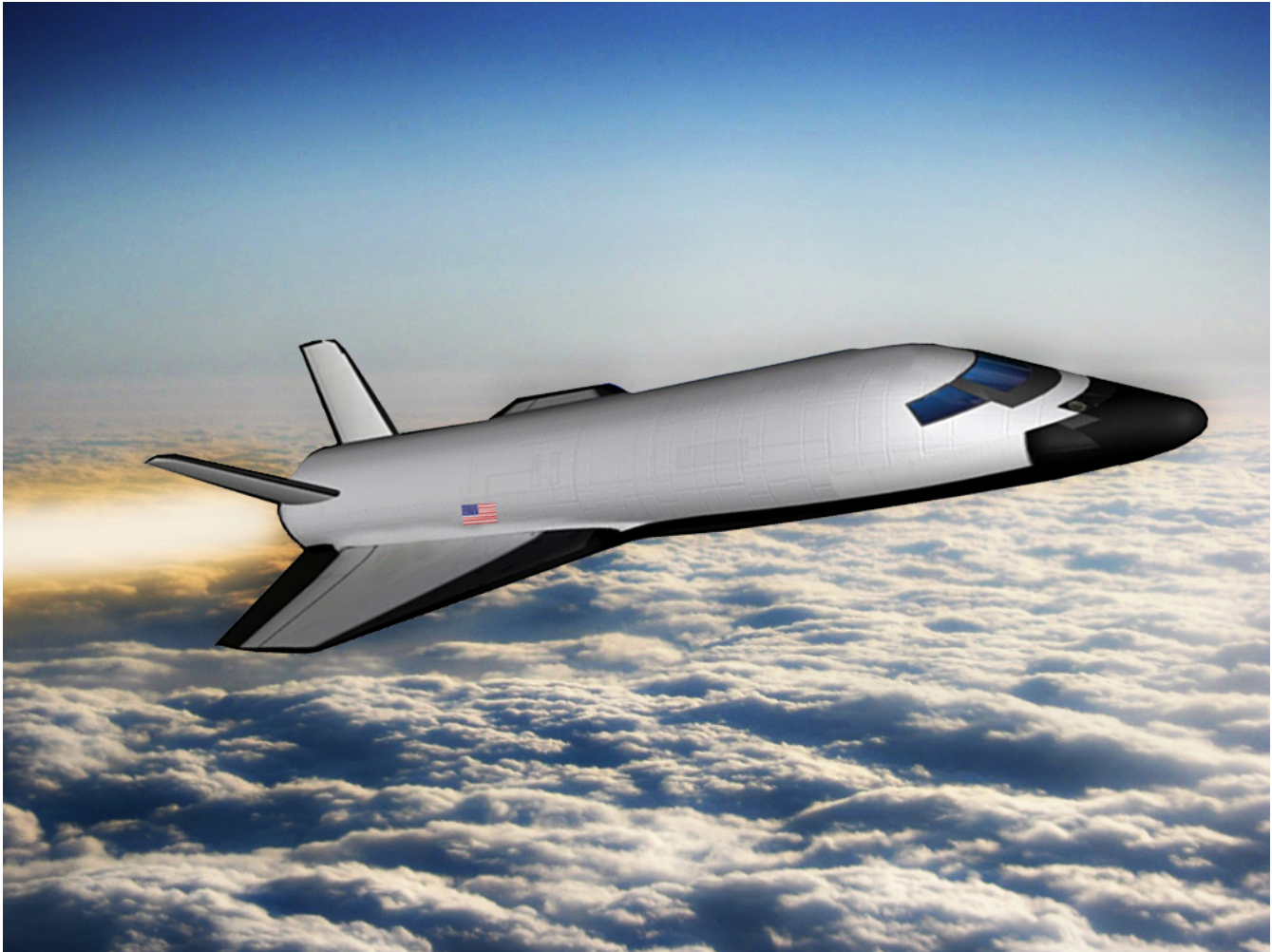# Rocket Plane Design

Figure 1 Rocket-Plane Vehicle

In this example we will analyze a rocket-plane vehicle during level flight. It is similar to the vehicle shown in Figure 1 and it is controlled by five aerosurfaces and a fixed engine. The control surfaces are: two flaps which are almost horizontal and they are used mostly for roll control, two rudders (forming V-tail at 45°) and used for pitch and yaw control and a body-flap in the back below the rudders used mainly for trimming, but also for pitch control at high angles of attack when the rudders are not very effective. The engine is fixed and it does not gimbal. Its nominal thrust is 2,000 (lbf) and it can be throttled from zero to 4,000 (lbf) as needed for acceleration and speed control. The control system controls altitude and airspeed in the longitudinal axes and in the lateral axes it controls the flight direction by means of roll control. We will analyze a single flight condition, at Mach 0.85, altitude 45,000 (ft), and dynamic pressure of 150 (psf). The analysis begins by creating dynamic models of the vehicle in this flight condition, design and analyze pitch and lateral control systems, introduce structural flexibility, aero-elasticity, and then evaluated the overall vehicle system stability and performance with respect to commands and gusts.

The example files are located in directory *"C:\Flixan\Examples\Rocket Plane"*. The analysis is separated in three parts. In Section 1 we create rigid-body models and perform control system design, analyze stability and simulations. In Section 2 we include flexibility in the model using modal data without aero-elasticity. We select the dominant modes, combine them with the vehicle dynamics, analyze flex stability, and perform simulations. In Section 3 we go one step further and include aero-elasticity data in the flexibility analysis and h-parameters. We finally repeat the flex analysis and simulations using the more refined aero-elastic model.

1.0 Rigid-Body Analysis and Control System Description

The rigid-body modeling and control analysis files for this flight condition are in directory *"C:\Flixan\ Examples\ Rocket Plane\1-Rigid Body Control Design"*. It has three subdirectories that contain analysis files for: the longitudinal axes, lateral axes, and simulations for the coupled pitch and lateral axes. There are three separate vehicle data files for each subdirectory that create the vehicle models, perform the control design using the LQR method and prepare the data for Matlab analysis.

1.1 Rigid-Body Vehicle Model

The title of the vehicle dataset in the input data files is *"Rocket Plane at Mach=0.85, Q=150, Rigid Body"*. The top part of the vehicle data contains the mass properties, trajectory, and the basic aero coefficients. The wind-gust disturbance input in the system is in (feet/sec). The gust direction relative to the vehicle is defined in the input data by two angles: an elevation angle of 90° which means that the gust is perpendicular to the body x-axis, and the azimuth angle of 45° which is between the +z and the +y axes and a gust would cause an increase in both the angles of attack α and sideslip β.
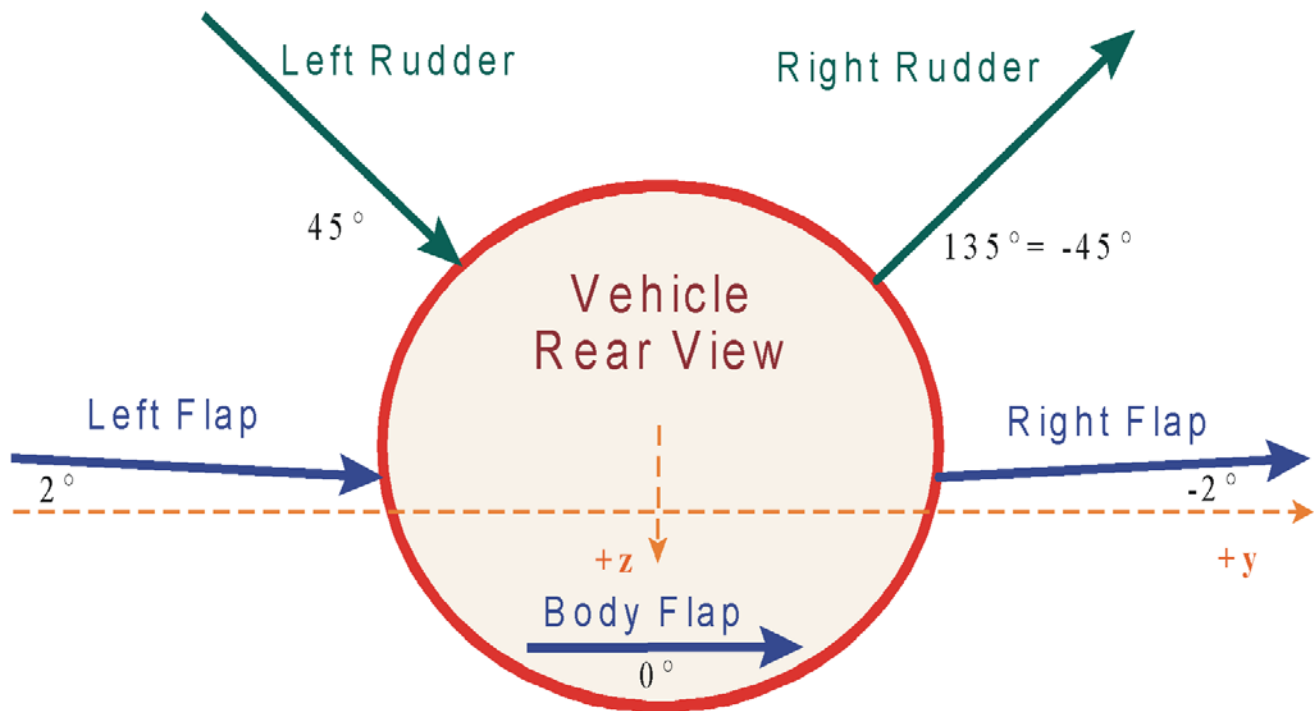

Figure 2 The arrows show the directions of the hinge vectors and the hinge orientation angles (ϕ_h)

The vehicle has five aerosurfaces. Positive deflection is considered to be a clockwise rotation about the hinge vector. The vehicle dataset includes the data for the five aerosurfaces which are: the left and right flaps, the left and right rudders, and the body-flap. The aerosurface data also include: trim angles, hinge vector orientation angles, surface mass, inertia about the hinge, distance between the surface CG to the hinge line, surface area, hinge moment coefficients, locations of the hinge lines in vehicle coordinates and the aerodynamic force and moment increment coefficients for each aero-surface. In this initial design the tail-wags-dog/ hinge moments dynamics option is turned off (NO TWD). It will be included later when we will analyze the structural flexibility. Figure 2 shows the hinge vectors of the 5 aerosurfaces and the roll orientation angles (ϕ_h) of the hinges. The ϕ_h angle is defined positive clockwise from horizontal about the vehicle x axis. All the hinge lines are perpendicular to the vehicle x-axis, i.e. the (λ_h) angles are zero. See Figure (2.5.3) in the vehicle equations. The two flaps are located in the trailing edge of the wings and their hinge vector angles are slightly tilted at ($\phi_h = \pm 2°$) from the vehicle x-y plane due to a small dihedral in the wing. The hinge line angles of the two rudders are even bigger, forming a 45° V-tail. The direction of the left rudder hinge vector is at +45° and the direction of the right rudder hinge vector is at -45°. When a positive command is applied to both rudders it causes a negative pitch torque on the vehicle. When a positive command is applied on the left and an equal but negative command is applied on the right rudder, it would cause a negative yaw and positive roll torque on the vehicle. Note that in this formulation we assume that the control surfaces are not included in the calculation of the vehicle mass properties because the aerosurfaces are coupled with the vehicle via the reaction forces and moments.

In addition to the aerosurfaces the vehicle also has a throttling engine. This engine is mounted at a fixed orientation of -1.3° in pitch. It does not gimbal but it can vary its thrust between zero and 4,000 (lbf). It is, therefore, defined in the dataset as having a nominal thrust of 2,000 (lbf) and a maximum thrust of 4,000 (lbf). The thrust variation is used to control the vehicle speed. Note, that in this case the engine must be included in the vehicle mass property calculations because it does not gimbal. However, the engine mass, inertia, and moment arm are shown in the input data. They are just place holders and not used in the formulation of the state-space model. The (NO TWD) flag in the engine data is irrelevant because the engine doesn't gimbal. If you change it into gimbaling engine, then the engine must be excluded from the vehicle mass properties because it couples with the vehicle via the equations. There are no sensors and flexibility dynamics in this model but they will be included later in Sections 2 and 3.

1.2 Longitudinal Axes Analysis

The longitudinal analysis data files are in folder: "Flixan\Examples\18-Rocket Plane\1-Rigid Body Control Design\1-Pitch Design". The vehicle modeling and design datasets are in the input file: "*Rocket_Pitch_RB.Inp*" and the output systems file is: "*Rocket_Pitch_RB.Qdr*". The input file includes a batch set on the top that creates the vehicle model, performs the LQR design and exports the data for Matlab analysis.

The input data file: "*Rocket_Pitch_RB.Inp*" is shown below. The vehicle has five aerosurfaces and one throttling engine. The mixing logic dataset "Pitch axis Mixing Matrix for Rocket-Plane, Kmix_qa" creates a mixing logic matrix that converts the pitch and axial acceleration demands to combined aerosurface deflections and throttle commands. The pitch design model is extracted from the combined system by selecting only the longitudinal variables.

Batch Set for Creating Rigid-Body Models for the Rocket-Plane
! This batch set is used to create pitch systems for control design and simulations
! of the rocket-plane vehicle. It creates also a mixing-logic matrix and converts them to
! Matlab format to be used in Simulink
!
```
Retain Matrix       : State Penalty Matrix Qc4
Retain Matrix       : Control Penalty Rc
Flight Vehicle      : Rocket Plane at Mach=0.85, Q=150, Rigid Body
Mixing Matrix       : Pitch axis Mixing Matrix for Rocket-Plane, Kmix_qa
Transf-Functions    : First Order Gust Lag
Transf-Functions    : Integrator
System Modificat    : Rocket Plane at Mach=0.85, Q=150, Rigid Body, Pitch Axis
System Modificat    : Pitch Design Model
System Connection:  Pitch Design Model with Alpha Integral (2-inputs, 4-states)
System Modificat    : Pitch Design Model with Alpha Integral (1-input, 4-states)
LQR Control Des     : Pitch LQR Control Design
!
To Matlab Format    : Rocket Plane at Mach=0.85, Q=150, Rigid Body
To Matlab Format    : Rocket Plane at Mach=0.85, Q=150, Rigid Body, Pitch Axis
To Matlab Format    : Pitch Design Model with Alpha Integral (1-input, 4-states)
To Matlab Format    : Pitch axis Mixing Matrix for Rocket-Plane, Kmix_qa
To Matlab Format    : LQR State-Feedback Control for Pitch Axis
```

FLIGHT VEHICLE INPUT DATA ......
Rocket Plane at Mach=0.85, Q=150, Rigid Body
! The following vehicle model is a rigid body rocket plane. It has five control surfaces,
! 2 flaps, 2 rudders, and a body-flap. It also has a fixed engine with variable thrust for
! speed control. In this model the tail-wags-dog option is turned off.
! It will be used to create state-space models for control design.
!
Body Axes Output,Attitude=Euler Angles,Without GAFD, No Turn Coordination

```
Vehicle Mass (lb-sec^2/ft), Gravity Accelerat. (g) (ft/sec^2), Earth Radius (Re) (ft)     : 198.32       32.17       0.20896E+08
Moments and products of Inertias Ixx, Iyy, Izz, Ixy, Ixz, Iyz, in (lb-sec^2-ft)          : 1098.0       10933.      11290.       0.0000    123.75   0.0000
CG location with respect to the Vehicle Reference Point, Xcg, Ycg, Zcg, in (feet)         : -15.167      0.0000      0.467
Vehicle Mach Number, Velocity Vo (ft/sec), Dynamic Pressure (psf), Altitude (feet)        : 0.85000      822.80      150.00       45880.
Inertial Acceleration Vo_dot, Sensed Body Axes Accelerations Ax,Ay,Az (ft/sec^2)          : -0.81        -1.14       0.0000       -32.15
Angles of Attack and Sideslip (deg), alpha, beta rates (deg/sec)                          : 2.0          0.0         1.76         0.0000
Vehicle Attitude Euler Angles, Phi_o,Thet_o,Psi_o (deg), Body Rates Po,Qo,Ro (deg/sec)    : -0.16079     2.0000      0.0000       0.0000    0.0000   0.0000
Wind Gust Vel wrt Vehi (Azim & Elev) angles (deg), or Force(lb), Torque(ft-lb), locat:xyz: Gust         45.0        90.0
Surface Reference Area (feet^2), Mean Aerodynamic Chord (ft), Wing Span in (feet)         : 79.069       6.1170      14.910
Aero Moment Reference Center (Xmrc,Ymrc,Zmrc) Location in (ft), {Partial_rho/ Partial_H}  : -14.792      0.0000      0.54000      0.0000
Aero Force Coef/Deriv (1/deg), Along -X, {Cao,Ca_alf,PCa/PV,PCa/Ph,Ca_alfdot,Ca_q,Ca_bet}: 0.143,      -0.0039,    0.0004, 0.0,      0.0,     -0.244,  0.0
Aero Force Coeffic/Derivat (1/deg), Along Y, {Cyo,Cy_bet,Cy_r,Cy_alf,Cy_p,Cy_betdot,Cy_V}: 0.0,        -0.0245,    1.77,   0.0,      0.00838, 0.0,     0.0
Aero Force Coeff/Deriv (1/deg), Along Z, {Czo,Cz_alf,Cz_q,Cz_bet,PCz/Ph,Cz_alfdot,PCz/PV}: -0.14,      -0.073,     -9.93,  0.0,      0.0,     0.0,     0.00093
Aero Moment Coeffic/Derivat (1/deg), Roll: {Clo, Cl_beta, Cl_betdot, Cl_p, Cl_r, Cl_alfa}: 0.0,        -0.00212,   0.0,    -0.393,   0.427,   0.0
Aero Moment Coeff/Deriv (1/deg), Pitch: {Cmo,Cm_alfa,Cm_alfdot,Cm_bet,Cm_q,PCm/PV,PCm/Ph}: -0.0838,    -0.015,     0.0,    0.0,      -12.83,  0.0004, 0.0
Aero Moment Coeffic/Derivat (1/deg), Yaw : {Cno, Cn_beta, Cn_betdot, Cn_p, Cn_r, Cn_alfa}: 0.0,        0.001,      0.0,    0.184,   -1.49,    0.0
```

Number of Control Surfaces, With or No TWD (Tail-Wags-Dog and Hinge Moment Dynamics) ?   : 5   NO TWD

```
Control Surface No:  1                                                                    Left Flap
Trim Angle, Max/Min Deflection Angles from Trim, Hinge Line Angles: phi_h, lamda_h  (deg): 0.0          30.000      -30.000      +2.0000   0.000
Surface Mass, Inertia about Hinge, Moment Arm (Hinge to Surface CG), Surface Chord, Area : 1.185        0.2867      0.283        1.2070    5.5530
Hinge Moment Derivatives (1/deg), { Chm_Alpha, Chm_Beta, Chm_Delta, Chm_Mach }          : -0.0047      -0.00055    -0.0097      0.0000
Location of the Hinge Line Center with respect to Vehicle Reference (feet), {Xcs,Ycs,Zcs}: -18.7        -2.64       2.0733
Forces (-x,y,z) due to Deflect. and Rates {Ca_del,Cy_del,Cz_del, Ca_deld,Cy_deld,Cz_deld}: 0.45432E-03 -0.24668E-02 -0.60478E-02  0.0000    0.0000      0
Moments due to Deflections and Rates {Cl_del,Cm_del,Cn_del,Cl_deldot,Cm_deldot,Cn_deldot}: 0.11893E-02 -0.26625E-02  0.81515E-03  0.0000    0.0000      0
Control Surface No:  2                                                                    Right Flap
Trim Angle, Max/Min Deflection Angles from Trim, Hinge Line Angles: phi_cs,lamda_cs (deg): 0.0          30.000      -30.000      -2.0000   0.000
Surface Mass, Inertia about Hinge, Moment Arm (Hinge to Surface CG), Surface Chord, Area : 1.185        0.2867      0.283        1.2070    5.5530
Hinge Moment Derivatives (1/deg), { Chm_Alpha, Chm_Beta, Chm_Delta, Chm_Mach }          : -0.0047      0.00055     -0.0097      0.0000
Location of the Hinge Line Center with respect to Vehicle Reference (feet), {Xcs,Ycs,Zcs}: -18.7        2.64        2.0733
Forces (-x,y,z) due to Deflect. and Rates {Ca_del,Cy_del,Cz_del, Ca_deld,Cy_deld,Cz_deld}: 0.45432E-03  0.24668E-02 -0.60478E-02  0.0000    0.0000      0
Moments due to Deflections and Rates {Cl_del,Cm_del,Cn_del,Cl_deldot,Cm_deldot,Cn_deldot}: -0.11893E-02 -0.26625E-02 -0.81515E-03  0.0000    0.0000      0
Control Surface No:  3                                                                    Left Rudder
Trim Angle, Max/Min Deflection Angles from Trim, Hinge Line Angles: phi_cs,lamda_cs (deg): -1.2         30.000      -30.000      48.000    0.000
Surface Mass, Inertia about Hinge, Moment Arm (Hinge to Surface CG), Surface Chord, Area : 2.19         3.914       0.833        2.2830    10.382
Hinge Moment Derivatives (1/deg), { Chm_Alpha, Chm_Beta, Chm_Delta, Chm_Mach }          : -0.019       0.0229      -0.0236      0.0000
Location of the Hinge Line Center with respect to Vehicle Reference (feet), {Xcs,Ycs,Zcs}: -25.3333     -3.395      -1.6242
Forces (-x,y,z) due to Deflect. and Rates {Ca_del,Cy_del,Cz_del, Ca_deld,Cy_deld,Cz_deld}: 0.46197E-03  0.47413E-02 -0.51664E-02  0.0000    0.0000      0
Moments due to Deflections and Rates {Cl_del,Cm_del,Cn_del,Cl_deldot,Cm_deldot,Cn_deldot}: 0.17964E-02 -0.98720E-02 -0.35668E-02  0.0000    0.0000      0
Control Surface No:  4                                                                    Right Rudder
Trim Angle, Max/Min Deflection Angles from Trim, Hinge Line Angles: phi_cs,lamda_cs (deg): -1.2         30.000      -30.000      -48.000   0.000
Surface Mass, Inertia about Hinge, Moment Arm (Hinge to Surface CG), Surface Chord, Area : 2.19         3.914       0.833        2.2830    10.382
Hinge Moment Derivatives (1/deg), { Chm_Alpha, Chm_Beta, Chm_Delta, Chm_Mach }          : -0.019       -0.0229     -0.0236      0.0000
Location of the Hinge Line Center with respect to Vehicle Reference (feet), {Xcs,Ycs,Zcs}: -25.3333     3.395       -1.6242
Forces (-x,y,z) due to Deflect. and Rates {Ca_del,Cy_del,Cz_del, Ca_deld,Cy_deld,Cz_deld}: 0.46197E-03 -0.47413E-02 -0.51664E-02  0.0000    0.0000      0
Moments due to Deflections and Rates {Cl_del,Cm_del,Cn_del,Cl_deldot,Cm_deldot,Cn_deldot}: -0.17964E-02 -0.98720E-02  0.35668E-02  0.0000    0.0000      0
Control Surface No:  5                                                                    Body Flap
Trim Angle, Max/Min Deflection Angles from Trim, Hinge Line Angles: phi_cs,lamda_cs (deg): -10.0        40.000      -40.000      0.0000    0.0000
Surface Mass, Inertia about Hinge, Moment Arm (hinge to surface CG), Surface Chord & Area: 1.8          2.2         0.6          1.6670    5.7430
Hinge Moment Derivatives (1/deg), { Chm_Alpha, Chm_Beta, Chm_Delta, Chm_Mach }          : -0.1e-03     0.0000      -0.10E-03    0.0000
Location of the Hinge Line Center with respect to Vehicle Reference (feet), {Xcs,Ycs,Zcs}: -25.8        0.0000      0.80000
Forces (-x,y,z) due to Deflect. and Rates {Ca_del,Cy_del,Cz_del, Ca_deld,Cy_deld,Cz_deld}: -0.83830E-05 0.0000     -0.59235E-03  0.0000    0.0000      0
Moments due to Deflections and Rates {Cl_del,Cm_del,Cn_del,Cl_deldot,Cm_deldot,Cn_deldot}: 0.0000      -0.15765E-02  0.0000       0.0000    0.0000      0
```

Number of Thruster Engines, Include or Not the Tail-Wags-Dog and Load-Torque Dynamics ? : 1   NO TWD

```
TVC Engine No: 1               (Gimbaling  Throttling   Single_Gimbal) : Engine Throtl   Throttling
Engine Nominal Thrust, and Maximum Thrust in (lb)   (for throttling)  : 2000.0         4000.0
Mounting Angles wrt Vehicle (Dyn,Dzn), Maximum Deflections from Mount (Dymax,Dzmax) (deg): -1.3          0.0         0.0          0.0
Eng Mass (slug), Inertia about Gimbal (lb-sec^2-ft), Moment Arm, engine CG to gimbal (ft): 2.00         65.0        0.8
Gimbal location with respect to the Vehicle Reference Axes, Xgimb, Ygimb, Zgimb, in (ft) : -26.5        0.0         0.0
```

```
MIXING LOGIC MATRIX DATA .........    (MATRIX TITLE, NAME, VEHICLE TITLE, CONTROL DIRECTIONS)
Pitch axis Mixing Matrix for Rocket-Plane, Kmix_qa
! Mixing Logic Matrix for the rocket-plane in the pitch axis. It converts the pitch and
! axial acceleration demands to five aero-surface deflections and engine thrust variation
Kmix_qa
Rocket Plane at Mach=0.85, Q=150, Rigid Body
Q-dot Pitch Acceleration About Y Axis
Ax  Forward Acceleration Along X Axis
--------------------------------------------------------------------------------------------
SYSTEM OF TRANSFER FUNCTIONS ...
First Order Gust Lag
! A low-pass filter 0.5 (rad/sec) to smooth out the input gust
Continuous
TF. Block #  1 First Order Lag                           Order of Numer, Denom=  0  1
Numer 0.0       0.5
Denom 1.0       0.5
--------------------------------------------------------------------------------------------
Block #, from Input #, Gain
  1  1    1.0
.........................
Outpt #, from Block #, Gain
  1  1    1.0
.........................
--------------------------------------------------------------------------------------------
SYSTEM OF TRANSFER FUNCTIONS ...
Integrator
Continuous
TF. Block #  1 First Order Lag                           Order of Numer, Denom=  0  1
Numer 0.0       1.0
Denom 1.0       0.0
------------------------------------------------------------------------------
Block #, from Input #, Gain
  1  1    1.0
.........................
Outpt #, from Block #, Gain
  1  1    1.0
.........................
--------------------------------------------------------------------------------------------
CREATE A NEW SYSTEM FROM AN OLD SYSTEM... (TITLES OF THE NEW AND OLD SYSTEMS)
Rocket Plane at Mach=0.85, Q=150, Rigid Body, Pitch Axis
Rocket Plane at Mach=0.85, Q=150, Rigid Body
! The rigid pitch axis model is extracted from the previously created coupled
! rigid-body model
TRUNCATE OR REORDER THE SYSTEM INPUTS, STATES, AND OUTPUTS
Extract States :   3   4   7   9  10
Extract Outputs:   3   4   7   9  10  12  14
--------------------------------------------------------------------------------------------
CREATE A NEW SYSTEM FROM AN OLD SYSTEM... (TITLES OF THE NEW AND OLD SYSTEMS)
Pitch Design Model
Rocket Plane at Mach=0.85, Q=150, Rigid Body
! The pitch axis control design system is extracted from the coupled system
! The wind-gust input is not used.
! The states and outputs are: theta, q, and alpha
!
TRUNCATE OR REORDER THE SYSTEM INPUTS, STATES, AND OUTPUTS
Extract Inputs :   1   2   3   4   5   6
Extract States :   3   4   7
Extract Outputs:   3   4   7
--------------------------------------------------------------------------------------------
```

The pitch design model is augmented by including an additional state, the alpha-integral. The mixing logic matrix Kmix_qa is also included at the input. This reduces the number of inputs from 6 to 2, that is, the two acceleration demands, pitch and axial. However, only the pitch input will be included in the LQR design to control alpha. The engine throttle to control speed will be designed by classical control means.

The LQR state-feedback dataset "*Pitch LQR Control Design*" is included in the input file. It uses the design system "*Pitch Design Model with Alpha Integral (1-input, 4-states)*" to calculate the state-feedback gain Kq. The gain matrix is saved in the systems file and its title is "*LQR State-Feedback Control for Pitch Axis*". The state and control weight matrices Qc4 and Rc for the LQR design are read from, and permanently saved in the systems file. The vehicle models, mixing logic and state-feedback gains are converted to Matlab format.

INTERCONNECTION OF SYSTEMS .....
Pitch Design Model with Alpha Integral (2-inputs, 4-states)
! The pitch axis control design model is augmented with the integral of the angle
! of attack for control design.
! The states and outputs are: theta, q, alpha, and alpha-integral
! The mixing matrix Kmix_qa is included in the input which reduces the inputs to two
! Pitch and Axial Acceleration Demands
!
Titles of Systems to be Combined
Title 1 Pitch Design Model
Title 2 Integrator
SYSTEM INPUTS TO SUBSYSTEM 1
Via Matrix +Kmix_qa   Pitch, Axial Demands
....
SYSTEM OUTPUTS FROM SUBSYSTEM 1   All Outputs
Via Matrix +I3
....
SYSTEM OUTPUTS FROM SUBSYSTEM 2
System Output 4 from Subsystem 2, Output 1, Gain= 1.0   Alpha Integral
....
SUBSYSTEM NO 1 GOES TO SUBSYSTEM NO 2   Vehicle alpha to Integrator
Subsystem 1, Output 3 to Subsystem 2, Input 1, Gain= 1.0   Alpha Integral
....
Definitions of Inputs =   2
Pitch Acceleration
Axial Acceleration

Definitions of States =   4
Pitch Attitude   (theta-rigid) (radians)
Pitch Rate   (q -rigid)   (rad/sec)
Angle of attack   (alpha)   (radians)
Alpha Integral   (rad-sec)

Definitions of Outputs =   4
Pitch Attitude   (theta-rigid) (radians)
Pitch Rate   (q -rigid)   (rad/sec)
Angle of attack   (alpha)   (radians)
Alpha Integral   (rad-sec)

CREATE A NEW SYSTEM FROM AN OLD SYSTEM... (TITLES OF THE NEW AND OLD SYSTEMS)
Pitch Design Model with Alpha Integral (1-input, 4-states)
Pitch Design Model with Alpha Integral (2-inputs, 4-states)
! Eliminate the second input (Ax acceleration) from the pitch design model
TRUNCATE OR REORDER THE SYSTEM INPUTS, STATES, AND OUTPUTS
Extract Inputs :   1

LINEAR QUADRATIC REGULATOR STATE-FEEDBACK CONTROL DESIGN
Pitch LQR Control Design
Plant Model Used to Design the Control System from: Pitch Design Model with Alpha Integral (1-input, 4-states)
Criteria Optimization Output is Matrix C
State Penalty Weight (Qc) is Matrix: Qc4   State Penalty Matrix Qc4
Control Penalty Weight (Rc) is Matrix: Rc   Control Penalty Rc
Continuous LQR Solution Using Laub Method
LQR State-Feedback Control Gain Matrix Kq   LQR State-Feedback Control for Pitch Axis
----
CONVERT TO MATLAB FORMAT ....   (TITLE, SYSTEM/MATRIX, M-FILENAME)
Rocket Plane at Mach=0.85, Q=150, Rigid Body
System
Vehi_Coupled_rb.m

CONVERT TO MATLAB FORMAT ....   (TITLE, SYSTEM/MATRIX, M-FILENAME)
Rocket Plane at Mach=0.85, Q=150, Rigid Body, Pitch Axis
System
Vehi_Pitch_rb.m

CONVERT TO MATLAB FORMAT ....   (TITLE, SYSTEM/MATRIX, M-FILENAME)
Pitch Design Model with Alpha Integral (1-input, 4-states)
System
Vehi_PDes_4x.m

CONVERT TO MATLAB FORMAT ....   (TITLE, SYSTEM/MATRIX, M-FILENAME)
Pitch axis Mixing Matrix for Rocket-Plane, Kmix_qa
Matrix Kmix_qa
---
CONVERT TO MATLAB FORMAT ....   (TITLE, SYSTEM/MATRIX, M-FILENAME)
LQR State-Feedback Control for Pitch Axis
Matrix Kq

Processing the Input File

To process the input file in batch mode, start the Flixan program, select the pitch design folder, and from the top menu select "*File Management*", "*Managing Input Files*", and then "*Edit/ Process Input Files*", as shown. The input file manager utility comes up and from the left menu select the input file "*Rocket_Pitch_RB.Inp*" and click on "Select Input File" button. The right menu will show all the datasets which are in the input file. Select the batch set "*Batch Set for Creating Rigid-Body Models for the Rocket-Plane*" and click on "Process Input Data" to process the entire file. The data are saved in the systems file and Matlab files. A detailed description of the vehicle modeling, mixing logic, and LQR control design processes is given in Section 1.3.
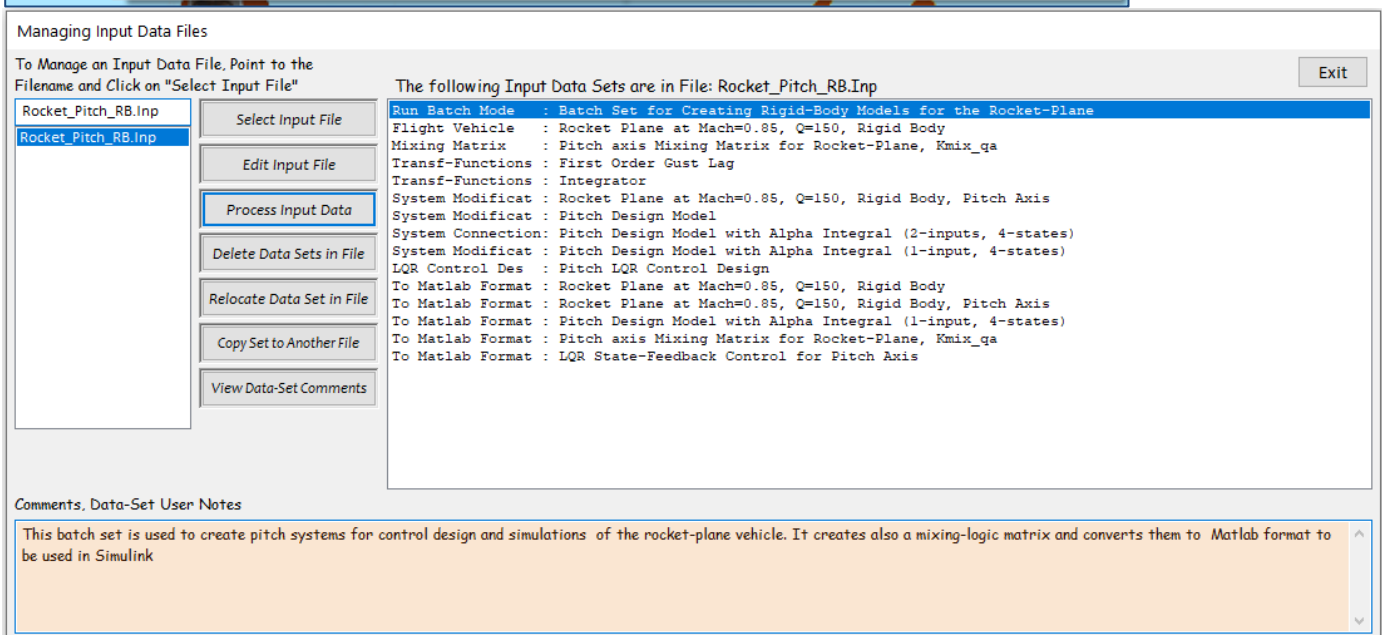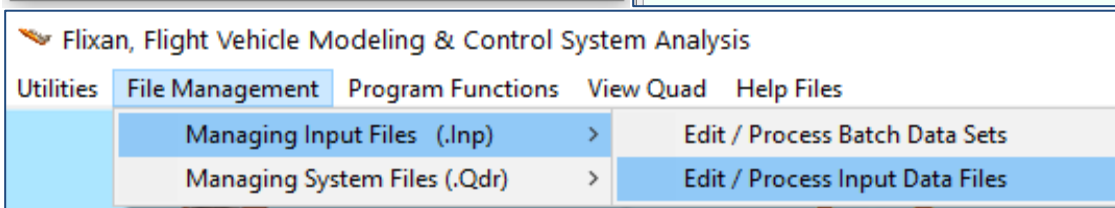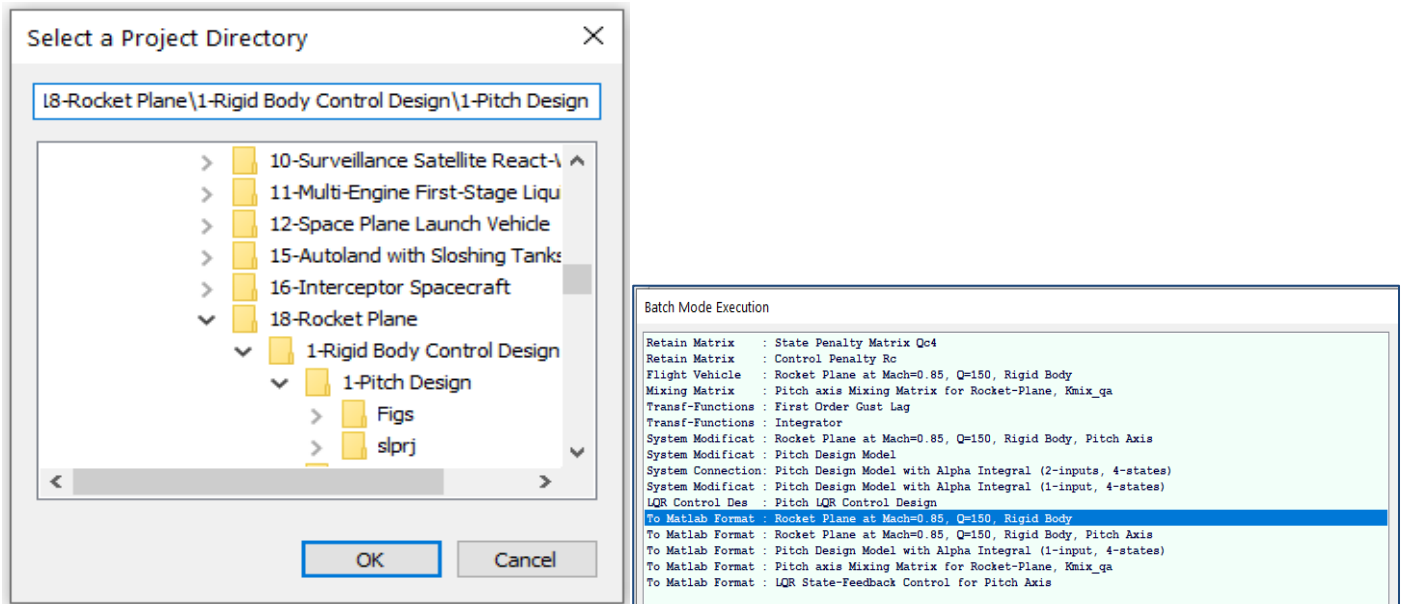
Longitudinal Control System Simulation Model

Figure 1.1 shows the longitudinal control system Simulink model "*Closed_Pitch.slx*" in folder "*1-Pitch Design*". It consists of two control loops: a ground speed control loop that controls the vehicle speed by varying the engine thrust and an altitude control loop that controls the vehicle altitude by changing the angle of attack as a function of altitude error. The simulation calculates the longitudinal system response to altitude and ground speed commands and also to wind-gust disturbances. The LQR controller requires feedback from the pitch attitude, rate and angle of attack. An estimator is used to estimate α from the normal acceleration $\ddot{z}$. The simulation is initialized by the file "init.m", which loads the systems, matrices, actuator, estimator parameters and calculates the control gains. The guidance system receives altitude and velocity change commands and issues a normal acceleration and throttle commands. The Nz-command is converted to an alpha command by the alpha estimator that controls the pitch loop. The throttle control adjusts the vehicle thrust and ground speed.
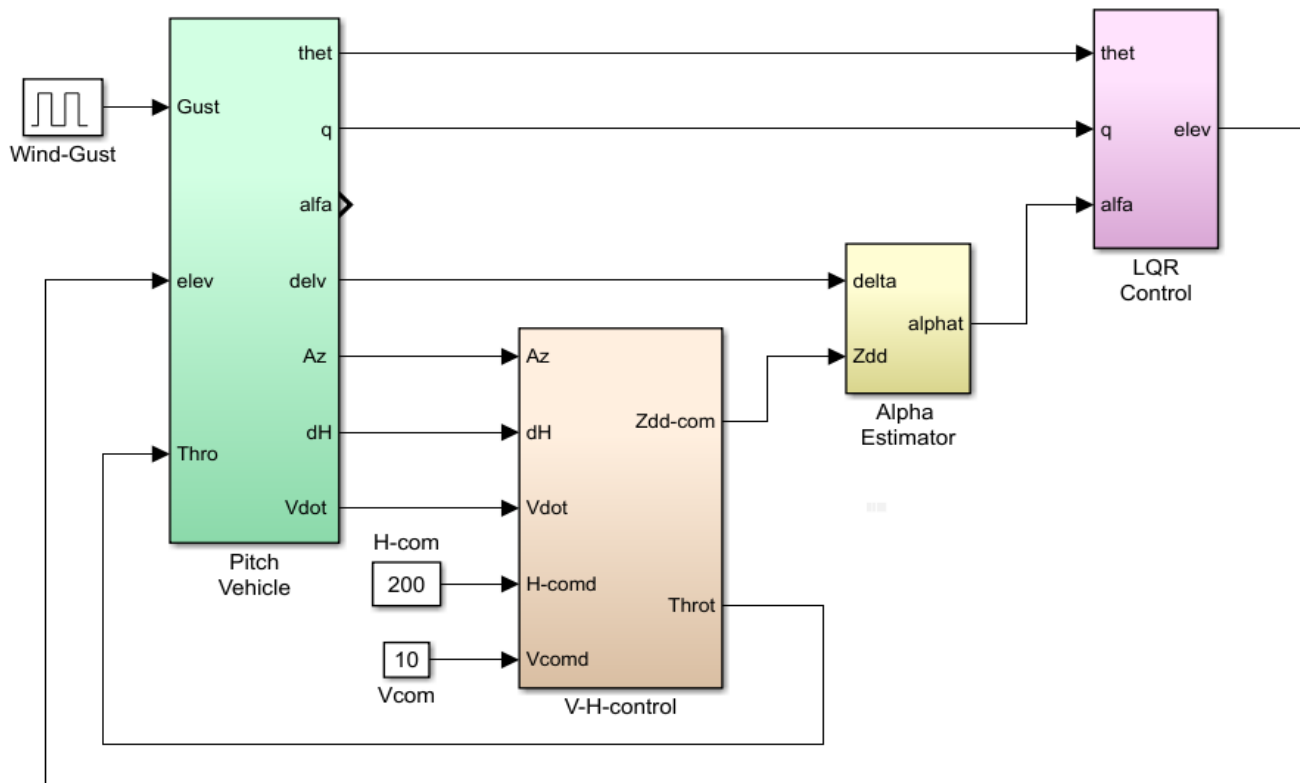
Figure 1.1 Longitudinal Simulation Model "Closed_Pitch.slx"

```
% Initialization File
d2r=pi/180; r2d=180/pi;
[Ap,Bp,Cp,Dp]= vehi_pitch_rb;              % Pitch Rigid Body Model
[Ad,Bd,Cd,Dd]= vehi_pdes_4x;               % LQR Design Model
load Kmix_qa.mat Kmix_qa -ascii             % Throttle/Control Surface Mix
load Kq.mat      Kq      -ascii             % LQR State-Feedback Matrix

zet=0.7; omg=40;                            % Actuator Model
Aact=[0, 1; -omg^2, -2*zet*omg]; Bact=[0; omg^2];
Cact=[1, 0]; Dact=0;

% Alpha Estimator Parameters
Qbar=150; Mass=198.32; Sref= 79.069; Cza=-0.073;
Czelv=[0.51664,0.51664,0.60478,0.60478,0.06]/100;   % Cz for the 5 control surfaces
```

