total Gain of Amplifier + Torque Motor  (ft-lb/rad)  0.91000
Kact   Power Valve and Actuator Gain .........(ft/s/ft-lb)   53.950
Kt     Piston Ram Stiffness ..................  (lb/ft)    0.20280E+07
R      Moment Arm of Actuator Ram from Gimbal    (feet)      2.4800
Ie     Engine Inertia about Gimbal ...........(ft-lb-s^2)   4516.0
Be     Engine Viscous Damping ................(ft-lb-sec)   16500.
Kb     Engine Gimbal Bearing Spring Constant   (ft-lb/rad)   27160.0
Kl     Engine Mount Structural Stiffness ......  (lb/ft)    0.27960E+07
Tc     Different. Pressure Feedbk Time Constant  (seconds)  0.12660
Kdpf   Differ Pressure Feedbk Linearizat. Gain  (ft-lb/lb)  0.40400E-06
Kfb    Position Feedback Gain ................. (rad/feet)  0.4
-----------------------------------------------------------------------------
```

ACTUATOR INPUT DATA .... HYDRAULIC TYPE B
Shuttle Main Engine Actuator (with 1st order filter)
! Shuttle Main Engine Actuator, same as above, with 10/(s+10) Compensator
! in the control loop Using the Hydraulic Actuator Model Type (B)

```
Symbol       Parameter Description                (Units)      Value
C(s)   Order of Compensat:(0,1,2), Coefficients   (---)       1, 0.0, 0.1
Kav    Total Gain of Amplifier + Torque Motor  (ft-lb/rad)   0.91000
Kact   Power Valve and Actuator Gain .........(ft/s/ft-lb)   53.950
Kt     Piston Ram Stiffness ..................  (lb/ft)      0.20280E+07
R      Moment Arm of Actuator Ram from Gimbal    (feet)      2.4800
Ie     Engine Inertia about Gimbal ...........(ft-lb-s^2)   4516.0
Be     Engine Viscous Damping ................(ft-lb-sec)   16500.
Kb     Engine Gimbal Bearing Spring Constant   (ft-lb/rad)   27160.0
Kl     Engine Mount Structural Stiffness ......  (lb/ft)     0.27960E+07
Tc     Different. Pressure Feedbk Time Constant  (seconds)   0.12660
Kdpf   Differ Pressure Feedbk Linearizat. Gain  (ft-lb/lb)   0.40400E-06
Kfb    Position Feedback Gain ................. (rad/feet)   0.4
-----------------------------------------------------------------------------
```

ACTUATOR INPUT DATA .... HYDRAULIC TYPE B
Shuttle Elevon Actuator (without filter)
! Hydraulic Actuator Type (B) for the Space Shuttle Elevon, Without Filter

```
Symbol       Parameter Description                (Units)      Value
C(s)   Order of Compensat:(0,1,2), Coefficients   (---)       0
Kav    Total Gain of Amplifier + Torque Motor  (ft-lb/rad)   198.329
Kact   Actuator Gain .........................(ft/s/ft-lb)   0.09438
Kt     Piston Ram Stiffness ..................  (lb/ft)      0.16020E+07
R      Moment Arm of Actuator Ram from Gimbal    (feet)      0.7226
Ie     Elevon Inertia about Gimbal ...........(ft-lb-s^2)   268.67
Be     Elevon Viscous Damping ................(ft-lb-sec)   1250.0
Kb     Elevon Gimbal Bearing Spring Constant   (ft-lb/rad)   0.0
Kl     Elevon Mount Structural Stiffness ......  (lb/ft)     0.204E+07
Tc     Different. Pressure Feedbk Time Constant  (seconds)   0.12
Kdpf   Differ Pressure Feedbk Linearizat. Gain  (ft-lb/lb)   0.26E-03
Kfb    Position Feedback Gain ................. (rad/feet)   1.38396
-----------------------------------------------------------------------------
```

ACTUATOR INPUT DATA .... HYDRAULIC TYPE B
Shuttle Elevon Actuator (with 2nd order filter)
! Hydraulic Actuator Type (B) for the Space Shuttle Elevon, Including
! a second order notch filter in the control loop at 65 (rad/sec)

```
Symbol       Parameter Description                (Units)      Value
C(s)   Order of Compensat:(0,1,2), Coefficients   (---)       2, 0.015, 65.0, 0.6, 65.0
Kav    Total Gain of Amplifier + Torque Motor  (ft-lb/rad)   198.329
Kact   Actuator Gain .........................(ft/s/ft-lb)   0.09438
Kt     Piston Ram Stiffness ..................  (lb/ft)      0.16020E+07
R      Moment Arm of Actuator Ram from Gimbal    (feet)      0.7226
Ie     Elevon Inertia about Gimbal ...........(ft-lb-s^2)   268.67
Be     Elevon Viscous Damping ................(ft-lb-sec)   1250.0
Kb     Elevon Gimbal Bearing Spring Constant   (ft-lb/rad)   0.0
Kl     Elevon Mount Structural Stiffness ......  (lb/ft)     0.204E+07
Tc     Different. Pressure Feedbk Time Constant  (seconds)   0.12
Kdpf   Differ Pressure Feedbk Linearizat. Gain  (ft-lb/lb)   0.26E-03
Kfb    Position Feedback Gain ................. (rad/feet)   1.38396
-----------------------------------------------------------------------------
```

```
ACTUATOR INPUT DATA ............ HYDRAULIC TYPE B
Shuttle Solid Rocket Booster Actuator
Symbol       Parameter Description                   (Units)      Value
C(s)   Order of Compensat:(0,1,2), Coefficients    (---)       0
Kav    Total Gain of Amplifier + Torque Motor  (ft-lb/rad)    1.8152
Kact   Power Valve and Actuator Gain .........(ft/s/ft-lb)    75.4
Kt     Piston Ram Stiffness ...................  (lb/ft)     0.45000E+07
R      Moment Arm of Actuator Ram from Gimbal    (feet)       5.8
Ie     Engine Inertia about Gimbal ............(ft-lb-s^2)    11000.0
Be     Engine Viscous Damping .................(ft-lb-sec)    17166.0
Kb     Engine Gimbal Bearing Spring Constant   (ft-lb/rad)   0.19166E+06
Kl     Engine Mount Structural Stiffness ......  (lb/ft)     0.60000E+07
Tc     Different. Pressure Feedbk Time Constant  (seconds)   0.1252
Kdpf   Differ Pressure Feedbk Linearizat. Gain  (ft-lb/lb)   0.40000E-06
Kfb    Position Feedback Gain ................. (rad/feet)   0.172
--------------------------------------------------------------------------------
ACTUATOR INPUT DATA ............ ELECTROMECHANICAL TYPE A
Electro-Mechanical Actuator (without motor and amplifier dynamics)
!
! This EMA actuator was developed for an Advanced Launch Booster Vehicle
!
Symbol       Parameter Description                   (Units)      Value
C(s)   Order of Compensat:(0,1,2), Coefficients    (---)       0
       Include Motor and Amplif. Dynamics      (0=no,1=yes)  0
Gp     Input Command Angle Conversion .........(counts/rad)  12000.
Kpl    Position Feedback Gain from Load .......(counts/rad)  0.0
Kpm    Position Feedback Gain from Motor ......(counts/rad)  2.54
Gv     Position to Voltage Conversion Gain ....(volt/count)  0.393
Kv     Rate Feedback Gain from Motor ..........(volt/rad/s)  0.016
Ka     Amplifier Gain .........................(volt/volt)   1.0
Ta     Amplifier Time Constant ................ (seconds)    0.001
Rm     Motor Winding Resistance ...............  (ohms)      0.1
Tm     Motor Time Constant .................... (seconds)    0.9e-3
Kemf   Motor Back EMF Gain ....................(volt/rad/s)  0.435e-01
Kt     Motor Current to Torque Gain ...........(ft-lb/amp)   0.3217e-01
Jm     Motor Moment of Inertia ................(ft-lb-s^2)   0.71660e-04
Kmd    Motor Viscous Damping ..................(ft-lb/rd/s)  0.00000
N      Motor to Load Gear Ratio ............... (rad/rad)    4723.
Je     Engine Inertia about Gimbal ............(ft-lb-s^2)   80.6
R      Moment Arm of Actuator from Gimbal .....   (feet)     1.16
Fv     Engine Viscous Damping Coefficient ....(ft-lb/rad/s)  10770.
Ksp    Engine Gimbal Bearing Spring Constant   (ft-lb/rad)   0.00000
Km     Attach Point Flexion Spring Constant ...  (lb/ft)     0.36e+06
Gt     Mechanical Conversion Efficiency Factor     (---)     1.1
Bi     Sensor Bias Coefficient ................ (rad/rad)    0.0
----------------------------------------------------------------------------------------------------
ACTUATOR INPUT DATA ............ ELECTROMECHANICAL TYPE B
Electro-Mechanical Rudder Actuator, Type-B (feet)
! This EMA actuator Uses an Extendable Push Rod to Drive a Load.
! The end of the rod is attached to a lever arm that rotates a control Surface.
!
Symbol       Parameter Description                   (Units)      Value
C(s)   Order of Compensat:(0,1,2), Coefficients    (---)       1, 0.0, 0.01
Kpl    Position Error Loop Gain                   (Volt/ft)    40.0
Krf    Rate Feedback Gain                     (Volt/in/sec)    0.0
Ki     Position Error Integral Gain           (Volt/in-sec)    0.0
Wm     Servo Motor Bandwidth,                   (rad/sec)      3000.0
Kv     Servo Motor Torque Gain                 (ft-lb/volt)    490.196
Jm     Motor Rotor Moment of Inertia          (in-lb-sec^2)    6.536e-4
Ngr    Gear Ratio (Motor Turns/ Screw Turns)        ( - )      17.0
Nscr   Screw Ratio (Piston Extension/Screw Turns) (in/rad)     0.0318
Kgs    Motor Gear Stiffness                     (in-lb/rad)    8376.0
Kmfr   Motor/ Gear Friction                 (ft-lb/rad/sec)    0.0
Kdmp   Shaft Damping Friction               (ft-lb/rad/sec)    0.001
Keff   Gear Effectiveness Coefficient               ( - )      0.85
Ja     Gear plus Screw Inertia                (in-lb-sec^2)    0.0035
Kact   Actuator Stiffness (Piston+Electric).... (lb/in)        140000.0
Klod   Load Stiffness,(Con. Surface or Nozzle)  (lb/in)        181000.0
Kbck   Vehicle Backup Structure Stiffness ..... (lb/in)        350000.0
R      Moment Arm of Actuator Rod from Gimbal..    (in)        3.6
Je     Load Inertia about the Gimbal ....... (in-lb-sec^2)     52.2
Be     Nozzle Bearing Viscous Damping ....... (in-lb-sec)      1600.0
Kg     Gimbal Bearing Spring Constant           (in-lb/rad)    0.0000
--------------------------------------------------------------------------------------------
```

```
ACTUATOR INPUT DATA ............ ELECTROMECHANICAL TYPE B
Electro-Mechanical Actuator for an Elevator
! This EMA system has a full PID controller with a second order compensator
!
Symbol       Parameter Description               (Units)      Value
C(s)   Order of Compensat:(0,1,2), Coefficients   (---)       2, 1.,2100., 0.7,240.0
Kpl    Position Error Loop Gain                 (Volt/ft)     12600.0
Krf    Rate Feedback Gain                   (Volt/ft/sec)     0.0126
Ki     Position Error Integral Gain         (Volt/ft-sec)     378000.0
Wm     Servo Motor Bandwidth,                 (rad/sec)       1000.0
Kv     Servo Motor Torque Gain               (ft-lb/volt)     208.0
Jm     Motor Rotor Moment of Inertia         (ft-lb-sec^2)    0.02
Ngr    Gear Ratio (Motor Turns/ Screw Turns)       ( - )      8.195
Nscr   Screw Ratio (Piston Extension/Screw Turns) (ft/rad)    0.002605
Kgs    Motor Gear Stiffness                    (ft-lb/rad)    80.0
Kmfr   Motor/ Gear Friction                (ft-lb/rad/sec)    8.0
Kdmp   Shaft Damping Friction              (ft-lb/rad/sec)    0.001
Keff   Gear Effectiveness Coefficient              ( - )      0.85
Ja     Gear plus Screw Inertia               (ft-lb-sec^2)    0.000423
Kact   Actuator Stiffness (Piston+Electric).... (lb/ft)       1.0e7
Klod   Load Stiffness,(Con. Surface or Nozzle)  (lb/ft)       456000.0
Kbck   Vehicle Backup Structure Stiffness ..... (lb/ft)       456000.0
R      Moment Arm of Actuator Shaft from Gimbal..  (feet)     0.42
Je     Load Inertia about the Gimbal ....... (ft-lb-sec^2)    4.2
Be     Aero-Surface Bearing Viscous Damping   (ft-lb-sec)     26.
Kg     Aero-Surface Bearing Spring Constant   (ft-lb/rad)     0.0
--------------------------------------------------------------------------------

ACTUATOR INPUT DATA ............ SIMPLE GENERIC MODEL
Electro-Mechanical Actuator with an Extendable Push Rod Simplified
! This EMA actuator is a Simplified version of the above EMA system
! The end of the rod is attached to a lever arm that rotates a control Surface.
! A first order compensator (1000/s+1000) is used to model the motor dynamics
Symbol Parameter Description                    (Units)       Value
C(s)   Order of Compensat:(0,1,2), Coefficients   (---)       1, 0.0, 0.001
Kc     Input Command Gain ..................... (volt/rad)    0.3
Ka     Gain of Amplifier ...................... (amps/volt)   120.0
Ksv    Closed-Loop Actuator Servo Gain ....... (ft/sec/amp)   0.039
Kact   Actuator Stiffness (Piston+Oil+Electric) (lb/ft)       2340000.0
Klod   Load Stiffness,(Con. Surface or Nozzle)  (lb/ft)       3600000.0
Kbck   Vehicle Backup Structure Stiffness ....  (lb/ft)       8400000.0
R      Moment Arm of Actuator Rod from Gimbal..  (feet)       0.3
Jl     Load Inertia about the Gimbal .......... (ft-lb-s^2)   3.93
Kg     Load Gimbal Bearing Spring Constant      (ft-lb/rad)   0.0000
Bg     Load Gimbal Bearing Viscous Damping .... (ft-lb-sec)   84.0
Kfb    Actuator Position Feedback Gain ........ (volts/ft)    1.0
----------------------------------------------------------------------------------------------------
END-END-END-END-END-END-END-END-END-END-END-END-END-END-END-END-END-END-END-END-END-END-END-END-END-
```

4.7 The Systems File “Actor_Models.Qdr”

```
STATE-SPACE SYSTEM ...
TVC Engine Actuator Example ...
Number of Inputs, States, Outputs, Sample Time dT (for discrete)=    2    3    3    0.0000
Matrices: (A,B,C,D)
Matrix A                    Size =  3 X  3
           1-Column            2-Column            3-Column
   1-Row -0.241076622222E+02 -0.778862933333E+01  0.000000000000E+00
   2-Row  0.000000000000E+00  0.000000000000E+00  0.100000000000E+01
   3-Row  0.925431571454E+05 -0.277629471436E+05 -0.211865354791E+01
---------------------------------------------------------------------------------------------------------Matrix
B                    Size =  3 X  2
           1-Column            2-Column
   1-Row  0.146803800000E+02  0.000000000000E+00
   2-Row  0.000000000000E+00  0.000000000000E+00
   3-Row  0.000000000000E+00  0.254239442707E+00
---------------------------------------------------------------------------------------------------------Matrix
C                    Size =  3 X  3
           1-Column            2-Column            3-Column
   1-Row  0.000000000000E+00  0.100000000000E+01  0.000000000000E+00
   2-Row  0.000000000000E+00  0.000000000000E+00  0.100000000000E+01
   3-Row  0.925431571454E+05 -0.277629471436E+05 -0.211865354791E+01
---------------------------------------------------------------------------------------------------------Matrix
D                    Size =  3 X  2
           1-Column            2-Column
   1-Row  0.000000000000E+00  0.000000000000E+00
   2-Row  0.000000000000E+00  0.000000000000E+00
   3-Row  0.000000000000E+00  0.254239442707E+00
---------------------------------------------------------------------------------------------------------
Definition of System Variables

Inputs  =   2
       Load Deflection Command (Delta_com), (rad)
       External Load Torque (Tl),    (ft-lb)

Outputs =   3
       Load Rotation at Gimbal  (Delta)   (rad)
       Load Rate at Gimbal  (Delta-dot)   (rad/sec)
       Load Accelerat. (Delta-dot-dot) (rad/sec^2)

States  =   3
       Actuator Piston Position (Xp)  (feet)
       Load Rotation, (Delta)  (radians)
       Load Rate, (Delta-dot)  (rad/sec)
----------------------------------------------------------------------------------------------------
```

STATE-SPACE SYSTEM ...
Missile Actuator

```
Number of Inputs, States, Outputs, Sample Time dT (for discrete)=    2    4    3    0.0000
Matrices: (A,B,C,D)
Matrix A                    Size =  4 X  4
           1-Column            2-Column            3-Column            4-Column
   1-Row -0.744322690128E+01 -0.178688078873E+10 -0.167007694337E+09 -0.221192412945E+02
   2-Row  0.000000000000E+00  0.000000000000E+00  0.100000000000E+01  0.000000000000E+00
   3-Row  0.803571428571E-02 -0.198214285714E+06 -0.732142857143E+03  0.000000000000E+00
   4-Row -0.744322690128E+01 -0.178688078873E+10 -0.167007694337E+09 -0.321192412945E+02
-----------------------------------------------------------------------------------------------------Matrix
B                    Size =  4 X  2
           1-Column            2-Column
   1-Row  0.208108439334E+10  0.000000000000E+00
   2-Row  0.000000000000E+00  0.000000000000E+00
   3-Row  0.000000000000E+00  0.178571428571E+01
   4-Row  0.208108439334E+10  0.000000000000E+00
-----------------------------------------------------------------------------------------------------Matrix
C                    Size =  3 X  4
           1-Column            2-Column            3-Column            4-Column
   1-Row  0.000000000000E+00  0.100000000000E+01  0.000000000000E+00  0.000000000000E+00
   2-Row  0.000000000000E+00  0.000000000000E+00  0.100000000000E+01  0.000000000000E+00
   3-Row  0.803571428571E-02 -0.198214285714E+06 -0.732142857143E+03  0.000000000000E+00
-----------------------------------------------------------------------------------------------------Matrix
D                    Size =  3 X  2
           1-Column            2-Column
   1-Row  0.000000000000E+00  0.000000000000E+00
   2-Row  0.000000000000E+00  0.000000000000E+00
   3-Row  0.000000000000E+00  0.178571428571E+01
-----------------------------------------------------------------------------------------------------
Definition of System Variables