The green block is shown in detail in Figure 1.2. It contains the vehicle system "*Rocket Plane at Mach=0.85, Q=150, Rigid Body, Pitch Axis*" and is loaded into Matlab workspace from the m-file "*Vehi_pitch_rb.m*". It includes also the mixing matrix and a simple 2nd order actuator. A wind-gust velocity impulse is applied to the vehicle and a low-pass filter is used to shape the gust impulse. The gust direction with respect to the vehicle is defined by two angles in the input data. The pink outputs are saving simulation data and plotting them in the end by the script m-file "pl.m".
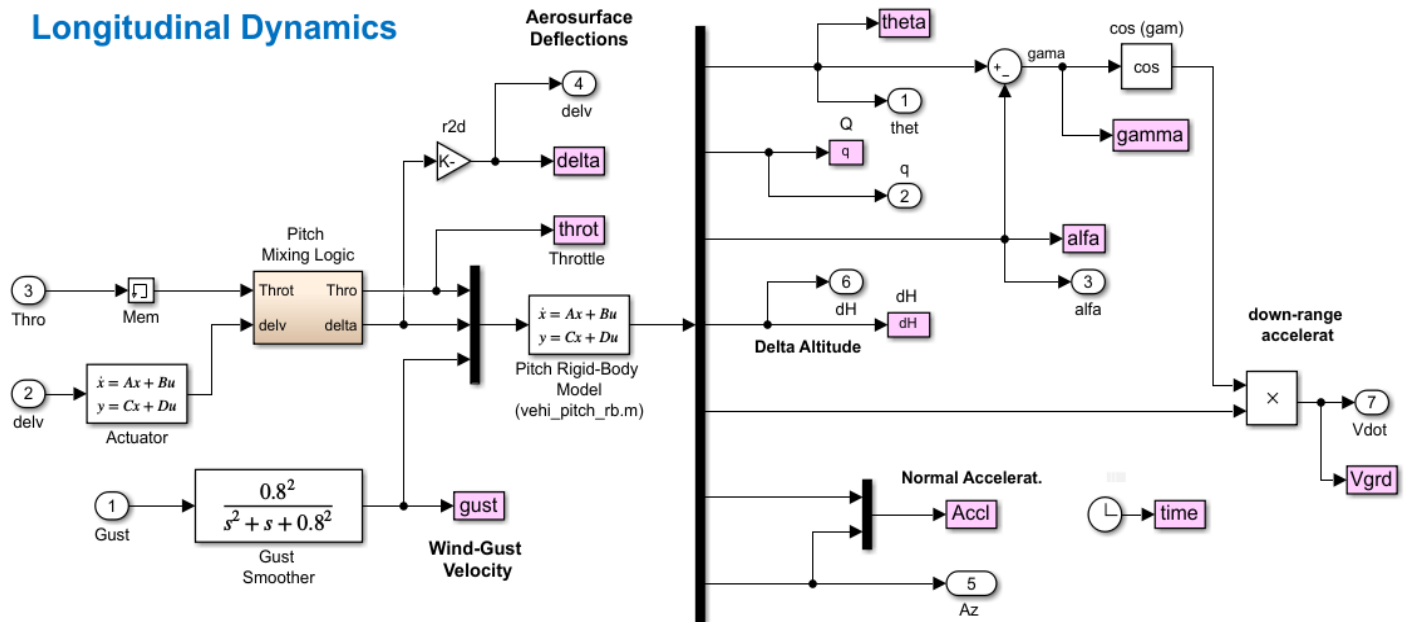
Figure 1.2 Vehicle Dynamic Subsystem, Includes the Actuator, Mixing-Logic, and Wind-Gust Impulse Shaping

The Pitch LQR State-Feedback Gain

The LQR gain combines feedback signals from the four plant states: pitch attitude, pitch rate, alpha, and alpha-integral, as shown in figure 1.3. It was designed using either Matlab or Flixan from the four-state design plant "*vehi_pdes_4x.m*" that was imported from system: "*Pitch Design Model with Alpha Integral (1-input, 4-states)*". The Matlab LQR implementation is in file "lqr_des.m". A low-pass filter is included in the output to attenuate flex modes.
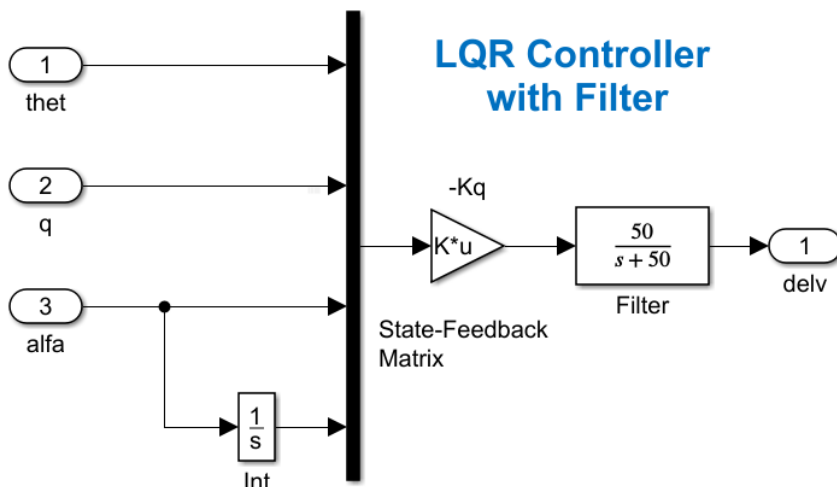
Figure 1.3 Pitch Axis State Feedback Controller

The Angle of Attack Estimator

The LQR controller inputs are from the four plant states. The pitch attitude and rate are measurable. The other two states, however, alpha, and alpha-integral are not directly measurable and we need an estimator block to estimate alpha from the normal acceleration and the aerosurface forces. The estimator is shown in Figure 1.4 and it solves the normal force equation (F=ma) in real-time. The inputs are normal acceleration and deflections of the five aerosurfaces. The output is the estimated alpha, and it will converge to the real angle of attack when the vehicle aerodynamic coefficients are reasonably known. The output of the summing junction goes to zero when the integrator converges to an alpha where the normal aero force due to alpha and the force due to surface deflections balance the vehicle normal acceleration force (ma). The estimated α and α-integral will replace the actual vehicle α and α-integral as shown in Figure 1.1. The estimator parameters (dynamic pressure, vehicle mass, and aero coefficients) are loaded into Matlab from the initialization file.
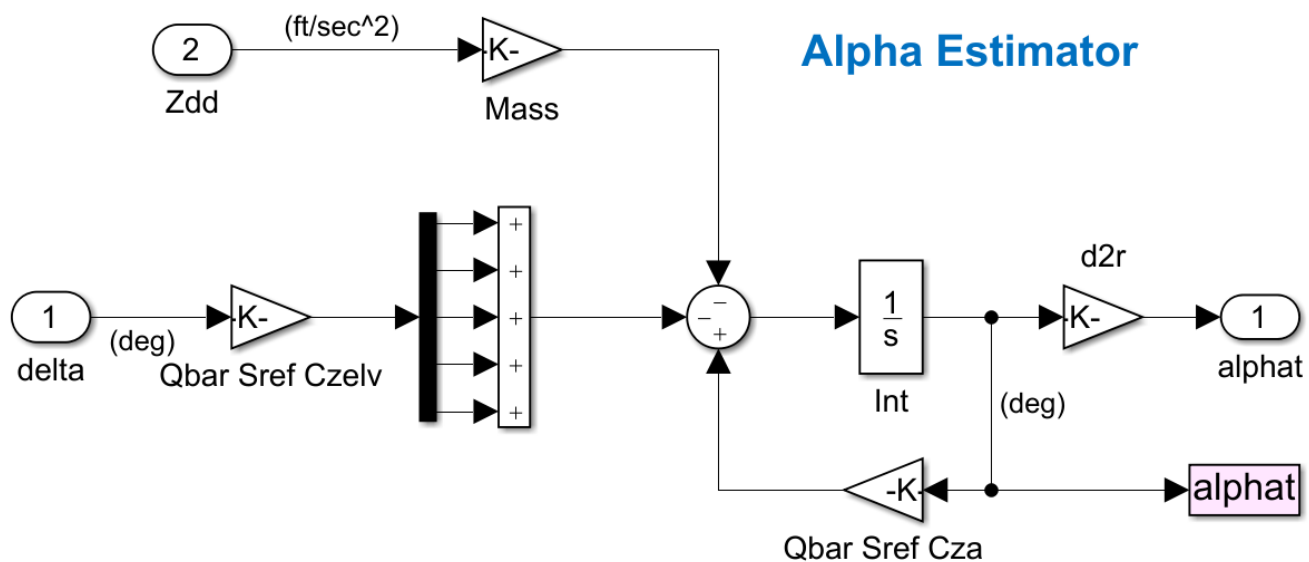
Figure 1.4 Angle of Attack Estimator Calculates Alpha from the Normal Force Equation

Longitudinal Guidance System

The Longitudinal Guidance system controls the vehicle speed and altitude by varying the engine thrust and the angle of attack. The ground speed controller is a PID that measures the vehicle ground speed error and issues a throttle command that varies from -1 to +1. Zero thrust corresponds to (-1) and maximum thrust of 4,000 (lb) corresponds to (+1). The altitude control system is also a PID that issues a normal acceleration command to the alpha estimator and it is translated to an alpha command.
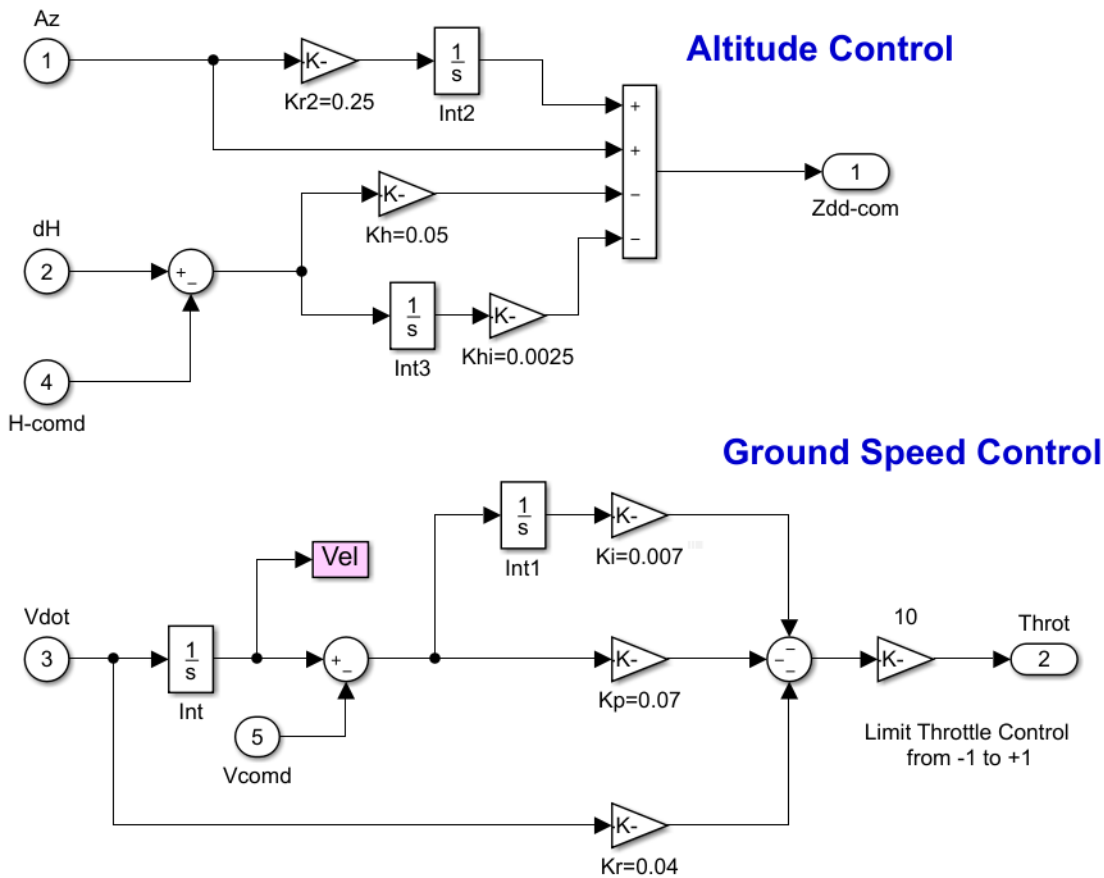
Figure 1.5 Longitudinal Guidance System Calculates the Nz and Throttle Commands

Longitudinal Simulation Results

Figures 1.6 show the longitudinal system response to simultaneous altitude and velocity change commands and to a wind-gust disturbance of 40 (ft/sec) in the direction described. The commands are: 500 (feet) increase in altitude, and 8 (feet/sec) increase in ground-speed. To perform this maneuver the vehicle temporarily increases its thrust 40% and deflects its aerosurfaces in the negative (up) direction that increases alpha (red line) which causes an upwards acceleration (negative Nz) and it increases the altitude. Both flaps and rudders are contributing to the pitch maneuver. Notice that alpha is measured relative to the trim alpha (α_0).

The altitude and velocity eventually approach the commanded values and the aerosurface deflections decay back to the original trim positions (zero). The thrust decays to a value 3% higher than its original nominal thrust. The flight path angle gamma starts from zero, increases to 4° as it gains altitude and it decays back to zero (horizontal flight) when the aircraft reaches a steady altitude.

Rocket-Plane Longitudinal Response to Gust, delta H and delta V Commands
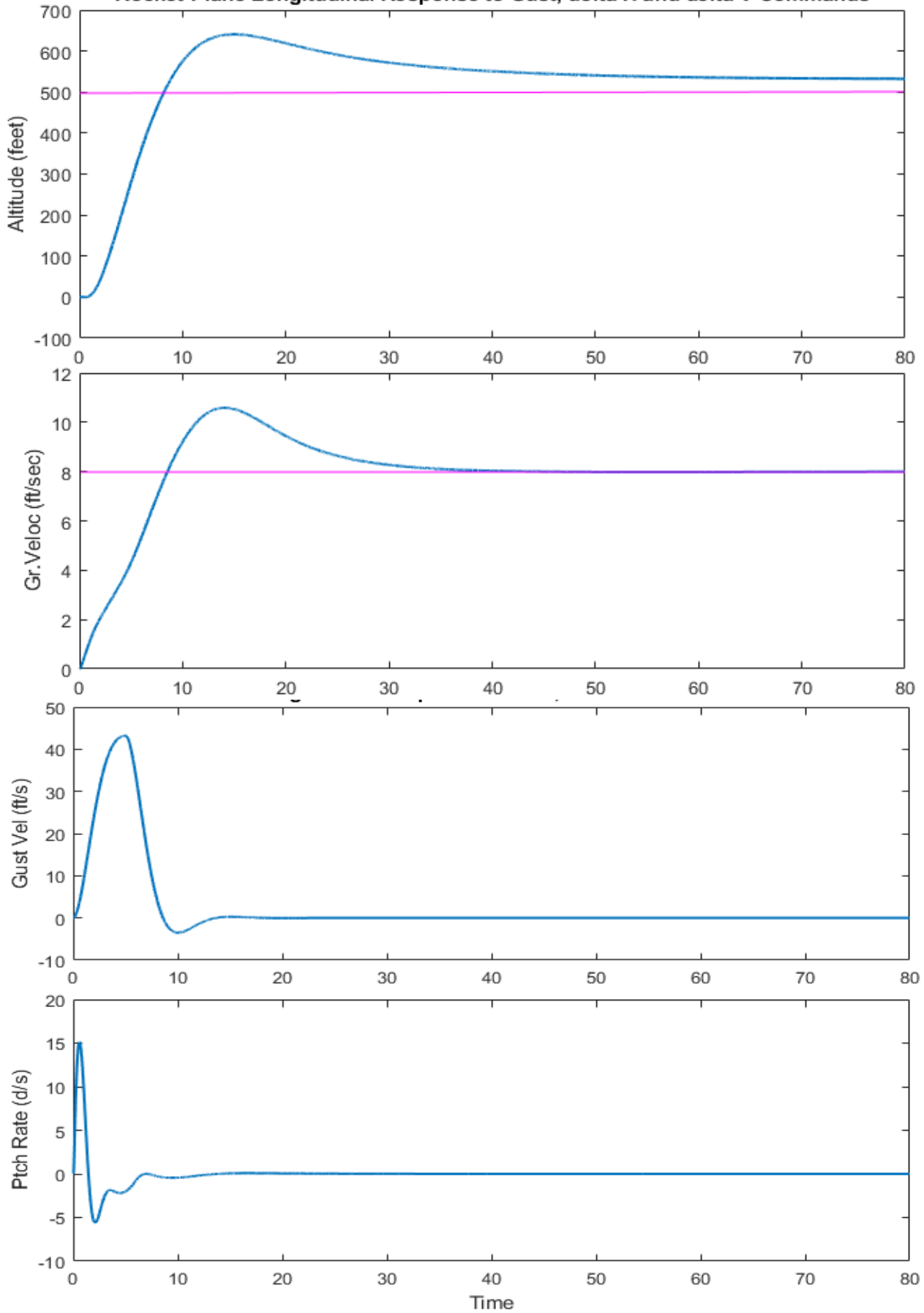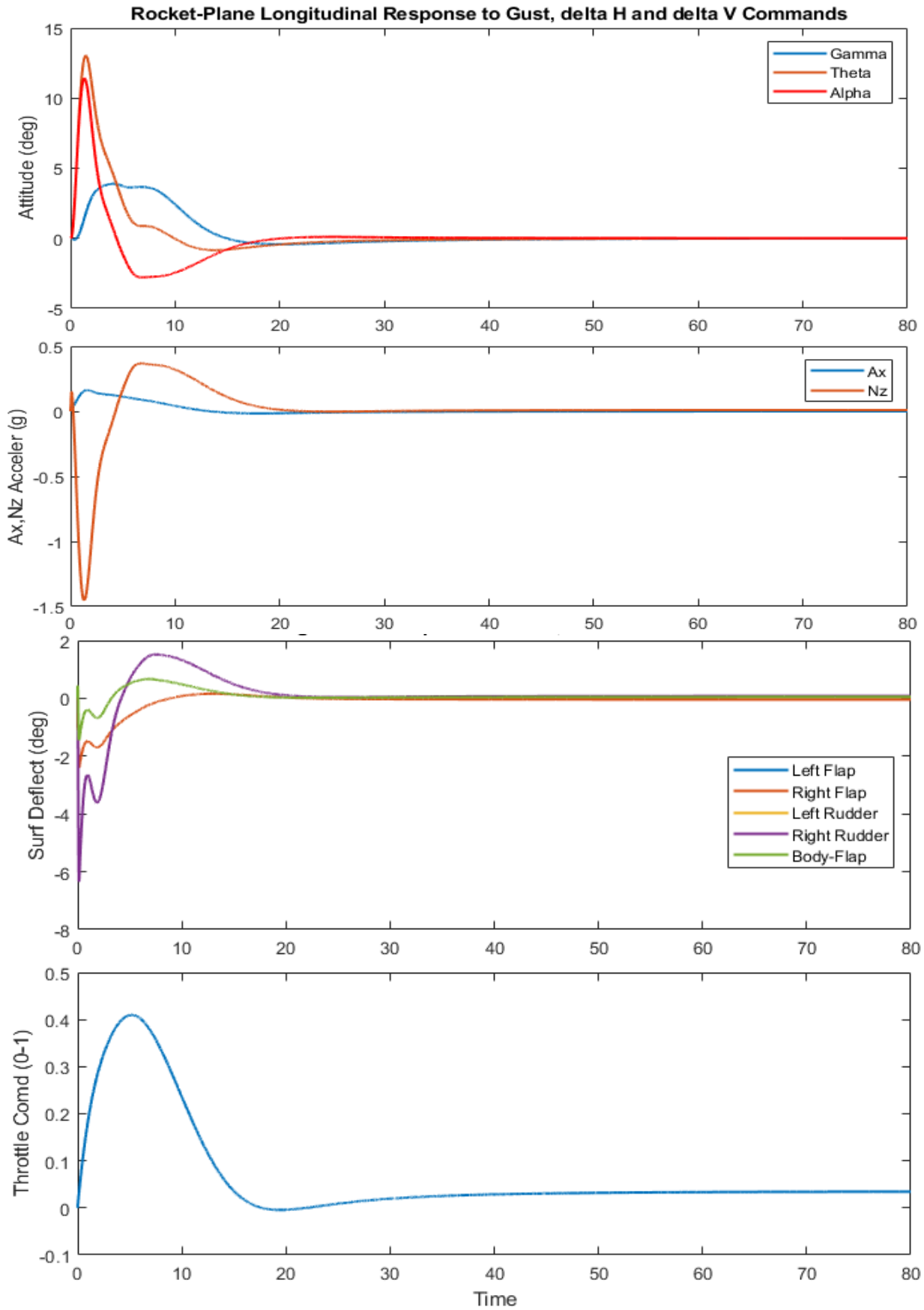
Figure 1.6 Longitudinal System Response to δV and δH Commands and to the Wind-Gust Disturbance

Longitudinal System Stability Analysis

The Simulink model: "Open_Pitch.slx", in Figure 1.7 is used to analyze pitch stability. It consists of the same subsystems as the simulation model. The system has two control loops: the elevon loop and throttle control loop. When checking the elevon stability we open the elevon loop and close the throttle loop and vise-versa. The Matlab file "frequ.m" calculates the frequency response of this open-loop system and plots the Bode and Nichols plots for measuring the system's stability margins.
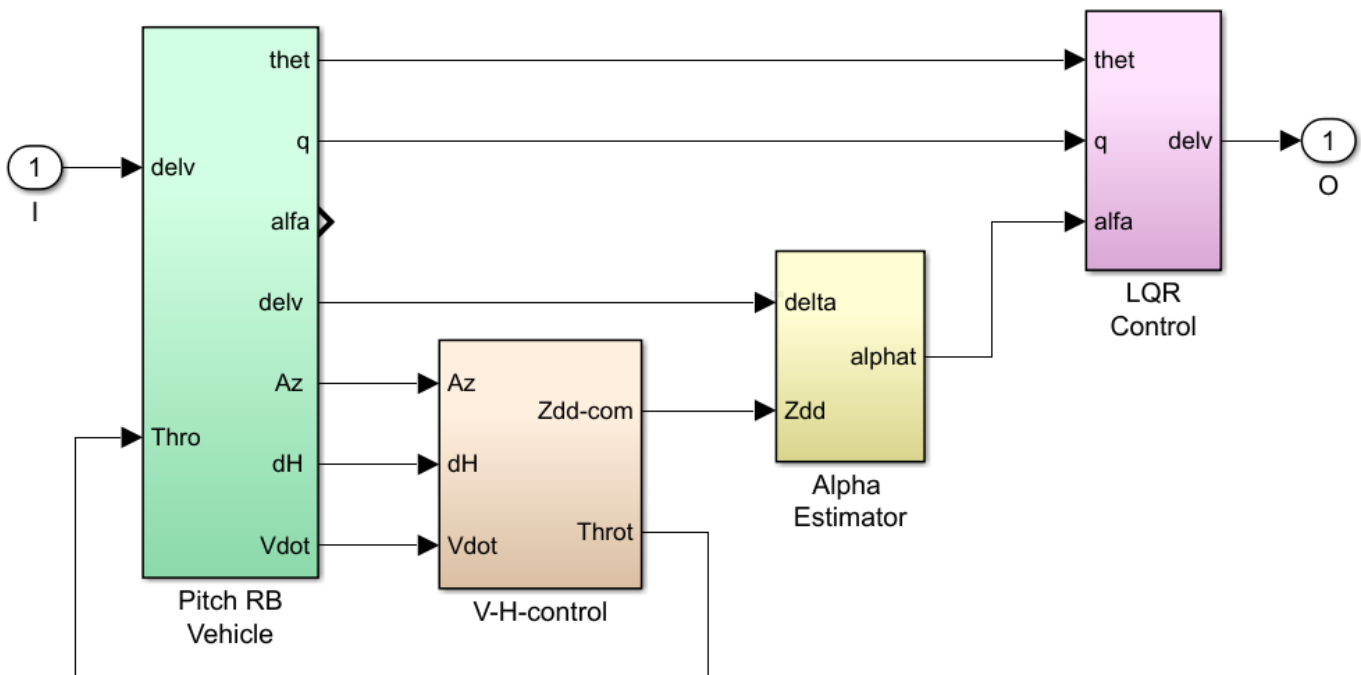
Figure 1.7 Simulink Model "Open_Pitch.slx" Used for Pitch Frequency Response Stability Analysis

The plots in Figure 1.8 show that the system has excellent phase and gain margins and a cross-over frequency of 3.5 (rad/sec). The alpha integrator provides high gain at low frequencies which is needed for alpha-command tracking.
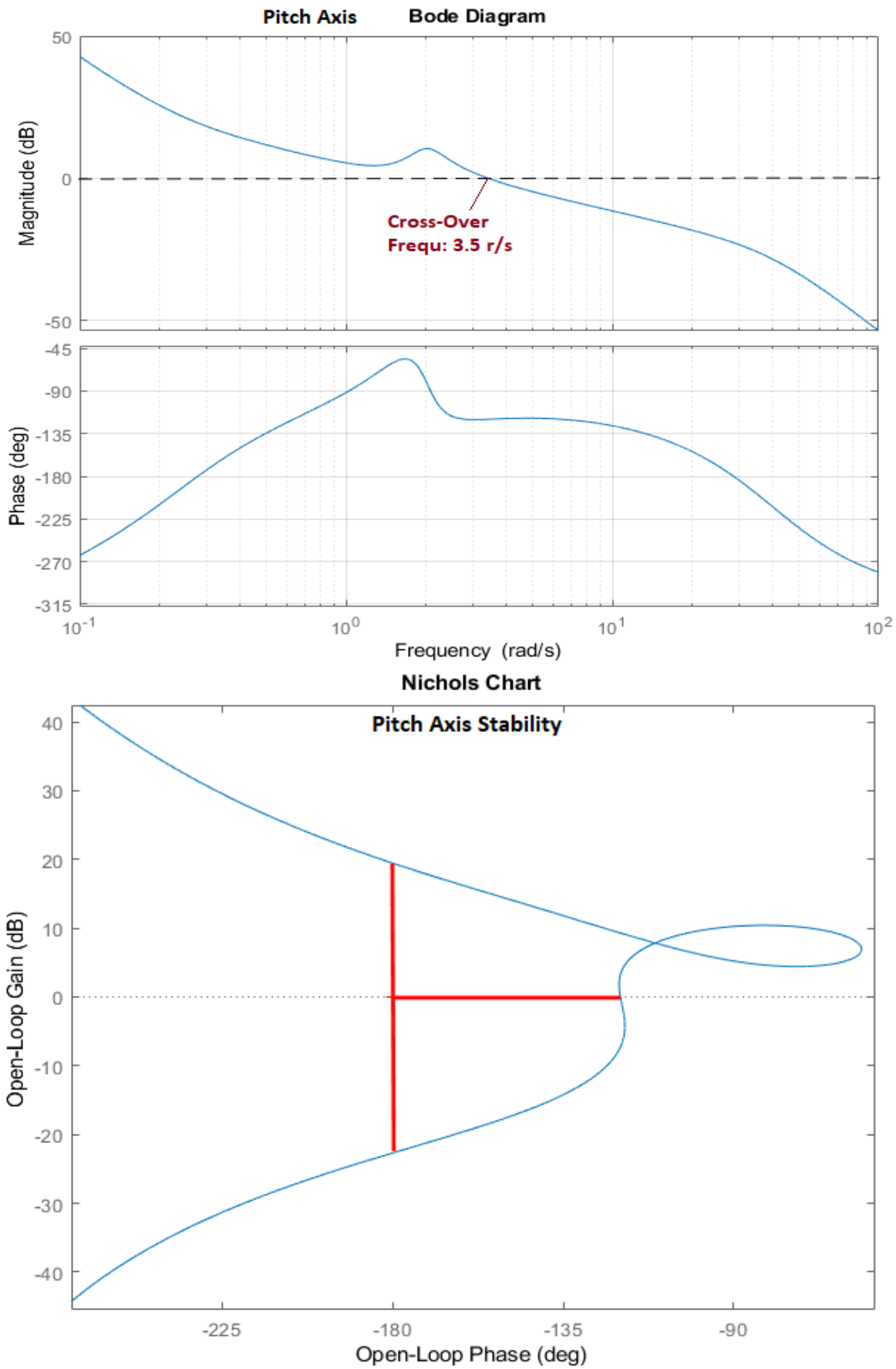
Figure 1.8 Pitch Axis Bode and Nichols Plots Showing Cross-Over Frequency, Gain and Phase Margins

1.3 Interactive Processing of the Pitch Vehicle Data

We will now demonstrate how to process the input file "Rocket_Pitch_RB.Inp" interactively for tutorial purposes in order to familiarize the user with the Flixan program. We begin by creating the vehicle model, the mixing logic matrix, the LQR design plant, the LQR design, and finally exporting the systems and matrices to Matlab.

Vehicle Modeling: We start the Flixan program and go to directory *"Flixan\ Examples\18-Rocket Plane\1-Rigid Body Control Design\1-Pitch Design"*. From the main menu go to *"Program Functions"*, *"Flight Vehicle/ Spacecraft Modeling Tools"*, and then select *"Flight Vehicle State-Space Modeling"*.

From the filename selection menu select the vehicle input and system filenames and click on *"Process Files"*. The program scans through the input data file *"Rocket_Pitch_RB.Inp"* searching for vehicle data and it shows their titles in the following menu. Select the only vehicle data title: *"Rocket Plane at Mach=0.85, Q=150, Rigid Body"*, and click on *"Run Input Set"* to process it.

The flight vehicle modeling program interactive dialog comes up that shows the vehicle title, modeling options, and vehicle data at the fixed flight condition. The data appear in separate tabs. The aero moment coefficients are shown in this case. There are some buttons in the upper right-hand corner where the user can create a new dataset or modify the existing dataset and save it under a different title. You can also view and edit the input file. Click on "Run" and the program will process the data, create the vehicle state-space system for this configuration, and save it in file "Rocket_Pitch_RB.Qdr" under the same title and comments. If a vehicle system already exists in the systems file under the same title, the user is given the options to either (a) replace the old system with the new, (b) keep old system as is and save the new one under a different title, or (c) do not save the new vehicle system but keep the old system. The state variable definitions of the inputs, states, and outputs are included below the (A,B,C,D) matrices.

Extracting the Pitch System: The next step is to extract a pitch system from the coupled vehicle system that we just created. This system will be used for pitch axis linear analysis. A second rigid-body model will also be extracted and it will be used for control design using the LQR method. The systems modification program will be used to extract the reduced pitch systems from the original system. The system modification instructions are already included in the input data file: "*Rocket_Pitch_RB.Inp*". The program reads the coupled system "*Rocket Plane at Mach=0.85, Q=150, Rigid Body*" that was created by the vehicle modeling program, extracts the pitch states and outputs, and saves the reduced pitch system in the systems file under the following title "*Rocket Plane at Mach=0.85, Q=150, Rigid Body, Pitch Axis*". From the main menu go to "*Program Functions*", "*Creating and Modifying Linear Systems*" and then "*Modifying, Scaling State-Space Systems*". From the filenames selection menu select the input and the system filenames. The program searches for system modification datasets and it shows their titles in the menu below. Select the set "*Rocket Plane at Mach=0.85, Q=150, Rigid Body, Pitch Axis*" and click on the "*Run Selected Input Set*" button to process the data and extract the pitch system.
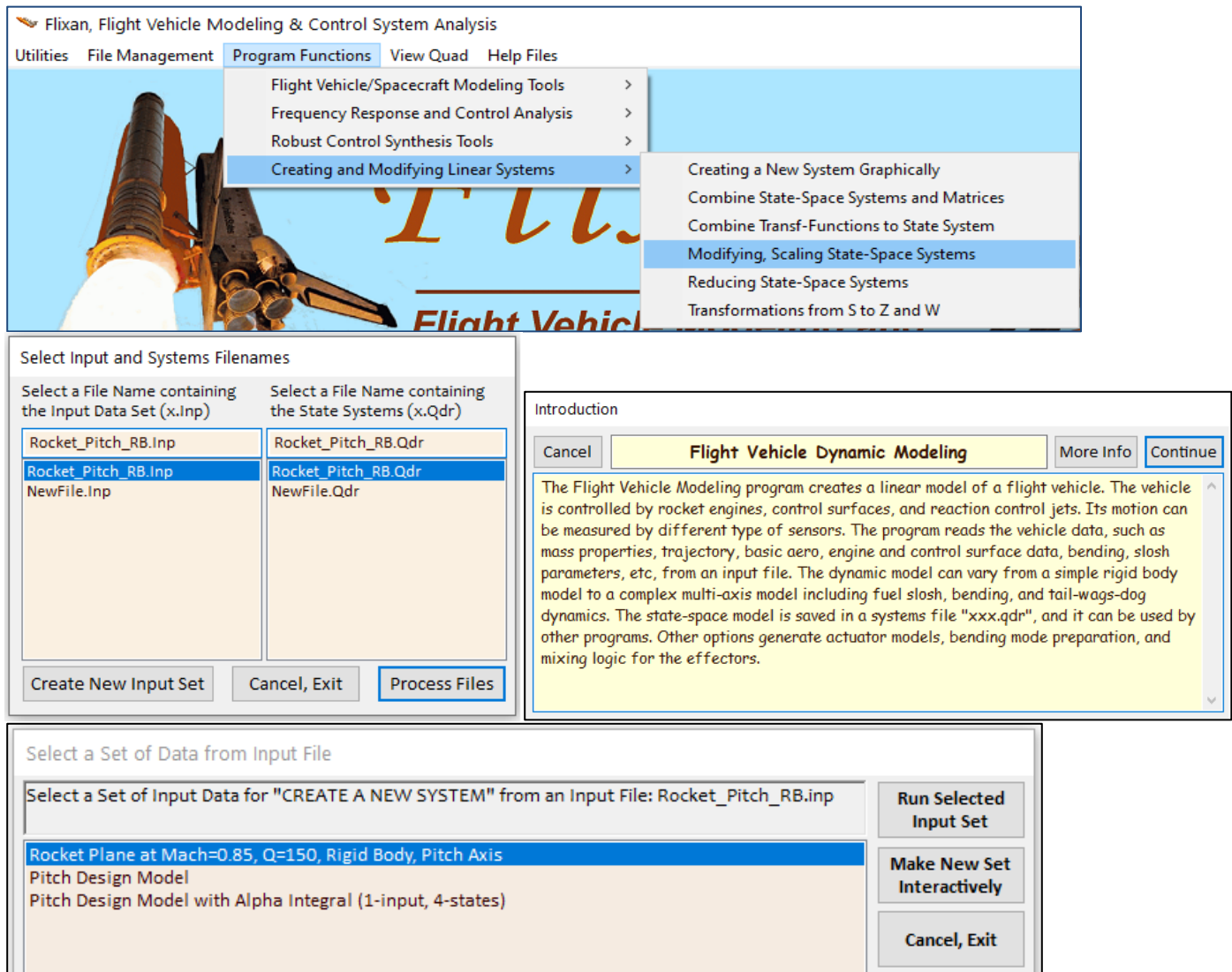

The program will extract the pitch states and outputs from the coupled vehicle system and save it in the systems file under the new title: "*Rocket Plane at Mach=0.85, Q=150, Rigid Body, Pitch Axis*". This system will also be exported into Matlab and used for pitch analysis. To eliminate the two extra states: δH and δV, we re-run the system modification program and from the titles menu select the "*Pitch Design Model*". This dataset creates an even smaller pitch system from the previous system "*Rocket Plane at Mach=0.85, Q=150, Rigid Body*". It consists only of three states: pitch attitude, pitch rate, and alpha and it is saved in the systems file under the title: "*Pitch Design Model*". The inputs are: engine throttle (from 0 to ±1), plus five aerosurface deflections in (rad). The design model is not complete yet because it is missing one more state, the alpha-integral

Derivation of the Pitch Mixing Logic Matrix: The Flixan generated vehicle system has six control inputs: a throttling engine that controls the vehicle speed, plus five aero-surfaces mainly for pitch control. The purpose of the longitudinal control system is to independently control the pitch attitude and the vehicle speed using the available controls. We will now use the mixing logic program to derive a mixing logic matrix that pre-multiplies the open-loop vehicle and attempts to decouple the two longitudinal control directions: the pitch angular acceleration and the forward acceleration. It converts the pitch and axial acceleration demands from the flight control system to a combination of engine throttling plus aero-surface deflections that produce the required accelerations in the corresponding directions, open-loop. The mixing logic matrix attempts to diagonalize the plant and minimizes the dynamic coupling between the two longitudinal control loops. The algorithm uses the pseudo-inversion method and the vehicle mass properties, aero data, and the aerosurface coefficients. Remember that zero throttle command corresponds to applying nominal thrust of 2,000 (lbf). A throttle command of (+1) corresponds to a maximum thrust of 4,000 (lbf), and a throttle command of (-1) means zero thrust.

The mixing logic program is used to calculate the pitch mixing logic matrix. To run it, from the Flixan main menu go to "*Program Functions*", and select "*Create Mixing Logic/ TVC*". From the filenames selection menu select the input and the system filenames "*Rocket_Pitch_RB.Inp*" and "*Rocket_Pitch_RB.Qdr*", as before. Select the vehicle data title: "*Rocket Plane at Mach=0.85, Q=150, Rigid Body*", and click on "*Run Input Set*" to create the mixing matrix from the vehicle data.

The next step is to define the longitudinal directions that will be decoupled by the mixing logic. The following menu is used for selecting the acceleration control directions from a total of 3 rotations and 3 translations. We usually select only directions that are affected by the vehicle effectors. In this case we select the two directions that will be controlled by the longitudinal control system, which are: the pitch acceleration (q-dot), and axial acceleration (Ax). We must also enter a name for the effector combination matrix "Kmix_qa". Click "OK" to continue.
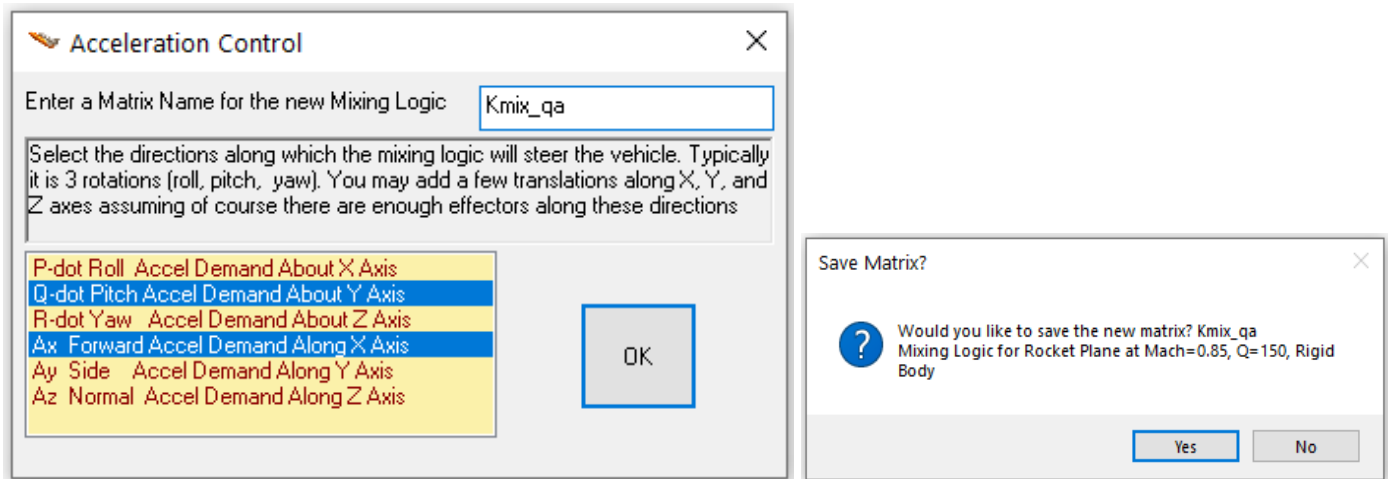
The mixing logic matrix is saved in the systems file "*Rocket_Pitch_RB.Qdr*". Intuitively, one would attempt to use the engine for axial acceleration control and the two V-tail rudders for pitch control. The derived matrix is similar but it includes more terms that provide decoupling between the two longitudinal directions. The matrix is also exported into Matlab for further analysis.
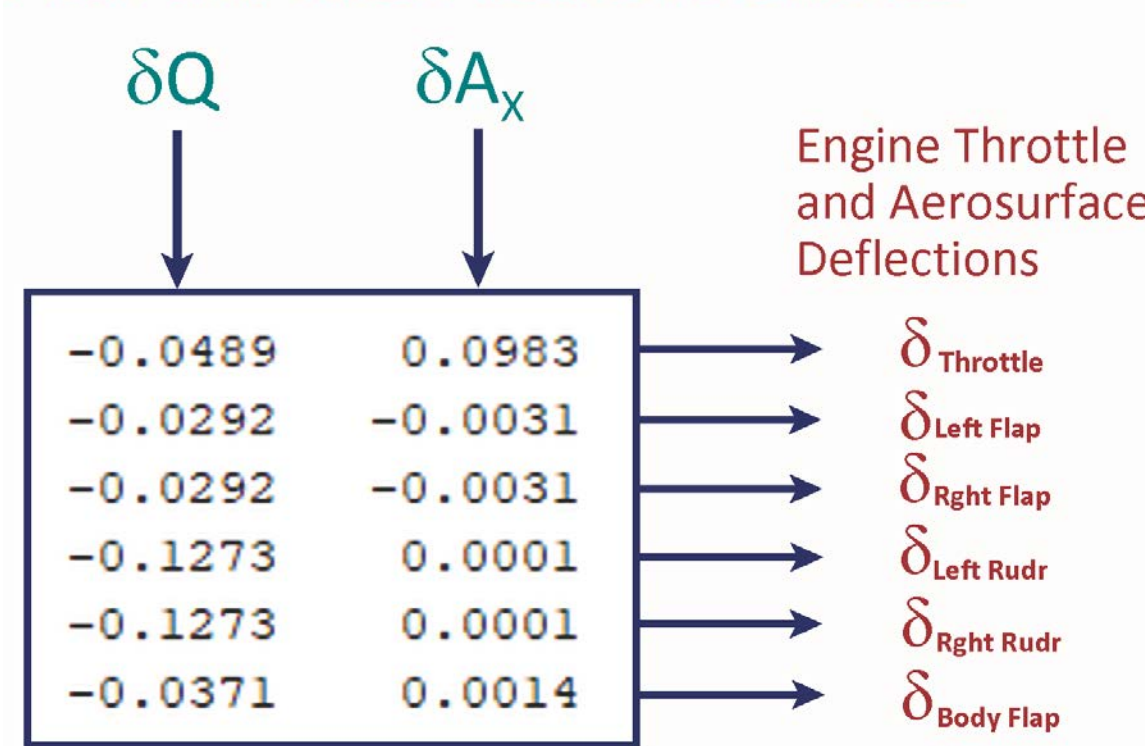

Figure 1.9 The Longitudinal Mixing Logic Matrix Kmix_qa

Creating the Pitch LQR Design Plant: The previously extracted pitch system "*Rocket Plane at Mach=0.85, Q=150, Rigid Body, Pitch Axis*" is used for stability analysis and simulations but it is not suitable for pitch LQR control design because it contains two additional states (changes in altitude and velocity) that we do not intend to control directly by the pitch flight control system. In the LQR design plant we remove the δH and δV states and include the α-integral state. It will help us regulate the angle of attack more precisely. The δH and δV variables will be controlled by the outer guidance loop that was designed using classical control.