Inputs  =   2
       Engine Deflection Command (Delta_com)  (rad)
       External Load-Torque (Tl),  (ft-lb)

Outputs =   3
       Engine Gimbal Rotation  (Delta)   (rad)
       Engine Gimbal Rate    (Del-dot)   (rad/sec)
       Gimbal Accelerat. (Delta-dot-dot) (rad/sec^2)

States  =   4
       Load Pressure           (PL)     (lb/ft^2)
       Engine Gimbal Rotation  (Delta)  (rad)
       Engine Gimbal Rate, (Delta-dot)  (rad/sec)
       Differential Pressure Feedback (DPF)  (ft-lb)
--------------------------------------------------------------------------------------------------
```

STATE-SPACE SYSTEM ...

Shuttle Main Engine Actuator (with 1st order filter)

! Shuttle Main Engine Actuator, same as above, with 10/(s+10) Compensator in the control loop

! Using the Hydraulic Actuator Model Type (B)

Number of Inputs, States, Outputs, Sample Time dT (for discrete)= 2 5 3 0.0000

Matrices: (A,B,C,D)

Matrix A Size = 5 X 5

	1-Column	2-Column	3-Column	4-Column	5-Column
1-Row	-0.521007765548E+02	0.000000000000E+00	0.000000000000E+00	-0.203189376000E+01	0.402237129840E+02
2-Row	-0.539500000000E+02	0.000000000000E+00	0.000000000000E+00	0.000000000000E+00	0.490945000000E+02
3-Row	0.000000000000E+00	0.000000000000E+00	0.000000000000E+00	0.100000000000E+01	0.000000000000E+00
4-Row	0.000000000000E+00	0.111369353410E+04	-0.276797413640E+04	-0.365367581931E+01	0.000000000000E+00
5-Row	0.000000000000E+00	-0.290128755365E+01	-0.272480686695E+01	0.000000000000E+00	-0.100000000000E+02

Matrix B Size = 5 X 2

	1-Column	2-Column
1-Row	0.000000000000E+00	0.000000000000E+00
2-Row	0.000000000000E+00	0.000000000000E+00
3-Row	0.000000000000E+00	0.000000000000E+00
4-Row	0.000000000000E+00	0.221434898140E-03
5-Row	0.100000000000E+02	0.000000000000E+00

Matrix C Size = 3 X 5

	1-Column	2-Column	3-Column	4-Column	5-Column
1-Row	0.000000000000E+00	0.000000000000E+00	0.100000000000E+01	0.000000000000E+00	0.000000000000E+00
2-Row	0.000000000000E+00	0.000000000000E+00	0.000000000000E+00	0.100000000000E+01	0.000000000000E+00
3-Row	0.000000000000E+00	0.111369353410E+04	-0.276797413640E+04	-0.365367581931E+01	0.000000000000E+00

Matrix D Size = 3 X 2

	1-Column	2-Column
1-Row	0.000000000000E+00	0.000000000000E+00
2-Row	0.000000000000E+00	0.000000000000E+00
3-Row	0.000000000000E+00	0.221434898140E-03

Definition of System Variables

Inputs = 2
- Nozzle Deflection Command (Delta_com) (rad)
- Load-Torque at the Gimbal, (Tl) (ft-lb)

Outputs = 3
- Nozzle Gimbal Rotation (Delta) (rad)
- Nozzle Gimbal Rate (Delta-dot) (rad/sec)
- Gimbal Accelerat. (Delta-dot-dot) (rad/sec^2)

States = 5
- Differ. Pressure Feedback (DPF) (ft-lb)
- Piston Displacement (Xr) (feet)
- Engine Gimbal Rotation (Delta) (rad)
- Engine Gimbal Rate (Delta-dot) (rad/sec)
- First Order Compensator State

STATE-SPACE SYSTEM ...

Shuttle Elevon Actuator (with 2nd order filter)

! Hydraulic Actuator Type (B) for the Space Shuttle Elevon, Including a second order notch filter
! in the control loop at 65 (rad/sec)

```
Number of Inputs, States, Outputs, Sample Time dT (for discrete)=    2    6    3    0.0000
Matrices: (A,B,C,D)
Matrix A                    Size =  6 X  6
          1-Column            2-Column            3-Column            4-Column            5-Column            6-Column
   1-Row -0.476444909333E+02 -0.847340446418E+04 -0.167404640751E+04 -0.300977352000E+03  0.000000000000E+00  0.779654257565E+04
   2-Row -0.943800000000E-01 -0.203433315667E+02 -0.401912611041E+01  0.000000000000E+00  0.000000000000E+00  0.187182910200E+02
   3-Row  0.000000000000E+00  0.000000000000E+00  0.000000000000E+00  0.100000000000E+01  0.000000000000E+00  0.000000000000E+00
   4-Row  0.000000000000E+00  0.430865076116E+04 -0.311343104001E+04 -0.465254773514E+01  0.000000000000E+00  0.000000000000E+00
   5-Row  0.000000000000E+00  0.000000000000E+00  0.000000000000E+00  0.000000000000E+00  0.000000000000E+00 -0.422500000000E+04
   6-Row  0.000000000000E+00  0.826523299588E+02  0.163291905426E+02  0.000000000000E+00  0.100000000000E+01 -0.780000000000E+02
----------------------------------------------------------------------------------------------------
Matrix B                    Size =  6 X  2
          1-Column            2-Column
   1-Row  0.779654257565E+04  0.000000000000E+00
   2-Row  0.187182910200E+02  0.000000000000E+00
   3-Row  0.000000000000E+00  0.000000000000E+00
   4-Row  0.000000000000E+00  0.372203818811E-02
   5-Row  0.000000000000E+00  0.000000000000E+00
   6-Row -0.760500000000E+02  0.000000000000E+00
----------------------------------------------------------------------------------------------------
Matrix C                    Size =  3 X  6
          1-Column            2-Column            3-Column            4-Column            5-Column            6-Column
   1-Row  0.000000000000E+00  0.000000000000E+00  0.100000000000E+01  0.000000000000E+00  0.000000000000E+00  0.000000000000E+00
   2-Row  0.000000000000E+00  0.000000000000E+00  0.000000000000E+00  0.100000000000E+01  0.000000000000E+00  0.000000000000E+00
   3-Row  0.000000000000E+00  0.430865076116E+04 -0.311343104001E+04 -0.465254773514E+01  0.000000000000E+00  0.000000000000E+00
----------------------------------------------------------------------------------------------------
Matrix D                    Size =  3 X  2
          1-Column            2-Column
   1-Row  0.000000000000E+00  0.000000000000E+00
   2-Row  0.000000000000E+00  0.000000000000E+00
   3-Row  0.000000000000E+00  0.372203818811E-02
-------------------------------------------------------------------------------------------------Definition
of System Variables

Inputs  =   2
       Nozzle Deflection Command (Delta_com) (rad)
       Load-Torque at the Gimbal,  (Tl)  (ft-lb)

Outputs =   3
       Nozzle Gimbal Rotation  (Delta)   (rad)
       Nozzle Gimbal Rate    (Delta-dot) (rad/sec)
       Gimbal Accelerat. (Delta-dot-dot) (rad/sec^2)

States  =   6
       Differ. Pressure Feedback (DPF)   (ft-lb)
       Piston Displacement       (Xr)    (feet)
       Engine Gimbal Rotation  (Delta)   (rad)
       Engine Gimbal Rate   (Delta-dot)  (rad/sec)
       Second Order Compens. State # 1
       Second Order Compens. State # 2
-------------------------------------------------------------------------------------------------
```

STATE-SPACE SYSTEM ...
Electro-Mechanical Actuator (without motor and amplifier dynamics)
! This EMA actuator was developed for an Advanced Launch Booster Vehicle

```
Number of Inputs, States, Outputs, Sample Time dT (for discrete)=    2    4    3    0.0000
Matrices: (A,B,C,D)
Matrix A                    Size =  4 X  4
           1-Column            2-Column            3-Column            4-Column
   1-Row  0.000000000000E+00  0.100000000000E+01  0.000000000000E+00  0.000000000000E+00
   2-Row -0.481461241333E+04 -0.267110661457E+03  0.157440483560E+07  0.000000000000E+00
   3-Row  0.000000000000E+00  0.000000000000E+00  0.000000000000E+00  0.100000000000E+01
   4-Row  0.127252256394E+01  0.000000000000E+00 -0.601012406948E+04 -0.133622828784E+03
-----------------------------------------------------------------------------------------------------------Matrix
B                    Size =  4 X  2
           1-Column            2-Column
   1-Row  0.000000000000E+00  0.000000000000E+00
   2-Row  0.211713257047E+08  0.000000000000E+00
   3-Row  0.000000000000E+00  0.000000000000E+00
   4-Row  0.000000000000E+00  0.124069478908E-01
-----------------------------------------------------------------------------------------------------------Matrix
C                    Size =  3 X  4
           1-Column            2-Column            3-Column            4-Column
   1-Row  0.000000000000E+00  0.000000000000E+00  0.100000000000E+01  0.000000000000E+00
   2-Row  0.000000000000E+00  0.000000000000E+00  0.000000000000E+00  0.100000000000E+01
   3-Row  0.127252256394E+01  0.000000000000E+00 -0.601012406948E+04 -0.133622828784E+03
-----------------------------------------------------------------------------------------------------------Matrix
D                    Size =  3 X  2
           1-Column            2-Column
   1-Row  0.000000000000E+00  0.000000000000E+00
   2-Row  0.000000000000E+00  0.000000000000E+00
   3-Row  0.000000000000E+00  0.124069478908E-01
-----------------------------------------------------------------------------------------------------------
Definition of System Variables