The systems combination program will be used to combine the "*Pitch Design Model*" with the alpha-integrator to produce the α-integral state. It also multiplies the control inputs with the mixing logic matrix "Kmix_qa" to replace the 6 effector inputs with two plant inputs: pitch and axial acceleration demands, δQ and δAx. The title of the system combination set is "*Pitch Design Model with Alpha Integral (2-inputs, 4-states)*" which is located in the input data file "*Rocket_Pitch_RB.Inp*". To create this new system, from the Flixan main menu select: "*Program Functions*", "*Creating and Modifying Linear Systems*", and then "*Combine State-Space Systems and Matrices*". From the filenames selection menu select the input and the system filenames, as before. The program searches the input data file for systems interconnection datasets and shows their titles in the following menu. From the menu select the systems interconnection set "*Pitch Design Model with Alpha Integral (2-inputs, 4-states)*", click on the "*Run Selected Input Set*" button to create the pitch design system augmented with alpha-integral.

The following systems interconnection dialog comes up showing the system interconnections info. Click on "Run" to process the dataset and the new system will be saved in the systems file "*Rocket_Pitch_RB.Qdr*" under the title: "*Pitch Design Model with Alpha Integral (2-inputs, 4-states)*". It will also be converted to Matlab format for LQR design using Matlab.

Transferring Systems to Matlab: In the previous steps we used the Flixan program to create several vehicle state-space systems, a mixing logic matrix, and a state-feedback gain for the pitch axis. The data are saved in the systems file: "*Rocket_Pitch_RB.Qdr*". We must now convert those systems and matrices to Matlab format for analysis. To reformat the pitch vehicle system, from the Flixan main menu go to "*Utilities*", then "*Matlab Conversions*", and select "*Export to Matlab*". From the systems selection menu select the filename "*Rocket_Pitch_RB.Qdr*". From the Matlab directory selection window, select the Matlab analysis subdirectory "*1-Pitch Design*" where the system "*Rocket Plane at Mach=0.85, Q=150, Rigid Body, Pitch Axis*" will be transferred.
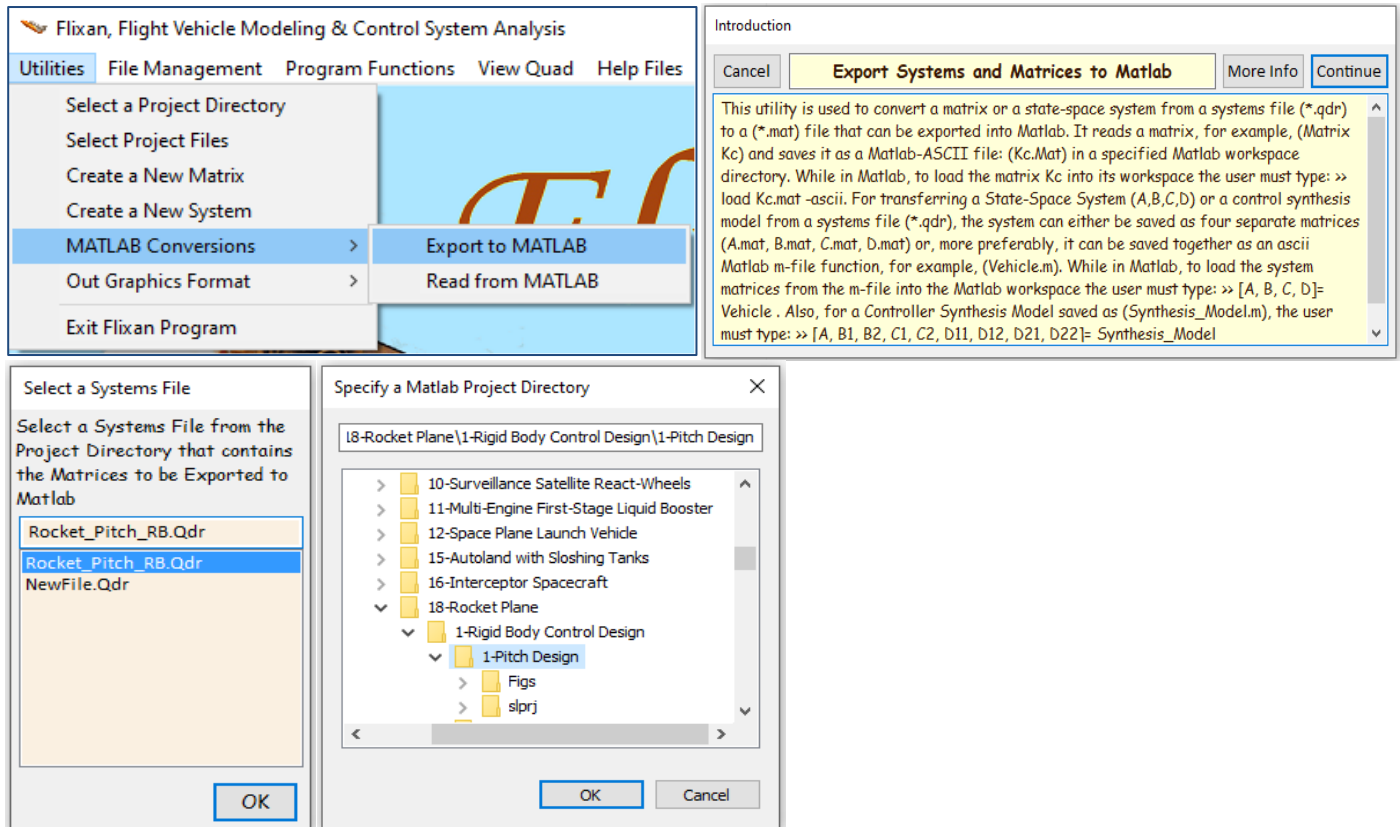
The following dialog is for selecting Matlab transferring options. Select to convert a "System (A,B,C,D)" to a Matlab function (m-file) format. The option on the bottom right is selected in order to save the Matlab conversion process you just described as a "To Matlab" conversion dataset in the input file which can be used later in batch processing. In this case choose "Do Not Save" because there is already a data-set for batch processing created in the input file. The next step is to select the system from the systems file to be converted to an m-file function. The systems selection menu is showing the system titles in file "*Rocket_Pitch_RB.Qdr*". Select one of the titles: "*Rocket Plane at Mach=0.85, Q=150, Rigid Body, Pitch Axis*" to be converted and click the "Select" button. You must also enter the name of the function file "*Vehi_Pitch_rb*". The system's quadruple matrices will be converted to an m-file function and saved in file "*vehi_pitch_rb.m*". Do not type the filename extension (.m). The same procedure is also used to convert the LQR design system "*Pitch Design Model with Alpha Integral (1-input, 4-states)*" to a Matlab m-function. The filename of the control design system is "*vehi_pdes_4x.m*".
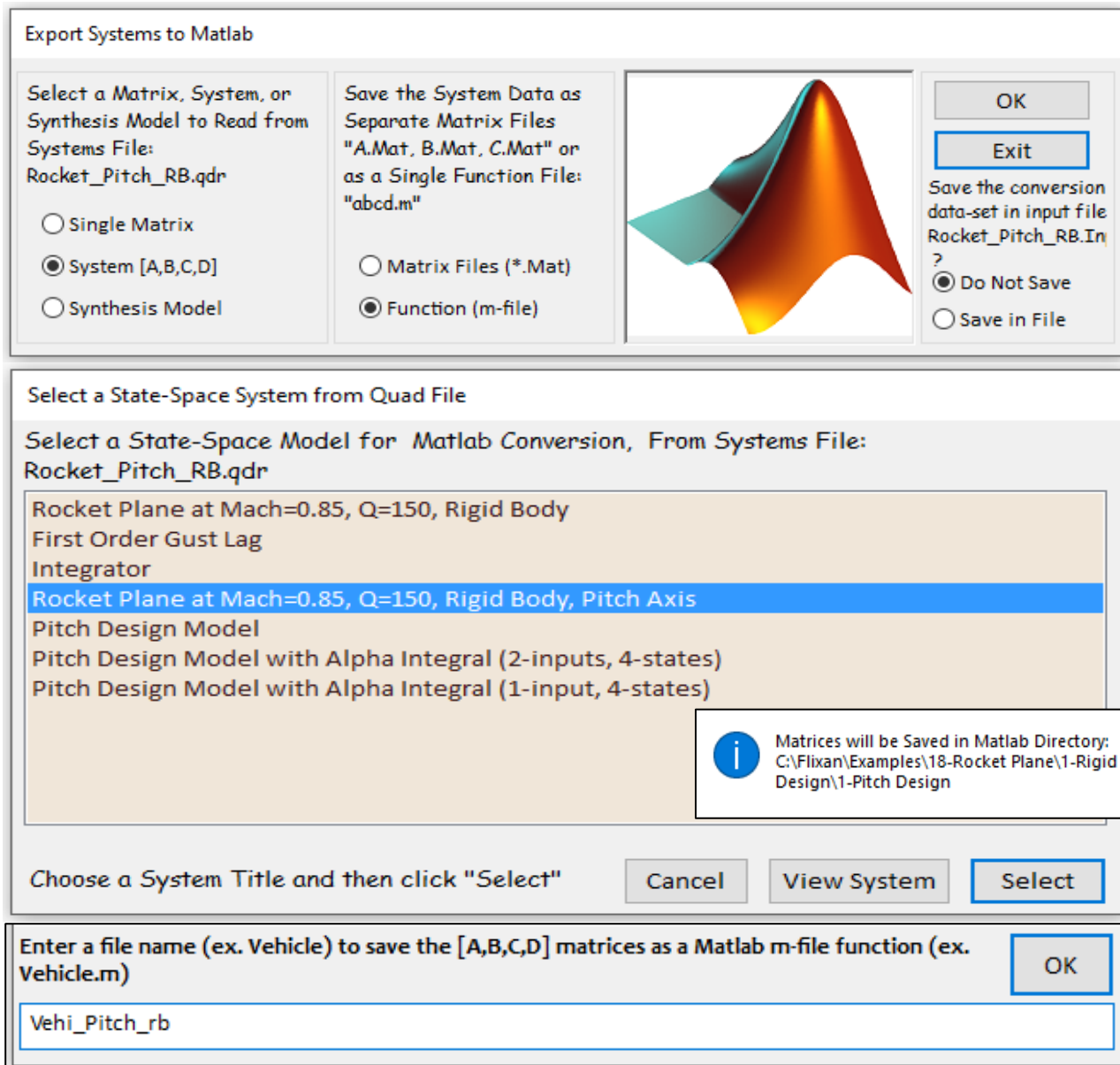
The "*Export to Matlab*" utility is also used to convert the (6x2) mixing logic matrix "Kmix_qa" from the systems file to a Matlab matrix. This time you must select to convert a single matrix, from the "Export to Matlab" dialog, instead of a system. From the matrix selection menu, select the 6x2 matrix "Kmix_qa", and the matrix will be converted to a Matlab matrix in –ascii format in file "Kmix_qa.mat". Repeat the matrix conversion for the state-feedback matrix Kq.
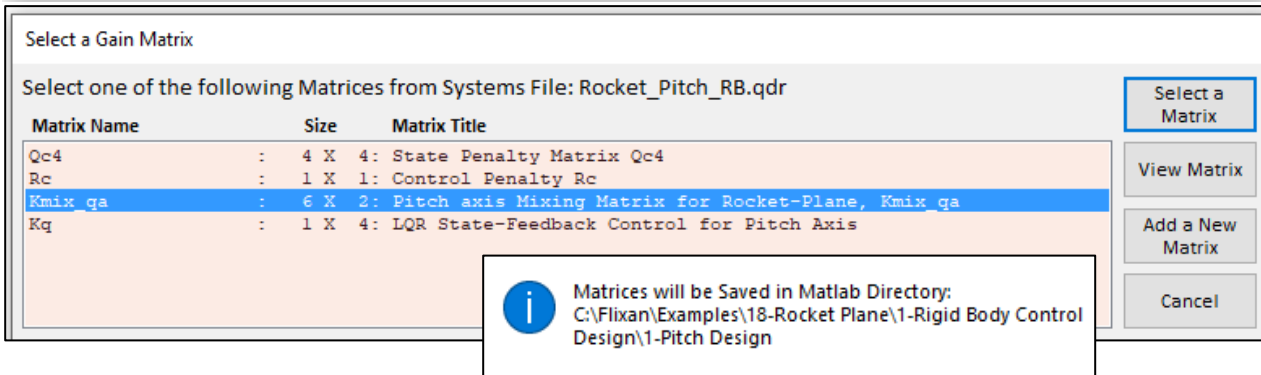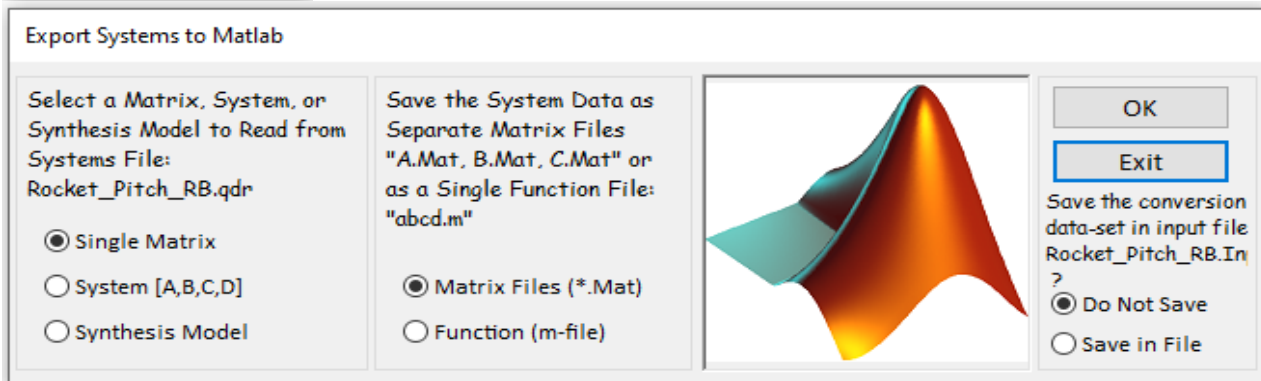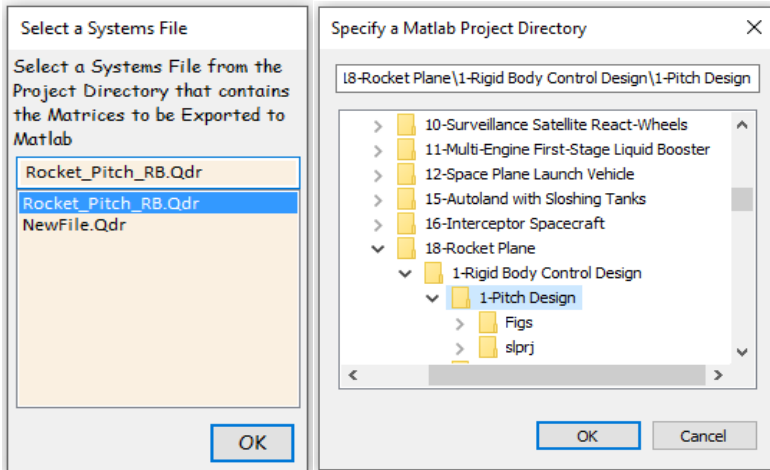
LQR Control Design: The LQR control design dataset is already created in the input file and Its title is "*Pitch LQR Control Design*". It uses the vehicle design model "*Pitch Design Model with Alpha Integral (1-input, 4-states)*" that has only one input, the pitch control δQ. The δH and δV states are taken out and it includes the α-integral state. The design algorithm also requires the state and control weight matrices Qc4 and Rc which are already permanently saved in the systems file. The state-feedback controller will also be saved in the systems file.

To start the LQR program, select "*Program Functions*", "*Robust Control Synthesis Tools*", and then "*Linear Quadratic Control Design*". Select also the input and system files, as before. The first step is to check the Controllability and the Observability of the design system. From the LQR main menu select the first option and from the systems menu select the design system "*Pitch Design Model with Alpha Integral (1-input, 4-states)*". This system is both: Controllable and Observable. The program returns to the main LQR menu and we select the second option which solves the Steady-State Linear Quadratic Regulator problem. It searches the input file and finds one LQR design dataset "*Pitch LQR Control Design*". Click on "*Run Selected Input Set*" to process it. The state-feedback controller "*LQR State-Feedback Control for Pitch Axis*" will be saved in the systems file as a gain matrix Kq.

Flixan, Flight Vehicle Modeling & Control System Analysis

Utilities   File Management   Program Functions   View Quad   Help Files

- Flight Vehicle/Spacecraft Modeling Tools   >
- Frequency Response and Control Analysis   >
- Robust Control Synthesis Tools   >
  - Modeling Vehicle Parameter Uncertainties
  - H-Infinity Control Design
  - Linear Quadratic Control Design
  - LQG / LTR
- Creating and Modifying Linear Systems   >

Select a Project Directory   ✕

l8-Rocket Plane\1-Rigid Body Control Design\1-Pitch Design

- > 10-Surveillance Satellite React-\
- > 11-Multi-Engine First-Stage Liqu
- > 12-Space Plane Launch Vehicle
- > 15-Autoland with Sloshing Tanks
- > 16-Interceptor Spacecraft
- ∨ 18-Rocket Plane
  - ∨ 1-Rigid Body Control Design
    - ∨ 1-Pitch Design
      - > Figs
      - > slprj

OK   Cancel

Select Input and Systems Filenames

Select a File Name containing the Input Data Set (x.Inp)

Rocket_Pitch_RB.Inp

Rocket_Pitch_RB.Inp
NewFile.Inp

Select a File Name containing the State Systems (x.Qdr)

Rocket_Pitch_RB.Qdr

Rocket_Pitch_RB.Qdr
NewFile.Qdr

Create New Input Set   Cancel, Exit   Process Files

LQR Control Design, Main Menu   ✕

Double-Click to Select one of the Following LQR Design Options:

Check a System's Controllability and Observability
Steady-State Linear Quadratic Regulator State-Feedback
Time-Varying LQR with Terminal Time Constraint on State
Steady-State Kalman Filter State Estimator
Output Feedback LQG Control Design
LQG with Frequency Shaped Cost Functions
LQG with Loop Transfer Recovery (LQG/LTR)

Exit Menu   Select

Select a State-Space System from Quad File

Select a State-Space Model for the Design Plant,   From Systems File: Rocket_Pitch_RB.qdr

Rocket Plane at Mach=0.85, Q=150, Rigid Body
First Order Gust Lag
Integrator
Rocket Plane at Mach=0.85, Q=150, Rigid Body, Pitch Axis
Pitch Design Model
Pitch Design Model with Alpha Integral (2-inputs, 4-states)
Pitch Design Model with Alpha Integral (1-input, 4-states)

ⓘ   The Pair (A, B) is Controllable from the Controls (u)

The Pair (A, C) is Observable from the Measurements (y)

Choose a System Title and then click "Select"   Cancel   View System   Select

---

Select a Set of Data from Input File

Select a Set of Input Data for "LINEAR QUADRATIC REGULATOR" from an Input File: Rocket_Pitch_RB.inp

Pitch LQR Control Design

Run Selected Input Set

Make New Set Interactively

Cancel, Exit

LQR Control Design, Main Menu   ✕

Double-Click to Select one of the Following LQR Design Options:

Check a System's Controllability and Observability
Steady-State Linear Quadratic Regulator State-Feedback
Time-Varying LQR with Terminal Time Constraint on State
Steady-State Kalman Filter State Estimator
Output Feedback LQG Control Design
LQG with Frequency Shaped Cost Functions
LQG with Loop Transfer Recovery (LQG/LTR)

Exit Menu   Select

1.4 Lateral Control System Analysis

From the coupled rigid vehicle model will now extract two lateral systems: an analysis system and a smaller system for lateral LQR control design. The second system will be used to calculate the lateral mixing logic matrix that combines four aero-surface deflections, the 2 flaps and the 2 rudders. The throttling engine and the body-flap are not included because they do not contribute in the lateral axes. The mixing logic will decouple the roll and yaw axes and it will be included in the LQR control design system that will be processed by the LQR program to create the lateral state-feedback gain. The feedback signal from the angle of sideslip will be replaced with a beta-estimate. We will perform stability analysis and use a simulation to analyze the system performance to guidance commands and to wind-gusts.

The analysis files for the lateral axes are in folder: "*Flixan\Examples\18-Rocket Plane\1-Rigid Body Control Design\2-Lateral Design*". The vehicle input file is: "*Rocket_Later_RB.Inp*" and the systems file is: "*Rocket_Later_RB.Qdr*". The input file includes a batch set on the top that creates the vehicle model, performs the LQR design and exports the data for Matlab analysis. The input data file is shown below. There are two vehicle systems. The first one includes the engine and all 5 aerosurfaces. The second vehicle system "*Rocket Plane at Mach=0.85, Q=150, Rigid Body (for computing the lateral mixing matrix Kmix)*" is used to create the lateral design system and the mixing matrix, and uses only four aerosurfaces. The mixing logic dataset "*Lateral axes Mixing Matrix for Rocket-Plane, Kmix*" creates a mixing logic matrix that converts the roll and yaw acceleration demands to aerosurface deflections. The lateral design model is extracted from the combined system by selecting only the lateral variables.

Input File "*Rocket_Later_RB.Inp*"

```
BATCH MODE INSTRUCTIONS ...............
Batch Set for Creating Rigid-Body Models for the Rocket-Plane
! This batch set is used to create pitch and lateral models for control design and simulations
! of the rocket-plane vehicle. It creates also a mixing-logic matrix and converts them to
! Matlab format to be used in Simulink
!
Retain Matrix      : State Penalty Matrix Qc4
Retain Matrix      : Control Penalty Matrix Rc2
Flight Vehicle     : Rocket Plane at Mach=0.85, Q=150, Rigid Body
Flight Vehicle     : Rocket Plane at Mach=0.85, Q=150, Rigid Body (for computing the lateral mixing matrix Kmix )
Transf-Functions : First Order Gust Lag
Transf-Functions : Integrator
System Modificat : Rocket Plane at Mach=0.85, Q=150, Rigid Body, Lateral Axes
Mixing Matrix      : Lateral axes Mixing Matrix for Rocket-Plane, Kmix
System Modificat : Lateral Design Model
System Connection: Lateral Design Model with p-Integral (4-states)
LQR Control Des  : Lateral LQR Control Design
!
To Matlab Format : Rocket Plane at Mach=0.85, Q=150, Rigid Body
To Matlab Format : Rocket Plane at Mach=0.85, Q=150, Rigid Body, Lateral Axes
To Matlab Format : Lateral Design Model with p-Integral (4-states)
To Matlab Format : Lateral axes Mixing Matrix for Rocket-Plane, Kmix
To Matlab Format : LQR State-Feedback Control for Lateral Axis
-------------------------------------------------------------------------------------------------
```

```
FLIGHT VEHICLE INPUT DATA ......
Rocket Plane at Mach=0.85, Q=150, Rigid Body
! The following vehicle model is a rigid body rocket plane. It has five control surfaces,
! 2 flaps, 2 rudders, and a body-flap. It also has a fixed engine with variable thrust for
! speed control. In this model the tail-wags-dog option is turned off.
! It will be used to create state-space models for control design.
!
Body Axes Output,Attitude=Euler Angles,Without GAFD, No Turn Coordination

Vehicle Mass (lb-sec^2/ft), Gravity Accelerat. (g) (ft/sec^2), Earth Radius (Re) (ft)    :  198.32       32.17        0.20896E+08
Moments and products of Inertias Ixx, Iyy, Izz, Ixy, Ixz, Iyz, in (lb-sec^2-ft)          :  1098.0       10933.       11290.       0.0000       123.75
CG location with respect to the Vehicle Reference Point, Xcg, Ycg, Zcg, in (feet)         : -15.167       0.0000       0.467
Vehicle Mach Number, Velocity Vo (ft/sec), Dynamic Pressure (psf), Altitude (feet)        :  0.85000      822.80       150.00       45880.
Inertial Acceleration Vo_dot, Sensed Body Axes Accelerations Ax,Ay,Az (ft/sec^2)          : -0.81        -1.14         0.0000      -32.15
Angles of Attack and Sideslip (deg), alpha, beta rates (deg/sec)                          :  2.0          0.0          1.76         0.0000
Vehicle Attitude Euler Angles, Phi_o,Thet_o,Psi_o (deg), Body Rates Po,Qo,Ro (deg/sec)    : -0.16079      2.0000       0.0000       0.0000       0.0000
Wind Gust Vel wrt Vehi (Azim & Elev) angles (deg), or Force(lb), Torque(ft-lb), locat:xyz:  Gust         45.0         90.0
Surface Reference Area (feet^2), Mean Aerodynamic Chord (ft), Wing Span in (feet)         :  79.069       6.1170       14.910
Aero Moment Reference Center (Xmrc,Ymrc,Zmrc) Location in (ft), {Partial_rho/ Partial_H} : -14.792       0.0000       0.54000      0.0000
Aero Force Coef/Deriv (1/deg), Along -X, {Cao,Ca_alf,PCa/PV,PCa/Ph,Ca_alfdot,Ca_q,Ca_bet}: 0.143,       -0.0039,      0.0004, 0.0,     0.0,        -0.244,      0.0
Aero Force Coeffic/Derivat (1/deg), Along Y, {Cyo,Cy_bet,Cy_r,Cy_alf,Cy_p,Cy_betdot,Cy_V}: 0.0,         -0.0245,      1.77,   0.0,     0.00838, 0.0,        0.0
Aero Force Coeff/Deriv (1/deg), Along Z, {Czo,Cz_alf,Cz_q,Cz_bet,PCz/Ph,Cz_alfdot,PCz/PV}: -0.14,       -0.073,      -9.93,   0.0,     0.0,         0.0,        0.00093
Aero Moment Coeffic/Derivat (1/deg), Roll: {Clo, Cl_beta, Cl_betdot, Cl_p, Cl_r, Cl_alfa}: 0.0,         -0.00212,     0.0,   -0.393,   0.427,       0.0
Aero Moment Coeff/Deriv (1/deg), Pitch: {Cmo,Cm_alfa,Cm_alfdot,Cm_bet,Cm_q,PCm/PV,PCm/Ph}: -0.0838,     -0.015,       0.0,    0.0,    -12.83,       0.0004, 0.0
Aero Moment Coeffic/Derivat (1/deg), Yaw : {Cno, Cn_beta, Cn_betdot, Cn_p, Cn_r, Cn_alfa}: 0.0,          0.001,       0.0,    0.184, -1.49,        0.0


Number of Control Surfaces, With or No TWD (Tail-Wags-Dog and Hinge Moment Dynamics) ?   :  5    NO TWD

Control Surface No:  1                                                    Left Flap
Trim Angle, Max/Min Deflection Angles from Trim, Hinge Line Angles: phi_h, lamda_h  (deg): 0.0          30.000      -30.000       +2.0000      0.000
Surface Mass, Inertia about Hinge, Moment Arm (Hinge to Surface CG), Surface Chord, Area : 1.185        0.2867       0.283        1.2070       5.5530
Hinge Moment Derivatives (1/deg), { Chm_Alpha, Chm_Beta, Chm_Delta, Chm_Mach }          : -0.0047      -0.00055     -0.0097       0.0000
Location of the Hinge Line Center with respect to Vehicle Reference (feet), {Xcs,Ycs,Zcs}: -18.7        -2.64        2.0733
Forces (-x,y,z) due to Deflect. and Rates {Ca_del,Cy_del,Cz_del, Ca_deld,Cy_deld,Cz_deld}: 0.45432E-03 -0.24668E-02 -0.60478E-02  0.0000       0.0000
Moments due to Deflections and Rates {Cl_del,Cm_del,Cn_del,Cl_deldot,Cm_deldot,Cn_deldot}: 0.11893E-02 -0.26625E-02  0.81515E-03  0.0000       0.0000
Control Surface No:  2                                                    Right Flap
Trim Angle, Max/Min Deflection Angles from Trim, Hinge Line Angles: phi_cs,lamda_cs (deg): 0.0          30.000      -30.000      -2.0000       0.000
Surface Mass, Inertia about Hinge, Moment Arm (Hinge to Surface CG), Surface Chord, Area : 1.185        0.2867       0.283        1.2070       5.5530
Hinge Moment Derivatives (1/deg), { Chm_Alpha, Chm_Beta, Chm_Delta, Chm_Mach }          : -0.0047       0.00055     -0.0097       0.0000
Location of the Hinge Line Center with respect to Vehicle Reference (feet), {Xcs,Ycs,Zcs}: -18.7         2.64        2.0733
Forces (-x,y,z) due to Deflect. and Rates {Ca_del,Cy_del,Cz_del, Ca_deld,Cy_deld,Cz_deld}: 0.45432E-03  0.24668E-02 -0.60478E-02  0.0000       0.0000
Moments due to Deflections and Rates {Cl_del,Cm_del,Cn_del,Cl_deldot,Cm_deldot,Cn_deldot}: -0.11893E-02 -0.26625E-02 -0.81515E-03  0.0000       0.0000
Control Surface No:  3                                                    Left Rudder
Trim Angle, Max/Min Deflection Angles from Trim, Hinge Line Angles: phi_cs,lamda_cs (deg): -1.2         30.000      -30.000       48.000       0.000
Surface Mass, Inertia about Hinge, Moment Arm (Hinge to Surface CG), Surface Chord, Area : 2.19         3.914        0.833        2.2830       10.382
Hinge Moment Derivatives (1/deg), { Chm_Alpha, Chm_Beta, Chm_Delta, Chm_Mach }          : -0.019        0.0229      -0.0236       0.0000
Location of the Hinge Line Center with respect to Vehicle Reference (feet), {Xcs,Ycs,Zcs}: -25.3333     -3.395       -1.6242
Forces (-x,y,z) due to Deflect. and Rates {Ca_del,Cy_del,Cz_del, Ca_deld,Cy_deld,Cz_deld}: 0.46197E-03  0.47413E-02 -0.51664E-02  0.0000       0.0000
Moments due to Deflections and Rates {Cl_del,Cm_del,Cn_del,Cl_deldot,Cm_deldot,Cn_deldot}: 0.17964E-02 -0.98720E-02 -0.35668E-02  0.0000       0.0000
Control Surface No:  4                                                    Right Rudder
Trim Angle, Max/Min Deflection Angles from Trim, Hinge Line Angles: phi_cs,lamda_cs (deg): -1.2         30.000      -30.000      -48.000       0.000
Surface Mass, Inertia about Hinge, Moment Arm (Hinge to Surface CG), Surface Chord, Area : 2.19         3.914        0.833        2.2830       10.382
Hinge Moment Derivatives (1/deg), { Chm_Alpha, Chm_Beta, Chm_Delta, Chm_Mach }          : -0.019       -0.0229      -0.0236       0.0000
Location of the Hinge Line Center with respect to Vehicle Reference (feet), {Xcs,Ycs,Zcs}: -25.3333      3.395       -1.6242
Forces (-x,y,z) due to Deflect. and Rates {Ca_del,Cy_del,Cz_del, Ca_deld,Cy_deld,Cz_deld}: 0.46197E-03 -0.47413E-02 -0.51664E-02  0.0000       0.0000
Moments due to Deflections and Rates {Cl_del,Cm_del,Cn_del,Cl_deldot,Cm_deldot,Cn_deldot}: -0.17964E-02 -0.98720E-02  0.35668E-02  0.0000       0.0000
Control Surface No:  5                                                    Body Flap
Trim Angle, Max/Min Deflection Angles from Trim, Hinge Line Angles: phi_cs,lamda_cs (deg): -10.0        40.000      -40.000       0.0000       0.0000
Surface Mass, Inertia about Hinge, Moment Arm (hinge to surface CG), Surface Chord & Area: 1.8          2.2          0.6          1.6670       5.7430
Hinge Moment Derivatives (1/deg), { Chm_Alpha, Chm_Beta, Chm_Delta, Chm_Mach }          : -0.1e-03      0.0000      -0.10E-03     0.0000
Location of the Hinge Line Center with respect to Vehicle Reference (feet), {Xcs,Ycs,Zcs}: -25.8        0.0000       0.80000
Forces (-x,y,z) due to Deflect. and Rates {Ca_del,Cy_del,Cz_del, Ca_deld,Cy_deld,Cz_deld}: -0.83830E-05 0.0000      -0.59235E-03  0.0000       0.0000
Moments due to Deflections and Rates {Cl_del,Cm_del,Cn_del,Cl_deldot,Cm_deldot,Cn_deldot}: 0.0000       -0.15765E-02  0.0000       0.0000       0.0000


Number of Thruster Engines, Include or Not the Tail-Wags-Dog and Load-Torque Dynamics ?  :  1    NO TWD

TVC Engine No:  1                                (Gimbaling  Throttling  Single_Gimbal) : Engine Throtl    Throttling
Engine Nominal Thrust, and Maximum Thrust in (lb)    (for throttling)                    :  2000.0       4000.0
Mounting Angles wrt Vehicle (Dyn,Dzn), Maximum Deflections from Mount (Dymax,Dzmax) (deg): -1.3          0.0          0.0          0.0
Eng Mass (slug), Inertia about Gimbal (lb-sec^2-ft), Moment Arm, engine CG to gimbal (ft):  2.00         65.0         0.8
Gimbal location with respect to the Vehicle Reference Axes, Xgimb, Ygimb, Zgimb, in (ft) : -26.5         0.0          0.0
-----------------------------------------------------------------------------------------------------------------------------------------
```

The vehicle system "*Rocket Plane at Mach=0.85, Q=150, Rigid Body (for computing the lateral mixing matrix Kmix*)" is used to create the LQR design system and the mixing logic matrix Kmix. The mixing logic program processes the dataset title: "*Lateral axes Mixing Matrix for Rocket-Plane, Kmix",* which includes only four aerosurfaces, to calculate the (4x2) lateral mixing-logic matrix "Kmix" that converts the roll and yaw flight control demands δP and δR to 4 aerosurface deflection commands. The matrix Kmix has only two control inputs: the roll acceleration (p-dot), and the yaw acceleration (r-dot) which are the two directions to be decoupled by the mixing logic matrix.

A systems modification dataset is used to create two lateral systems by extracting the lateral variables from the original vehicle system: (a) the "*Lateral Design Model*" for the LQR design. It includes only the four control-surfaces (2-flaps and 2-rudders) and 3 states: roll and yaw body rates, and sideslip beta. The output is equal to the states, C=I, and (b) the lateral analysis system "*Rocket Plane at Mach=0.85, Q=150, Rigid Body, Lateral Axes*" by extracting the lateral states and outputs from the original system. The lateral design model is further augmented with one additional state, p-integral, because we want to control the bank angle. The systems combination dataset "*Lateral Design Model with p-Integral (4-states)"* introduces p-integral and pre-multiplies the system with matrix Kmix to decouple roll and yaw and to reduce the number of inputs to two: roll and yaw control demands. The final LQR design system is "*Lateral Design Model with p-Integral (4-states)*".

Rocket Plane at Mach=0.85, Q=150, Rigid Body (for computing the lateral mixing matrix K mix)
! The following vehicle model is a rigid body rocket plane. It has four control surfaces,
! 2 flaps, and 2 rudders. It is used to calculate the lateral mixing matrix Kmix
!
Body Axes Output, Attitude=Euler Angles, Without GAFD, No Turn Coordination

```
Vehicle Mass (lb-sec^2/ft), Gravity Accelerat. (g) (ft/sec^2), Earth Radius (Re) (ft)    : 198.32      32.17       0.20896E+08
Moments and products of Inertias Ixx, Iyy, Izz, Ixy, Ixz, Iyz, in (lb-sec^2-ft)          : 1098.0     10933.      11290.       0.0000      123.75
CG location with respect to the Vehicle Reference Point, Xcg, Ycg, Zcg, in (feet)        : -15.167     0.0000      0.467
Vehicle Mach Number, Velocity Vo (ft/sec), Dynamic Pressure (psf), Altitude (feet)       : 0.85000     822.80      150.00       45880.
Inertial Acceleration Vo_dot, Sensed Body Axes Accelerations Ax,Ay,Az (ft/sec^2)         : -0.81      -1.14        0.0000      -32.15
Angles of Attack and Sideslip (deg), alpha, beta rates (deg/sec)                          : 2.0        0.0         1.76         0.0000
Vehicle Attitude Euler Angles, Phi_o,Thet_o,Psi_o (deg), Body Rates Po,Qo,Ro (deg/sec)   : -0.16079    2.0000      0.0000       0.0000      0.0000
Wind Gust Vel wrt Vehi (Azim & Elev) angles (deg), or Force(lb), Torque(ft-lb), locat:xyz: Gust       45.0        90.0
Surface Reference Area (feet^2), Mean Aerodynamic Chord (ft), Wing Span in (feet)        : 79.069      6.1170      14.910
Aero Moment Reference Center (Xmrc,Ymrc,Zmrc) Location in (ft), {Partial_rho/ Partial_H} : -14.792     0.0000      0.54000      0.0000
Aero Force Coef/Deriv (1/deg), Along -X, {Cao,Ca_alf,PCa/PV,PCa/Ph,Ca_alfdot,Ca_q,Ca_bet}: 0.143,  -0.0039,   0.0004, 0.0,      0.0,     -0.244,  0.0
Aero Force Coeffic/Derivat (1/deg), Along Y, {Cyo,Cy_bet,Cy_r,Cy_alf,Cy_p,Cy_betdot,Cy_V}: 0.0,    -0.0245,   1.77,   0.0,      0.00838, 0.0,    0.0
Aero Force Coeff/Deriv (1/deg), Along Z, {Czo,Cz_alf,Cz_q,Cz_bet,PCz/Ph,Cz_alfdot,PCz/PV}: -0.14,  -0.073,   -9.93,   0.0,      0.0,     0.0,    0.00093
Aero Moment Coeffic/Derivat (1/deg), Roll: {Clo, Cl_beta, Cl_betdot, Cl_p, Cl_r, Cl_alfa}: 0.0,    -0.00212,  0.0,   -0.393,    0.427,   0.0
Aero Moment Coeff/Deriv (1/deg), Pitch: {Cmo,Cm_alfa, Cm_alfdot,Cm_bet,PCm/PV,PCm/Ph}: -0.0838, -0.015,   0.0,    0.0,     -12.83,   0.0004, 0.0
Aero Moment Coeffic/Derivat (1/deg), Yaw : {Cno, Cn_beta, Cn_betdot, Cn_p, Cn_r, Cn_alfa}: 0.0,     0.001,    0.0,    0.184, -1.49,    0.0


Number of Control Surfaces, With or No TWD (Tail-Wags-Dog and Hinge Moment Dynamics) ?   :  4   NO TWD


Control Surface No:  1                                                                    Left Flap
Trim Angle, Max/Min Deflection Angles from Trim, Hinge Line Angles: phi_h, lamda_h  (deg): 0.0        30.000      -30.000      +2.0000     0.000
Surface Mass, Inertia about Hinge, Moment Arm (Hinge to Surface CG), Surface Chord, Area : 1.185      0.2867      0.283        1.2070      5.5530
Hinge Moment Derivatives (1/deg), { Chm_Alpha, Chm_Beta, Chm_Delta, Chm_Mach }           : -0.0047   -0.00055    -0.0097       0.0000
Location of the Hinge Line Center with respect to Vehicle Reference (feet), {Xcs,Ycs,Zcs}: -18.7     -2.64        2.0733
Forces (-x,y,z) due to Deflect. and Rates {Ca_del,Cy_del,Cz_del, Ca_deld,Cy_deld,Cz_deld}: 0.45432E-03 -0.24668E-02 -0.60478E-02  0.0000      0.0000      0.0000
Moments due to Deflections and Rates {Cl_del,Cm_del,Cn_del,Cl_deldot,Cm_deldot,Cn_deldot}: 0.11893E-02 -0.26625E-02  0.81515E-03  0.0000      0.0000      0.0000
Control Surface No:  2                                                                    Right Flap
Trim Angle, Max/Min Deflection Angles from Trim, Hinge Line Angles: phi_cs,lamda_cs (deg): 0.0        30.000      -30.000      -2.0000     0.000
Surface Mass, Inertia about Hinge, Moment Arm (Hinge to Surface CG), Surface Chord, Area : 1.185      0.2867      0.283        1.2070      5.5530
Hinge Moment Derivatives (1/deg), { Chm_Alpha, Chm_Beta, Chm_Delta, Chm_Mach }           : -0.0047    0.00055    -0.0097       0.0000
Location of the Hinge Line Center with respect to Vehicle Reference (feet), {Xcs,Ycs,Zcs}: -18.7      2.64        2.0733
Forces (-x,y,z) due to Deflect. and Rates {Ca_del,Cy_del,Cz_del, Ca_deld,Cy_deld,Cz_deld}: 0.45432E-03 0.24668E-02 -0.60478E-02  0.0000      0.0000      0.0000
Moments due to Deflections and Rates {Cl_del,Cm_del,Cn_del,Cl_deldot,Cm_deldot,Cn_deldot}: -0.11893E-02 -0.26625E-02 -0.81515E-03  0.0000      0.0000      0.0000
Control Surface No:  3                                                                    Left Rudder
Trim Angle, Max/Min Deflection Angles from Trim, Hinge Line Angles: phi_cs,lamda_cs (deg): -1.2       30.000      -30.000      48.000      0.000
Surface Mass, Inertia about Hinge, Moment Arm (Hinge to Surface CG), Surface Chord, Area : 2.19       3.914       0.833        2.2830      10.382
Hinge Moment Derivatives (1/deg), { Chm_Alpha, Chm_Beta, Chm_Delta, Chm_Mach }           : -0.019     0.0229     -0.0236       0.0000
Location of the Hinge Line Center with respect to Vehicle Reference (feet), {Xcs,Ycs,Zcs}: -25.3333  -3.395      -1.6242
Forces (-x,y,z) due to Deflect. and Rates {Ca_del,Cy_del,Cz_del, Ca_deld,Cy_deld,Cz_deld}: 0.46197E-03 0.47413E-02 -0.51664E-02  0.0000      0.0000      0.0000
Moments due to Deflections and Rates {Cl_del,Cm_del,Cn_del,Cl_deldot,Cm_deldot,Cn_deldot}: 0.17964E-02 -0.98720E-02 -0.35668E-02  0.0000      0.0000      0.0000
Control Surface No:  4                                                                    Right Rudder
Trim Angle, Max/Min Deflection Angles from Trim, Hinge Line Angles: phi_cs,lamda_cs (deg): -1.2       30.000      -30.000      -48.000     0.000
Surface Mass, Inertia about Hinge, Moment Arm (Hinge to Surface CG), Surface Chord, Area : 2.19       3.914       0.833        2.2830      10.382
Hinge Moment Derivatives (1/deg), { Chm_Alpha, Chm_Beta, Chm_Delta, Chm_Mach }           : -0.019    -0.0229     -0.0236       0.0000
Location of the Hinge Line Center with respect to Vehicle Reference (feet), {Xcs,Ycs,Zcs}: -25.3333   3.395      -1.6242
Forces (-x,y,z) due to Deflect. and Rates {Ca_del,Cy_del,Cz_del, Ca_deld,Cy_deld,Cz_deld}: 0.46197E-03 -0.47413E-02 -0.51664E-02  0.0000      0.0000      0.0000
Moments due to Deflections and Rates {Cl_del,Cm_del,Cn_del,Cl_deldot,Cm_deldot,Cn_deldot}: -0.17964E-02 -0.98720E-02  0.35668E-02  0.0000      0.0000      0.0000
```

MIXING LOGIC MATRIX DATA ....   (MATRIX TITLE, NAME, VEHICLE TITLE, CONTROL DIRECTIONS)
Lateral axes Mixing Matrix for Rocket-Plane, Kmix
! This mixing logic uses only four control surfaces for lateral (roll, yaw) control.
! It is based on a vehicle model that does not use the engine and the body-flap
!
Kmix
Rocket Plane at Mach=0.85, Q=150, Rigid Body (for computing the lateral mixing matrix K mix)
P-dot Roll Acceleration About X Axis
R-dot Yaw   Acceleration About Z Axis

SYSTEM OF TRANSFER FUNCTIONS ...
First Order Gust Lag
! A low-pass filter 0.5 (rad/sec) to smooth out the input gust
Continuous
```
TF. Block #  1 First Order Lag                                   Order of Numer, Denom=  0  1
Numer 0.0        0.5
Denom 1.0        0.5
--------------------------------------------------------------------------------
Block #, from Input #, Gain
  1  1    1.0
...........................
Outpt #, from Block #, Gain
  1  1    1.0
...........................
```

SYSTEM OF TRANSFER FUNCTIONS ...
Integrator
Continuous
```
TF. Block #  1 First Order Lag                                   Order of Numer, Denom=  0  1
Numer 0.0        1.0
Denom 1.0        0.0
--------------------------------------------------------------------------------
Block #, from Input #, Gain
  1  1    1.0
...........................
Outpt #, from Block #, Gain
  1  1    1.0
...........................
```

```
CREATE A NEW SYSTEM FROM AN OLD SYSTEM... (TITLES OF THE NEW AND OLD SYSTEMS)
Rocket Plane at Mach=0.85, Q=150, Rigid Body, Lateral Axes
Rocket Plane at Mach=0.85, Q=150, Rigid Body
! The lateral axes rigid-body model is extracted from the coupled
! rigid-body model. The states are: (phi,p, psi,r, and beta)
TRUNCATE OR REORDER THE SYSTEM INPUTS, STATES, AND OUTPUTS
Extract Inputs :    2    3    4    5    7
Extract States :    1    2    5    6    8
Extract Outputs:    1    2    5    6    8   11   13
-----------------------------------------------------------------------------
CREATE A NEW SYSTEM FROM AN OLD SYSTEM... (TITLES OF THE NEW AND OLD SYSTEMS)
Lateral Design Model
Rocket Plane at Mach=0.85, Q=150, Rigid Body
! A further simplified lateral axes system is extracted from the coupled
! rigid-body model to be used for LQR control design.
! It consists of three states: (p, r, and beta)
!
TRUNCATE OR REORDER THE SYSTEM INPUTS, STATES, AND OUTPUTS
Extract Inputs :    2    3    4    5
Extract States :    2    6    8
Extract Outputs:    2    6    8
-----------------------------------------------------------------------------
INTERCONNECTION OF SYSTEMS .....
Lateral Design Model with p-Integral (4-states)
! The Lateral Axes control design model is augmented with the integral of roll rate.
! The states for LQR design are: (p,r, beta, and p-Integral)
! The aileron/ rudder Mixing Logic matrix is included in the input
!
Titles of Systems to be Combined
Title 1 Lateral Design Model
Title 2 Integrator
SYSTEM INPUTS TO SUBSYSTEM  1
Via Matrix +Kmix                                                    aileron, rudder
.....................................................................
SYSTEM OUTPUTS FROM SUBSYSTEM  1                                    All Outputs
Via Matrix +I3
.....................................................................
SYSTEM OUTPUTS FROM SUBSYSTEM  2
System Output  4 from Subsystem  2, Output  1, Gain= 1.0           p-integral
.....................................................................
SUBSYSTEM NO  1 GOES TO SUBSYSTEM NO  2                            Vehicle Beta to Integrator
Subsystem  1, Output  1 to Subsystem  2, Input  1, Gain= 1.0      p-integral
.....................................................................
Definitions of Inputs  =    2
Aileron Deflection (rad)
Rudder Deflection (rad)

Definitions of States  =    4
Roll Rate       (p-body)   (rad/sec)
Yaw  Rate       (r-body)   (rad/sec)
Angle of sideslip, beta,   (radian)
p-Integral                 (rad)

Definitions of Outputs =    4
Roll Rate       (p-body)   (rad/sec)
Yaw  Rate       (r-body)   (rad/sec)
Angle of sideslip, beta,   (radian)
p-Integral                 (rad)
-----------------------------------------------------------------------------
```

The LQR state-feedback dataset "*Lateral LQR Control Design*" is included in the input file. It uses the design system "*Lateral Design Model with p-Integral (4-states)*" to calculate the 2x4 state-feedback gain matrix Kpr. The gain matrix is saved in the systems file and its title is "*LQR State-Feedback Control for Lateral Axes*". The state and control penalizing matrices Qc4 and Rc2 for the lateral LQR design are read from the systems file and they are permanently saved there. The vehicle systems, the mixing logic and the state-feedback gains are converted to Matlab format (Kmix & Kpr).

```
LINEAR QUADRATIC REGULATOR STATE-FEEDBACK CONTROL DESIGN
Lateral LQR Control Design
Plant Model Used to Design the Control System from:        Lateral Design Model with p-Integral (4-states)
Criteria Optimization Output is Matrix C
State Penalty Weight (Qc) is Matrix:    Qc4              State Penalty Matrix Qc4
Control Penalty Weight (Rc) is Matrix: Rc2               Control Penalty Matrix Rc2
Continuous LQR Solution Using Laub Method
LQR State-Feedback Control Gain Matrix Kpr               LQR State-Feedback Control for Lateral Axis
-------------------------------------------------------------------------------------------------------------
CONVERT TO MATLAB FORMAT ........        (TITLE, SYSTEM/MATRIX, M-FILENAME)
Rocket Plane at Mach=0.85, Q=150, Rigid Body
System
Vehi_Coupled_rb.m
-------------------------------------------------------------------------------------------------------------
CONVERT TO MATLAB FORMAT ........        (TITLE, SYSTEM/MATRIX, M-FILENAME)
Rocket Plane at Mach=0.85, Q=150, Rigid Body, Lateral Axes
System
Vehi_rblat.m
-------------------------------------------------------------------------------------------------------------
CONVERT TO MATLAB FORMAT ........        (TITLE, SYSTEM/MATRIX, M-FILENAME)
Lateral Design Model with p-Integral (4-states)
System
Vehi_Lat_4x.m
-------------------------------------------------------------------------------------------------------------
CONVERT TO MATLAB FORMAT ........        (TITLE, SYSTEM/MATRIX, M-FILENAME)
Lateral axes Mixing Matrix for Rocket-Plane, Kmix
Matrix Kmix
-------------------------------------------------------------------------------------------------------------
CONVERT TO MATLAB FORMAT ........        (TITLE, SYSTEM/MATRIX, M-FILENAME)
LQR State-Feedback Control for Lateral Axis
Matrix Kpr
-------------------------------------------------------------------------------------------------------------
```

Processing the Input File in Batch Mode

We will now process the input file in batch mode to extract the lateral systems and design the LQR control gain. Start the Flixan program, select the lateral design folder "*2-Lateral Design*", and from the top menu select "*File Management*", "*Managing Input Files*", and then "*Edit/ Process Input Files*", as shown. The input file manager utility comes up and from the left menu select the input file "*Rocket_Later_RB.Inp*" and click on "Select Input File" button. The right menu shows all the datasets which are in the input file. Select the batch set "*Batch Set for Creating Rigid-Body Models for the Rocket-Plane*" and click on "*Process Input Data*" to process the entire file. The data are saved in the systems file and Matlab files. Batch processing is a lot faster way to create the dynamic systems in comparison with the interactive processing. A detailed description of the interactive vehicle modeling, mixing logic, and LQR control design processes will be given in Section 1.3.
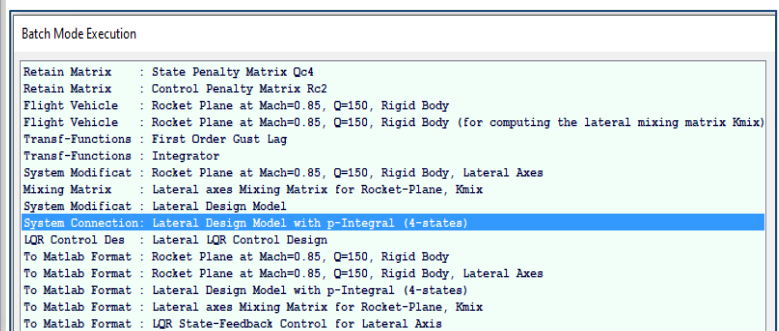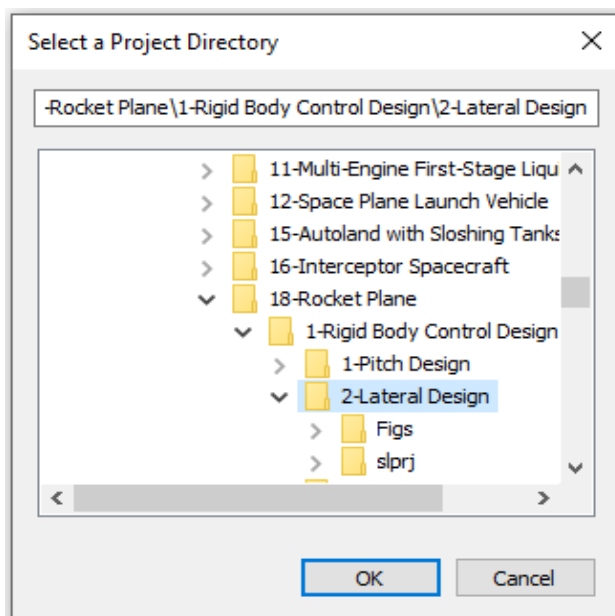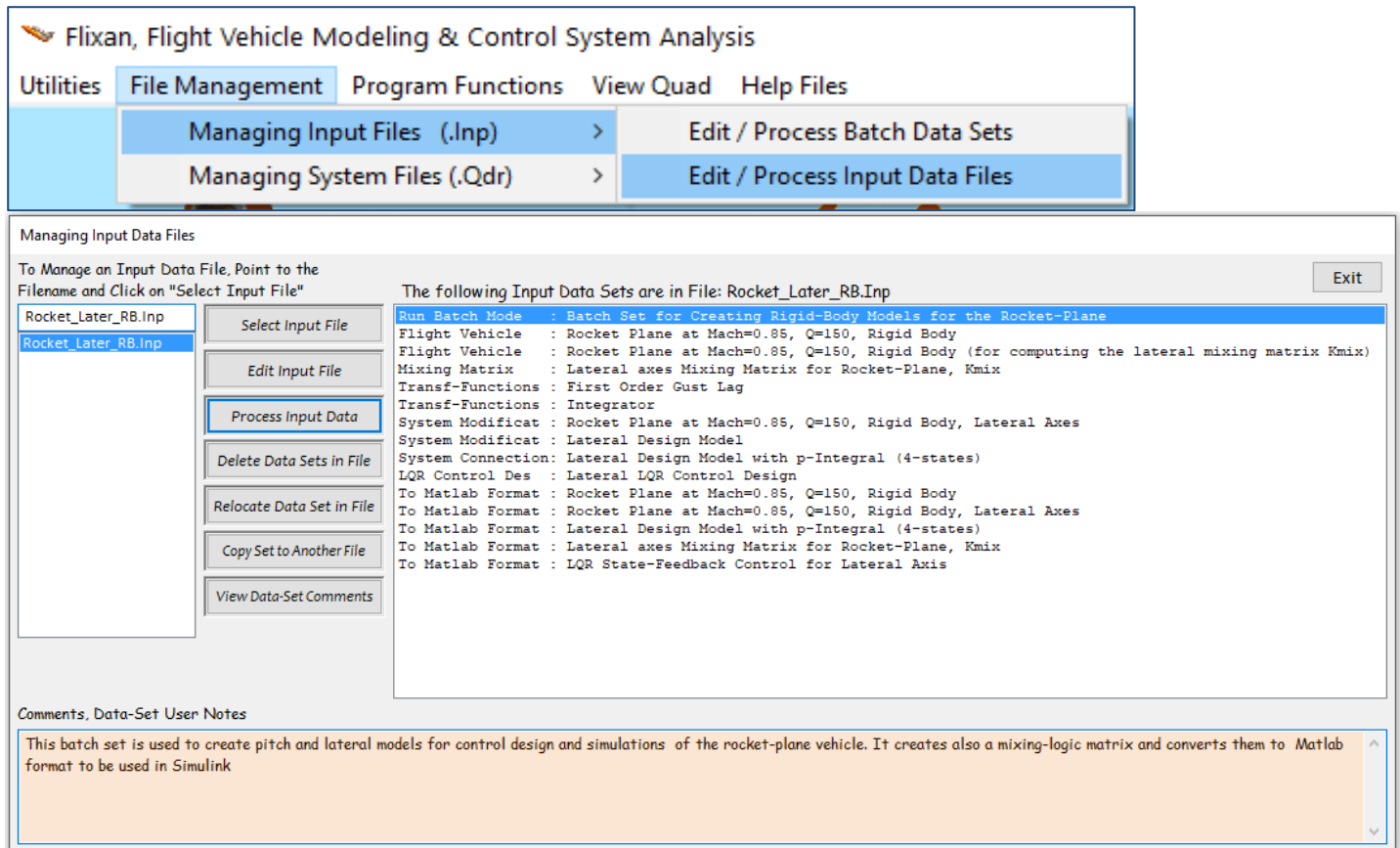
Lateral Control System Simulation Model

Figure 1.10 shows the Simulink model " *Closed_Later.slx*" in folder "*2-Lateral Design*" used for lateral closed-loop simulations. It consists of two control loops: the aileron loop that controls the vehicle in roll and the rudder loop that controls the yaw axis. The lateral vehicle block, in Figure 1.11, includes the system "*Rocket Plane at Mach=0.85, Q=150, Rigid Body, Lateral Axes*" from file "*vehi_rblat.m*" and it does not include the mixing matrix. The control system produces roll and yaw control demands (δ_P and δ_R) which are converted to 2-flap and 2-V-tail deflections by the mixing logic matrix Kmix which is included in the input of the lateral vehicle model. It reduces the number of vehicle inputs from four aerosurfaces to two controls. It also attempts to decouple the roll and yaw axes by minimizing interaction between the two loops and producing the commanded accelerations, open-loop.

A beta-estimator is used replace β-feedback with an estimated $\hat{\beta}$ calculated from the lateral accelerometer signal $\ddot{y}$. Two 2nd order actuator subsystems of bandwidth 50 (rad/sec) are also included in the vehicle block. The command input is roll ϕ_{cmd} in (deg). There is also a wind-gust input disturbance impulse of velocity 50 (ft/sec). A low-pass filter is included to shape the wind-gust impulse. The LQR state-feedback controller Kpr converts the roll and yaw rates (p, r), the angle of sideslip (β) and the roll angle error (ϕ_e) to roll and yaw control demands. The bank angle will be later used to control the heading direction. The parameters are initialized by running the file "init.m" which loads the systems, matrices, actuator, estimator parameters and calculates the control gains. The simulation calculates the response of the lateral system to phi-commands and to lateral wind-gust disturbances. The pink outputs are saving the simulation data in the Matlab workspace and plotting them using the script m-file "pl.m".
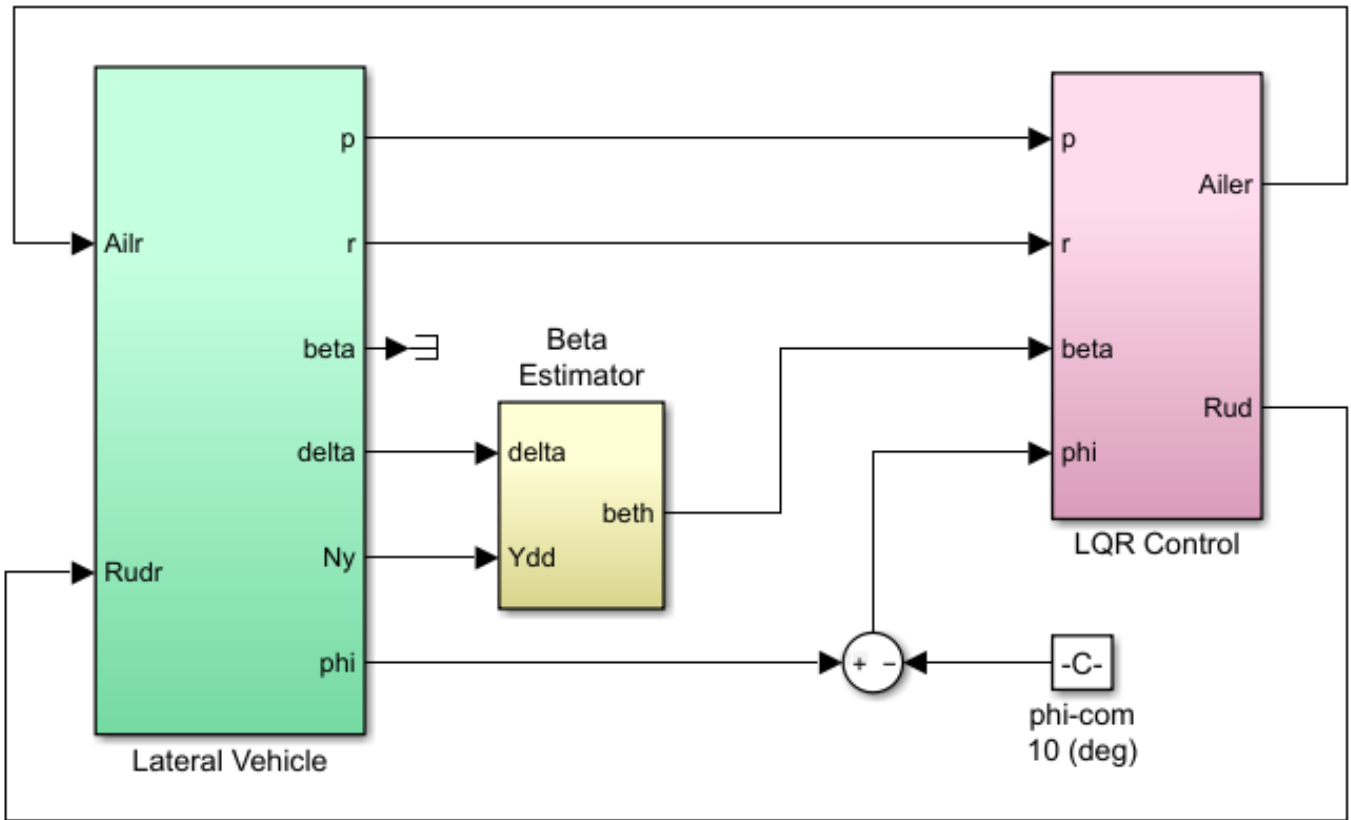
Figure 1.10 Lateral Closed-Loop Simulation Model "Closed_Later.slx"
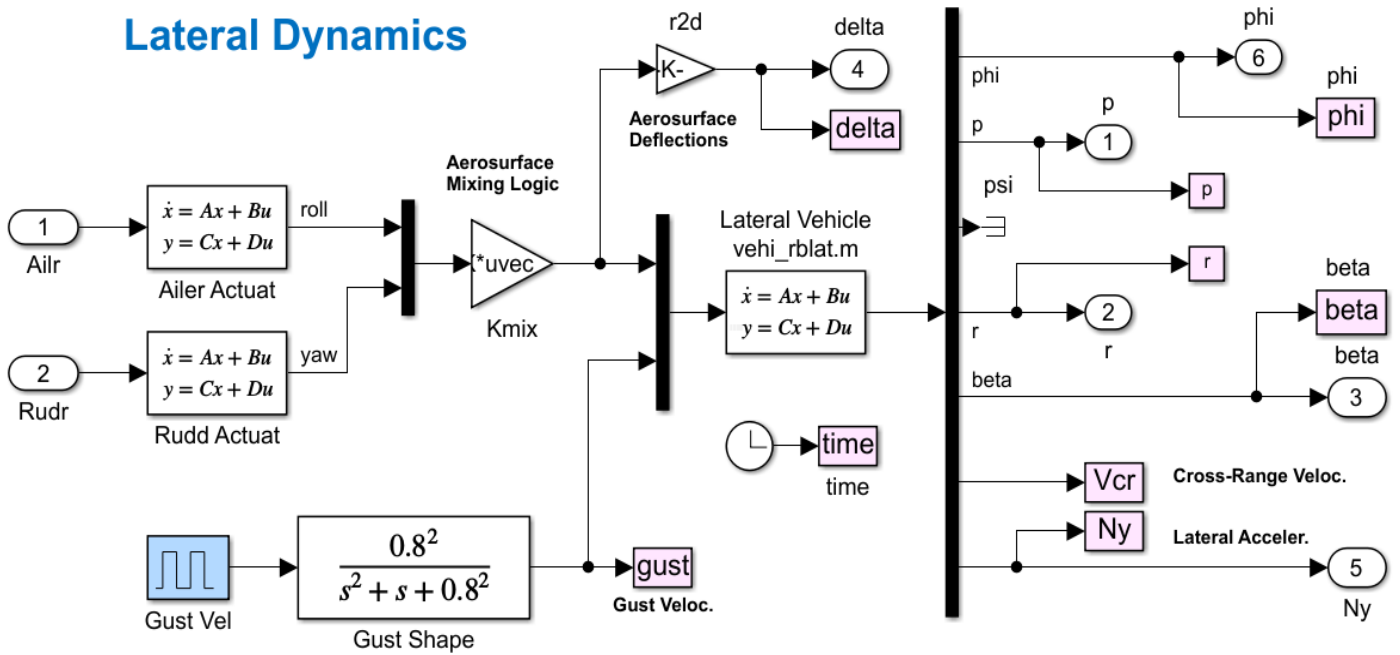
Figure 1.11 Lateral Vehicle Dynamics Block in Detail
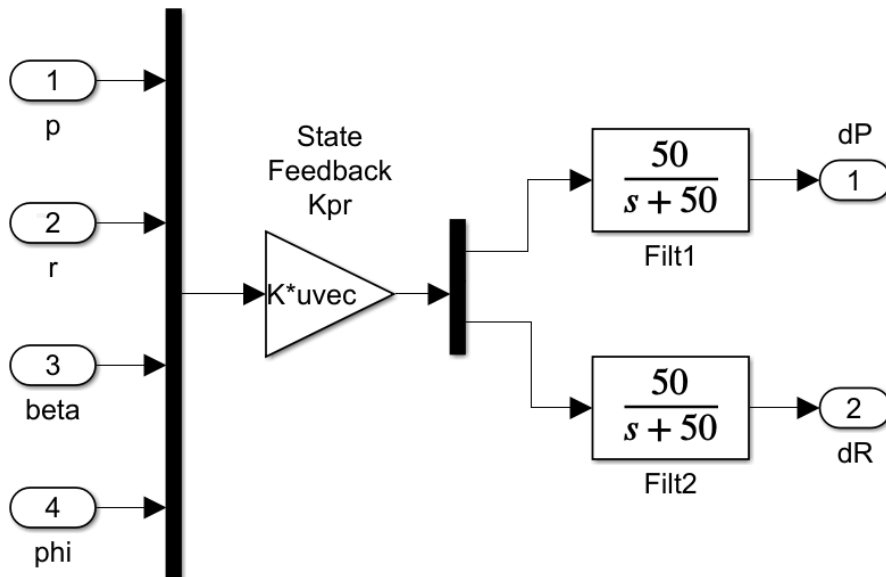
Figure 1.12 Lateral State-Feedback Controller
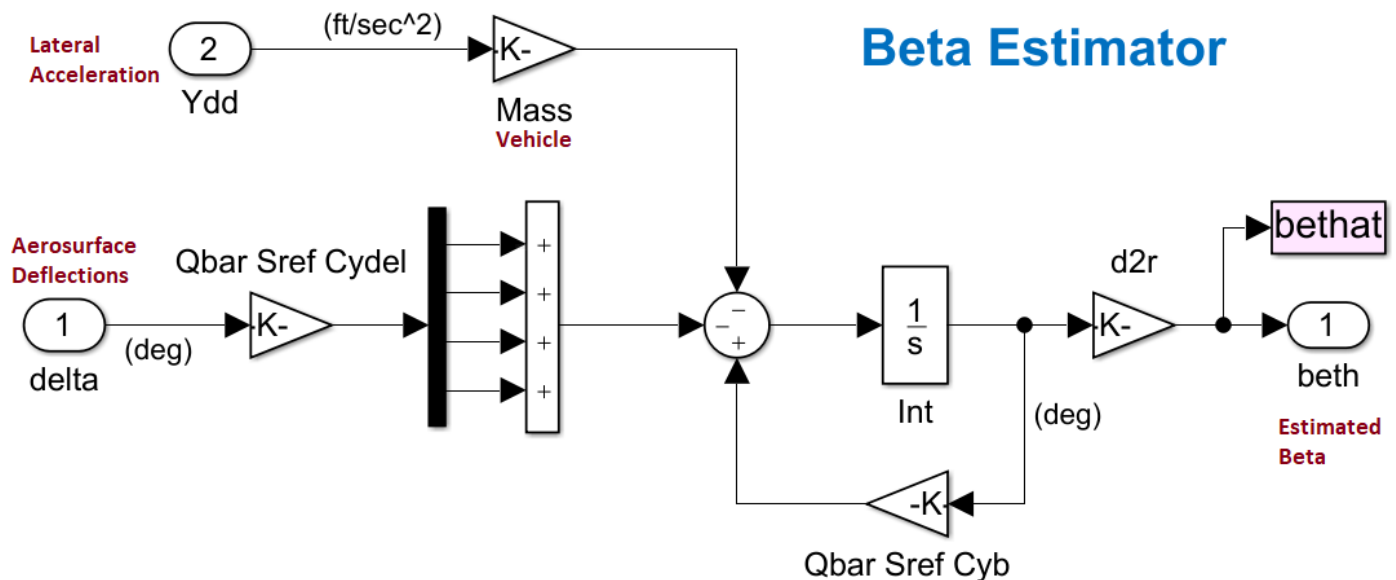
Figure 1.13 Beta Estimator Estimates Beta from the Lateral Accelerometer and the Aerosurface Deflections

The Angle of Sideslip Estimator

The LQR controller assumes that the inputs are from the roll and yaw rates (p, r), β and p-integral. The sideslip β state, however, is not measurable and we will use an estimator to estimate it from the lateral acceleration Ny and the aerosurface forces. The estimator is shown in Figure 1.13 and it solves the lateral force equation in real-time. The inputs are lateral acceleration and deflections of the four aerosurfaces. The output is the estimated β and it will converge to the real sideslip angle β_{wind} when the vehicle aerodynamic coefficients are reasonably known. The estimated β will replace the actual vehicle β as shown in Figure 1.10. The estimator parameters (dynamic pressure, vehicle mass, and aero coefficients) are loaded into Matlab from the initialization file.

The LQR Design System

The system used for LQR design is "Lateral Design Model with p-Integral (4-states)", shown in Figure 1.14. It consists of the "Lateral Design Model", the p-integral and the mixing logic matrix Kmix.
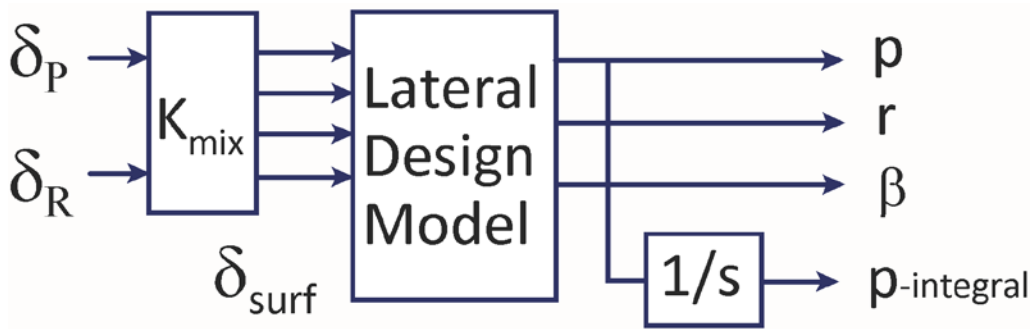
Figure 1.14 Lateral Design Model with p-Integral (4-states)

Lateral Simulation Results

Figures 1.15 show the lateral system's response to a 10° roll step attitude command followed by a wind-gust disturbance of 45 (ft/sec) in the lateral direction which occurs 5 seconds after the attitude command. The vehicle is using mostly asymmetric flap deflections to perform the roll maneuver and to counteract the wind-gust. The roll angle responds fast and it is tracking the command. There is a small transient occurring due to the wind-gust. The estimated beta is almost identical to the actual beta angle. The side acceleration (Ny) in (ft/sec²) is almost asymmetric to beta.
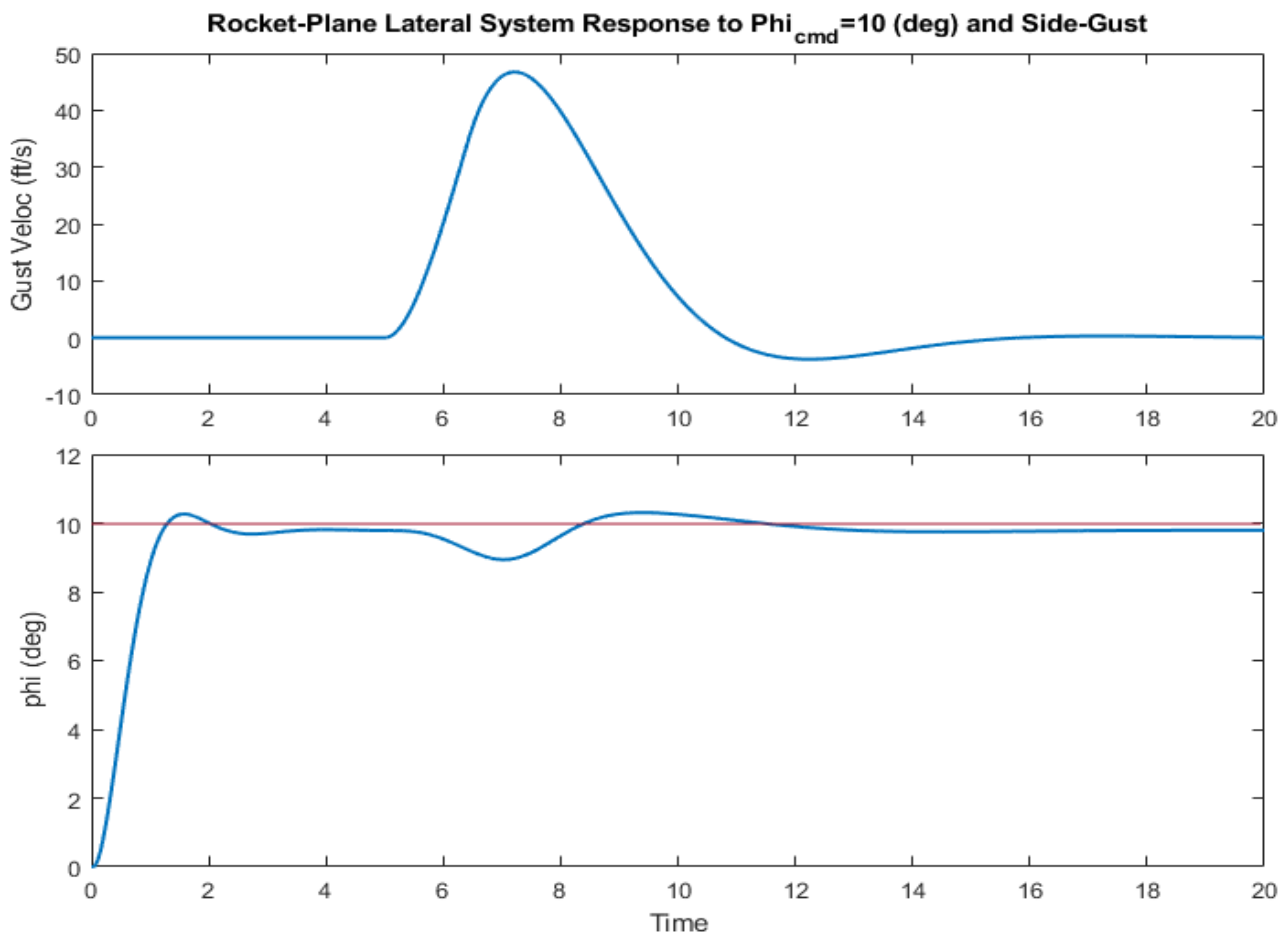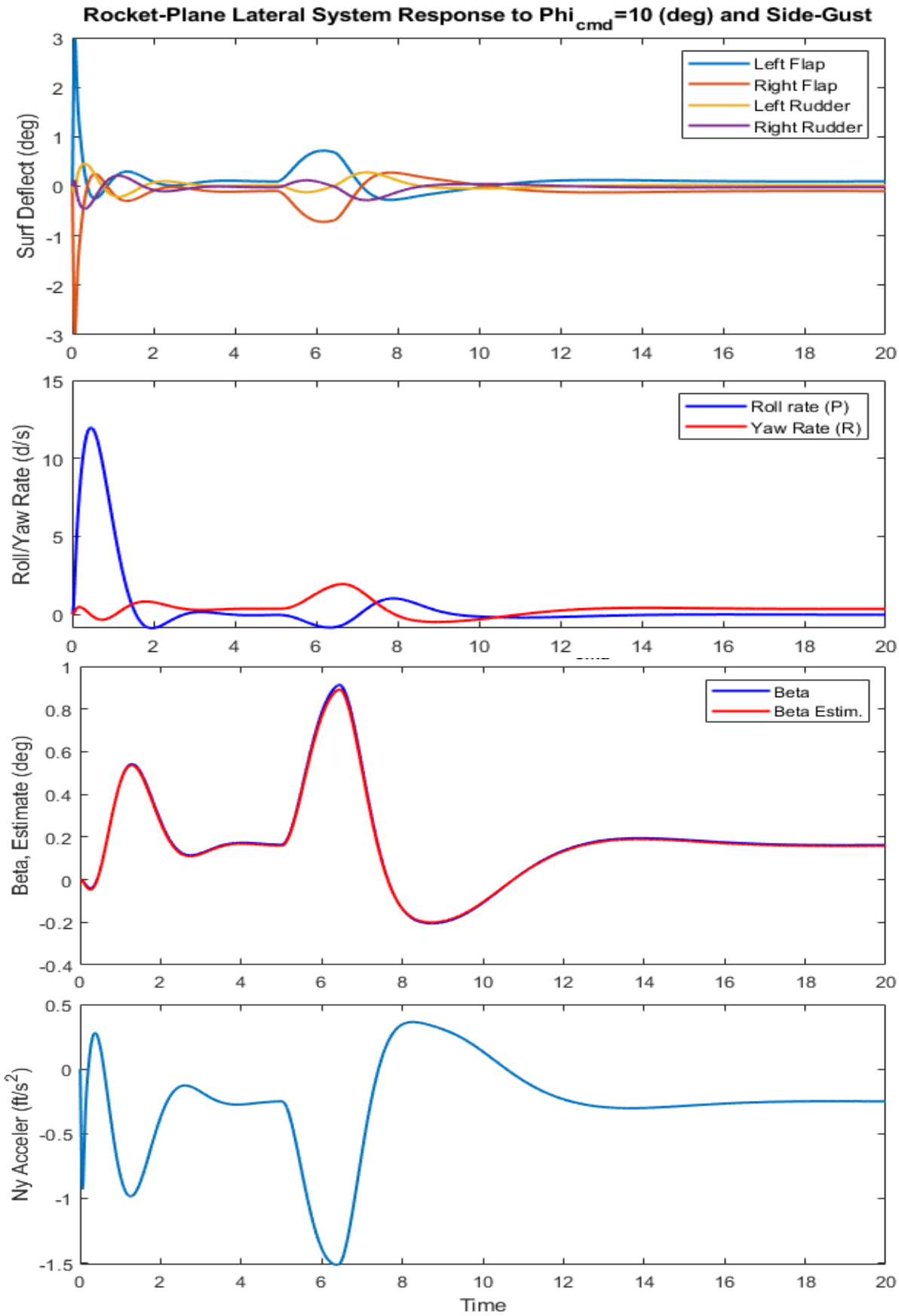
Figure 1.15 Lateral Vehicle Response to the Roll Attitude Command

Lateral System Stability Analysis

The Simulink model: "*Open_Later.slx*", in Figure 1.16 is used to analyze lateral axes stability. It consists of the same subsystems as in the lateral simulation model with two control loops: roll and yaw loops. The Matlab file "frequ.m" calculates the frequency response of this open-loop system and plots the Bode and Nichols plots that show the system's stability margins. The Bode and Nichols plots in Figures 1.17 and 1.18 show that the system has excellent phase and gain margins and a cross-over frequency of 3.76 (rad/sec).
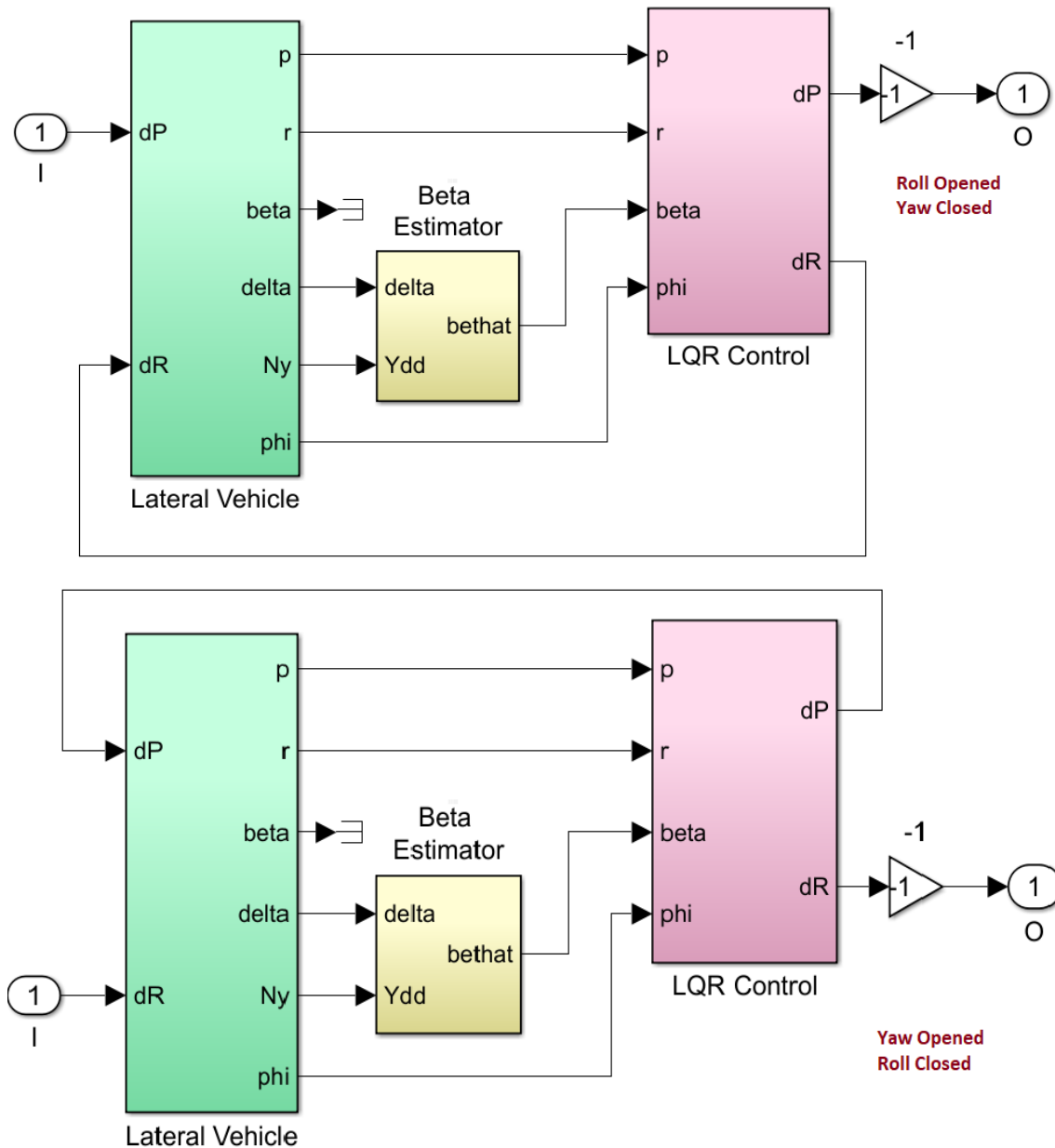
Figure 1.16 Simulink Model "Open_Later.slx" Used for Lateral Frequency Response Stability Analysis