Inputs  =   2
       Engine Deflection Command (Del_com) (rad)
       External Load-Torque (Tl),  (ft-lb)

Outputs =   3
       Engine Gimbal Rotation  (Delta)    (rad)
       Engine Gimbal Rate      (Del-dot)  (rad/sec)
       Engine Gimbal Acceler. (Del-d-dot) (rad/sec^2)

States  =   4
       Torque Motor Angle  (theta),    (radians)
       Torque Motor Rate  (theta-dot), (rad/sec)
       Engine Gimbal Rotation (Delta), (radians)
       Engine Gimbal Rate (Delta-dot), (rad/sec)
--------------------------------------------------------------------------------------------------------
```

STATE-SPACE SYSTEM ...

Electro-Mechanical Rudder Actuator, Type-B (feet)

! This EMA actuator Uses an Extendable Push Rod to Drive a Load. The end of the rod is attached
! to a lever arm that rotates a control Surface.

```
Number of Inputs, States, Outputs, Sample Time dT (for discrete)=    2    8    3    0.0000
Matrices: (A,B,C,D)
Matrix A                    Size =  8 X  8
           1-Column            2-Column            3-Column            4-Column            5-Column            6-Column            7-
   1-Row  0.000000000000E+00  0.100000000000E+01  0.000000000000E+00  0.000000000000E+00  0.000000000000E+00  0.000000000000E+00
   2-Row -0.205278194611E+07 -0.285714285714E+00  0.210685104220E+07  0.000000000000E+00  0.119657142857E+06  0.000000000000E+00
   3-Row  0.000000000000E+00  0.000000000000E+00  0.000000000000E+00  0.100000000000E+01  0.000000000000E+00  0.000000000000E+00
   4-Row  0.141263958768E+03  0.000000000000E+00 -0.159921462756E+05 -0.306513409962E+02  0.000000000000E+00  0.000000000000E+00
   5-Row  0.000000000000E+00  0.000000000000E+00  0.000000000000E+00  0.000000000000E+00  0.000000000000E+00  0.100000000000E+01
   6-Row  0.753833969328E+06  0.000000000000E+00  0.000000000000E+00  0.000000000000E+00 -0.443431746664E+05 -0.300000000000E+04
   7-Row -0.171690899847E-01  0.000000000000E+00 -0.165632943569E+01  0.000000000000E+00  0.000000000000E+00  0.000000000000E+00
   8-Row -0.686763599390E+02  0.000000000000E+00 -0.662531774276E+04  0.000000000000E+00  0.000000000000E+00  0.000000000000E+00
------------------------------------------------------------------------------------------------------------------------
Matrix B                    Size =  8 X  2
           1-Column            2-Column
   1-Row  0.000000000000E+00  0.000000000000E+00
   2-Row  0.000000000000E+00  0.000000000000E+00
   3-Row  0.000000000000E+00  0.000000000000E+00
   4-Row  0.000000000000E+00  0.191570881226E-01
   5-Row  0.000000000000E+00  0.000000000000E+00
   6-Row  0.000000000000E+00  0.000000000000E+00
   7-Row  0.360000000000E+01  0.000000000000E+00
   8-Row  0.144000000000E+05  0.000000000000E+00
------------------------------------------------------------------------------------------------------------------------
Matrix C                    Size =  3 X  8
           1-Column            2-Column            3-Column            4-Column            5-Column            6-Column            7-
   1-Row  0.000000000000E+00  0.000000000000E+00  0.100000000000E+01  0.000000000000E+00  0.000000000000E+00  0.000000000000E+00
   2-Row  0.000000000000E+00  0.000000000000E+00  0.000000000000E+00  0.100000000000E+01  0.000000000000E+00  0.000000000000E+00
   3-Row  0.141263958768E+03  0.000000000000E+00 -0.159921462756E+05 -0.306513409962E+02  0.000000000000E+00  0.000000000000E+00
------------------------------------------------------------------------------------------------------------------------
Matrix D                    Size =  3 X  2
           1-Column            2-Column
   1-Row  0.000000000000E+00  0.000000000000E+00
   2-Row  0.000000000000E+00  0.000000000000E+00
   3-Row  0.000000000000E+00  0.191570881226E-01
------------------------------------------------------------------------------------------------------------------------
Definition of System Variables

Inputs  =   2
       Deflection Command (Delta_com) (radians)
       External Load-Torque (Tl),  (ft-lb)

Outputs =   3
       Gimbal Deflection  (Delta)   (rad)
       Gimbal Rate      (Delta-dot)   (rad/sec)
       Gimbal Accelerat (Delta-dot-dot) (rad/sec^2)

States  =   8
       Screw Gear Rotation Angle (theta), (rad)
       Screw Gear Rate (theta-dot)   (rad/sec)
       Gimbal Deflection  (Delta)     (rad)
       Gimbal Rate    (Delta-dot)    (rad/sec)
       Torque Motor Rot Angle (mu),  (radians)
       Motor Rot Rate (mu-dot),   (radian/sec)
       Position Error Integral,     (ft-sec)
       First Order Compensator State
----------------------------------------------------------------------------------------------------
```

STATE-SPACE SYSTEM ...

Electro-Mechanical Actuator for an Elevator

! This EMA system has a full PID controller with a second order compensator

```
Number of Inputs, States, Outputs, Sample Time dT (for discrete)=    2    9    3    0.0000
Matrices: (A,B,C,D)
Matrix A                    Size =  9 X  9
           1-Column            2-Column            3-Column            4-Column            5-Column            6-Column            7-
   1-Row  0.000000000000E+00  0.100000000000E+01  0.000000000000E+00  0.000000000000E+00  0.000000000000E+00  0.000000000000E+00
   2-Row -0.164332679910E+06 -0.236406619385E+01  0.576581599115E+06  0.000000000000E+00  0.196164125909E+05  0.000000000000E+00
   3-Row  0.000000000000E+00  0.000000000000E+00  0.000000000000E+00  0.100000000000E+01  0.000000000000E+00  0.000000000000E+00
   4-Row  0.580700039108E+02  0.000000000000E+00 -0.936253421979E+04 -0.619047619048E+01  0.000000000000E+00  0.000000000000E+00
   5-Row  0.000000000000E+00  0.000000000000E+00  0.000000000000E+00  0.000000000000E+00  0.000000000000E+00  0.100000000000E+01
   6-Row -0.387107734092E+04  0.400000000000E+03 -0.160243785686E+05  0.000000000000E+00 -0.595610129988E+02 -0.105052179301E+04
   7-Row -0.254692999609E-02  0.000000000000E+00 -0.936253421979E-02  0.000000000000E+00  0.000000000000E+00  0.000000000000E+00
   8-Row -0.139674252249E+09  0.000000000000E+00 -0.513443623621E+09  0.000000000000E+00  0.000000000000E+00 -0.548402400000E+05
   9-Row -0.124000852562E+06  0.000000000000E+00 -0.455828086038E+06  0.000000000000E+00  0.000000000000E+00 -0.486864000000E+02
           9-Column
   1-Row  0.000000000000E+00
   2-Row  0.000000000000E+00
   3-Row  0.000000000000E+00
   4-Row  0.000000000000E+00
   5-Row  0.000000000000E+00
   6-Row  0.135836734694E+03
   7-Row  0.000000000000E+00
   8-Row -0.576000000000E+05
   9-Row -0.336000000000E+03
----------------------------------------------------------------------------------------------------
Matrix B                    Size =  9 X  2
           1-Column            2-Column
   1-Row  0.000000000000E+00  0.000000000000E+00
   2-Row  0.000000000000E+00  0.000000000000E+00
   3-Row  0.000000000000E+00  0.000000000000E+00
   4-Row  0.000000000000E+00  0.238095238095E+00
   5-Row  0.000000000000E+00  0.000000000000E+00
   6-Row  0.718848000000E+06  0.000000000000E+00
   7-Row  0.420000000000E+00  0.000000000000E+00
   8-Row  0.230329008000E+11  0.000000000000E+00
   9-Row  0.204482880000E+08  0.000000000000E+00
----------------------------------------------------------------------------------------------------
Matrix C                    Size =  3 X  9
           1-Column            2-Column            3-Column            4-Column            5-Column            6-Column            7-
   1-Row  0.000000000000E+00  0.000000000000E+00  0.100000000000E+01  0.000000000000E+00  0.000000000000E+00  0.000000000000E+00
   2-Row  0.000000000000E+00  0.000000000000E+00  0.000000000000E+00  0.100000000000E+01  0.000000000000E+00  0.000000000000E+00
   3-Row  0.580700039108E+02  0.000000000000E+00 -0.936253421979E+04 -0.619047619048E+01  0.000000000000E+00  0.000000000000E+00
           9-Column
   1-Row  0.000000000000E+00
   2-Row  0.000000000000E+00
   3-Row  0.000000000000E+00
----------------------------------------------------------------------------------------------------
Matrix D                    Size =  3 X  2
           1-Column            2-Column
   1-Row  0.000000000000E+00  0.000000000000E+00
   2-Row  0.000000000000E+00  0.000000000000E+00
   3-Row  0.000000000000E+00  0.238095238095E+00
----------------------------------------------------------------------------------------------------
Definition of System Variables

Inputs  =   2
       Deflection Command (Delta_com) (radians)
       External Load-Torque (Tl),  (ft-lb)

Outputs =   3
       Gimbal Deflection  (Delta)   (rad)
       Gimbal Rate      (Delta-dot)   (rad/sec)
       Gimbal Accelerat (Delta-dot-dot) (rad/sec^2)

States  =   9
       Screw Gear Rotation Angle (theta), (rad)
       Screw Gear Rate (theta-dot)   (rad/sec)
       Gimbal Deflection  (Delta)     (rad)
       Gimbal Rate    (Delta-dot)    (rad/sec)
       Torque Motor Rot Angle (mu),  (radians)
       Motor Rot Rate (mu-dot),   (radian/sec)
       Position Error Integral,     (ft-sec)
       Second Order Compens. State # 1
       Second Order Compens. State # 2
----------------------------------------------------------------------------------------------------
```

```
STATE-SPACE SYSTEM ...
Electro-Mechanical Actuator with an Extendable Push Rod Simplified
! This EMA actuator is a Simplified version of the above EMA system  The end of the rod is
! attached to a lever arm that rotates a control Surface.  A first order compensator (1000/s+1000)
! is used to model the motor dynamics
Number of Inputs, States, Outputs, Sample Time dT (for discrete)=    2    4    3    0.0000
Matrices: (A,B,C,D)
Matrix A                    Size =  4 X  4
           1-Column            2-Column            3-Column            4-Column
   1-Row  0.000000000000E+00  0.000000000000E+00  0.000000000000E+00  0.390000000000E-01
   2-Row  0.000000000000E+00  0.000000000000E+00  0.100000000000E+01  0.000000000000E+00
   3-Row  0.926208651399E+05 -0.277862595420E+05 -0.213740458015E+02  0.000000000000E+00
   4-Row -0.577777777778E+05 -0.186666666667E+05  0.000000000000E+00 -0.100000000000E+04
-------------------------------------------------------------------------------------------------------
Matrix B                    Size =  4 X  2
           1-Column            2-Column
   1-Row  0.000000000000E+00  0.000000000000E+00
   2-Row  0.000000000000E+00  0.000000000000E+00
   3-Row  0.000000000000E+00  0.254452926209E+00
   4-Row  0.360000000000E+05  0.000000000000E+00
-------------------------------------------------------------------------------------------------------
Matrix C                    Size =  3 X  4
           1-Column            2-Column            3-Column            4-Column
   1-Row  0.000000000000E+00  0.100000000000E+01  0.000000000000E+00  0.000000000000E+00
   2-Row  0.000000000000E+00  0.000000000000E+00  0.100000000000E+01  0.000000000000E+00
   3-Row  0.926208651399E+05 -0.277862595420E+05 -0.213740458015E+02  0.000000000000E+00
-------------------------------------------------------------------------------------------------------
Matrix D                    Size =  3 X  2
           1-Column            2-Column
   1-Row  0.000000000000E+00  0.000000000000E+00
   2-Row  0.000000000000E+00  0.000000000000E+00
   3-Row  0.000000000000E+00  0.254452926209E+00
-------------------------------------------------------------------------------------------------------
Definition of System Variables

Inputs  =   2
       Load Deflection Command (Delta_com), (rad)
       External Load Torque (Tl),    (ft-lb)

Outputs =   3
       Load Rotation at Gimbal  (Delta)   (rad)
       Load Rate at Gimbal  (Delta-dot)   (rad/sec)
       Load Accelerat. (Delta-dot-dot) (rad/sec^2)