1.5 Interactive Processing of the Lateral Vehicle Data

We will now process the input file "Rocket_Later_RB.Inp" interactively, one dataset at a time, beginning with the lateral vehicle model, the mixing logic matrix, the LQR design plant, the LQR design, and finally exporting the systems and matrices to Matlab.
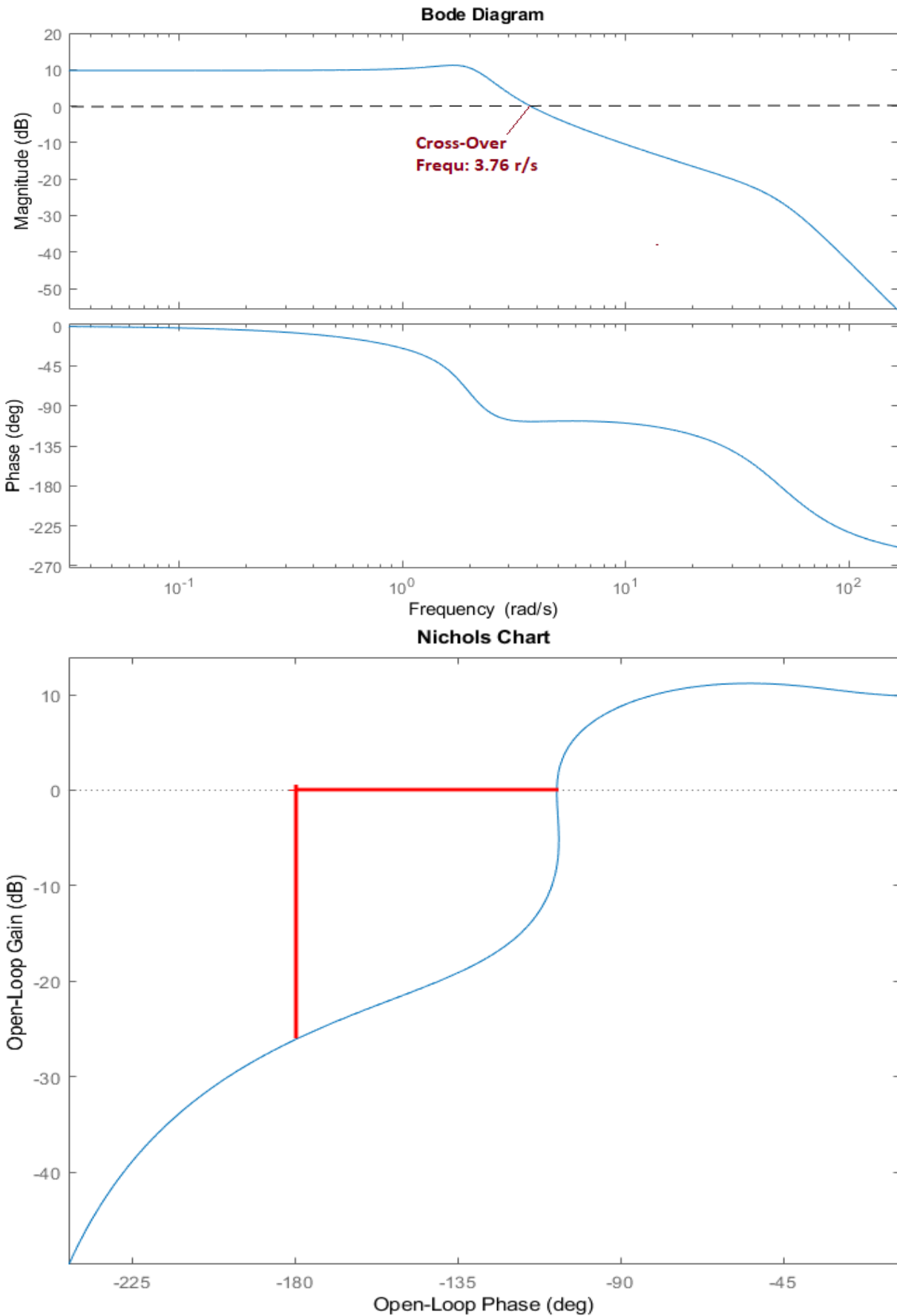
Figure 1.17 Roll Axis Bode and Nichols Plots Showing Gain and Phase Margins
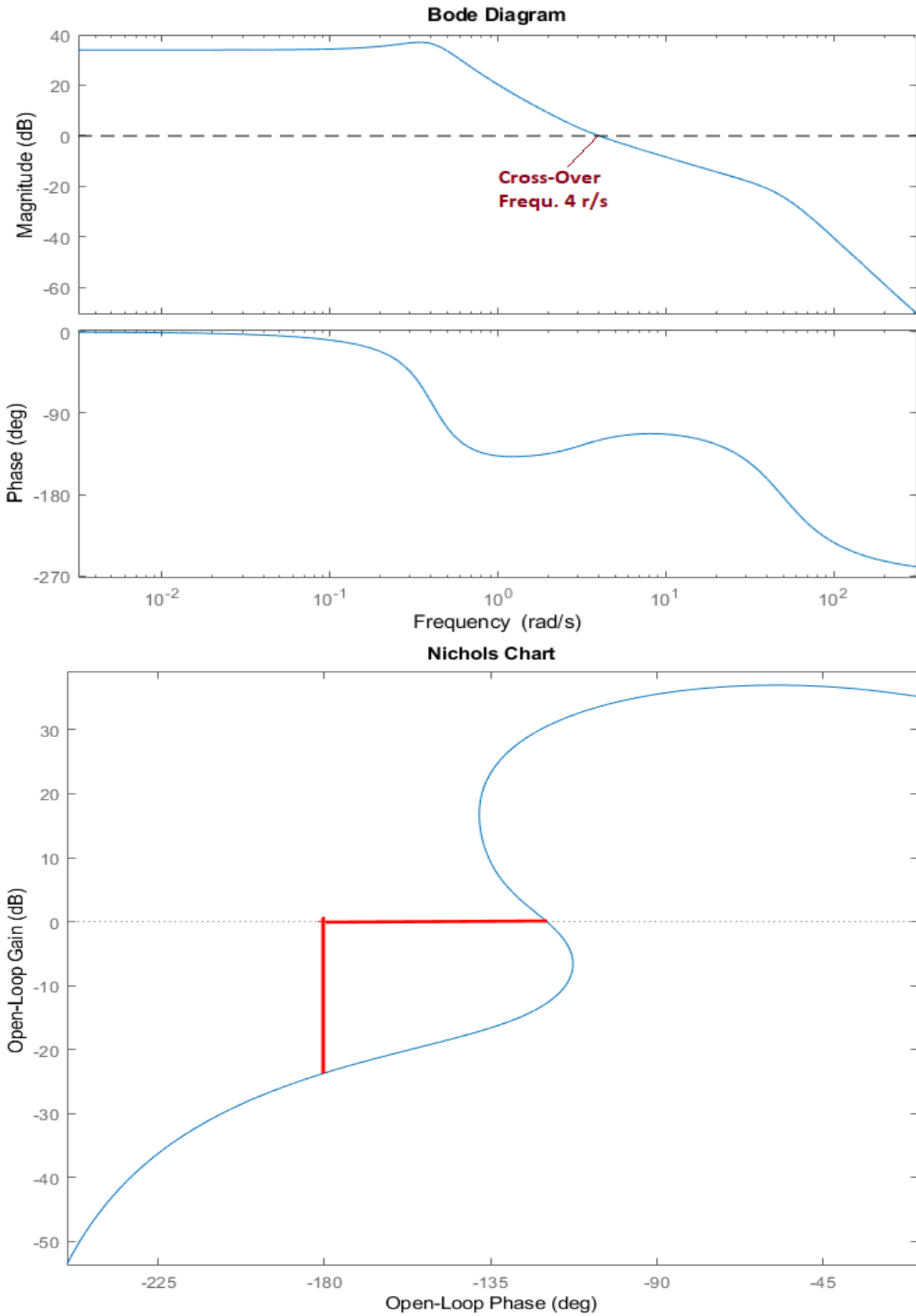
Figure 1.18 Yaw Axis Bode and Nichols Plots Showing Gain and Phase Margins

Vehicle Modeling:

The lateral input file includes two vehicle datasets. The first one is for simulation purposes and the second one is for creating the LQR design model and the mixing logic matrix Kmix. We start the Flixan program and go to directory *"Flixan\ Examples\18-Rocket Plane\1-Rigid Body Control Design\2-Lateral Design"*. From the main menu go to *"Program Functions"*, *"Flight Vehicle/ Spacecraft Modeling Tools"*, and then select *"Flight Vehicle State-Space Modeling"*. From the filename selection menu select the vehicle input and system filenames and click on *"Process Files"*. The program scans through the input data file *"Rocket_Later_RB.Inp"* searching for vehicle data and it shows their titles in the following menu. Select the second vehicle data title: *"Rocket Plane at Mach=0.85, Q=150, Rigid Body (for computing the lateral mixing matrix Kmix)"*, and click on *"Run Input Set"* to process it.

Flight Vehicle Parameters

Vehicle System Title
Rocket Plane at Mach=0.85, Q=150, Rigid Body (for computing the lateral mixing matrix Kmix)

Edit Input File   Exit
Update Data   Run
Save in File

Number of Vehicle Effectors

Gimbaling Engines or Jets. Include Tail-Wags-Dog?   0   WITH TWD / WITHOUT TWD

Rotating Control Surfaces. Include Tail-Wags-Dog?   4   WITH TWD / WITHOUT TWD

Reaction Wheels?   0   **Momentum Control Devices**

Single Gimbal CMGs?   0   Include a Centralized, 3-Axes Momentum Control System?   Yes / No

Number of Sensors

Gyros   0
Accelerometers   0
Aero Probes   0
External Torques   0

Modeling Options (Flags)

Output Rates in
Body Axes
Stability Axes

Turn Coordination ?
Include Turn Coordina
Without Turn Coordin

Aero-Elasticity Options
Include GAFD, H-param
Flex Coupl. data only
Neither Gafd nor Hpar

Attitude Angles
Euler Angles
Integrals of Rates
LVLH Attitude

Number of Modes
Structure Bending   0
Propellant Sloshing: 0

Single Gimbal CMGs | Momentum Control System | Slewing Appendages | Gyros | Accelerometer | Aero Sensors | Fuel Slosh | Flex Modes | User Notes
Mass Properties | Trajectory Data | Gust/ Aero Paramet. | Aero Force Coeffs | Aero Moment Coeffs | Aero-Surfaces | Gimbal Engines/ RCS | External Torques | Reaction Wheels

This Vehicle has 4 Control Surfaces   **Control Surface No: 3 Left Rudder**   Surface Definition   Next Surface

Surface Rotation Angles
Surface Trim Position (deg)   -1.200000
Largest Positive Deflection from Trim (deg)   30.00000
Largest Negative Deflection from Trim (deg)   -30.00000

Surface Location (ft) and Hinge Orientation Angles (deg)
Xcs   -25.33330
Ycs   -3.395000   Phi_cs   48.00000
Zcs   -1.624200   Lambda_cs   0.000000

Control Surface Mass Properties
Contol Surface Mass in (Slugs)   2.190000
Moment of Inertia about Hinge (slug-ft^2)   3.914000
Moment Arm (feet), Surface CG to Hinge   0.8330000
Control Surface Chord (feet)   2.283000
Control Surface Reference Area (ft^2)   10.38200

Aero Force Derivatives

|				
Ca_delta	0.4619700E-03	Ca_delta_dot	0.000000	Control Force Derivatives due to Surface Deflection (1/deg) and Control Force Derivatives due to Surface Rate (1/deg/sec)
Cy_delta	0.4741300E-02	Cy_delta_dot	0.000000	
Cz_delta	-0.5166400E-02	Cz_delta_dot	0.000000	

Aero Moment Derivatives

Cl_delta	0.1796400E-02	Cl_delta_dot	0.000000	Control Moment Derivatives due to Surface Deflection (1/deg) and Control Moment Derivatives due to Surface Rate (1/deg/sec)
Cm_delta	-0.9872000E-02	Cm_delta_dot	0.000000	
Cn_delta	-0.3566800E-02	Cn_delta_dot	0.000000	

Hinge Moment Derivatives
Chm_Alpha   -0.1900000E-01
Chm_Beta   0.2290000E-01
Chm_Delta   -0.2360000E-01
Chm_Mach   0.000000

Hinge Moment Derivatives with respect to Changes in: Alpha, Beta, Surf Deflection (1/deg) and changes in Mach Number

The flight vehicle modeling program interactive dialog comes up showing the vehicle title, modeling options, and the vehicle data at a fixed flight condition. This vehicle dataset has only 4 aerosurfaces. The data appear in separate tabs. The aerosurfaces data are shown in this case. There are buttons in the upper right-hand corner for creating a new dataset or modify the existing dataset and save it under a different title. You can also view and edit the input file. Click on "Run" and the program will process the dataset, create the vehicle state-space system for this configuration, and save it in file "*Rocket_Later_RB.Qdr*" under the same title and include the comment lines.

Extracting the Lateral Design System:

The next step is to extract two lateral systems from the coupled vehicle system. A system to be used for simulations and stability analysis, and a lateral design system for lateral control design using LQR. The systems modification program will be used to extract the reduced lateral systems from the original system. Two system modification datasets are already included in the input data file: "*Rocket_Later_RB.Inp*". We will show the second one "*Lateral Design Model*". The program reads the coupled system "*Rocket Plane at Mach=0.85, Q=150, Rigid Body*" that was created by the vehicle modeling program, extracts the 2-flaps and 2-rudder aerosurfaces, and the lateral variables (p, r, β). From the main menu go to "*Program Functions*", "*Creating and Modifying Linear Systems*" and then "*Modifying, Scaling State-Space Systems*". From the filenames selection menu select the input and the system filenames. The program searches for system modification datasets and it shows their titles in the menu below. Select the set "*Lateral Design Model*" and click on the "*Run Selected Input Set*" button to process the data and to extract the lateral design system. The reduced lateral system is saved in the systems file under the same title "*Lateral Design Model*".
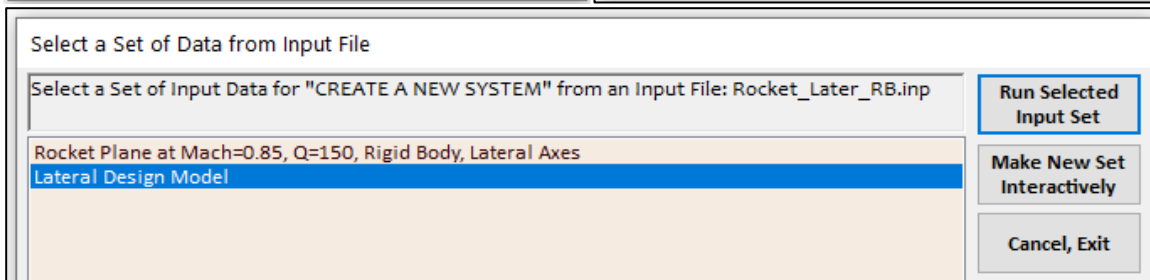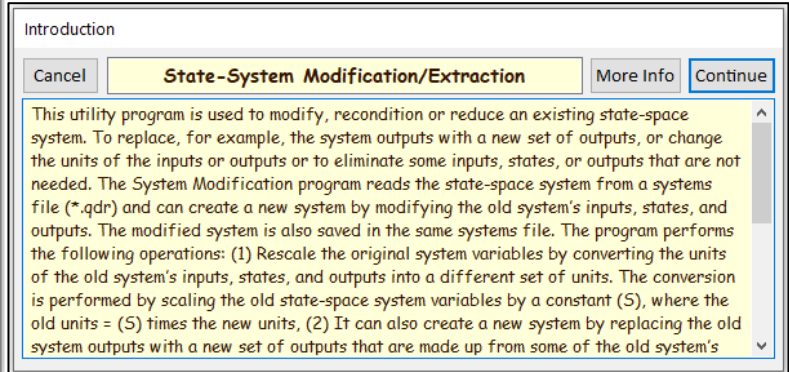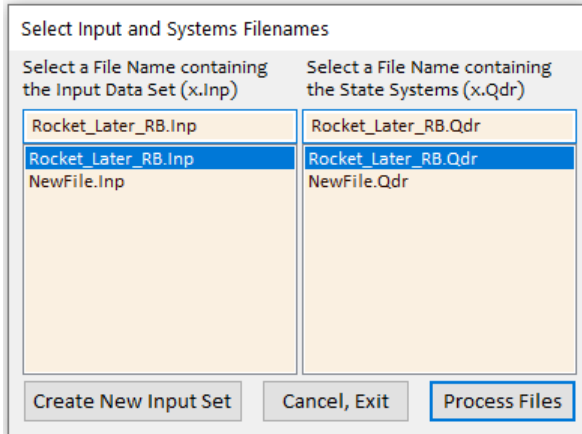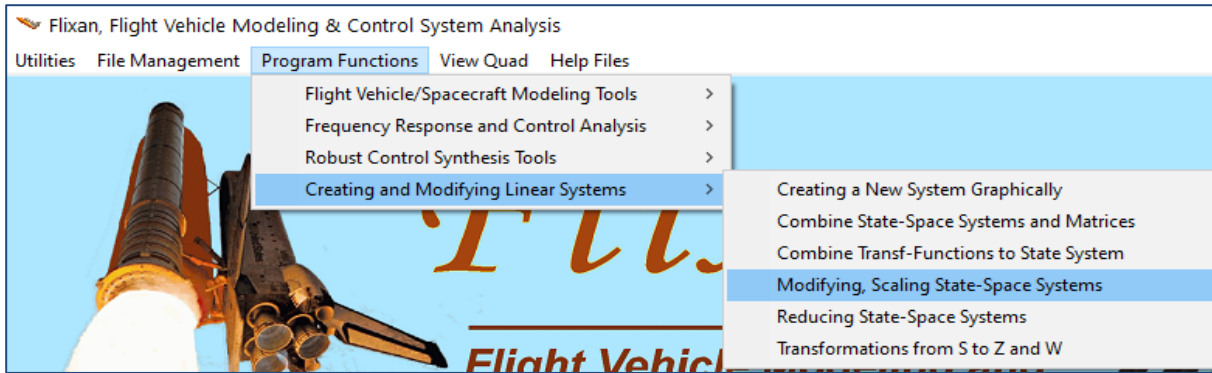
Derivation of the Lateral Mixing Logic Matrix:

The second vehicle system has only 4 aerosurface control inputs: the 2 flaps and the 2 rudders that will be used for roll and yaw control. We will use the mixing logic program to derive the lateral mixing logic matrix that pre-multiplies the open-loop vehicle and attempts to decouple the two lateral control directions. It converts the roll and yaw acceleration flight control demands (δP, δR) to 4 aerosurface deflections that produce the required accelerations in the corresponding directions, open-loop. The mixing logic matrix attempts to diagonalize the lateral design model and minimizes the dynamic coupling between the two lateral control loops. To run the mixing logic program, from the Flixan main menu go to "*Program Functions*", and select "*Create Mixing Logic/ TVC*". From the filenames selection menu select the input and the system filenames as before. Select the second vehicle data title: "*Rocket Plane at Mach=0.85, Q=150, Rigid Body (for computing the lateral mixing matrix Kmix)*", and click on "*Run Selected Input Set*" to create the mixing matrix from the vehicle data. The next step is to define the two lateral directions to be decoupled by the mixing logic. From the accelerations control menu select the roll and yaw accelerations. Enter also a name "Kmix" for the aerosurfaces combination matrix and click "OK" to continue.
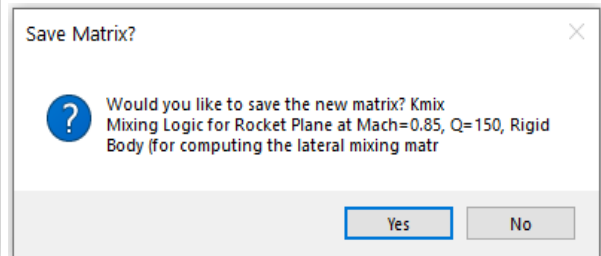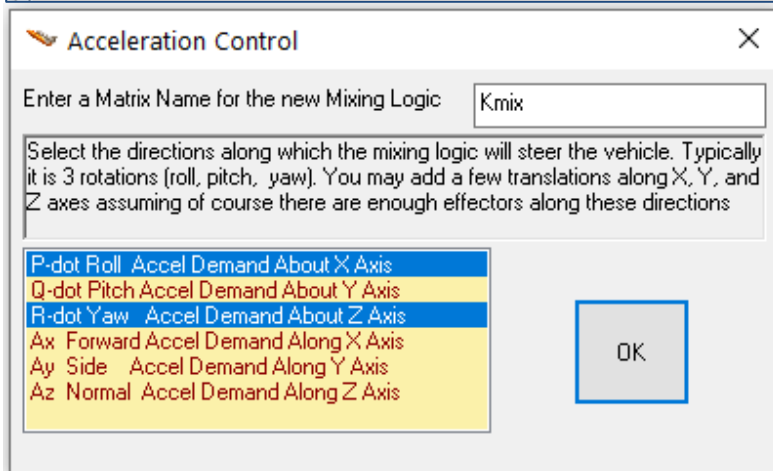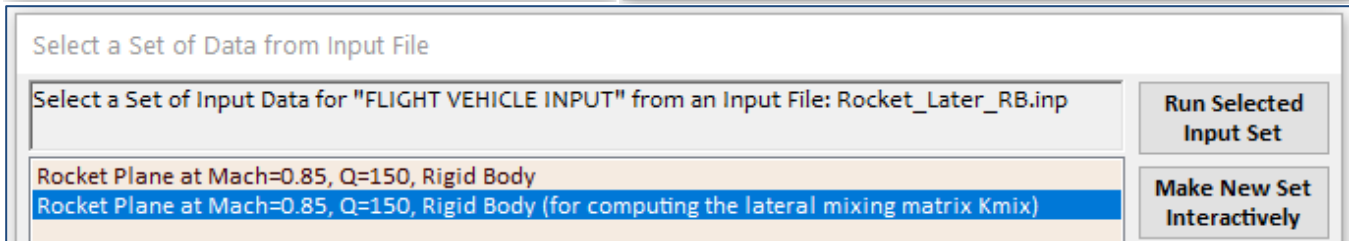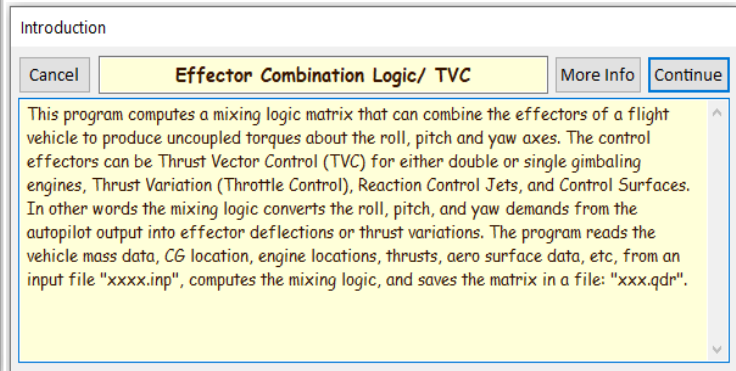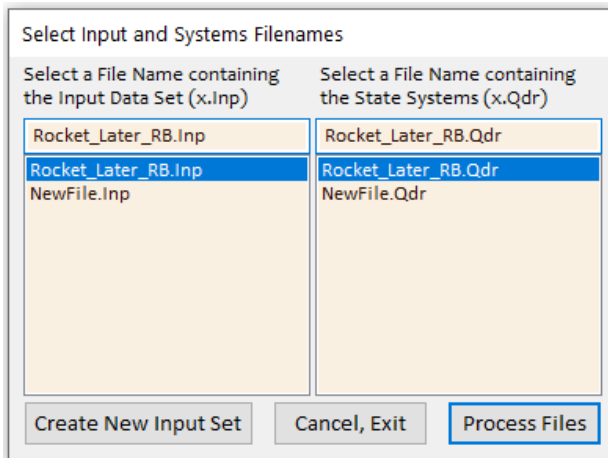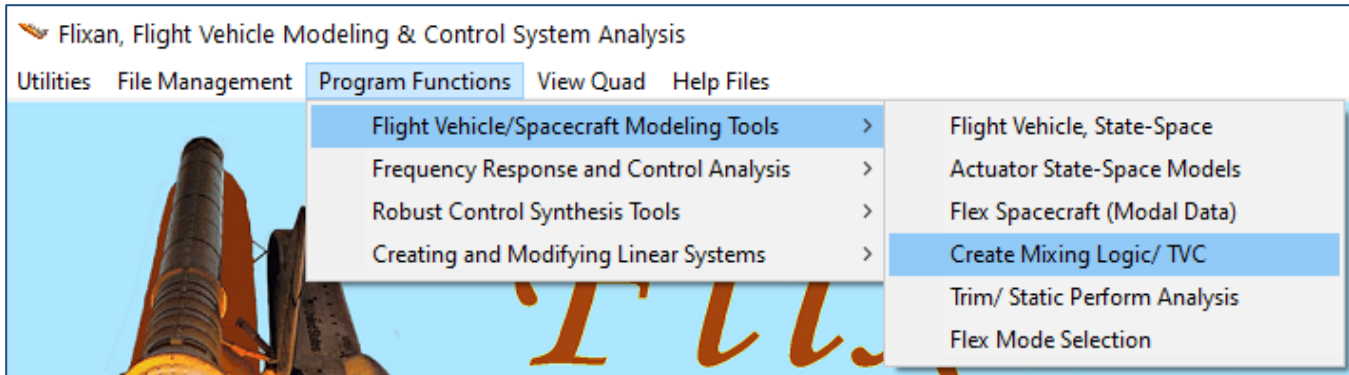
The lateral mixing logic matrix Kmix is saved in the systems file "*Rocket_Later_RB.Qdr*". It provides decoupling between the roll and yaw directions. Notice that the rudders are also contributing in roll. Yaw is controlled by differential rudder deflections. The flaps are also used to counteract the roll due to the rudder deflections. The matrix is also exported into Matlab for further analysis.
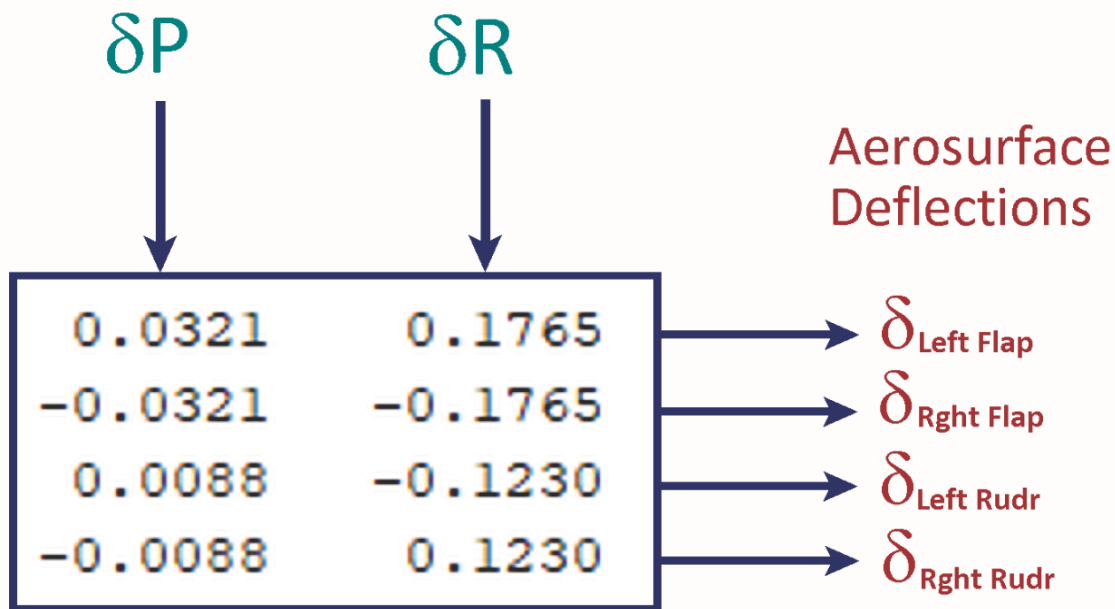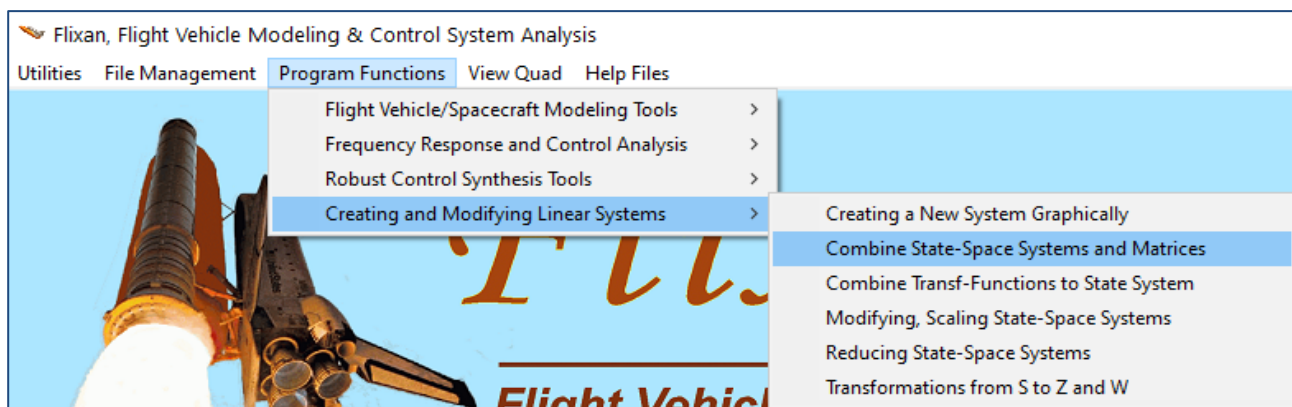
Roll and Yaw Acceler. Demands

$$\begin{array}{cc} \delta P & \delta R \\ 0.0321 & 0.1765 \\ -0.0321 & -0.1765 \\ 0.0088 & -0.1230 \\ -0.0088 & 0.1230 \end{array}$$

Aerosurface Deflections

$\delta_{Left\ Flap}$
$\delta_{Rght\ Flap}$
$\delta_{Left\ Rudr}$
$\delta_{Rght\ Rudr}$

Figure 1.19 The Lateral Mixing Logic Matrix Kmix

Creating the Lateral LQR Design Plant: The previously created "*Lateral Design Model*" includes the body rates (p, r) and the angle of sideslip (β) and the inputs are the 4 aerosurface deflections. However, in the design model we should also include p-integral which in level flight it is equal to the roll angle (ϕ). The mixing logic matrix is also included in the design model as shown in Figure 1.14. The systems combination program will be used to combine the "*Lateral Design Model*" with the p-integrator to produce the p-integral state and multiply the inputs with the mixing logic matrix "Kmix" to replace the 4 aerosurface inputs with two plant inputs, δP and δR. The title of the system combination dataset is "*Lateral Design Model with p-Integral (4-states)*" and it is located in the input data file "*Rocket_Later-RB.Inp*".

To create this new system, from the Flixan main menu select: "*Program Functions*", "*Creating and Modifying Linear Systems*", and then "*Combine State-Space Systems and Matrices*". From the filenames selection menu select the input and the system filenames, as before. The program searches the input data file for systems interconnection datasets and shows their titles in the following menu. From the menu select the systems interconnection set "*Lateral Design Model with p-Integral (4-states)*", click on the "*Run Selected Input Set*" button to create the lateral design system augmented with p-integral. The following systems interconnection dialog comes up showing the system interconnections info. Click on "Run" to process the dataset and the new system will be saved in the systems file "*Rocket_Later_RB.Qdr*" under the title: " *Lateral Design Model with p-Integral (4-states)*". It will also be converted to Matlab format for LQR design using Matlab.

LQR Control Design:

The LQR control design dataset is already created in the input file and Its title is "*Lateral LQR Control Design*". It uses the lateral design system "*Lateral Design Model with p-Integral (4-states)*" that has two inputs: the roll and yaw control demands, δP and δR. The design algorithm also requires the state and control weight matrices Qc4 and Rc2 which are permanently saved in the systems file.

To run the LQR program, select "*Program Functions*", "*Robust Control Synthesis Tools*", and then "*Linear Quadratic Control Design*". Select also the input and system files. From the systems menu select the design system "*Lateral Design Model with p-Integral (4-states)*" which is both: Controllable and Observable. The program returns to the main LQR menu and select the second option which solves the Steady-State Linear Quadratic Regulator problem. Select the LQR design dataset "*Lateral LQR Control Design*" and click on "*Run Selected Input Set*" to process it. The state-feedback controller "*LQR State-Feedback Control for Lateral Axes*" will be saved in the systems file as a gain matrix Kpr. Note, the LQR control design using Matlab is created by the m-file "*lqr_des.m*". It uses the lateral design model from file "*vehi_lat_4x.m*" and produces the state-feedback matrix Kg which is the same as Kpr.

Transferring Systems to Matlab:

We will now reformat some of the systems and matrices from the systems file "*Rocket_Later_RB.Qdr*" to Matlab format. To convert the lateral vehicle system, from the Flixan main menu go to "*Utilities*", then "*Matlab Conversions*", and select "*Export to Matlab*". From the systems selection menu select the filename "*Rocket_Later_RB.Qdr*". From the Matlab directory selection window, select the Matlab analysis subdirectory "*2-Lateral Design*" where the system "*Rocket Plane at Mach=0.85, Q=150, Rigid Body, Lateral Axes*" will be transferred.
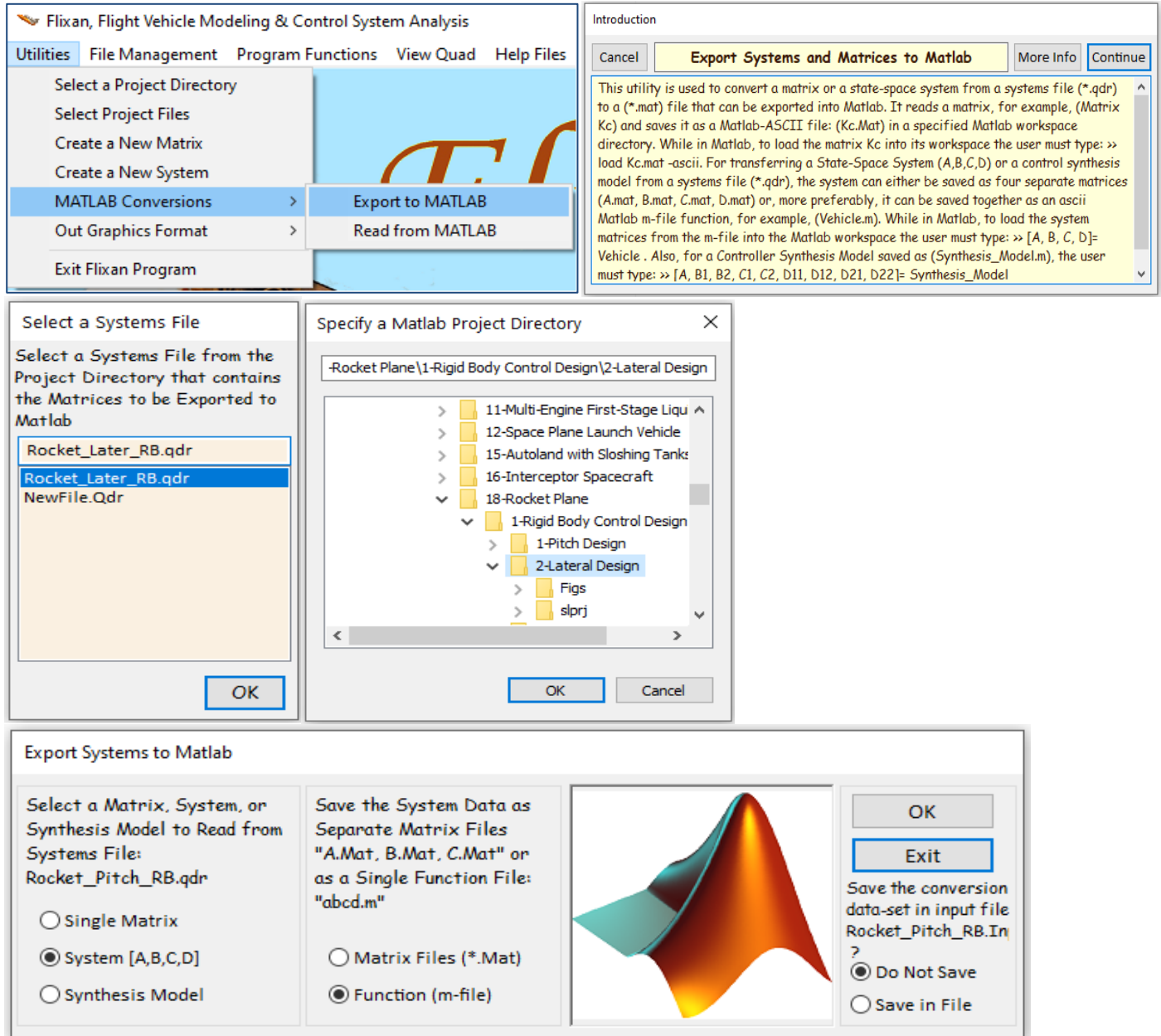
The following dialog is for selecting Matlab transferring options. Select to convert a "System (A,B,C,D)" to a Matlab function (m-file) format. The option on the bottom right is used to save the Matlab conversion "To Matlab" dataset in the input file. The next step is to select the system from the systems file to be converted to an m-file function. The systems selection menu is showing the systems in file "*Rocket_Later_RB.Qdr*". Select one of the titles: "*Rocket Plane at Mach=0.85, Q=150, Rigid Body, Lateral Axis*" to be converted and click the "Select" button. You must also enter the name of the function file "*Vehi_rblat.m*". The system's quadruple matrices will be converted to an m-file function and saved in file "*vehi_rblat.m*". You do not have to type the filename extension (.m). The same procedure is also used to convert the LQR design system "*Lateral Design Model with p-Integral (4-states)*" to a Matlab m-function. The filename of the control design system is "*vehi_lat_4x.m*".

Select a State-Space System from Quad File

Select a State-Space Model for Matlab Conversion, From Systems File:
Rocket_Later_RB.qdr

Rocket Plane at Mach=0.85, Q=150, Rigid Body
Rocket Plane at Mach=0.85, Q=150, Rigid Body (for computing the lateral mixing matrix Kmi:
First Order Gust Lag
Integrator
Rocket Plane at Mach=0.85, Q=150, Rigid Body, Lateral Axes
Lateral Design Model
Lateral Design Model with p-Integral (4-states)

Choose a System Title and then click "Select"   [Cancel] [View System] [Select]

Enter a file name (ex. Vehicle) to save the [A,B,C,D] matrices as a Matlab m-file function (ex. Vehicle.m)   [OK]

ⓘ Matrices will be Saved in Matlab Directory:
     C:\Flixan\Examples\18-Rocket Plane\1-Rigid Body Control
     Design\2-Lateral Design

Vehi_rblat

Matrix Conversion: The "*Export to Matlab*" utility can also be used to convert the (4x2) mixing logic matrix "Kmix" from the systems file to a Matlab matrix. This time from the "Export to Matlab" dialog, you must select to convert a single matrix instead of a system. Then, from the matrix selection menu, select the 4x2 matrix "Kmix" and the matrix will be converted to a Matlab matrix in –ascii format in file "Kmix.mat". Repeat the matrix conversion for the state-feedback matrix Kpr.

Export Systems to Matlab

Select a Matrix, System, or   Save the System Data as   [OK]
Synthesis Model to Read from   Separate Matrix Files
Systems File: "A.Mat, B.Mat, C.Mat" or   [Exit]
Rocket_Pitch_RB.qdr   as a Single Function File:
                                "abcd.m"   Save the conversion
                                                                data-set in input file
  ◉ Single Matrix   Rocket_Pitch_RB.In
                                                                ?
  ○ System [A,B,C,D]   ◉ Matrix Files (*.Mat)   ◉ Do Not Save

  ○ Synthesis Model   ○ Function (m-file)   ○ Save in File

Select a Gain Matrix

Select one of the following Matrices from Systems File: Rocket_Later_RB.qdr   [Select a Matrix]

Matrix Name	Size		Matrix Title
Qc4	:	4 X 4:	State Penalty Matrix Qc4
Rc2	:	2 X 2:	Control Penalty Matrix Rc2
Kmix	:	4 X 2:	Lateral axes Mixing Matrix for Rocket-Plane, Kmix
Kpr	:	2 X 4:	LQR State-Feedback Control for Lateral Axis

[View Matrix]

[Add a New Matrix]

ⓘ Matrices will be Saved in Matlab Directory:
     C:\Flixan\Examples\18-Rocket Plane\1-Rigid Body Control
     Design\2-Lateral Design

[Cancel]

1.6 Coupled Pitch and Lateral Analysis

Now that we have analyzed the pitch and lateral systems separately and designed the pitch and lateral flight control systems, we can go one step further to analyze them together as a coupled system. In this analysis we will use the coupled vehicle system "*Rocket Plane at Mach=0.85, Q=150, Rigid Body*" which is created from the input file "*RocketPlane_RB.Inp*" and saved in the systems file "*RocketPlane_RB.Qdr*". This system is converted to function m-file "*vehi-coupled_rb.m*" and loaded into Matlab. We will also use this system to create the mixing logic matrix *K4axmix* that combines the throttling engine with the 5 aerosurfaces. This analysis is performed in subdirectory "*Flixan\ Examples\18-Rocket Plane\1-Rigid Body Control Design\3-Coupled Vehicle Analysis*".