States  =   4
       Actuator Piston Position (Xp)  (feet)
       Load Rotation, (Delta)  (radians)
       Load Rate, (Delta-dot)  (rad/sec)
       First Order Compensator State
------------------------------------------------------------------------------------------------
END-END-END-END-END-END-END-END-END-END-END-END-END-END-END-END-END-END-END-END-END-END-END-END-
```

EM Actuator of a Launch Vehicle

In this example we analyze an electro-mechanical TVC actuator used to gimbal the engine of a launch vehicle. We will develop a non-linear simulation model using Simulink, a linear model for control analysis, and will recreate the linear model using the Flixan actuator modeling program, option: "EMA, type B" to compare results. The analysis files for this example are in: "*Actuator\Examples\EM-Actuators\Launch Vehicle*".

The Simulink file for the non-linear model is "*NonLin_EMA.slx*", shown in Figure 1a. It consists of a PID control system receiving shaft position and motor rate from resolvers and generates the current driving the motor through a current amplifier. The current in the amplifier is limited to ±2 (Amps). The motor generates the torque that rotates the screw, shown in Figure 2a. There is a gear reduction between the rotor and screw rotations that increases the screw torque. Figure 2b shows the screw/shaft dynamics. The screw is driven through the shaft (which is like a nut around the screw) by the motor torque and generates the shaft extension. The shaft position output x_p generates a force against the load that rotates the engine. The load force (FL) opposes the motor torque. There is also a static friction feedback resisting the rotation of the screw. Figure 2c is the engine dynamics as it rotates about the gimbal and it includes 200 (ft-lb) static friction at the gimbal. It is coded as a Matlab function "Gimbal" and calculates friction force and acceleration which is integrated twice for gimbal position.

Actuator Response to a 2° Step Command

Figures 3 show the EMA actuator system's response to 2º gimbal command. Static friction of 200 (ft-lb) is included at the engine gimbal, and static friction of 2 (ft-lb) is also included at the screw/shaft mechanism. Figure 3a shows the gimbal response as it catches up with the command. The 20 Hz oscillation is due to the combined stiffness K_T at the gimbal. It is shown more emphatically in the acceleration that also shows a high frequency oscillatory squeak, caused by the static friction, as the nozzle slowly approaches its commanded value. Figure 3b shows the shaft position and velocity. The shaft extends 0.35 (inch) to produce the 2º gimbal angle. The shaft velocity saturates at 2.9 (in/sec) due to the motor current limits. The high frequency oscillations in the velocity is caused by the gear stiffness mode. The actuator power is calculated by multiplying shaft velocity times the load force. Figure 3c shows the motor spin rate is limited to 670 (rad/sec) because the current supplying the motor is also limited by the amplifier to ±2 Amps. The load force oscillates at the 20 Hz gimbal mode. The gear stiffness between the motor and screw causes the torque and shaft velocity to oscillate at high frequency 1200 (rad/sec).

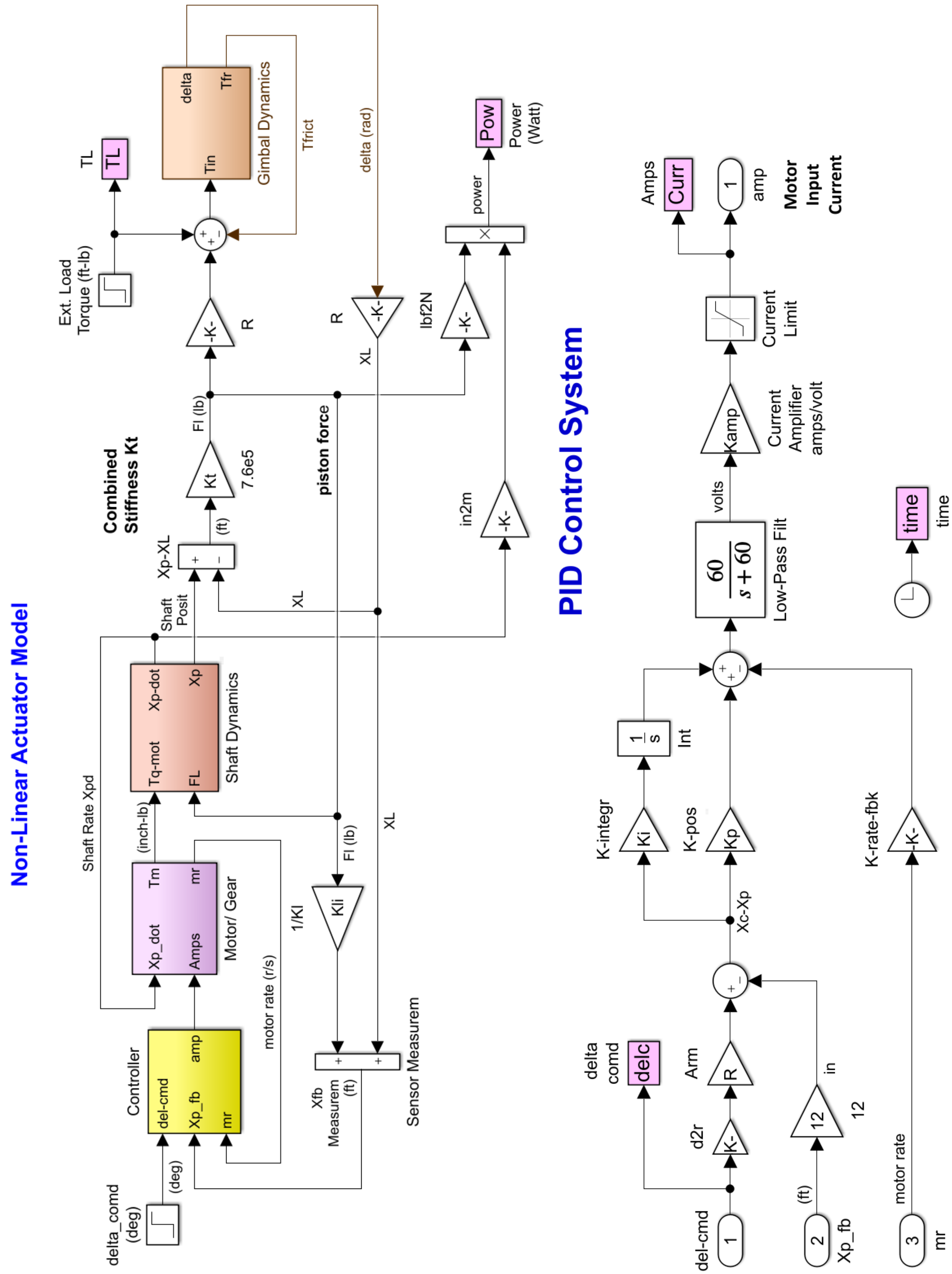


Figure 1 EMA System Block Diagram

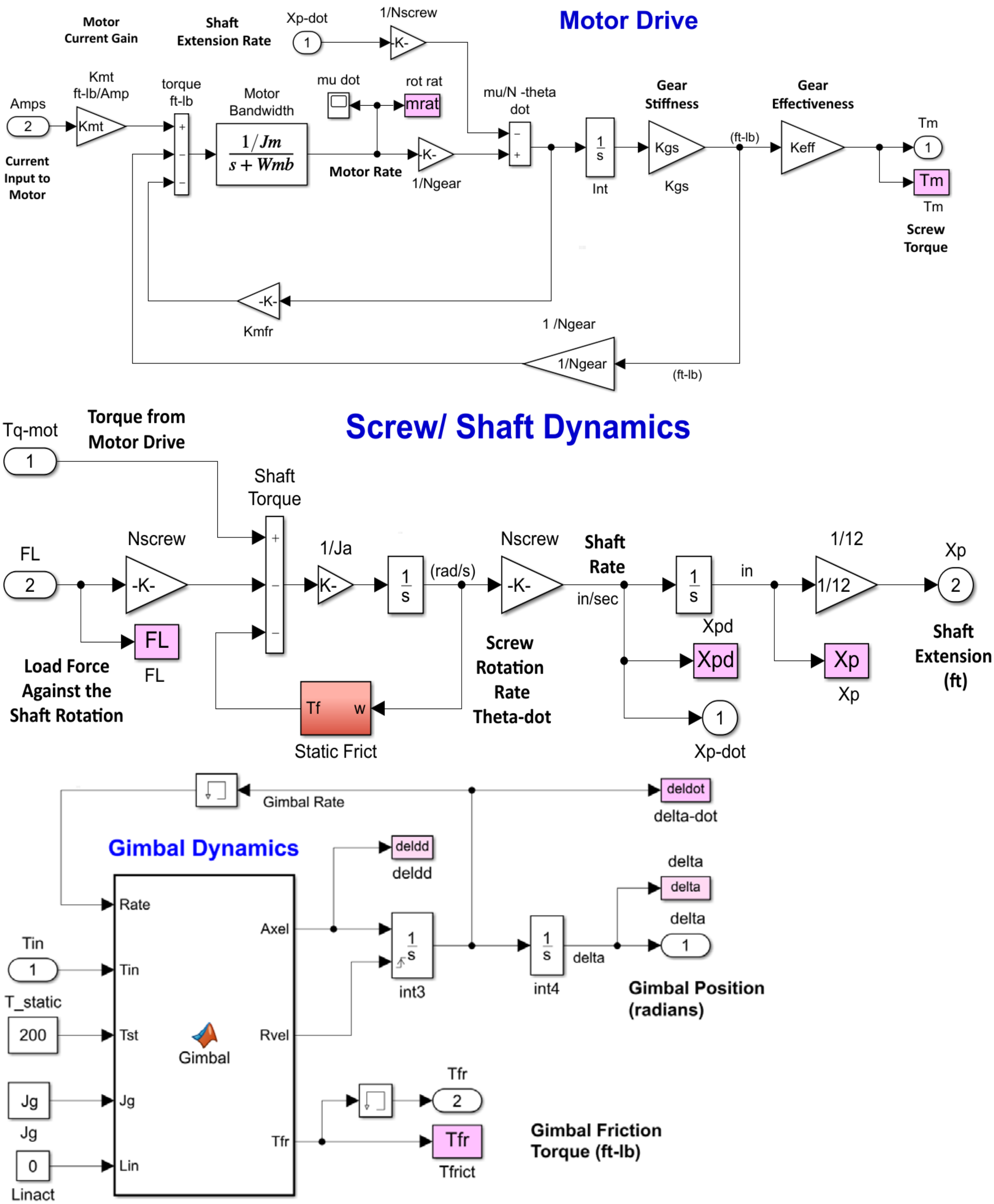


Figure 2 EM Actuator Subsystems

```
function [Axel,Rvel,Tfr] = Gimbal(Rate,Tin,Tst,Jg,Bvf,Lin)
% Gimbal Friction Dynamics
% Tin:  Input Torque (ft-lb)
% Rate: Gimbal Rate (rad/sec)
% Bvf:  Viscous Friction
% Tfr:  Gimbal Friction Torque (ft-lb)
% axel: Gimbal Acceleration (ft/sec2)
% Tst:  Gimbal Static Friction Torq (ft-lb)
% Jg:   Gimbal Inertia (slg-ft^2)

if Lin>0.5                                  % Linear Actuator (1)
    Tfr=Bvf*Rate;                           % Viscous Friction Torque
    Axel=(Tin-Tfr)/Jg;                      % Gimbal Acceleration
    Rvel=0;                                 % Dont Reset
else                                        % Non-Linear Actuator (0)
    if abs(Rate)<0.01                       % If Not Moving Much
        if abs(Tin)>Tst*1.05                % Exceeds Stiction, Start Moving
            Tfr=Tst*sign(Tin);              % Friction Torque resist motion
            Axel=(Tin-Tfr)/Jg;              % Gimbal Acceleration
            Rvel=0;
        else                                % Stop the Motion
            Axel=0;
            Tfr=0;                          % No Frict when not moving
            Rvel=1;                         % Reset Velocity to Zero
        end

    else                                    % Gimbal is Fast Enough
        Tfr=Tst*sign(Rate);                 % Friction Torque resist motion
        Axel=(Tin-Tfr)/Jg;                  % Gimbal Acceleration
        Rvel=0;
    end
end
end
```

```
% EMA Actuator Model
r2d= 180/pi; d2r=pi/180;
Kload=1.2e9;                        %  Load Stiffness
Kback=1.122e6;                      %  Backup Structure
Kact= 2.652e6;                      %  Shaft Stiffness Kact= 221,000 (lb/in)
Kti=(1/Kload)+(1/Kback)+(1/Kact); Kt=1/Kti; % Total Stiffness
Kli=(1/Kload)+(1/Kback); Kl=1/Kli;          % Stiffness of Load + Backup