Processing the Input File in Batch Mode

To process the input file in batch mode, start the Flixan program, select the coupled analysis folder, and from the top menu select "*File Management*", "*Managing Input Files*", and then "*Edit/ Process Input Files*", as shown. The input file manager utility comes up and from the left menu select the input file "*RocketPlane_RB.Inp*" and click on "Select Input File" button. The right menu will show all the datasets which are in the input file. Select the batch set "*Batch Set for Creating Rigid-Body Models for the Rocket-Plane*" and click on "*Process Input Data*" to process the input file. The coupled vehicle model and the mixing logic matrix will be saved in the systems file, and Matlab files will be created.
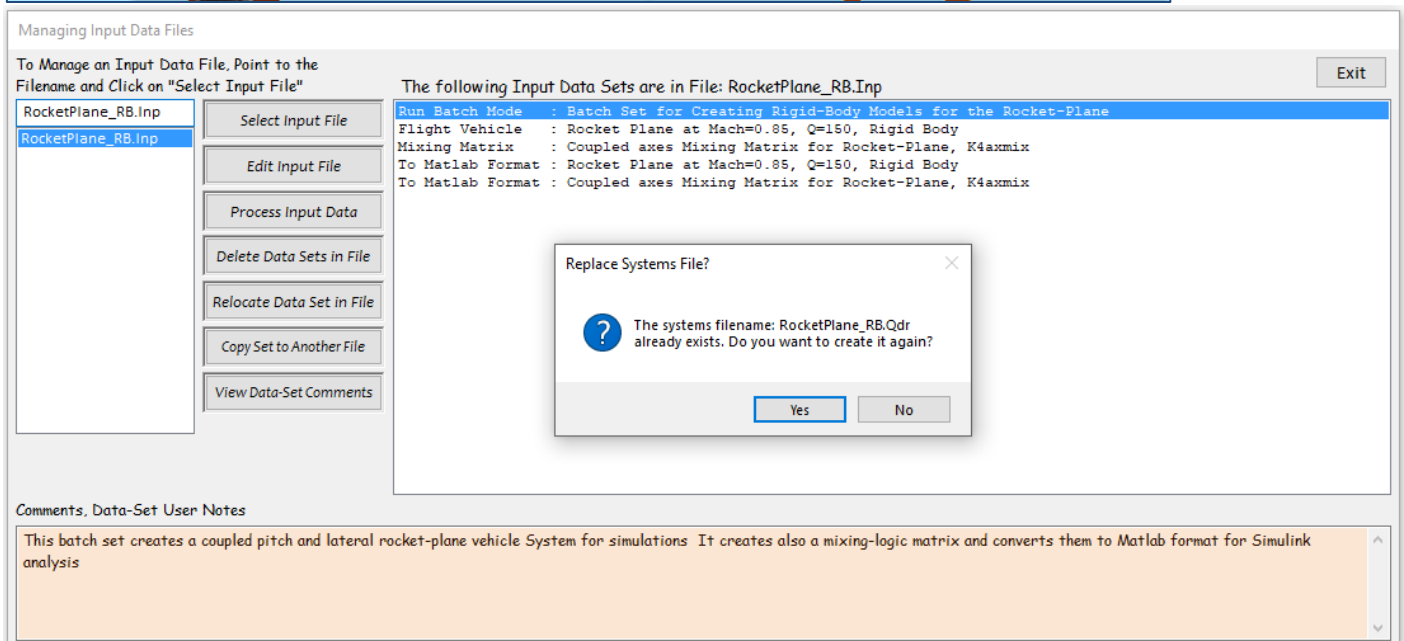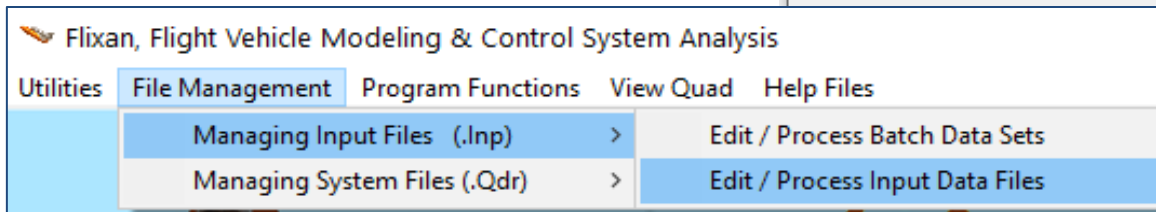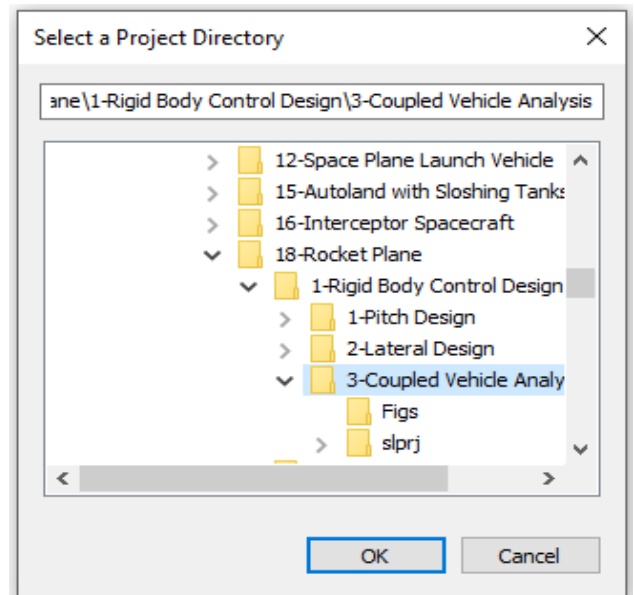
Mixing Logic Matrix for the Coupled System

The coupled vehicle system uses all five aerosurfaces and the throttling engine to control the vehicle in four directions: three rotational accelerations, plus linear acceleration along the x axis. This time we will use a (6x4) mixing logic matrix "*K4axmix*" which is created by processing the mixing logic dataset "*Coupled axes Mixing Matrix for Rocket-Plane, K4axmix*". The *K4axmix* matrix translates the four control demands: roll, pitch, yaw rotational accelerations and x-acceleration, to 6 controls: two flaps, two rudders, body-flap deflections and engine throttle control (that varies between 0 and ±1 as already described in the longitudinal analysis). The (6x4) mixing logic matrix "*K4axmix*" pre-multiplies the vehicle system and attempts to decouple the four directions and diagonalizes the open-loop plant (before feedback). It is saved in the systems file "*RocketPlane-RB.Qdr*" under the title: "*Coupled axes Mixing Matrix for Rocket-Plane, K4axmix*" and it is also saved as a Matlab matrix "*K4axmix*.mat" and loaded into Matlab.
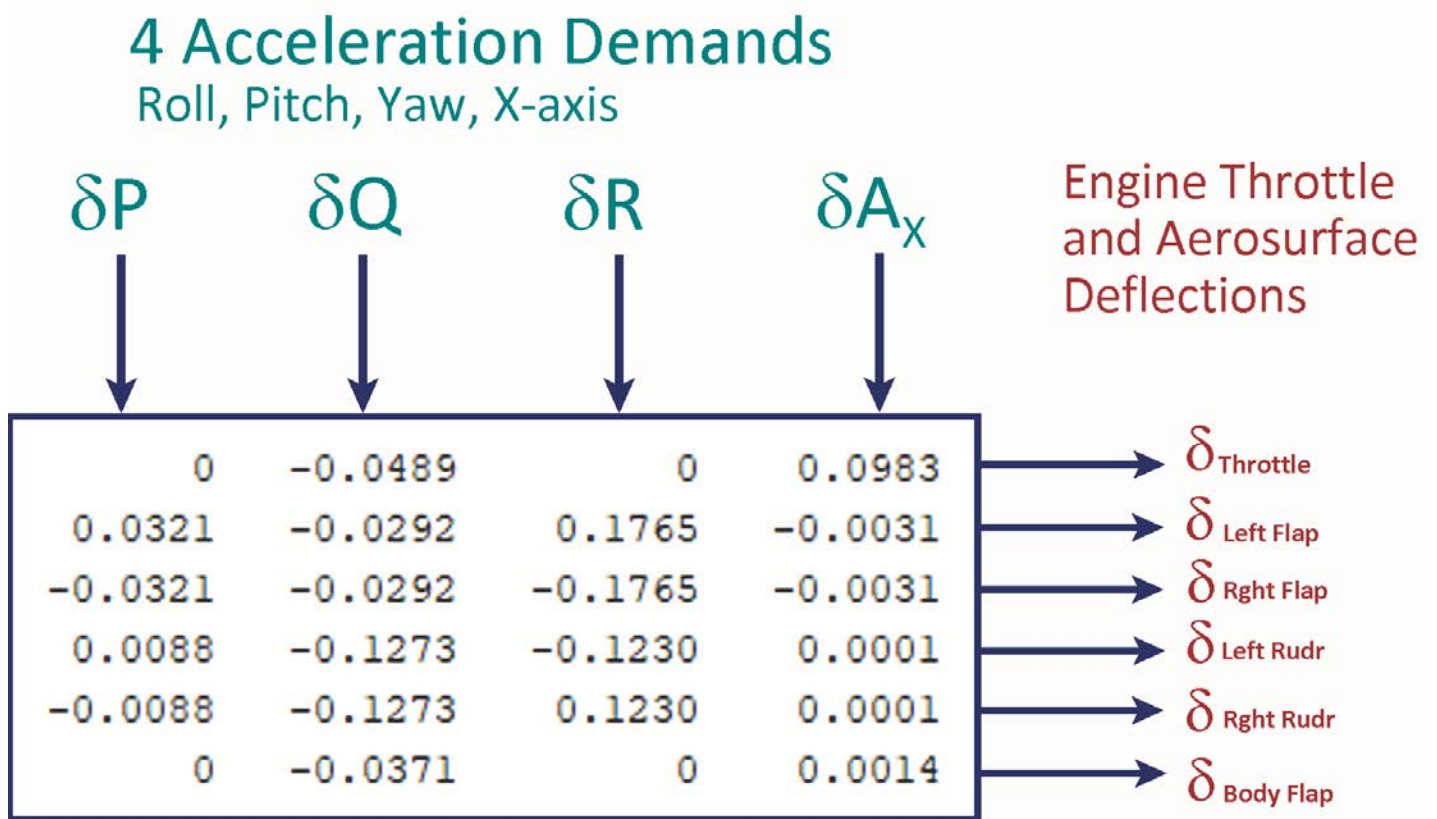
Figure 1.20 Mixing Logic Matrix "K4axmix" for the Coupled System

```
MIXING LOGIC MATRIX DATA .........     (MATRIX TITLE, NAME, VEHICLE TITLE, CONTROL DIRECTIONS)
Coupled axes Mixing Matrix for Rocket-Plane, K4axmix
! This mixing logic uses all five control surfaces and the variable throttling engine
! to achieve roll, pitch, yaw attitude control plus axial (Ax) acceleration control
K4axmix
Rocket Plane at Mach=0.85, Q=150, Rigid Body
P-dot Roll   Acceleration About X Axis
Q-dot Pitch Acceleration About Y Axis
R-dot Yaw    Acceleration About Z Axis
Ax  Forward Acceleration Along X Axis
-------------------------------------------------------------------------------------
```

Figure 1.21 Mixing Logic Dataset in file "RocketPlane_RB.Inp" that Calculates the Mixing Logic Matrix

Coupled Axes Analysis and 6-dof Modeling

The Simulink model "*Closed_Coupled.slx*" in Figure 1.22 is used to simulate the coupled axes vehicle model. It consists of four control loops: roll, pitch, and yaw attitude control loops and the axial acceleration loop that controls the vehicle speed. The velocity and altitude control systems are the same as before and they are described in the longitudinal axes analysis in Section 1.1. The heading control system is included in the lateral axes to control the heading direction by commanding the roll angle. The initialization file "init.m" loads the vehicle model, the mixing-logic matrix, the actuator, the control system gains, and the estimator parameters, which are used in the simulation.

```
% Initialization File (init.m)
d2r=pi/180; r2d=180/pi;
[Ap,Bp,Cp,Dp]=vehi_coupled_rb;            % Pitch & Lateral Simulation Model
load K4axmix.mat K4axmix -ascii           % Throttle/ Surface Mix Logic
load Kq.mat    Kq  -ascii                 % Pitch State-Feedback Matrix
load Kpr.mat  Kpr -ascii                  % Later State-Feedback Matrix
zet=0.6; omg=40;                          % Actuator Model
Aact=[0, 1; -omg^2, -2*zet*omg]; Bact=[0; omg^2];
Cact=[1,0]; Dact=0;

% Alpha Estimator Parameters
Qbar=150; Mass=198.32; Sref=79.069; V0=822.8;
Cza=-0.073; Cyb=-0.0245;
Cydel= [-0.24668,0.24668, 0.47413,-0.47413,0]/100;   % Cy due to surf deflect
Czdel= [0.51664,0.51664,0.60478,0.60478,0.06]/100;   % Cz due to contrl surface
```

The vehicle dynamics block is shown in detail in Figure 1.23. It includes the coupled vehicle model from file "*vehi_coupled_rb*", the actuators, the mixing logic from file "*K4axmix.mat*", and the wind-gust disturbance. The outputs from the mixing matrix are: throttle control, and five aerosurface deflections. The mixing logic block is shown in detail in Figure 1.24. The throttle command output is constrained to vary between (-1 and +1). Zero throttle corresponds to the nominal thrust 2000 (lbf), throttle=-1 corresponds to zero thrust, and throttle=1 corresponding to maximum thrust 4000 (lbf). The cross-range velocity (V_{cr}) is divided by the total ground speed to calculate the heading direction angle (chi). The heading is controlled by bank maneuvers in the lateral axes. The V-dot integrator which calculates the vehicle speed is initialized at the nominal vehicle speed which is 823 (ft/sec).

The initialization file creates a simple 2nd order state-space actuator model of bandwidth 50 (rad/sec) which is used in all 3 axes. A gust filter is included in the wind-gust velocity input to soften the rectangular impulse. The pitch and lateral LQR control systems were described in the previous sections. The pitch and lateral state-feedback gain matrices Kq and Kpr and also the alpha and beta estimator parameters are loaded into the Matlab workspace by the initialization file. The estimated alpha and beta replace the real alpha and beta required by the state-feedback controller.
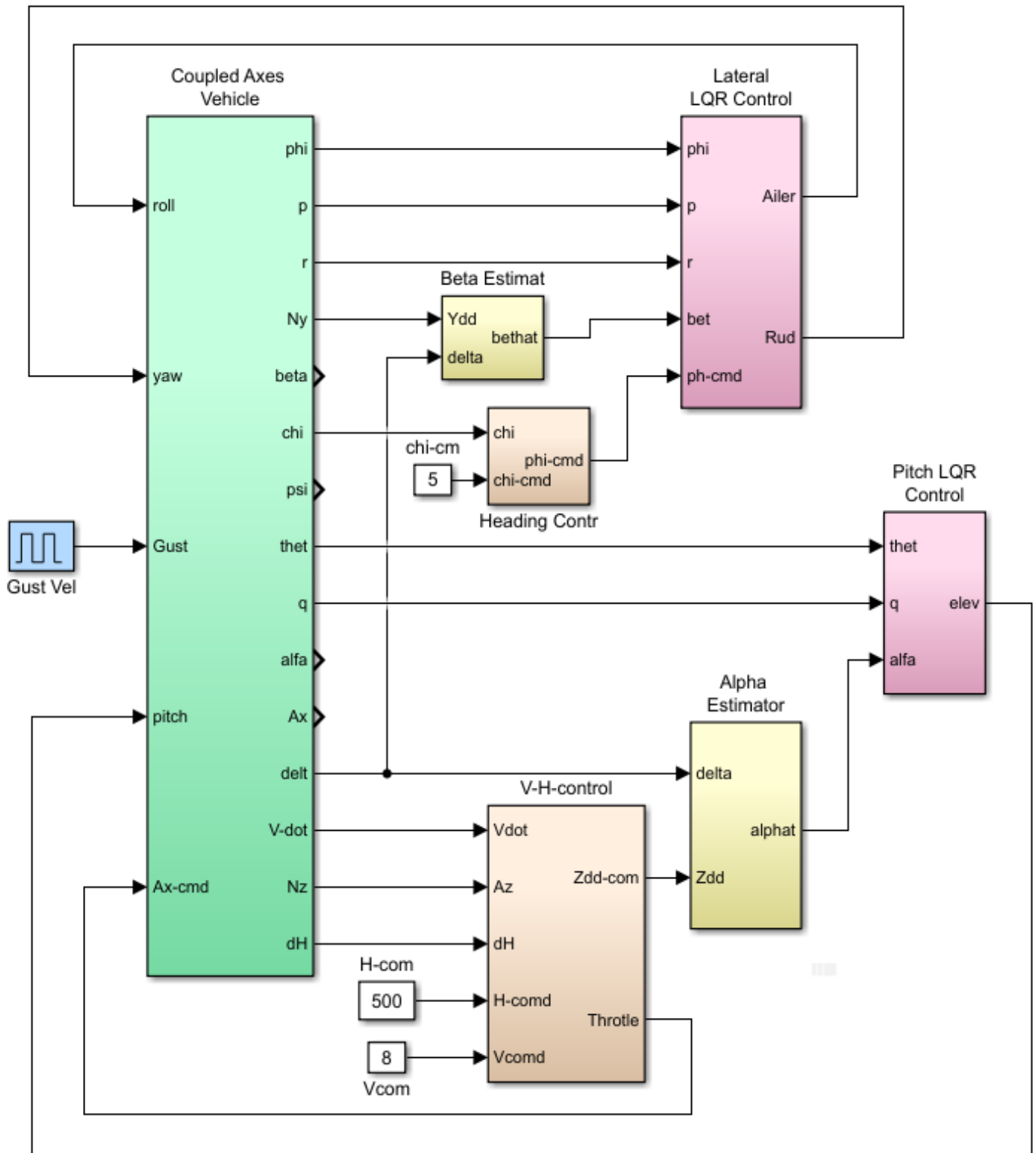
Figure 1.22 Closed-Loop Simulation Model of the Coupled Vehicle "Closed_Coupled.Slx"

Vehicle Dynamics/ Actuators/ Mixing Logic
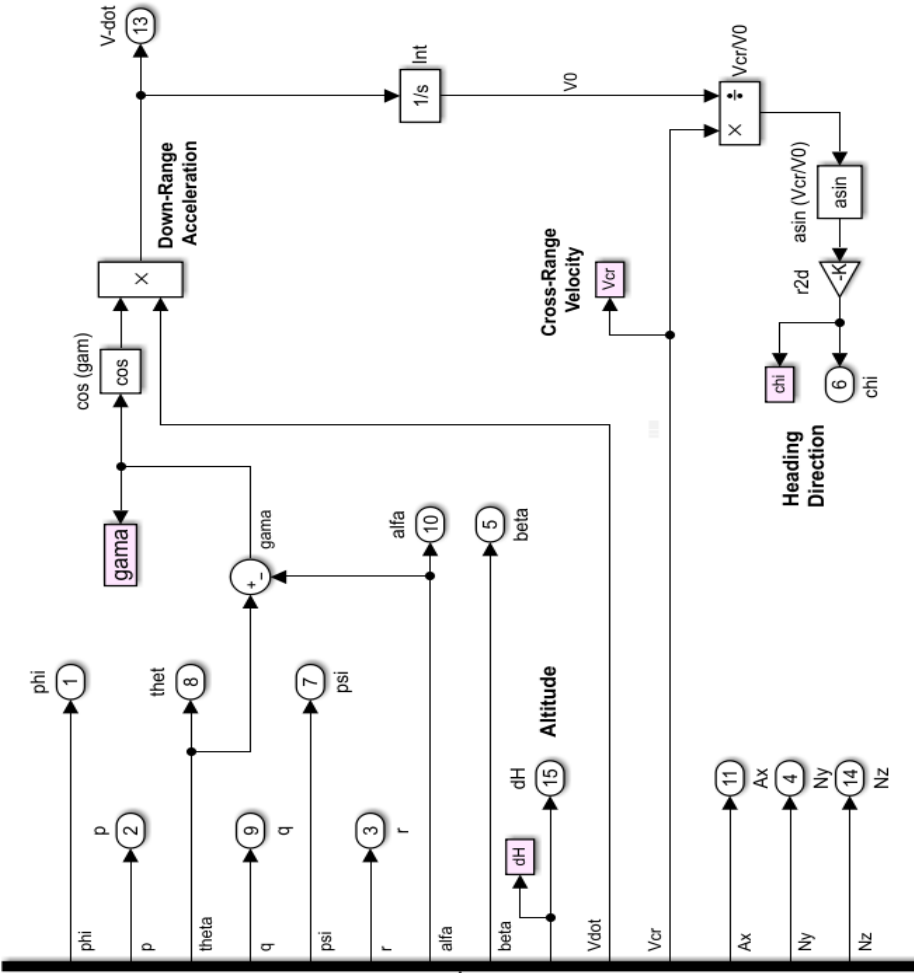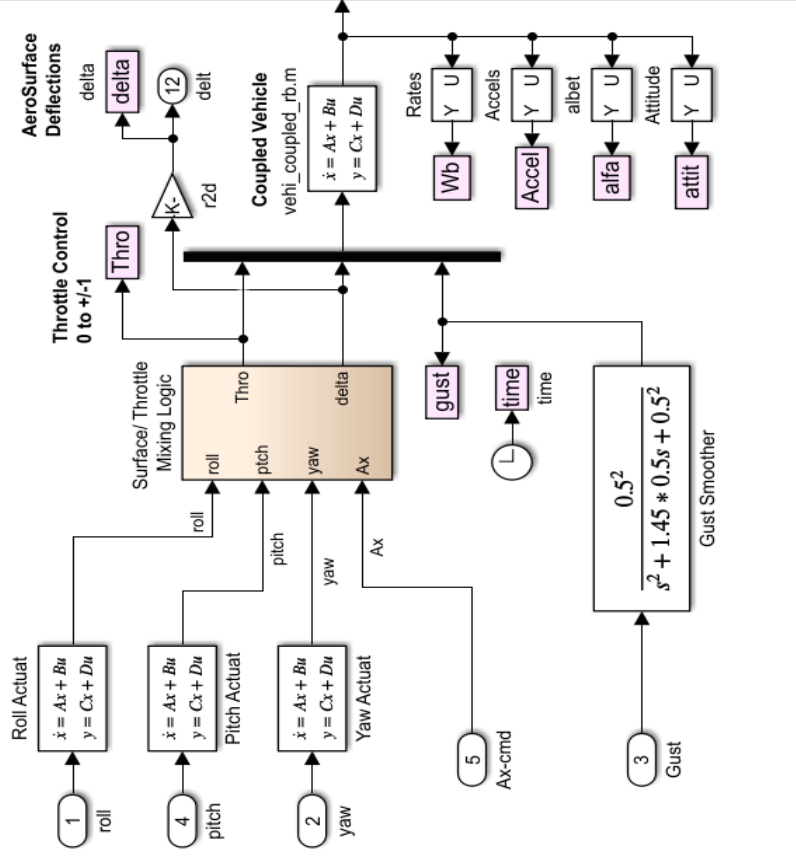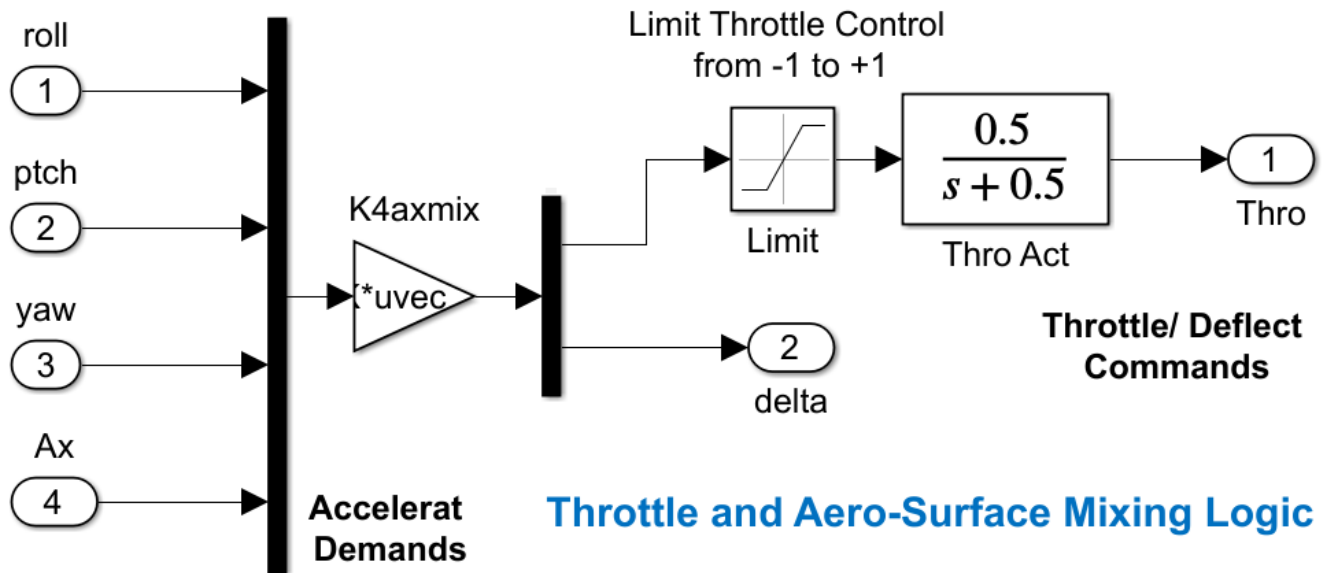
Figure 1.24 Mixing Logic Implementation Including Throttle Limit and Throttle Actuator

The only block in this simulation that has not been described yet is the Heading direction (χ) control block shown in Figure (1.25). It is a simple PI controller that receives the error in the heading direction (χ-err) and commands a change in the bank angle ϕ that changes the heading direction. When the change in heading direction is complete, the roll angle returns to zero.
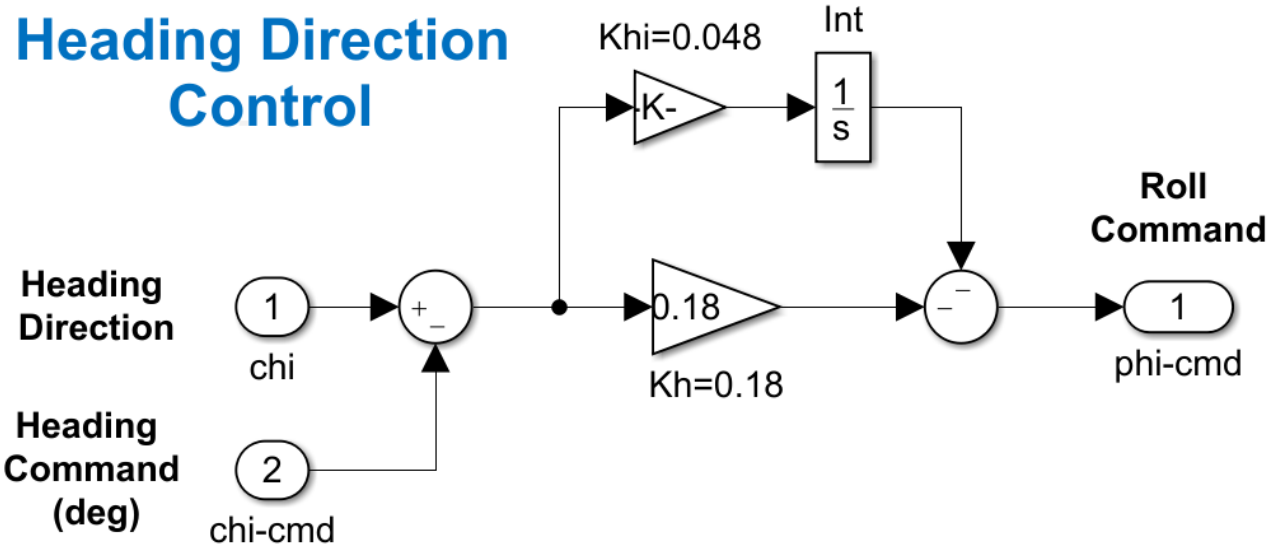
Figure 1.25 Heading Direction Control System

Six-DOF Simulation

We will now use the simulation model to analyze the control system's response to simultaneous commands and wind-gust disturbance. The system will be commanded to perform the velocity and altitude change maneuver that was shown earlier in Section 1.1. It is also commanded to perform a 5° change in heading direction and a wind-gust is applied after 20 seconds. The wind-gust direction relative to the vehicle is defined in the vehicle input data.
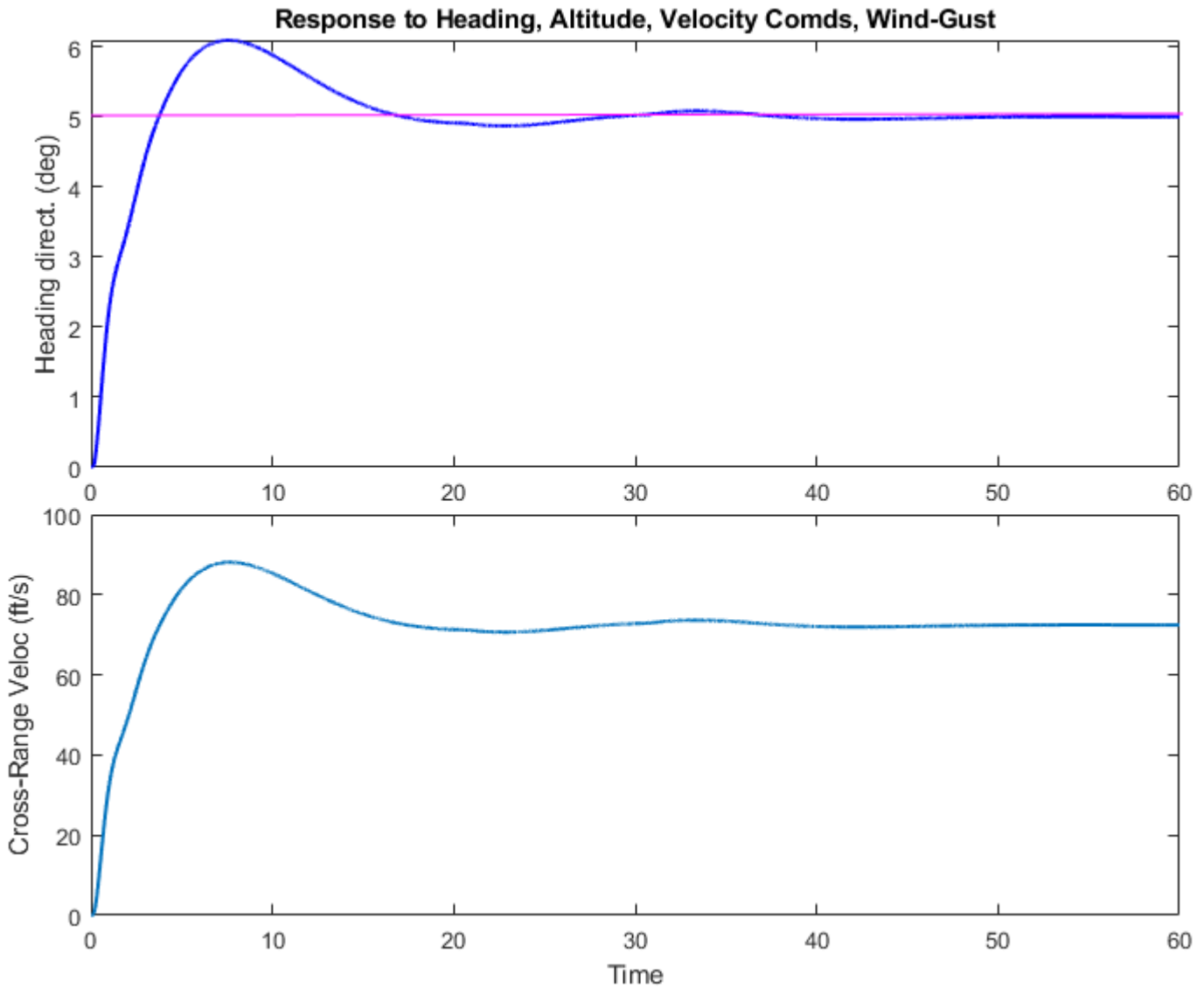
Figure 1.26 Change in Heading Direction and Cross-Range Velocity

Figure 1.26 shows the change in heading direction which converges to 5°. It also causes a steady change in cross-range velocity. The ground speed and altitude also respond to the commands. The altitude response is slower with some error. Figure 1.27 shows the vehicle controls, which are: the five aero-surface deflections that perform this multi-axis maneuver, and the throttle control. The throttle control momentarily increases to +42% corresponding to approx. 3000 (lbf) of thrust in order to achieve the increase in speed and altitude and then it stabilizes to a lower level (2070 lbf) to maintain the increase in speed. The temporary increase in thrust also causes a temporary increase in the axial acceleration (A_x).

In Figure 1.28 the wind-gust is an impulse starting at 20 sec and peaking at 50 (ft/sec). Its shape is smoothed out by a second order low-pass filter to make it more like a real gust. The angle of attack temporarily increases as needed for the vehicle to climb in altitude and then it stabilizes back to nominal. The sideslip angle also increases as the vehicle temporarily banks to the right to change its heading and it eventually stabilizes back to zero. The flight path angle (γ) also increases during the climb and then it converges to zero when the vehicle returns to level flight at 500 (feet) higher altitude.
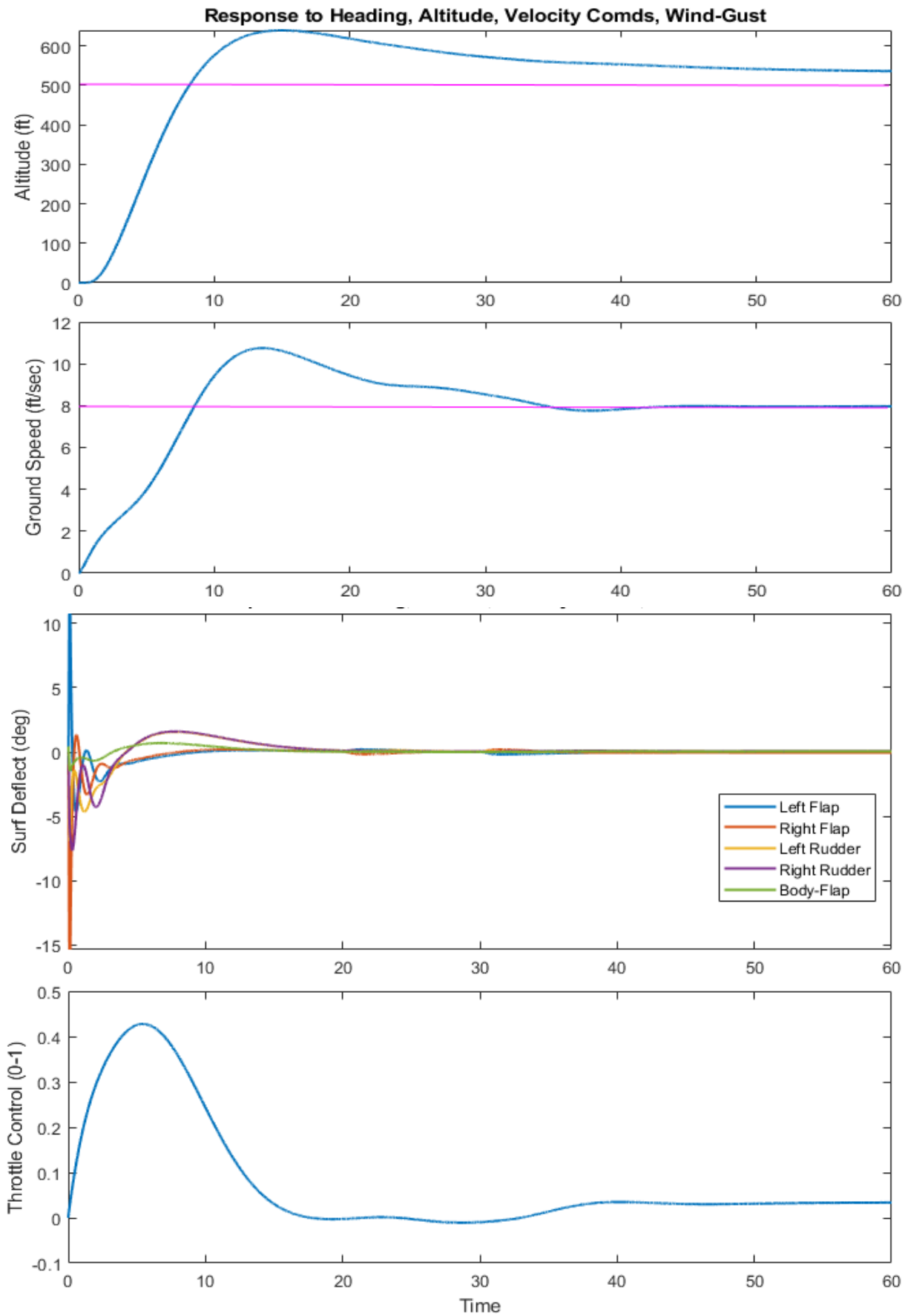
Figure 1.27 Change in Altitude and Speed, Aerosurface Deflections (deg) and Throttle Control
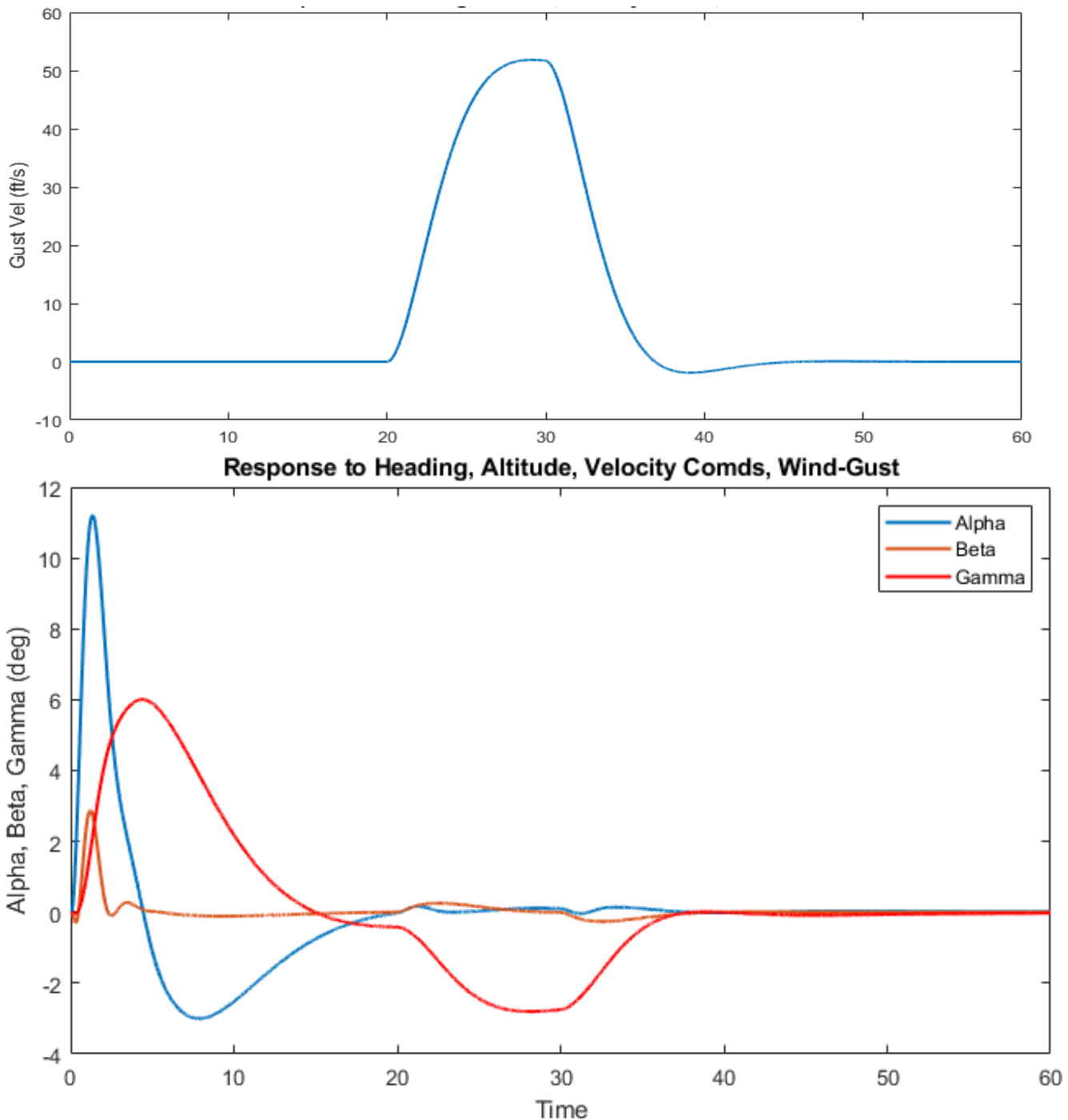
Figure 1.28 Changes in the Angles of Attack, Sideslip and Flight Path Angle

Figure 1.29 shows the body rates and accelerations. The sharp increase in normal acceleration (Nz) to -1.4 (g) is caused by the increase in altitude maneuver. This is an increase from the -1g nominal level flight. The command to change flight direction causes the vehicle to bank momentarily in (ϕ=46°), and as the flight direction (chi) approaches its commanded value of 5˚ the bank angle returns to zero. The flight-path angle and attitude are momentarily affected by the wind-gust transient but they eventually return to normal.
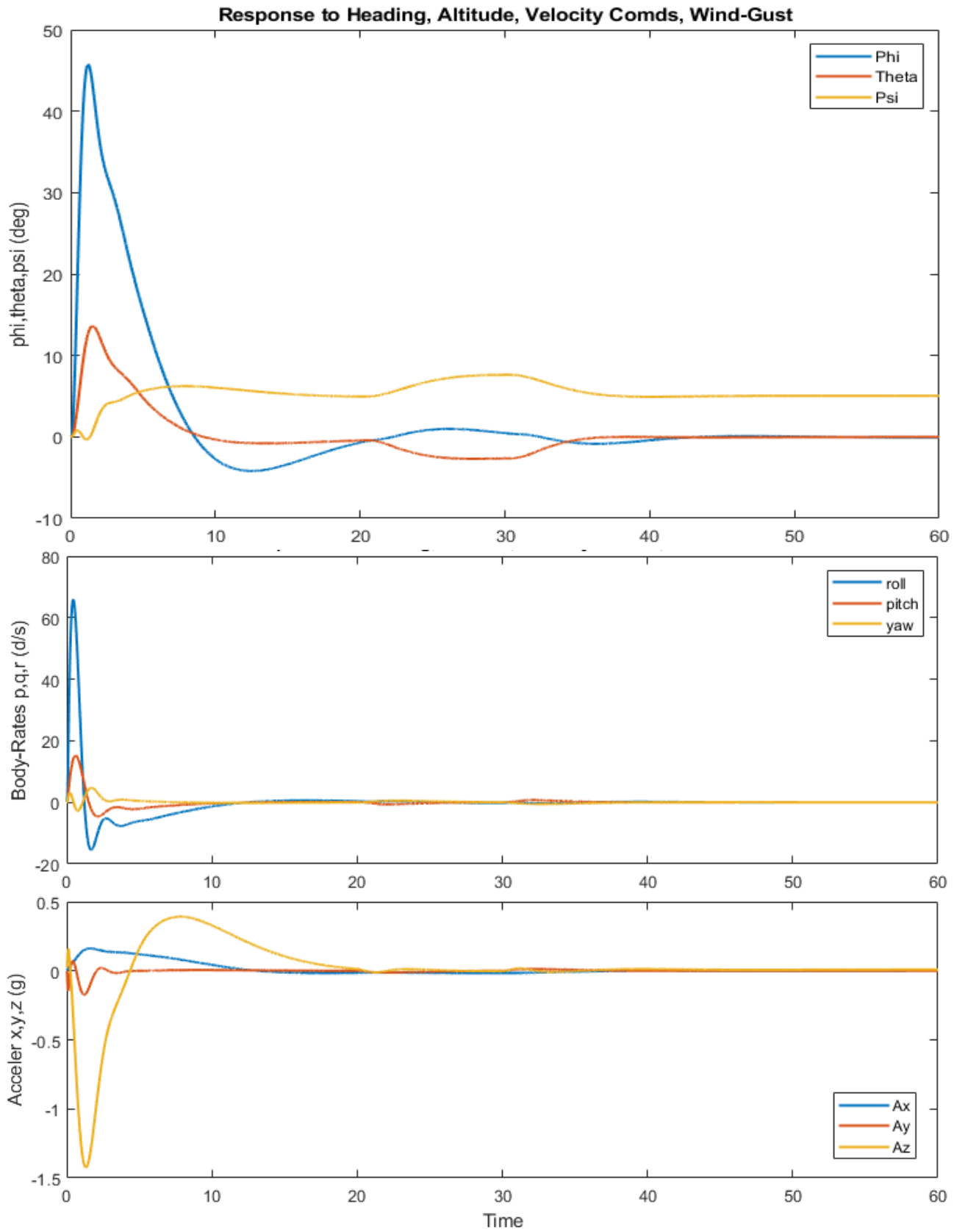
Figure 1.29 Vehicle Attitude Change, Body Rates and Accelerations

Control System Stability Analysis

The Simulink model "*Open_Loop_Coupled.Mdl*" in Figure 1.30 located in subdirectory "*3-Coupled Vehicle Analysis*" is used to perform stability analysis in frequency domain. It is a single-input-single-output system for classical control analysis and it contains the same elements as the simulation model. It includes the four control loops described but the model must be modified by the analyst for each loop. Only the loop to be analyzed should be opened while the other three loops must be closed.

The Matlab file "*frequ.m*" calculates the frequency response of the open-loop system and plots the Bode and Nichols chart for analyzing the system stability. To evaluate, for example, the pitch axis stability we must open the pitch loop (as shown below) with the roll, yaw, and throttle loops closed, and calculate the frequency response across the opened pitch loop. The (-1) gain in the open loop is introduced in order to set the phase correctly with respect to the (-1) point for classical Nichols or Nyquist analysis, which assume negative feedback. The following plots show the pitch and the roll Nichols charts and highlighting the phase and gain margins. It is shows that the two loops have excellent rigid-body stability margins. The yaw and ground velocity control loops can be evaluated the same way.
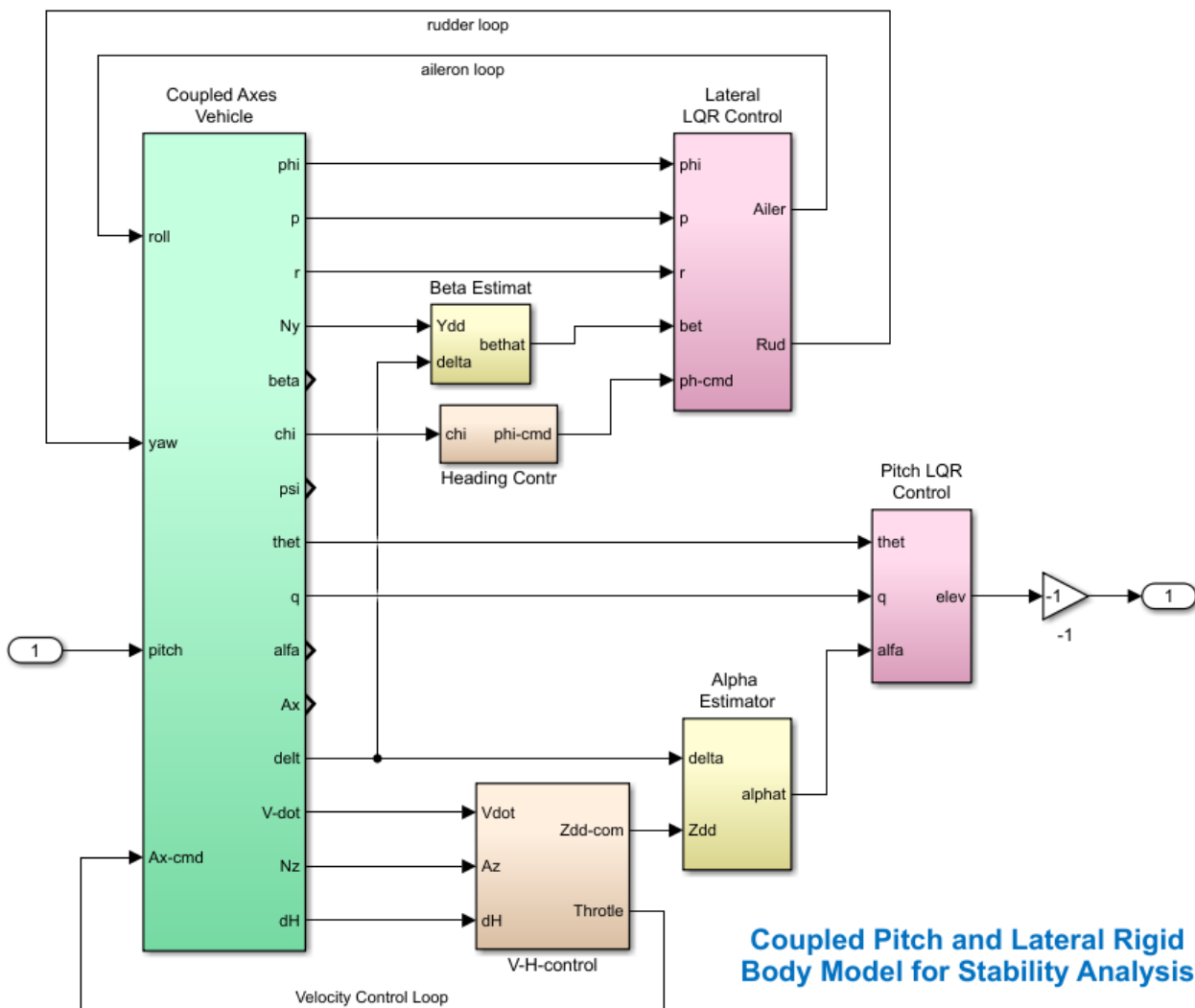
Figure 1.30a Simulink Model "Open_Loop_Coupled.Slx" Used for Stability Analysis, Configured for Analyzing Pitch Analysis Stability
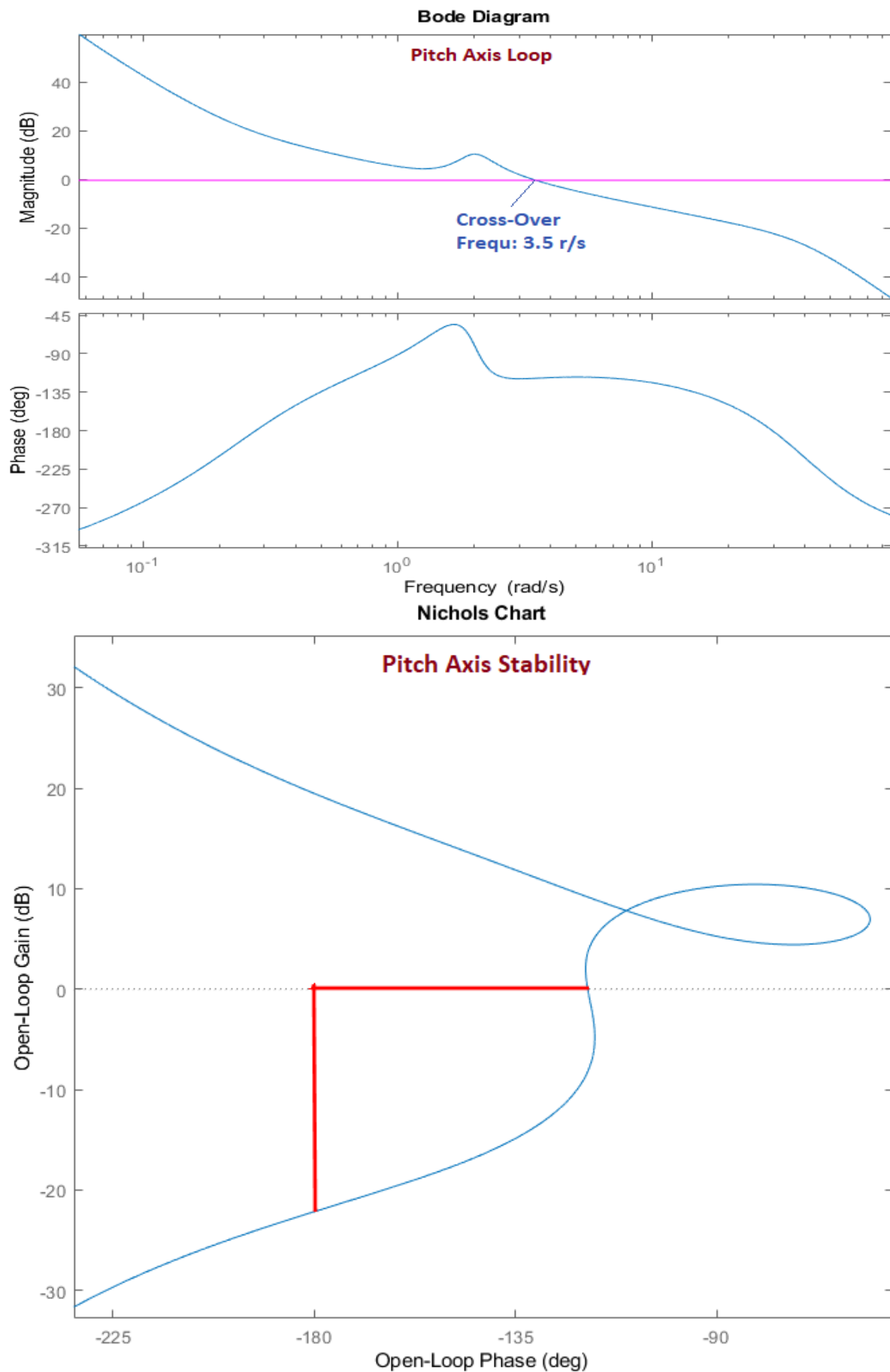
Figure 1.31 Bode and Nichols Plots for the Pitch Axis
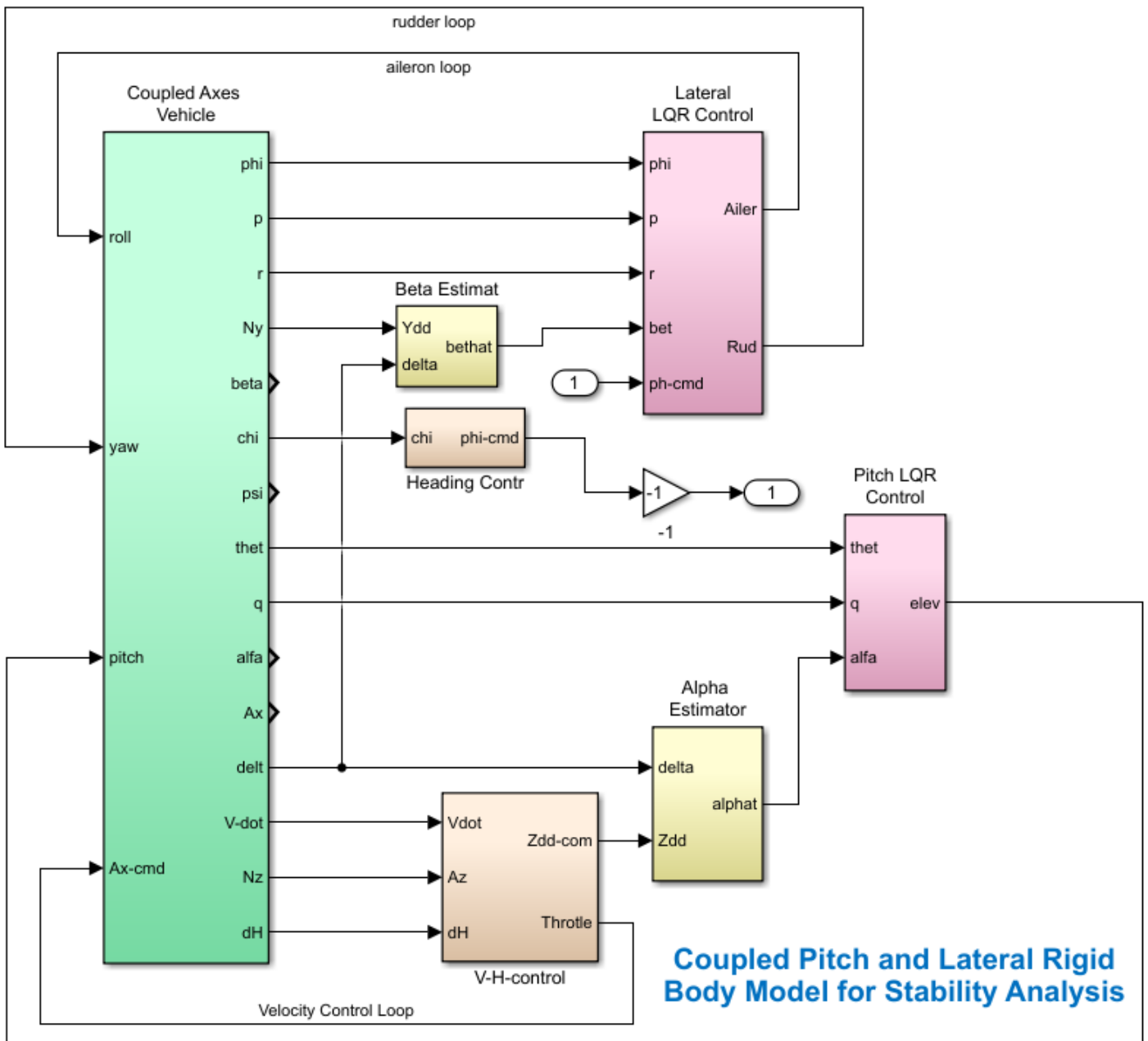
Figure 1.30b Simulink Model "Open_Loop_Coupled.Slx" Configured for Analyzing Stability of the Heading Direction Control Loop

To analyze stability of the heading control loop we must open the heading loop at the phi-command, as shown in Fig. 1.30b, with the roll, pitch, yaw, and throttle loops closed, and calculate the frequency response across the opened phi-command loop.
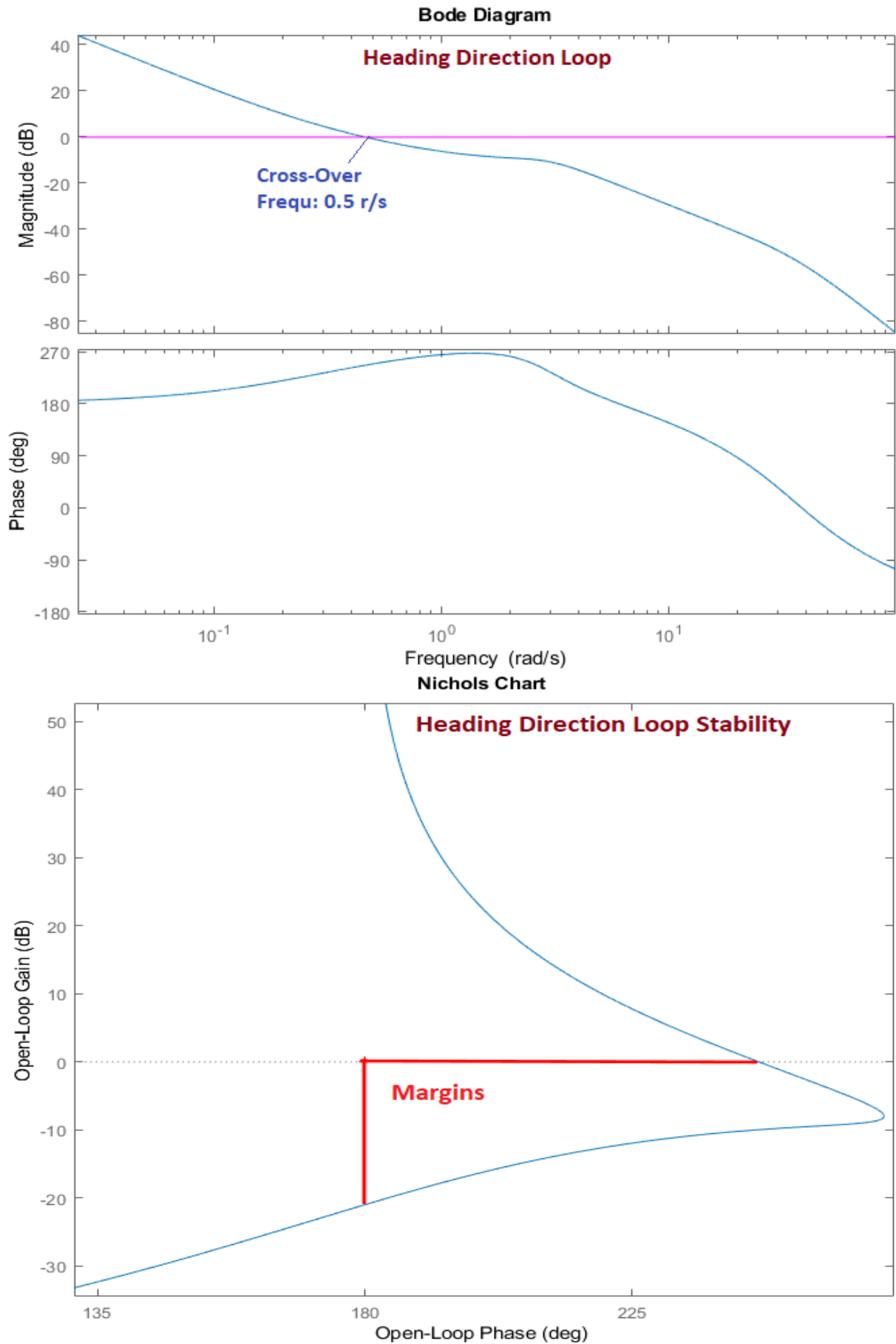
Figure 1.32 Bode and Nichols Plots for the Heading Control Loop

2.0 Flexible Vehicle Analysis (Without Aero-Elastic Coefficients)

In this section we will continue analyzing the rocket-plane by introducing structural flexibility in the vehicle model and repeating the analysis. We will modify the vehicle model to include 30 flexible modes and we will refine the control system by introducing filters that will attenuate the structural modes and avoiding to excite flex oscillations. The structural flexibility is defined by modal data which are created from a finite-elements model (FEM) of the rocket vehicle. We must first process the modal data file, select the dominant modes, and scale the data so they can be combined with the rigid vehicle data. Aero-elasticity coefficients will not be included in this model but they will be introduced later in Section 3. We will also include "tail-wag-dog" dynamics for the aero-surfaces and create more efficient actuator models for the flaps, rudders and body-flap, using the Flixan actuator modeling program. They will be used to model the dynamic coupling between actuator and vehicle structure. The simulation models will also include the mixing logic matrix and the LQR control gains that were derived in Section-1. The Flixan models and analysis is performed in directory *"Flixan\ Examples\18-Rocket Plane\2-Flex Model"*. The input data file is *"RocketPlane_Flx.Inp"* shown below.

2.1 Input Data File

The title of the vehicle data is "*Rocket Plane at Mach=0.85, Q=150, Flex Model*". It is similar to the rigid-body vehicle data-set that was used in Section 1. The control surfaces and the engine data are the same as before but there are some differences.

1. The "tail-wags-dog" option in the control surfaces is turned-on, "WITH TWD". This flag creates 10 additional inputs in the vehicle system. In addition to the aerosurface deflection inputs (rad), this model will also include five additional inputs for the control surface rates in (rad/sec) and another five inputs for the control surface accelerations in (rad/sec^2) which are used for modeling the TWD. The TWD flag also creates five additional hinge-moments outputs. They are also known as load-torque outputs because they represent torques at the aerosurface hinges due to the vehicle translational and rotational accelerations. They react against the actuator control torques. Clockwise moments about the hinge vector are considered positive. The hinge moment outputs are fed-back into the actuator load-torque inputs to close a mechanical feedback loop, as it will be described later in this section.
2. This vehicle model includes sensors. In the rigid-body model the rotations and accelerations were measured at the CG. This time we define the positions of 3 gyros (roll, pitch, yaw) measuring (rad/sec), and two accelerometers: lateral and normal accelerometers (Ny and Nz) in (ft/sec^2). All sensors are located at the "Navigation Base". The total measurement at a sensor consists of rigid-body plus flex motion.
3. The flexible vehicle dataset also requires a set of modal data. The modes are already pre-selected, scaled and the modes set is included at the bottom of the input data file. The title of the modal dataset is "*Rocket Plane at Mach=0.85, Q=150, Flex Model, (30 Mixed Modes)*". The number of the flex modes to be included is defined in the vehicle dataset, and it is 30 modes, "*Number of Bending Modes: 30*". The title of the selected set of modes to be combined with the vehicle data is also included at the bottom of the vehicle dataset, see above.
4. The selected set of modes are saved in the same input file. The input file may contain more than one set of modes using different titles for different applications. In this case we have two sets of selected modes in file "*RocketPlane-Flx.Inp*": a set of pitch modes and a set of mixed modes. We will be using the second set, which is the mixed modes. The modal dataset contains the mode shapes, slopes and frequencies of 30 modes that were selected via a mode-selection process. It is a reduced set of modes that was extracted from a separate, much bigger, modal data file that was created from a finite elements program, such as Nastran. The mode shapes and slopes correspond to important vehicle locations which are defined in the vehicle model, such as: aero-surface hinges, engine, gyros, and accelerometers.
5. The mode-selection program was used to create the selected set of modes by comparing their modal strengths between excitations and sensors and selecting the 30 strongest modes. The mode selection process will be discussed later.

Batch for Creating the Flexible Rocket Plane
! This batch creates a flexible model for the rocket plane including 30 modes from all directions.
! It creates also electro-mechanical actuator models for the flaps, rudders and body-flap aerosurfaces
! It preserves the previously calculated effectors mixing logic for the five aero-surfaces and
! the engine throttle control.
!
Retain Matrix   : Coupled axes Mixing Matrix for Rocket-Plane, K4axmix
Flight Vehicle   : Rocket Plane at Mach=0.85, Q=150, Flex Model
Actuator Model   : Electro-Mechanical Flap Type-B Actuator
Actuator Model   : Electro-Mechanical Rudder Type-B Actuator
Actuator Model   : Electro-Mechanical Body-Flap Type-B Actuator
!
!   Save Systems and Matrices for Matlab
To Matlab Format : Rocket Plane at Mach=0.85, Q=150, Flex Model
To Matlab Format : Coupled axes Mixing Matrix for Rocket-Plane, K4axmix
To Matlab Format : Electro-Mechanical Flap Type-B Actuator
To Matlab Format : Electro-Mechanical Rudder Type-B Actuator
To Matlab Format : Electro-Mechanical Body-Flap Type-B Actuator
----

FLIGHT VEHICLE INPUT DATA ......
Rocket Plane at Mach=0.85, Q=150, Flex Model
! The following vehicle is a Rocket Plane. It is controlled by 5 aerosurfaces which are:
! 2 flaps, 2 rudders, and a body-flap. It also has a non-gimbaling throttling engine.
! The tail-wags-dog option in the aerosurfaces is turned on.
!
Body Axes Output, Attitude=Euler Angles, Without GAFD, No Turn Coordination

Vehicle Mass (lb-sec^2/ft), Gravity Accelerat. (g) (ft/sec^2), Earth Radius (Re) (ft)   : 198.32   32.17   0.20896E+08
Moments and products of Inertias Ixx, Iyy, Izz, Ixy, Ixz, Iyz, in (lb-sec^2-ft)   : 1098.0   10933.   11290.   0.0000   123.75
CG location with respect to the Vehicle Reference Point, Xcg, Ycg, Zcg, in (feet)   : -15.167   0.0000   0.467
Vehicle Mach Number, Velocity Vo (ft/sec), Dynamic Pressure (psf), Altitude (feet)   : 0.85000   822.80   150.13   45880.
Inertial Acceleration Vo_dot, Sensed Body Axes Accelerations Ax,Ay,Az (ft/sec^2)   : -0.81   -1.14   0.0000   -32.15
Angles of Attack and Sideslip (deg), alpha, beta rates (deg/sec)   : 2.0   0.0   1.76   0.0000
Vehicle Attitude Euler Angles, Phi_o,Thet_o,Psi_o (deg), Body Rates Po,Qo,Ro (deg/sec)   : -0.16079   2.0000   0.0000   0.0000   0.0000
Wind Gust Vel wrt Vehicle (Azim & Elev) angles, or Force (lb), location, Torque (ft-lb) : Gust   45.0   90.0
Surface Reference Area (feet^2), Mean Aerodynamic Chord (ft), Wing Span in (feet)   : 79.0   6.1   15.0
Aero Moment Reference Center (Xmrc,Ymrc,Zmrc) Location in (ft), {Partial_rho/ Partial_H} : -14.792   0.0000   0.54000   0.0000
Aero Force Coef/Deriv (1/deg), Along -X, {Cao,Ca_alf,PCa/PV,PCa/Ph,Ca_alfdot,Ca_q,Ca_bet}: 0.143,   -0.0039,   0.0004, 0.0,   0.0,   -0.244, 0.0
Aero Force Coeffic/Derivat (1/deg), Along Y, {Cyo,Cy_bet,Cy_r,Cy_alf,Cy_p,Cy_betdot,Cy_V}: 0.0,   -0.0245,   1.77,   0.0,   0.00838, 0.0,   0.0
Aero Force Coeff/Deriv (1/deg), Along Z, {Czo,Cz_alf,Cz_q,Cz_bet,PCz/Ph,Cz_alfdot,PCz/PV}: -0.14,   -0.073,   -9.93, 0.0,   0.0,   0.0,   0.00093
Aero Moment Coeffic/Derivat (1/deg), Roll: {Clo, Cl_beta, Cl_betdot, Cl_p, Cl_r, Cl_alfa}: 0.0,   -0.00212,   0.0,   -0.393, 0.427,   0.0
Aero Moment Coeff/Deriv (1/deg), Pitch: {Cmo, Cm_alfa,Cm_alfdot,Cm_bet,Cm_q,PCm/PV,PCm/Ph}: -0.0838, -0.015,   0.0,   0.0,   -12.83, 0.0004, 0.0
Aero Moment Coeffic/Derivat (1/deg), Yaw : {Cno, Cn_beta, Cn_betdot, Cn_p, Cn_r, Cn_alfa}: 0.0,   0.001,   0.0,   0.184, -1.49,   0.0

Number of Control Surfaces, With or No TWD (Tail-Wags-Dog and Hinge Moment Dynamics) ?   : 5   WITH TWD

Control Surface No: 1   Left Flap
Trim Angle, Max/Min Deflection Angles from Trim, Hinge Line Angles: phi_h, lamda_h (deg): 0.0   30.000   -30.000   +2.0000   0.000
Surface Mass, Inertia about Hinge, Moment Arm (Hinge to Surface CG), Surface Chord, Area : 1.185   0.4   0.283   1.2070   5.5530
Hinge Moment Derivatives (1/deg), { Chm_Alpha, Chm_Beta, Chm_Delta, Chm_Mach }   : -0.0047   -0.00055   -0.0097   0.0000
Location of the Hinge Line Center with respect to Vehicle Reference (feet), {Xcs,Ycs,Zcs}: -18.7   -2.64   2.0733
Forces (-x,y,z) due to Deflect. and Rates {Ca_del,Cy_del,Cz_del, Ca_deld,Cy_deld,Cz_deld}: 0.45432E-03 -0.24668E-02 -0.60478E-02 0.0000   0.0000
Moments due to Deflections and Rates {Cl_del,Cm_del,Cn_del,Cl_deldot,Cm_deldot,Cn_deldot}: 0.11893E-02 -0.26625E-02 0.81515E-03 0.0000   0.0000
Control Surface No: 2   Right Flap
Trim Angle, Max/Min Deflection Angles from Trim, Hinge Line Angles: phi_cs,lamda_cs (deg): 0.0   30.000   -30.000   -2.0000   0.000
Surface Mass, Inertia about Hinge, Moment Arm (Hinge to Surface CG), Surface Chord, Area : 1.185   0.4   0.283   1.2070   5.5530
Hinge Moment Derivatives (1/deg), { Chm_Alpha, Chm_Beta, Chm_Delta, Chm_Mach }   : -0.0047   0.00055   -0.0097   0.0000
Location of the Hinge Line Center with respect to Vehicle Reference (feet), {Xcs,Ycs,Zcs}: -18.7   2.64   2.0733
Forces (-x,y,z) due to Deflect. and Rates {Ca_del,Cy_del,Cz_del, Ca_deld,Cy_deld,Cz_deld}: 0.45432E-03 0.24668E-02 -0.60478E-02 0.0000   0.0000
Moments due to Deflections and Rates {Cl_del,Cm_del,Cn_del,Cl_deldot,Cm_deldot,Cn_deldot}: -0.11893E-02 -0.26625E-02 -0.81515E-03 0.0000   0.0000
Control Surface No: 3   Left Rudder
Trim Angle, Max/Min Deflection Angles from Trim, Hinge Line Angles: phi_cs,lamda_cs (deg): -1.2   30.000   -30.000   48.000   0.000
Surface Mass, Inertia about Hinge, Moment Arm (Hinge to Surface CG), Surface Chord, Area : 2.19   4.0   0.833   2.2830   10.382
Hinge Moment Derivatives (1/deg), { Chm_Alpha, Chm_Beta, Chm_Delta, Chm_Mach }   : -0.019   0.0229   -0.0236   0.0000
Location of the Hinge Line Center with respect to Vehicle Reference (feet), {Xcs,Ycs,Zcs}: -25.3333   -3.395   -1.6242
Forces (-x,y,z) due to Deflect. and Rates {Ca_del,Cy_del,Cz_del, Ca_deld,Cy_deld,Cz_deld}: 0.46197E-03 0.47413E-02 -0.51664E-02 0.0000   0.0000
Moments due to Deflections and Rates {Cl_del,Cm_del,Cn_del,Cl_deldot,Cm_deldot,Cn_deldot}: -0.17964E-02 -0.98720E-02 -0.35668E-02 0.0000   0.0000
Control Surface No: 4   Right Rudder
Trim Angle, Max/Min Deflection Angles from Trim, Hinge Line Angles: phi_cs,lamda_cs (deg): -1.2   30.000   -30.000   -48.000   0.000
Surface Mass, Inertia about Hinge, Moment Arm (Hinge to Surface CG), Surface Chord, Area : 2.19   4.0   0.833   2.2830   10.382
Hinge Moment Derivatives (1/deg), { Chm_Alpha, Chm_Beta, Chm_Delta, Chm_Mach }   : -0.019   -0.0229   -0.0236   0.0000
Location of the Hinge Line Center with respect to Vehicle Reference (feet), {Xcs,Ycs,Zcs}: -25.3333   3.395   -1.6242
Forces (-x,y,z) due to Deflect. and Rates {Ca_del,Cy_del,Cz_del, Ca_deld,Cy_deld,Cz_deld}: 0.46197E-03 -0.47413E-02 -0.51664E-02 0.0000   0.0000
Moments due to Deflections and Rates {Cl_del,Cm_del,Cn_del,Cl_deldot,Cm_deldot,Cn_deldot}: -0.17964E-02 -0.98720E-02 0.35668E-02 0.0000   0.0000
Control Surface No: 5   Body Flap
Trim Angle, Max/Min Deflection Angles from Trim, Hinge Line Angles: phi_cs,lamda_cs (deg): -10.0   40.000   -40.000   0.0000   0.0000
Surface Mass, Inertia about Hinge, Moment Arm (hinge to surface CG), Surface Chord & Area: 1.8   2.2   0.6   1.6670   5.7430
Hinge Moment Derivatives (1/deg), { Chm_Alpha, Chm_Beta, Chm_Delta, Chm_Mach }   : -0.1e-03   0.0000   -0.10E-03   0.0000
Location of the Hinge Line Center with respect to Vehicle Reference (feet), {Xcs,Ycs,Zcs}: -25.8   0.0000   0.80000
Forces (-x,y,z) due to Deflect. and Rates {Ca_del,Cy_del,Cz_del, Ca_deld,Cy_deld,Cz_deld}: -0.83830E-05 0.0000   -0.59235E-03 0.0000   0.0000
Moments due to Deflections and Rates {Cl_del,Cm_del,Cn_del,Cl_deldot,Cm_deldot,Cn_deldot}: 0.0000   -0.15765E-02 0.0000   0.0000   0.0000

```
Number of Thruster Engines, Include or Not the Tail-Wags-Dog and Load-Torque Dynamics ?  :  1

TVC Engine No:   1                              (Gimbaling  Throttling   Single_Gimbal) : Engine Throtl     Throttling
Engine Nominal Thrust, and Maximum Thrust in (lb)    (for throttling)                   : 2000.0         4000.0
Mounting Angles wrt Vehicle (Dyn,Dzn), Maximum Deflections from Mount (Dymax,Dzmax) (deg): -1.3           0.0            0.0             0.0
Eng Mass (slug), Inertia about Gimbal (lb-sec^2-ft), Moment Arm, engine CG to gimbal (ft): 2.00           65.0           0.8
Gimbal location with respect to the Vehicle Reference Axes, Xgimb, Ygimb, Zgimb, in (ft) : -26.5          0.0            0.0

Number of Gyros, (Attitude and Rate)                                                     :  3
Gyro No 1 Axis:(Pitch,Yaw,Roll), (Attitude or Rate), Location in Vehicle Axes   (feet)   :  Roll Rate              -8.8, 0.0, -0.19
Gyro No 2 Axis:(Pitch,Yaw,Roll), (Attitude or Rate), Location in Vehicle Axes   (feet)   :  Pitch Rate             -8.8, 0.0, -0.19
Gyro No 3 Axis:(Pitch,Yaw,Roll), (Attitude or Rate), Location in Vehicle Axes   (feet)   :  Yaw Rate               -8.8, 0.0, -0.19

Number of Accelerometers, (x,y,z)                                                        :  2
Acceleromet No 1 Axis:(X,Y,Z), (Acceleration,Flex_Posit,Flex_Veloc,Flex_Accel), Locat(ft): Y-axis Acceleration    -8.8, 0.0, -0.19
Acceleromet No 2 Axis:(X,Y,Z), (Acceleration,Flex_Posit,Flex_Veloc,Flex_Accel), Locat(ft): Z-axis Acceleration    -8.8, 0.0, -0.19

Number of Bending Modes                                                                  :  30
Rocket Plane at Mach=0.85, Q=150, Flex Model, (30 Mixed Modes)
-------------------------------------------------------------------------------------------------------
```

Three different electro-mechanical actuator models are created for the flaps, the rudders, and the body-flap. They are implemented from 3 different actuator datasets that use the same actuator model type but different parameters for each aerosurface because the stiffnesses, load inertias, motors, and overall geometries are different. The 3 actuator datasets are processed by the Flixan program to create the 3 actuator systems. In addition to the electro-mechanical parameters the datasets include compensator filters that stabilize the actuator loop. The actuator design and stability analysis are presented for each aerosurface in Section-4.

The flex vehicle, the 3 actuator systems and the mixing-logic matrix are converted to Matlab function m-files using the "*Export to Matlab*" utility. The vehicle system is saved in file "*vehi_30flx.m*" and the actuators are saved in files: "*rudder_ema.m*", "*flap.m*", and "*bodyflap.m*". They will be used to analyze stability in Matlab.

```
-------------------------------------------------------------------------------------------------------
            3 ELECTRO-MECHANICAL ACTUATOR MODELS (2-Flaps, 2-Rudders and Body-Flap)
-------------------------------------------------------------------------------------------------------
ACTUATOR INPUT DATA ............ ELECTROMECHANICAL TYPE B
Electro-Mechanical Flap Type-B Actuator
! This EMA system includes a PID Controller with a Second Order Compensator
! Input-1 is the Deflection command in (rad)
! Input-2 is the Load-Torque in (foot pounds)
! The Outputs are in radians
!
Symbol        Parameter Description                  (Units)        Value
C(s)    Order of Compensat:(0,1,2), Coefficients    (---)         2, 1.2,2000.0, 0.6,250.0
Kpl     Position Error Loop Gain                    (Volt/ft)      60.0
Krf     Rate Feedback Gain                          (Volt/ft/sec)  0.00045
Ki      Position Error Integral Gain                (Volt/ft-sec)  10.0
Wm      Servo Motor Bandwidth,                      (rad/sec)      1200.0
Kv      Servo Motor Torque Gain                     (ft-lb/volt)   100.0
Jm      Motor Rotor Moment of Inertia               (ft-lb-sec^2)  2.0e-5
Ngr     Gear Ratio (Motor Turns/ Screw Turns)       ( - )          10.25
Nscr    Screw Ratio (Piston Extension/Screw Turns) (ft/rad)       0.0026
Kgs     Motor Gear Stiffness                        (ft-lb/rad)    350.0
Kmfr    Motor/ Gear Friction                        (ft-lb/rad/sec) 0.03
Kdmp    Shaft Damping Friction                      (ft-lb/rad/sec) 0.004
Keff    Gear Effectiveness Coefficient              ( - )          0.8
Ja      Gear plus Screw Inertia                     (ft-lb-sec^2)  4.6e-4
Kact    Actuator Stiffness (Piston+Electric).... (lb/ft)          2.0e+6
Klod    Load Stiffness,(Con. Surface or Nozzle)   (lb/ft)         0.5e+6
Kbck    Vehicle Backup Structure Stiffness ..... (lb/ft)          0.5e+6
R       Moment Arm of Actuator Shaft from Gimbal..  (feet)         0.4
Je      Load Inertia about the Gimbal ....... (ft-lb-sec^2)       0.4
Be      Aero-Surface Bearing Viscous Damping    (ft-lb-sec)       30.0
Kg      Aero-Surface Bearing Spring Constant    (ft-lb/rad)       0.0
-------------------------------------------------------------------------------------------------------
```

ACTUATOR INPUT DATA .... ELECTROMECHANICAL TYPE B
Electro-Mechanical Rudder Type-B Actuator
! This EMA actuator Uses an Extendable Shaft to Drive a Load.
! The end of the rod is attached to a lever arm that rotates the Aero-Surface.
! Input-1 is the Deflection command in (rad)
! Input-2 is the Load-Torque in (foot pounds)
! The Outputs are in radians
!

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)	480.0
Krf	Rate Feedback Gain	(Volt/in/sec)	0.004
Ki	Position Error Integral Gain	(Volt/ft-sec)	1.2
Wm	Servo Motor Bandwidth,	(rad/sec)	2000.0
Kv	Servo Motor Torque Gain	(ft-lb/volt)	300.0
Jm	Motor Rotor Moment of Inertia	(ft-lb-sec^2)	0.8e-4
Ngr	Gear Ratio (Motor Turns/ Screw Turns)	(-)	17.0
Nscr	Screw Ratio (Piston Extension/Screw Turns)	(ft/rad)	0.0027
Kgs	Motor Gear Stiffness	(ft-lb/rad)	700.0
Kmfr	Motor/ Gear Friction	(ft-lb/rad/sec)	0.005
Kdmp	Shaft Damping Friction	(ft-lb/rad/sec)	0.002
Keff	Gear Effectiveness Coefficient	(-)	0.85
Ja	Gear plus Screw Moment of Inertia ...	(ft-lb-sec^2)	2.5e-4
Kact	Actuator Stiffness (Piston+Electric)....	(lb/ft)	0.32e+7
Klod	Load Stiffness,(Con. Surface or Nozzle)	(lb/ft)	0.34e+7
Kbck	Vehicle Backup Structure Stiffness	(lb/ft)	0.42e+7
R	Moment Arm of Actuator Rod from Gimbal..	(ft)	0.3
Je	Load Inertia about the Gimbal	(ft-lb-sec^2)	4.0
Be	Nozzle Bearing Viscous Damping	(in-lb-sec)	80.0
Kg	Gimbal Bearing Spring Constant	(in-lb/rad)	0.0000

ACTUATOR INPUT DATA .... ELECTROMECHANICAL TYPE B
Electro-Mechanical Body-Flap Type-B Actuator
! This EMA actuator Uses an Extendable Shaft to Drive a Load.
! The end of the rod is attached to a lever arm that rotates the Aero-Surface.
! Input-1 is the Deflection command in (rad)
! Input-2 is the Load-Torque in (foot pounds)
! The Outputs are in radians
!

Symbol	Parameter Description	(Units)	Value
C(s)	Order of Compensat:(0,1,2), Coefficients	(---)	1, 0.0, 0.0125
Kpl	Position Error Loop Gain	(Volt/ft)	140.0
Krf	Rate Feedback Gain	(Volt/in/sec)	0.0005
Ki	Position Error Integral Gain	(Volt/ft-sec)	5.0
Wm	Servo Motor Bandwidth,	(rad/sec)	1800.0
Kv	Servo Motor Torque Gain	(ft-lb/volt)	260.0
Jm	Motor Rotor Moment of Inertia	(ft-lb-sec^2)	5.0e-5
Ngr	Gear Ratio (Motor Turns/ Screw Turns)	(-)	10.2
Nscr	Screw Ratio (Piston Extension/Screw Turns)	(ft/rad)	0.0026
Kgs	Motor Gear Stiffness	(ft-lb/rad)	400.0
Kmfr	Motor/ Gear Friction	(ft-lb/rad/sec)	0.03
Kdmp	Shaft Damping Friction	(ft-lb/rad/sec)	0.001
Keff	Gear Effectiveness Coefficient	(-)	0.85
Ja	Gear plus Screw Moment of Inertia ...	(ft-lb-sec^2)	2.0e-4
Kact	Actuator Stiffness (Piston+Electric)....	(lb/ft)	2.4e+7
Klod	Load Stiffness,(Con. Surface or Nozzle)	(lb/ft)	0.36e+7
Kbck	Vehicle Backup Structure Stiffness	(lb/ft)	0.36e+7
R	Moment Arm of Actuator Rod from Gimbal..	(ft)	0.287
Je	Load Inertia about the Gimbal	(ft-lb-sec^2)	2.2
Be	Nozzle Bearing Viscous Damping	(in-lb-sec)	20.0
Kg	Gimbal Bearing Spring Constant	(in-lb/rad)	0.0000

CONVERT TO MATLAB FORMAT ....   (TITLE, SYSTEM/MATRIX, M-FILENAME)
Rocket Plane at Mach=0.85, Q=150, Flex Model
System
Vehi_30flx

CONVERT TO MATLAB FORMAT ....   (TITLE, SYSTEM/MATRIX, M-FILENAME)
Coupled axes Mixing Matrix for Rocket-Plane, K4axmix
Matrix K4axmix

CONVERT TO MATLAB FORMAT ....   (Title, System/Matrix, m-filename)
Electro-Mechanical Flap Type-B Actuator
System
flap_ema

CONVERT TO MATLAB FORMAT ....   (Title, System/Matrix, m-filename)
Electro-Mechanical Rudder Type-B Actuator
System
rudder_ema

CONVERT TO MATLAB FORMAT ....   (Title, System/Matrix, m-filename)
Electro-Mechanical Body-Flap Type-B Actuator
System
bodyflap_ema

SELECTED MODAL DATA AND LOCATIONS FOR MIXED AXES MODES
Rocket Plane at Mach=0.85, Q=150, Flex Model, (30 Mixed Modes)
! Select 30 flex modes from all three, roll, pitch, and yaw axes
! Run the mode selection program to select 30 modes from all directions using the modal data
! file (RocketPlane.Mod) using the the Node locations from file (RocketPlane.Nod), Select
! 4 force excitation points at the center of the four control surfaces with the force
! directions along z.
! Select 2 torque excitation points at the two rudders and apply pitch moments,
! Select 2 translation sensor points at the left and right nav bases sensing along the z
! axis. Select 1 rotational sensor point at the center nav base sensing pitch rotations.
! Then using the node map menu identify the locations of the four control surfaces, the
! engine, the 3 gyros, the accelerometers, and one disturbance point in case that you
! want to apply an excitation force in the (A,B,C,D) model

MODE # 1/ 1, Frequency (rad/sec), Damping (zeta), Generalized Mass=   63.168   0.50000E-02   12.000
DEFINITION OF LOCATIONS (NODES)   phi along X   phi along Y   phi along Z   sigm about X   sigm about Y   sigm about Z

                          Node ID#   Modal Data at the 5 Control Surfaces (Hinges)
LEFT OUTBOARD FLAP HINGE LINE   60008   0.88837D-01   0.80693D-01 -0.31931D+00   0.55369D-01 -0.15543D-01   0.10639D-01
RIGHT OUTBOARD FLAP HINGE LINE 160008   -0.90890D-01   0.80487D-01   0.32028D+00   0.54879D-01   0.15552D-01   0.10600D-01
LEFT RUDDER HINGE LINE POINT   81441   0.11619D+00   0.11498D+00 -0.20924D+00   0.70946D-01 -0.21047D-01   0.19172D-01
RIGHT RUDDER HINGE LINE POINT   181441   -0.11864D+00   0.11503D+00   0.21196D+00   0.71042D-01   0.21263D-01   0.19094D-01
BODY FLAP HINGE (ENGINE GIMBAL   70270   -0.11188D-02 -0.16957D+00   0.13759D-02   0.61874D-01   0.41981D-04   0.28465D-01

                          Node ID#   Modal Data at the 1 Engines, (x,y,z)...
BODY FLAP HINGE (ENGINE GIMBAL   70270   -0.11188D-02 -0.16957D+00   0.13759D-02   0.61874D-01   0.41981D-04   0.28465D-01

                          Node ID#   Modal Data at the 3 Gyros ...
CENTER NAVIGATION BASE   22426   -0.18752D-02 -0.18791D+00 -0.11932D-02 -0.12250D+00   0.42723D-03   0.65102D-01
CENTER NAVIGATION BASE   22426   -0.18752D-02 -0.18791D+00 -0.11932D-02 -0.12250D+00   0.42723D-03   0.65102D-01
CENTER NAVIGATION BASE   22426   -0.18752D-02 -0.18791D+00 -0.11932D-02 -0.12250D+00   0.42723D-03   0.65102D-01

                          Node ID#   Modal Data at the 2 Accelerometers, along (x,y,z)...
CENTER NAVIGATION BASE   22426   -0.18752D-02 -0.18791D+00 -0.11932D-02
CENTER NAVIGATION BASE   22426   -0.18752D-02 -0.18791D+00 -0.11932D-02

                          Node ID#   Modal Data at the Disturbance Point
Thruster RUa, +Z   113538   -0.65461D-01   0.75161D-01   0.12025D+00   0.57916D-01   0.14990D-02   0.32534D-01

MODE # 2/ 2, Frequency (rad/sec), Damping (zeta), Generalized Mass=   80.049   0.50000E-02   12.000
DEFINITION OF LOCATIONS (NODES)   phi along X   phi along Y   phi along Z   sigm about X   sigm about Y   sigm about Z