Kp= 2.3;                            %  PID gain
Ki= 0.4;                            %  PID gain
Krfb= 0.014;                        %  Rate Feedback Gain
Alim= 2.0;                          %  Controller Output Current Limit 2 Amp:
Kamp=5.0;                           %  Current Amplifier Gain (amps/volt)
R= 10;                              %  Moment Arm (in) R=  3.6
Jg= 33.45;                          %  Engine Inertia Jg= 33.45
Ja= 0.0026562;                      %  Gear plus Screw Inertia
Kmt= 404;                           %  Motor Gain (ft-lb/Amps)
Jm= 1.2e-2;                         %  Motor Rotor Mom Inertia
Wmb= 100;                           %  Motor Bandwidth (rad/sec)
Kmfr= 0.02;                         %  Motor Friction 0.4
Keff= 0.85;                         %  Motor Gear Effectiveness 0.85
Kgs= 4000.0;                        %  Gear Stiffness Kgs=8376.0
Nscrew= 0.0313;                     %  Screw Ratio Nscrew (inch/rad)
Ngear= 7.11;                        %  Gear Ratio Ngear= 17.0
Kdmp= 0.02;                         %  Shaft Damping Kdmp= 0.285
Be=1000;                            %  Viscous Damping Coefficient at Gimbal
```

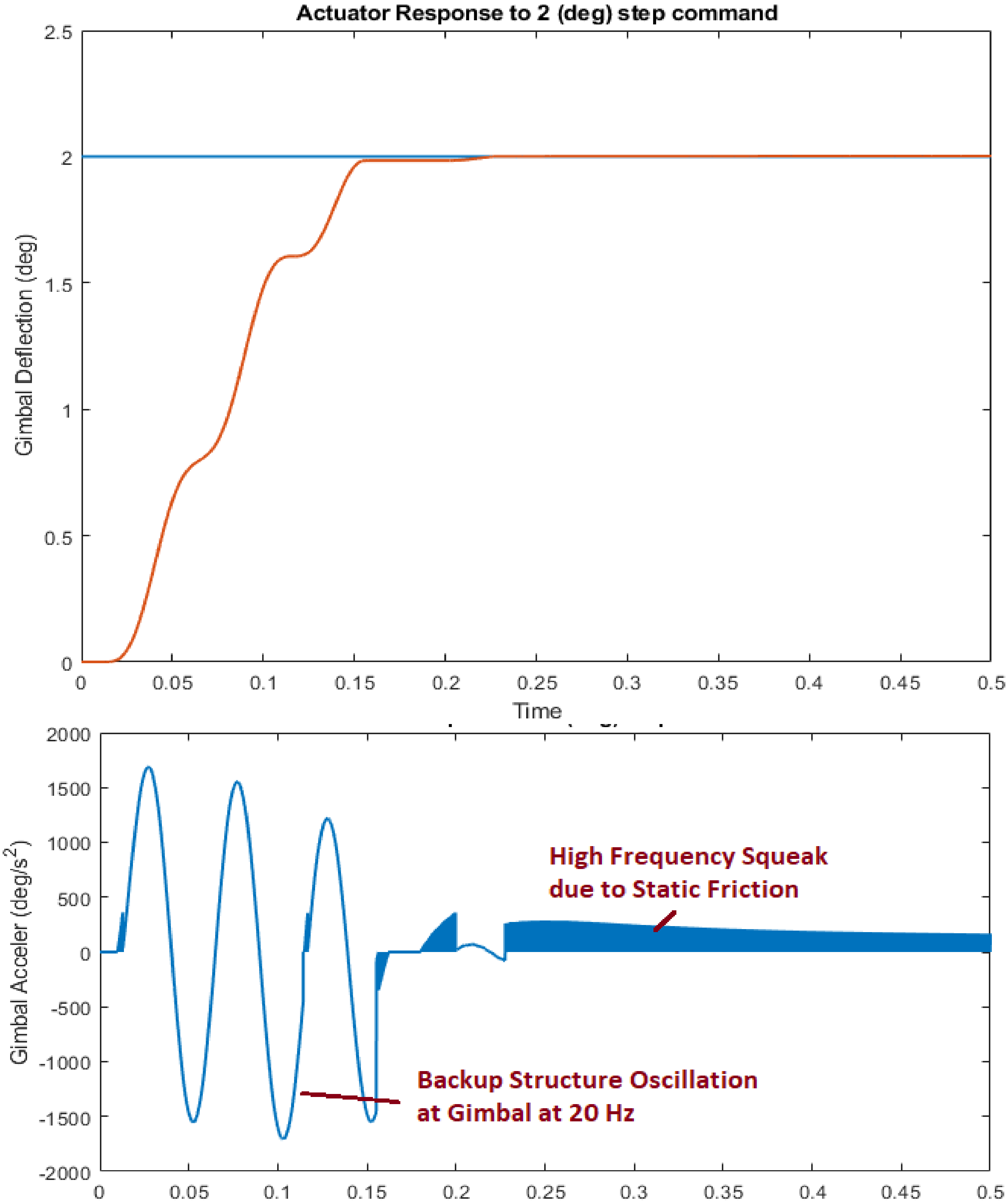


Figure 3a Gimbal Response to 2º Step Command

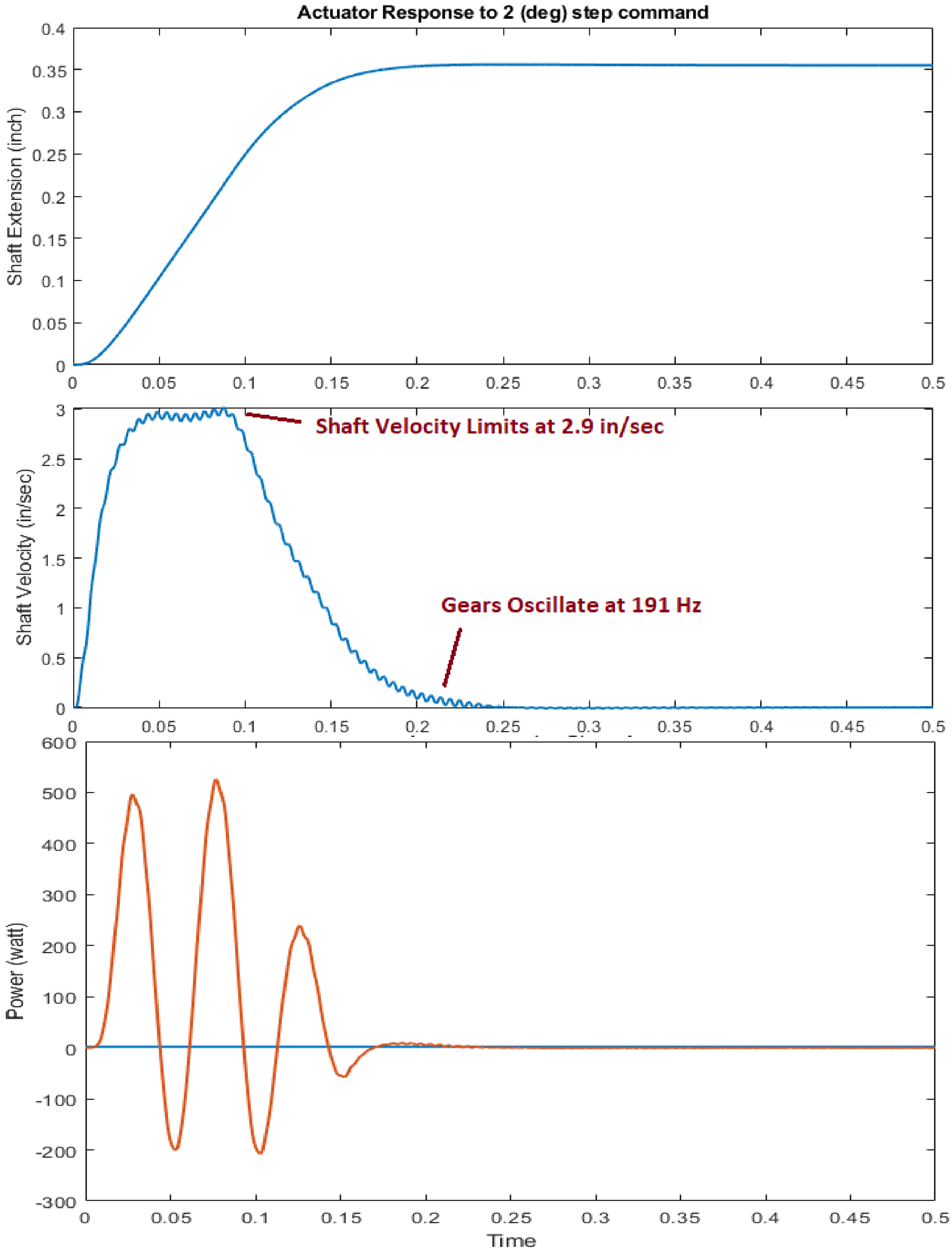


Figure 3b Shaft Position, Velocity, and Actuator Power

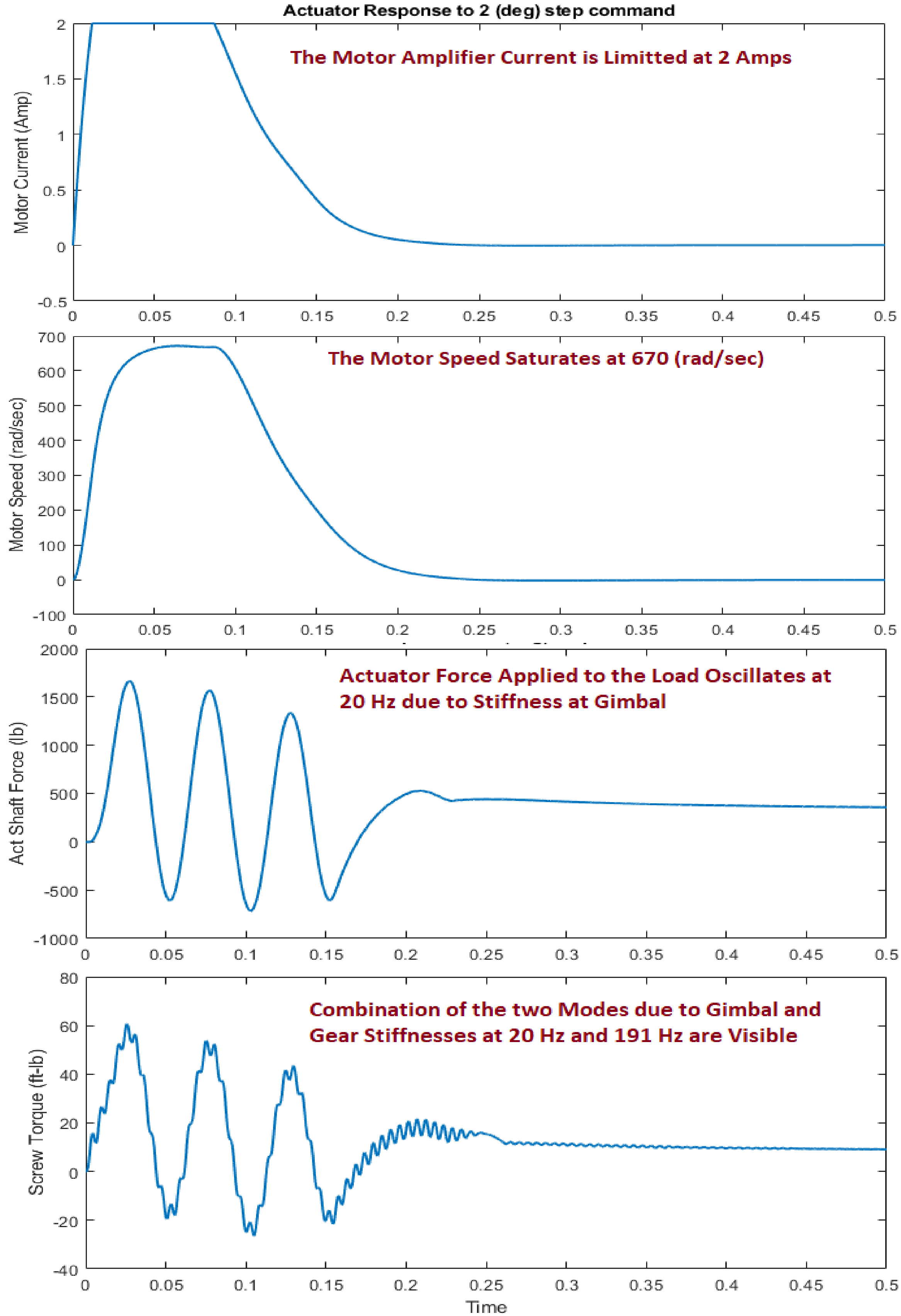


Figure 3c Motor Current and Speed, Shaft Force and Torque on Screw

Frequency Response Analysis

The input to the Flixan program that generates the linear actuator is in file "*EMA_Actuat.Inp*", and is shown below. The actuator system is saved in file "*EMA_Actuat.Qdr*". It is also saved as a function "*ema_stg1.m*" that can be loaded into Matlab.

Figure 4a shows the frequency response of the linear actuator/ gimbal system, gimbal response over gimbal command. The Coulomb frictions are replaced with viscous values that have similar responses. The control bandwidth is set at 15 (rad/sec). The gimbal TWD mode is at 120 (rad/sec), and the gear mode due to gear stiffness is at 1200 (rad/sec). The Nichols plot in Figure 4b shows the actuator control loop stability characteristics. The loop is opened at the control system output.

```
BATCH MODE INSTRUCTIONS ...............
Batch set for creating an EMA actuator model
!
Actuator Model    : Electro-Mechanical Stage-1 Actuator
To Matlab Format  : Electro-Mechanical Stage-1 Actuator
-----------------------------------------------------------------------------------
ACTUATOR INPUT DATA ............ ELECTROMECHANICAL TYPE B
Electro-Mechanical Stage-1 Actuator
! This is 1st Stage EMA actuator. Uses an Extendable Push Rod to Drive the Engine.
!
Symbol       Parameter Description                  (Units)      Value
C(s)    Order of Compensat:(0,1,2), Coefficients     (---)       1, 0.0, 0.0166
Kpl     Position Error Loop Gain                   (Volt/ft)     27.6
Krf     Rate Feedback Gain                     (Volt/ft/sec)     6.1947e-5
Ki      Position Error Integral Gain           (Volt/ft-sec)     4.8
Wm      Servo Motor Bandwidth,                   (rad/sec)       100.0
Kv      Servo Motor Torque Gain                 (ft-lb/volt)     2020.0
Jm      Motor Rotor Moment of Inertia          (in-lb-sec^2)     1.2e-2
Ngr     Gear Ratio (Motor Turns/ Screw Turns)         ( - )      7.11
Nscr    Screw Ratio (Piston Extension/Screw Turns) (ft/rad)      0.00261
Kgs     Motor Gear Stiffness                      (in-lb/rad)    4000.0
Kmfr    Motor/ Gear Friction                   (ft-lb/rad/sec)   0.02
Kdmp    Shaft Damping Friction                 (ft-lb/rad/sec)   0.02
Keff    Gear Effectiveness Coefficient                ( - )      0.85
Ja      Gear plus Screw Inertia                 (in-lb-sec^2)    0.002656
Kact    Actuator Stiffness (Piston+Electric).... (lb/in)         2.652e6
Klod    Load Stiffness,(Con. Surface or Nozzle)  (lb/in)         1.2e+9
Kbck    Vehicle Backup Structure Stiffness ..... (lb/in)         1.122e6
R       Moment Arm of Actuator Rod from Gimbal..    (in)         0.8333
Je      Load Inertia about the Gimbal ....... (in-lb-sec^2)      33.45
Be      Nozzle Bearing Viscous Damping ....... (ft-lb-sec)       1000.0
Kg      Gimbal Bearing Spring Constant           (ft-lb/rad)     0.0000
-----------------------------------------------------------------------------------
       MATLAB CONVERSIONS
-----------------------------------------------------------------------------------
CONVERT TO MATLAB FORMAT ........       (Title, System/Matrix, m-filename)
Electro-Mechanical Stage-1 Actuator
System
EMA_Stg1
-----------------------------------------------------------------------------------
```

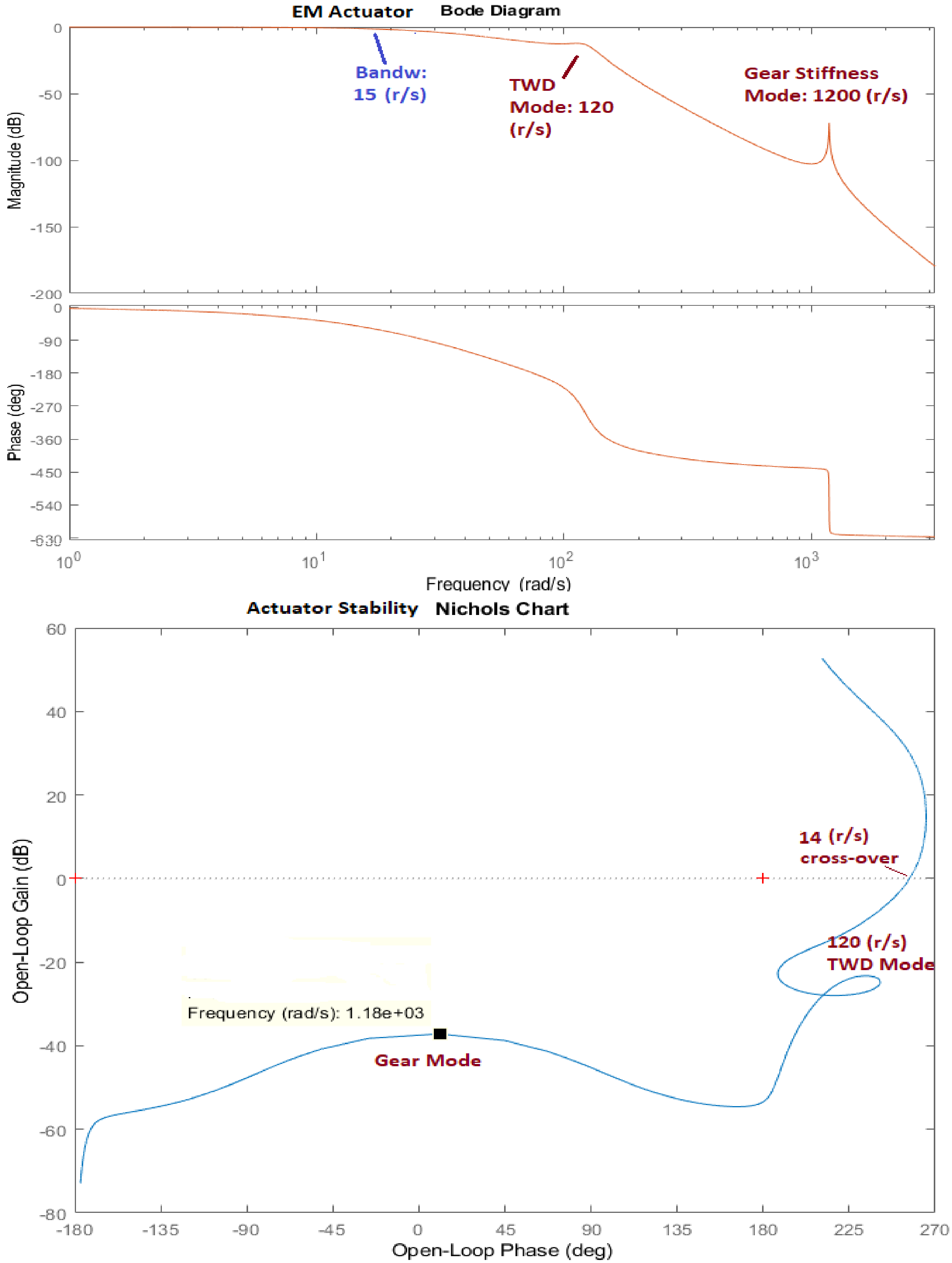


Figure 4 Nichols Plot Showing the Actuator Control Loop Gain and Phase Margins