2.2 Processing the Input File in Batch Mode

To process the input file in batch mode, start the Flixan program, select the analysis folder "*18-Rocket Plane\2-Flex Model*" and from the top menu select "*File Management*", "*Managing Input Files*", and then "*Edit/ Process Input Files*", as shown. The input file manager utility comes up and from the left menu select the input file "*Rocket_Later_RB.Inp*" and click on "Select Input File" button. The right menu shows all the datasets which are in the input file. Select the batch set "*Batch for Creating the Flexible Rocket Plane*" and click on "*Process Input Data*" to process the entire file. The data are saved in the systems file and Matlab files.
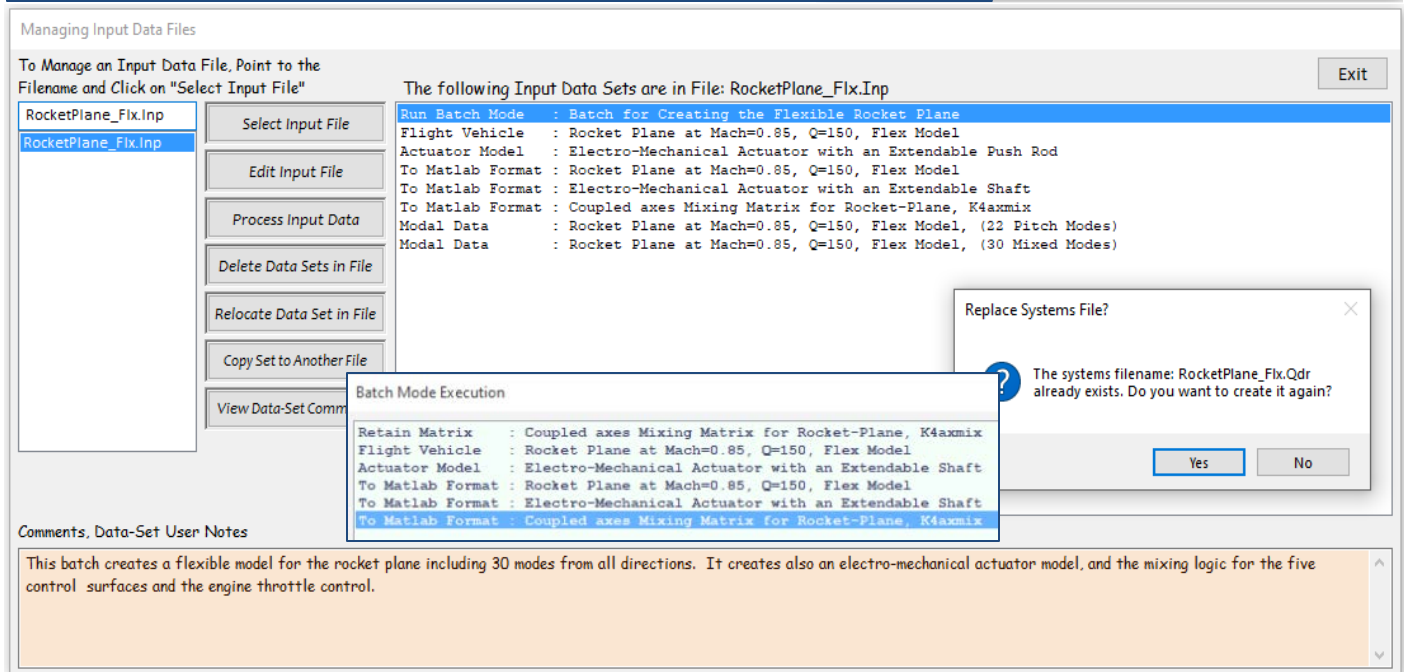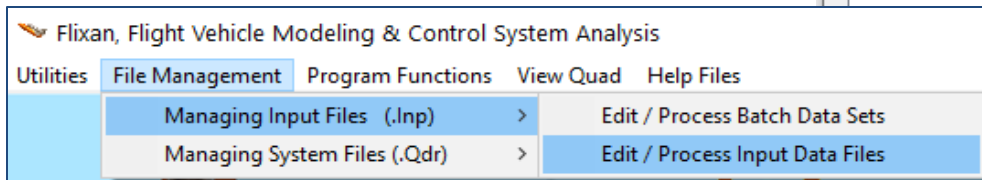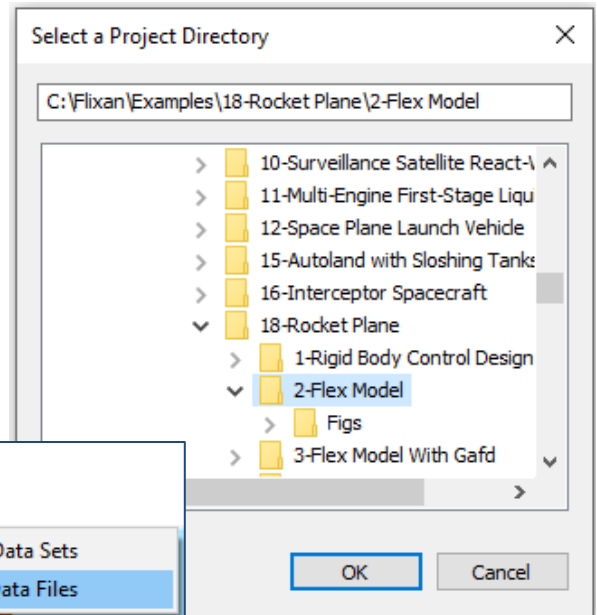
2.3 Creating the Vehicle System from Scratch by Entering the Vehicle Data
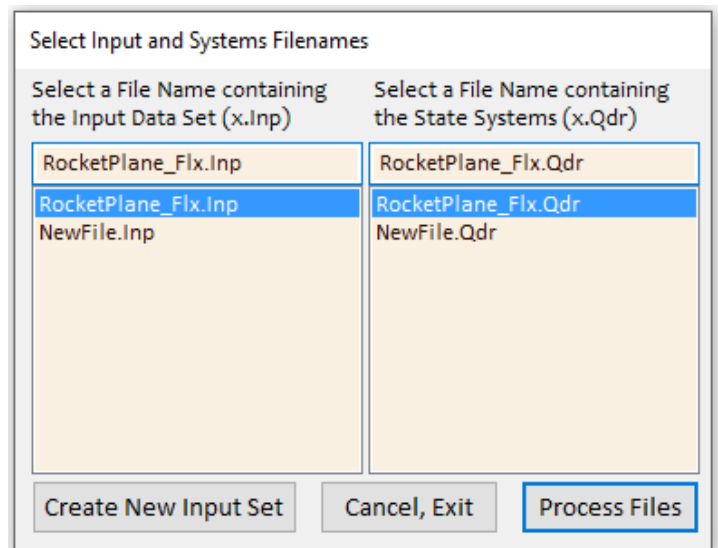
Let us assume for tutorial purposes that the vehicle data and the selected modal data do not exist in file "*RocketPlane_Flx.Inp*" and we have to create them from scratch. To create the vehicle dataset, start the Flixan program and select the directory *"Flixan\ Examples\ 18-Rocket Plane\2-Flex Model"*. From the Flixan main menu go to "*Program Functions*", "*Flight Vehicle/ Spacecraft Modeling Tools*", and then "*Flight Vehicle State-Space Modeling*".
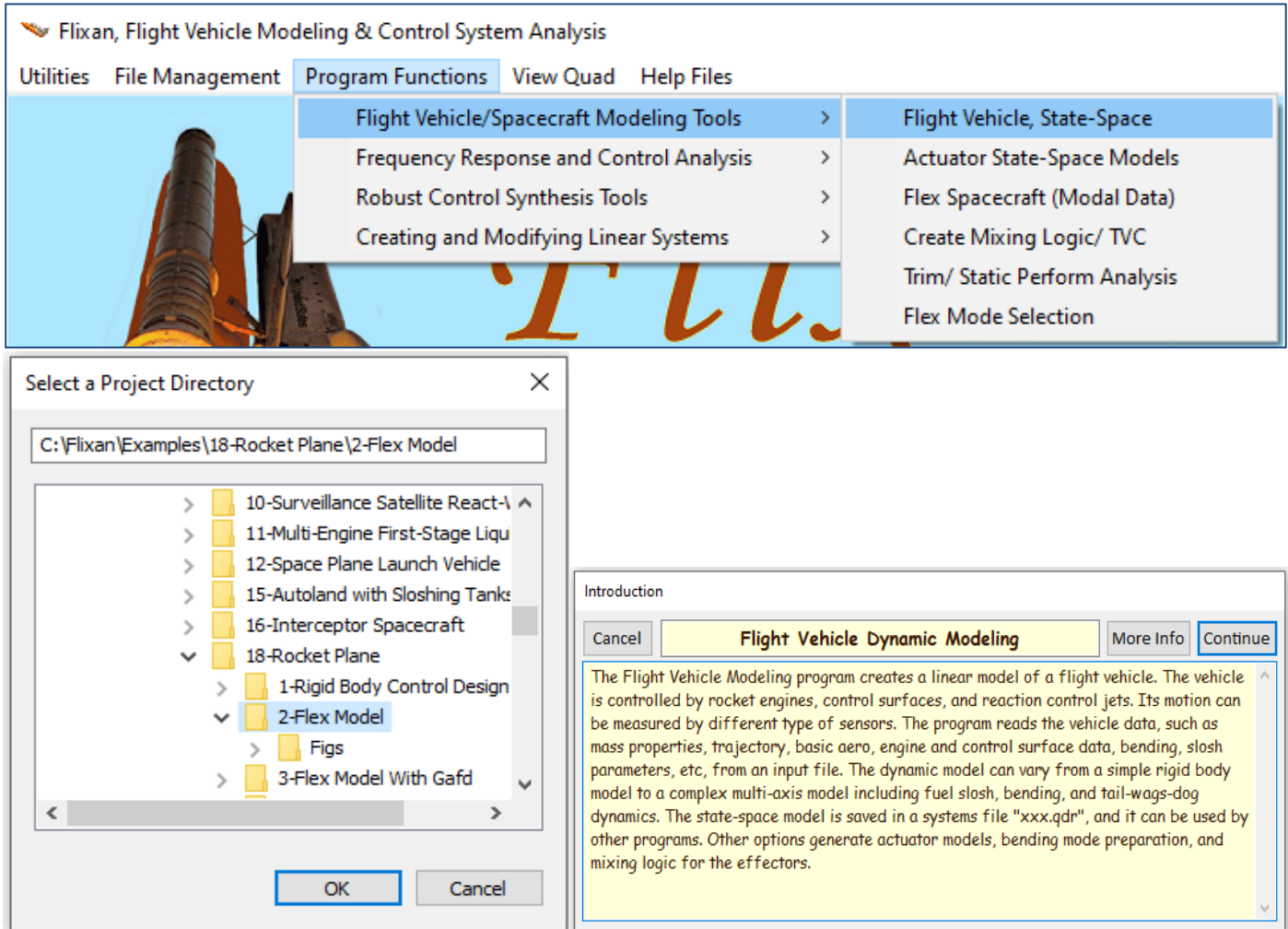
Select the input and the systems filenames from this menu. Do not process the already existing vehicle dataset but click on "*Create New Set*" to create a new vehicle dataset in the input file "*RocketPlane_Flx.Inp*".

The flight vehicle modeling dialog comes up where you can enter the vehicle rigid-body data, starting with the new title, the number of engines, aerosurfaces, sensors, flags, the number of flex modes, and then select the various tabs to enter different types of vehicle data, such as mass properties, aerosurfaces, engine, etc. Click on "*Update Data*" every time you finish a tab. The click on "*Save in File*" to save the vehicle dataset in the input file. To run it click on "*Run*".

Flight Vehicle Parameters

Vehicle System Title

Rocket Plane at Mach=0.85, Q=150, Flex Model-2

Edit Input File	Exit
Update Data	Run
Save in File	

Number of Vehicle Effectors

Gimbaling Engines or Jets.
Include Tail-Wags-Dog? `1` WITH TWD / WITHOUT TWD

Rotating Control Surfaces.
Include Tail-Wags-Dog? `5` WITH TWD / WITHOUT TWD

Reaction Wheels? `0`   **Momentum Control Devices**

Single Gimbal CMGs? `0`

Include a Centralized, 3-Axes Momentum Control System? Yes / No

Number of Sensors

Gyros `3`
Accelerometers `2`
Aero Probes `0`
External Torques `0`

Modeling Options (Flags)

Output Rates in
- Body Axes
- Stability Axes

Turn Coordination ?
- Include Turn Coordina
- Without Turn Coordir

Aero-Elasticity Options
- Include GAFD, H-param
- Flex Coupl. data only
- Neither Gafd nor Hpar

Attitude Angles
- Euler Angles
- Integrals of Rates
- LVLH Attitude

Number of Modes

Structure Bending `30`
Propellant Sloshing: `0`

Single Gimbal CMGs | Momentum Control System | Slewing Appendages | Gyros | Accelerometer | Aero Sensors | Fuel Slosh | Flex Modes | User Notes

Mass Properties | Trajectory Data | Gust/ Aero Paramet. | Aero Force Coeffs | Aero Moment Coeffs | Aero-Surfaces | Gimbal Engines/ RCS | External Torques | Reaction Wheels

Vehicle Mass Properties

Moments and Products of Inertia (slug-ft^2) | Center of Gravity Location (feet)

Ixx	1098.000	Ixy	0.000000	Xcg	-15.17000	Vehicle Mass in (slugs)	198.0000
Iyy	10933.00	Ixz	123.0000	Ycg	0.000000	Gravity Acceleration (ft/sec^2)	32.17000
Izz	11290.00	Iyz	0.000000	Zcg	0.4600000	Earth Radius (Re) in (feet)	0.2100000E+08

2.3 Flex Data Files

The set of modal data which are included in the input file "*RocketPlane_Flx.Inp*" have already been pre-selected and scaled using the mode-selection utility in Flixan. They contain mode shapes and slopes at the aerosurface hinges, the engine and at the sensors. The flex modes in this implementation are excited mainly by forces and torques which are applied at the aerosurface hinges. There are aerodynamic forces due to surface deflections and also reaction forces and torques at the hinges due to aerosurface accelerations, as it is described in the flight vehicle equations of motion documentation, Section 2.7. The modes are extracted from a bigger modal data file that was created from a finite elements model of the rocket vehicle and it contains many modes and a lot more vehicle locations (nodes). Before we get into the mode selection and scaling of the modal data, let's take a look into the original modal data file and also the nodes file (map).

Modal Data

The modal data file "*RocketPlane.Mod*" is a big file that contains in general many flex modes created by the FEM. In this case, however, it is not very big and it contains mode shapes and frequencies of the first 34 modes. An intermediate program was used to convert the Nastran output to a (.Mod) format which is recognizable by the Flixan mode selection program. The first two lines are titles. The next line includes the number of modes and the number of vehicle locations, 34 modes and 34 nodes. This modal data file includes 34 frames of data, a frame for each mode.

The first mode frame is shown in Figure 2.1 and they all have the same structure. The first line in each frame includes the mode number, the modal frequency in (rad/sec), the damping coefficient (ζ), and the modal mass (m_g) in (lb-sec^2/inch). The following lines of each frame consist of 7 columns. Each line corresponds to a vehicle location (node). The first column includes the node ID number from Nastran. The next 3 columns are the generalized modal displacements (in/in) along the x, y, z axes as defined in the FEM. The last 3 columns are the modal slopes (rad/inch), three rotations about x, y, z. They are calculated at 34 vehicle nodes which are more than the locations we need for creating this vehicle model.

```
STRUCTURAL MODAL DATA (units are in pounds and inches)
Rocket-Plane Vehicle
NUMBER OF MODES, NUMBER OF NODES                                   :  34, 34

Mode Number, Frequency (rad/sec), Damping (zeta), Generalized Mass (slug):  1     63.168      0.00500     1.0000
Node ID:    Along X          Along Y          Along Z          About X          About Y          About Z
  10090     0.201916D-02   0.111376D+00   0.683077D-02   0.115062D-01   0.653912D-04  -0.569218D-03
  10166    -0.289965D-01   0.136102D+00  -0.147636D+00   0.131684D-01   0.229789D-02  -0.359157D-02
  10208    -0.413012D-01   0.134740D+00  -0.190070D+00   0.118400D-01   0.118654D-02  -0.343731D-02
  13509    -0.886068D-01  -0.521235D-01   0.175243D+00  -0.470917D-02  -0.492131D-03  -0.272172D-02
  13511    -0.952493D-01  -0.275765D-01   0.185183D+00  -0.472717D-02  -0.816983D-03  -0.290010D-02
  13538    -0.630835D-01   0.751541D-01   0.117579D+00  -0.482783D-02  -0.118974D-03  -0.271161D-02
  13585    -0.929786D-01  -0.434397D-01   0.181776D+00  -0.463978D-02  -0.817482D-03  -0.276737D-02
  13591    -0.863121D-01  -0.683559D-01   0.171819D+00  -0.463550D-02  -0.446521D-03  -0.260681D-02
  13661    -0.630336D-01   0.589549D-01   0.118473D+00  -0.490819D-02  -0.118230D-03  -0.269733D-02
  21618    -0.752400D-01  -0.509957D-01   0.147152D+00  -0.482983D-02  -0.264887D-03  -0.251131D-02
  22423    -0.462971D-01  -0.186828D+00  -0.862749D-01   0.985333D-02  -0.848952D-03  -0.528802D-02
  22426     0.187520D-02  -0.187911D+00   0.119317D-02   0.102083D-01   0.356024D-04  -0.542516D-02
  60008    -0.888373D-01   0.806932D-01   0.319307D+00  -0.461408D-02  -0.129528D-02  -0.886574D-03
  60243    -0.706895D-01   0.737846D-01   0.235414D+00  -0.465481D-02  -0.127502D-02  -0.893124D-03
  70270     0.111877D-02  -0.169569D+00  -0.137594D-02  -0.515618D-02   0.349843D-05  -0.237211D-02
  70298     0.112730D-02  -0.178481D+00  -0.140549D-02  -0.501945D-02   0.359841D-05  -0.261205D-02
  81441    -0.116194D+00   0.114980D+00   0.209242D+00  -0.591220D-02  -0.175388D-02  -0.159766D-02
  81677    -0.144985D+00   0.156120D+00   0.273103D+00  -0.611940D-02  -0.185529D-02  -0.149629D-02
  84001    -0.407471D-01   0.607977D-01   0.947336D-01  -0.471673D-02  -0.109528D-02  -0.989511D-03
 110166     0.325089D-01   0.136229D+00   0.160513D+00   0.131985D-01  -0.219303D-02  -0.358195D-02
 110208     0.445374D-01   0.135047D+00   0.202205D+00   0.118592D-01  -0.105997D-02  -0.341557D-02
 113509     0.908647D-01  -0.521408D-01  -0.177939D+00  -0.470801D-02   0.493388D-03  -0.271793D-02
 113511     0.975121D-01  -0.276000D-01  -0.187876D+00  -0.472698D-02   0.816549D-03  -0.289482D-02
 113538     0.654606D-01   0.751609D-01  -0.120250D+00  -0.482635D-02   0.124917D-03  -0.271114D-02
 113585     0.952442D-01  -0.434406D-01  -0.184491D+00  -0.464022D-02   0.816446D-03  -0.276224D-02
 113591     0.885719D-01  -0.683556D-01  -0.174535D+00  -0.463546D-02   0.448085D-03  -0.260345D-02
 113661     0.654116D-01   0.589617D-01  -0.121183D+00  -0.490755D-02   0.124705D-03  -0.269739D-02
 121618     0.775396D-01  -0.509883D-01  -0.149880D+00  -0.482969D-02   0.267295D-03  -0.250508D-02
 122423     0.500104D-01  -0.186828D+00   0.886576D-01   0.985232D-02   0.924086D-03  -0.527811D-02
 160008     0.908899D-01   0.804870D-01  -0.320284D+00  -0.457328D-02   0.129604D-02  -0.883302D-03
 160243     0.728068D-01   0.736097D-01  -0.237211D+00  -0.461447D-02   0.127582D-02  -0.889943D-03
 181441     0.118636D+00   0.115028D+00  -0.211964D+00  -0.592020D-02   0.177188D-02  -0.159115D-02
 181677     0.147582D+00   0.156361D+00  -0.276150D+00  -0.612858D-02   0.187410D-02  -0.148925D-02
 184001     0.429484D-01  -0.605338D-01   0.976748D-01  -0.467734D-02  -0.109554D-02   0.986877D-03
---------------------------------------------------------------------------------------
```

Figure 2.1 Nastran Generated Modal Data File "RocketPlane.mod"

Nodes Map

The nodes map file for this vehicle is "*RocketPlane_Flx.Nod*". It is used as a look-up table by the mode selection program to help the analyst navigate through the modal data file and to match vehicle locations with nodes in the modal data. This file begins with 3 title lines on the top followed by a list of nodes in 6 columns. The nodes correspond and identify the locations in the modal data file (.Mod). The first column includes a short description of each location in the same sequence as in the modal data file. The second column is the node number (1 to 34) in ascending sequence (not the node id). The third column is the node id which is a large number (typically 4-5 digits long) created by the finite elements program and used for node identification. The next 3 columns include the x, y, z location of each node in vehicle coordinates.

The map file is used by the mode selection program. The nodes table pops-up in window menus when running the mode-selection program interactively. The analyst uses those menus to select vehicle locations and associate them with structural nodes in order to read the corresponding shapes and slopes from the modal data file. The nodes table is also used to select nodes and to perform mode strength comparison between specific structural points in order to select the dominant flex modes.

```
NODE IDENTIFICATION TABLE FOR THE ROCKET PLANE
Node Description                           Node No   Nastran ID   Node Location X,Y,Z (feet)
-----------------------------------------------------------------------------------------------
Thruster Frnt, Negative X                     1       10090      -0.9167    0.0000    0.0400
Thruster FDa, 40 Deg. off of -Z               2       10208      -2.0492   -1.3108    0.4692
Thruster FUa, 40 Deg. off of +Z               3       10166      -1.5092   -1.0175    0.3275
Thruster FDb, 40 Deg. off of -Z               4      110208      -2.0492    1.3108    0.4692
Thruster FUb, 40 Deg. off of +Z               5      110166      -1.5092    1.0175    0.3275
Thruster LNYa, -Y                             6       13511     -26.0833   -3.1058    0.2500
Thruster LNYb, 30 Deg. off of -Y              7       13585     -26.5833   -3.0342    0.2592
Thruster LDa, 15 Deg. off of -Z               8       13509     -26.0833   -2.9333    0.6800
Thruster LDb, 15 Deg. off of -Z               9       13591     -26.5833   -2.8600    0.6992
Thruster LUa, +Z                             10       13538     -26.0833   -1.9708   -1.5058
Thruster LUb, +Z                             11       13661     -26.5833   -1.9717   -1.5058
Thruster LAft, +X                            12       21618     -26.8333   -2.4433    0.2725
Thruster RPYa, +Y                            13      113511     -26.0833    3.1058    0.2500
Thruster RPYb, 30 Deg. off of Y              14      113585     -26.5833    3.0342    0.2592
Thruster RDa, 15 Deg. off of -Z              15      113509     -26.0833    2.9333    0.6800
Thruster RDb, 15 Deg. off of -Z              16      113591     -26.5833    2.8600    0.6992
Thruster RUa, +Z                             17      113538     -26.0833    1.9708   -1.5058
Thruster RUb, +Z                             18      113661     -26.5833    1.9717   -1.5058
Thruster RAft, +X                            19      121618     -26.8333    2.4433    0.2725
LEFT FLAP CENTER                             20       60243     -19.2583   -4.5083    1.8667
LEFT INBOARD FLAP HINGE LINE                 21       84001     -18.7000   -2.075     1.849
LEFT OUTBOARD FLAP HINGE LINE                22       60008     -18.7000   -6.1800    1.8733
RIGHT FLAP CENTER                            23      160243     -19.2583    4.5083    1.8667
RIGHT INBOARD FLAP HINGE LINE                24      184001     -18.7000    2.075     1.849
RIGHT OUTBOARD FLAP HINGE LINE               25      160008     -18.7000    6.1800    1.8733
LEFT RUDDER CENTER                           26       81677     -26.5500   -3.9075   -2.5000
LEFT RUDDER HINGE LINE POINT                 27       81441     -25.3333   -3.3950   -1.6242
RIGHT RUDDER CENTER                          28      181677     -26.5500    3.9075   -2.5000
RIGHT RUDDER HINGE LINE POINT                29      181441     -25.3333    3.3950   -1.6242
BODY FLAP CENTER POINT                       30       70298     -27.8667    0.0000    1.9683
BODY FLAP HINGE (ENGINE GIMBAL)              31       70270     -27.1750    0.0000    2.1667
LEFT NAVIGATION BASE                         32       22423      -8.8083   -0.7167   -0.1875
CENTER NAVIGATION BASE                       33       22426      -8.8083    0.0000   -0.1875
RIGHT NAVIGATION BASE                        34      122423      -8.8083    0.7167   -0.1875
-----------------------------------------------------------------------------------------------
```

Figure 2.2 Nodes Identification Table for the Modal Data

2.4 Modal Data Preparation

We will now describe the mode selection process that was used to create the selected set of modes "*Rocket Plane at Mach=0.85, Q=150, Flex Model, (30 Mixed Modes)*" which will be processed together with the vehicle data to create the flexible vehicle model. The selected set of modes is smaller, both, in terms of modes and nodes, in comparison with the original modal data file "*RocketPlane.Mod*". It is included as a dataset in the same input file below the vehicle data. In fact, in this example we will prepare two sets of selected modes: a set of predominantly pitch modes and a set of mixed modes that includes both: symmetric and anti-symmetric flex modes. The mode selection program also uses the vehicle dataset which is also used by the vehicle modeling program because it will extract modal data that correspond to the vehicle actuators and sensors.

Start the Flixan program and go to directory: *"C:\Flixan\Examples\18-Rocket Plane\2-Flex Model"*. From the main menu select: "*Program Functions*", "*Flight Vehicle/ Spacecraft Modeling Tools*", and then "*Flex Mode Selection*" to begin the mode selection program. Click "*Continue*" in the introduction. From the filenames selection menu select the modal data file "*RocketPlane.Mod*", the nodes (map) file "*RocketPlane.Nod*", and the vehicle input data file "*RocketPlane_Flx.Inp*". Select also the default output file that saves a list of mode strength versus mode frequency for all modes calculated between the excitation and sensor points, in specified directions. From the following menu select the title of the only vehicle input data-set "*Rocket Plane at Mach=0.85, Q=150, Flex Model*".
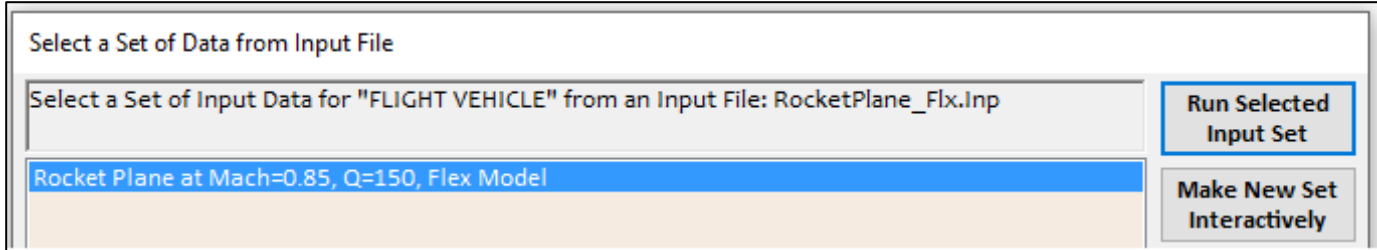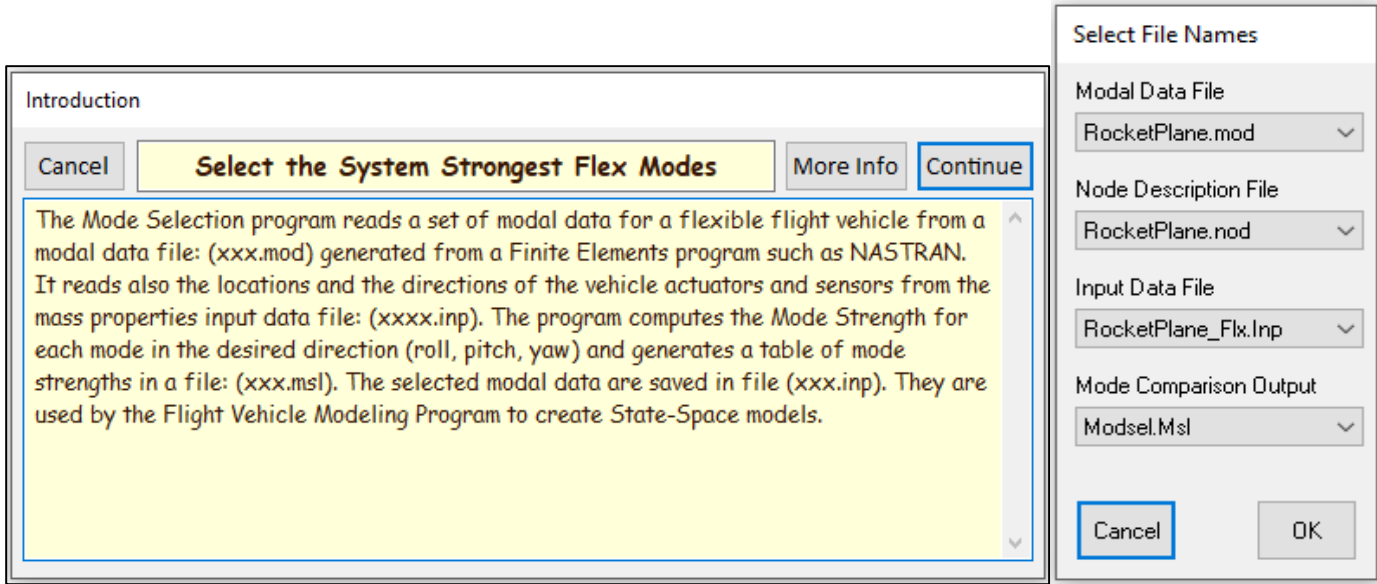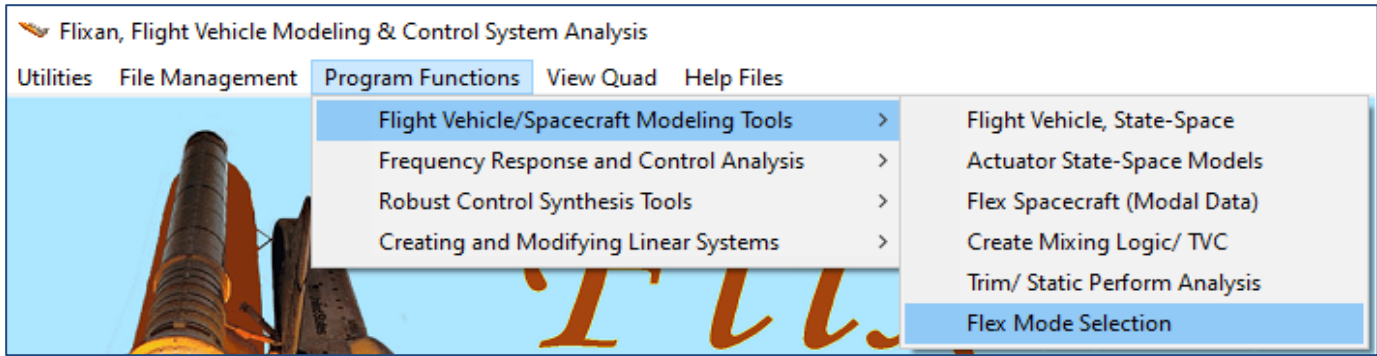
The next dialog is used to define the range of modes to be compared in strength and also the number of sensor and excitation points to be used in the mode selection. In this case we will compare all modes, from 1 to 34. Select the number of excitation forces (2) and torques (0), and also the number of translational (0) and rotational (1) measurements to be used in calculating the mode strength. Note that, the excitation and sensor locations chosen for mode selection are not necessarily the same as the actuator and sensor locations used in the vehicle model. They are only used for comparing the modal strength. Select the "*Graphics*" option in the dialog so that you will manually select the modes from a bar chart.
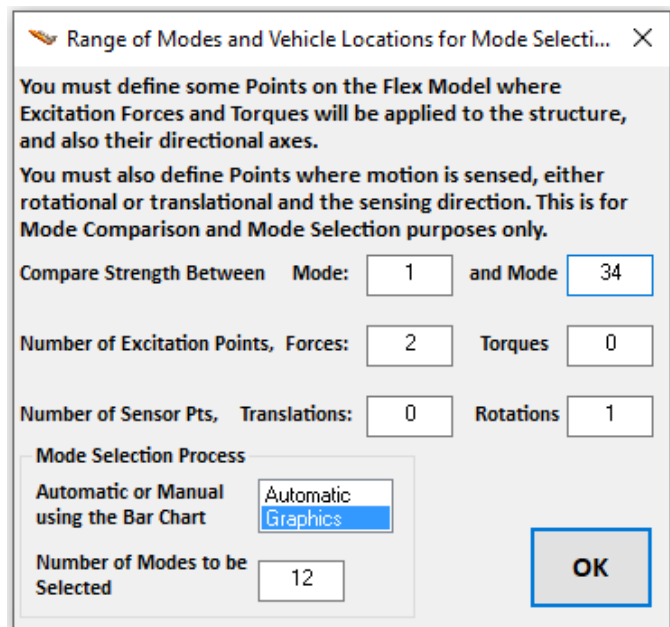
The next step is used for scaling and modifying the modal data. The mode shapes and slopes must be in units which are compatible with the vehicle data and not use the default Nastran units which are typically different from GN&C. The directions of the coordinate axes may also be different in the FEM. The x and z directions should be reversed because in Nastran models +x is usually defined towards the back of the vehicle and +z is up. The y direction is the same in both models. The modal data, therefore, are usually modified during mode selection. So, answer "Yes" in the following question "*Do you want to modify the modal data*"?

The generalized mass is defined in (lb-sec^2/inch) in which case it must be multiplied by 12 to be converted to (lb-sec^2/ft). Similarly, the modal slopes must be multiplied by 12 in order to be converted to (rad/feet). The mode selection program uses the following dialog which enables us to scale the modal data as needed to match the vehicle data. The default values were used in this case.

The next step is to define the excitation and sensor points on the structure to be used for mode strength comparison in order to select the stronger modes. This is not for defining modal data for the effectors and sensors. This will come later. In a previous dialog we specified that we will use two force excitation points and one rotational measurement point for mode-selection. We must now define those points and also the force directions using menus that include the nodes table. In the following menu select the location of the first force excitation point. For example, in selecting pitch modes we should apply the forces on the left and right flaps along the +Z direction to excite mainly the symmetric modes. Use the menus to choose node #20 "*Left Flap Center*" for force excitation #1, and node #23 "*Right Flap Center*" for force excitation #2, both in the +Z direction.

Definition of Vehicle Structural Nodes from FEM

In mode selection, you must define some node points in the Nastran model where the excitation forces and torques will be applied, and also their directions. It is used to calculate the mode strength and to compare the modes in specified directions

Similarly, you must define the sensor points, either translations or rotations and the sensing directions

OK   **Cancel**

Select a Location (Node) for Force Excitation : 1

Axis
Along-X
Along-Y
Along-Z

Direction
+ (positive)
- (negative)

Node Description	Node Number	Nastran Node ID Number	Location Coordinates (X, Y, Z)	
Thruster Frnt, Negative X	1	10090	-0.9167	0.0000
Thruster FDa, 40 Deg. off of -Z	2	10208	-2.0492	-1.3108
Thruster FUa, 40 Deg. off of +Z	3	10166	-1.5092	-1.0175
Thruster FDb, 40 Deg. off of -Z	4	110208	-2.0492	1.3108
Thruster FUb, 40 Deg. off of +Z	5	110166	-1.5092	1.0175
Thruster LNYa, -Y	6	13511	-26.0833	-3.1058
Thruster LNYb, 30 Deg. off of -Y	7	13585	-26.5833	-3.0342
Thruster LDa, 15 Deg. off of -Z	8	13509	-26.0833	-2.9333
Thruster LDb, 15 Deg. off of -Z	9	13591	-26.5833	-2.8600
Thruster LUa, +Z	10	13538	-26.0833	-1.9708
Thruster LUb, +Z	11	13661	-26.5833	-1.9717
Thruster LAft, +X	12	21618	-26.8333	-2.4433
Thruster RPYa, +Y	13	113511	-26.0833	3.1058
Thruster RPYb, 30 Deg. off of Y	14	113585	-26.5833	3.0342
Thruster RDa, 15 Deg. off of -Z	15	113509	-26.0833	2.9333
Thruster RDb, 15 Deg. off of -Z	16	113591	-26.5833	2.8600
Thruster RUa, +Z	17	113538	-26.0833	1.9708
Thruster RUb, +Z	18	113661	-26.5833	1.9717
Thruster RAft, +X	19	121618	-26.8333	2.4433
LEFT FLAP CENTER	20	60243	-19.2583	-4.5083
LEFT INBOARD FLAP HINGE LINE	21	84001	-18.7000	-2.075
LEFT OUTBOARD FLAP HINGE LINE	22	60008	-18.7000	-6.1800
RIGHT FLAP CENTER	23	160243	-19.2583	4.5083
RIGHT INBOARD FLAP HINGE LINE	24	184001	-18.7000	2.075
RIGHT OUTBOARD FLAP HINGE LINE	25	160008	-18.7000	6.1800
LEFT RUDDER CENTER	26	81677	-26.5500	-3.9075
LEFT RUDDER HINGE LINE POINT	27	81441	-25.3333	-3.3950
RIGHT RUDDER CENTER	28	181677	-26.5500	3.9075
RIGHT RUDDER HINGE LINE POINT	29	181441	-25.3333	3.3950
BODY FLAP CENTER POINT	30	70298	-27.8667	0.0000

Node Description,   Node Number,   Nastran Node ID Number,   Location Coordinates (X, Y, Z)

Similarly, for the rotational sensor, select node #33 "*Center Navigation Base*" and the measurement is in the positive pitch direction. The node selection dialogs are using the data from the nodes map file "*RocketPlane.Nod*" to make it easy for the analyst in choosing locations.

Definition of Vehicle Structural Nodes from FEM

In mode selection, you must define some node points in the Nastran model where the excitation forces and torques will be applied, and also their directions. It is used to calculate the mode strength and to compare the modes in specified directions

Similarly, you must define the sensor points, either translations or rotations and the sensing directions

OK

Cancel

Select a Location (Node) for Rotational Sensor: 1

Axis

Node Description	Node Number	Nastran Node ID	X	Y
Thruster FUb, 40 Deg. off of +Z	5	110166	-1.5092	1.0175 0
Thruster LNYa, -Y	6	13511	-26.0833	-3.1058 0
Thruster LNYb, 30 Deg. off of -Y	7	13585	-26.5833	-3.0342 0
Thruster LDa, 15 Deg. off of -Z	8	13509	-26.0833	-2.9333 0
Thruster LDb, 15 Deg. off of -Z	9	13591	-26.5833	-2.8600 0
Thruster LUa, +Z	10	13538	-26.0833	-1.9708
Thruster LUb, +Z	11	13661	-26.5833	-1.9717
Thruster LAft, +X	12	21618	-26.8333	-2.4433 0
Thruster RPYa, +Y	13	113511	-26.0833	3.1058 0
Thruster RPYb, 30 Deg. off of Y	14	113585	-26.5833	3.0342 0
Thruster RDa, 15 Deg. off of -Z	15	113509	-26.0833	2.9333 0
Thruster RDb, 15 Deg. off of -Z	16	113591	-26.5833	2.8600 0
Thruster RUa, +Z	17	113538	-26.0833	1.9708
Thruster RUb, +Z	18	113661	-26.5833	1.9717
Thruster RAft, +X	19	121618	-26.8333	2.4433 0
LEFT FLAP CENTER	20	60243	-19.2583	-4.5083 1
LEFT INBOARD FLAP HINGE LINE	21	84001	-18.7000	-2.075 1
LEFT OUTBOARD FLAP HINGE LINE	22	60008	-18.7000	-6.1800 1
RIGHT FLAP CENTER	23	160243	-19.2583	4.5083 1
RIGHT INBOARD FLAP HINGE LINE	24	184001	-18.7000	2.075 1
RIGHT OUTBOARD FLAP HINGE LINE	25	160008	-18.7000	6.1800 1
LEFT RUDDER CENTER	26	81677	-26.5500	-3.9075
LEFT RUDDER HINGE LINE POINT	27	81441	-25.3333	-3.3950
RIGHT RUDDER CENTER	28	181677	-26.5500	3.9075
RIGHT RUDDER HINGE LINE POINT	29	181441	-25.3333	3.3950
BODY FLAP CENTER POINT	30	70298	-27.8667	0.0000 1
BODY FLAP HINGE (ENGINE GIMBAL)	31	70270	-27.1750	0.0000 2
LEFT NAVIGATION BASE	32	22423	-8.8083	-0.7167
CENTER NAVIGATION BASE	33	22426	-8.8083	0.0000
RIGHT NAVIGATION BASE	34	122423	-8.8083	0.7167

Roll
Pitch
Yaw

Direction

+ (positive)
- (negative)

Node Description,   Node Number,   Nastran Node ID Number,   Location Coordinates (X, Y, Z)

The selection of the excitation and sensor points to be used for mode strength comparison is now complete. The next step is to select nodes in the flex model that correspond to important vehicle locations such as the aerosurface hinges, the fixed engine, and the sensors which are defined in the vehicle data. The locations entered here are not necessarily be the same as the nodes used in the mode selection. The program will display similar menus using the nodes map window and ask the user to identify locations for the 5 control surface hinges, the engine, the 3 gyros, the 2 accelerometers, and a disturbance point.

For example, the menu below is used for choosing a node for the first control surface. The user must select the "*Left Outboard Flap Hinge Line*" which is node #22, and clicks "OK". For the second control surface which is the "*Right Outboard Flap Hinge Line*" the user selects node #25, and also for the remaining aerosurfaces in the same order which they are defined in the vehicle data: left rudder, right rudder, and body-flap. For the engine we pick node #31 because it is near the body-flap. For the 3 gyros and the 2 accelerometers we pick node #33, and finally a disturbance point.

The program will read the mode shapes and slopes at the selected locations and it will perform a mode strength comparison from the excitation points and directions to the sensor points and directions. It will save the mode strength for each mode in file "*Modsel.Dat*". The user is also asked to enter a short title to identify the mode selection, such as "Pitch Modes".

Define Structure Nodes that Correspond to Vehicle Positions ✕

You must define some Points on the finite element model that correspond to important vehicle locations, as specified in the Vehicle Input Data. Such as points where Forces are Applied and Motion is Sensed, ex. TVC gimbals, CMG, RCS, Gyros, Accels, etc.

Select a Location (Node) for Control Surface : 1 | OK |

Node Description	Node Number	Nastran ID	Location (X, Y, Z)		
Thruster Frnt, Negative X	1	10090	-0.9167	0.0000	0.0
Thruster FDa, 40 Deg. off of -Z	2	10208	-2.0492	-1.3108	0.4
Thruster FUa, 40 Deg. off of +Z	3	10166	-1.5092	-1.0175	0.3
Thruster FDb, 40 Deg. off of -Z	4	110208	-2.0492	1.3108	0.4
Thruster FUb, 40 Deg. off of +Z	5	110166	-1.5092	1.0175	0.3
Thruster LNYa, -Y	6	13511	-26.0833	-3.1058	0.2
Thruster LNYb, 30 Deg. off of -Y	7	13585	-26.5833	-3.0342	0.2
Thruster LDa, 15 Deg. off of -Z	8	13509	-26.0833	-2.9333	0.6
Thruster LDb, 15 Deg. off of -Z	9	13591	-26.5833	-2.8600	0.6
Thruster LUa, +Z	10	13538	-26.0833	-1.9708	-
Thruster LUb, +Z	11	13661	-26.5833	-1.9717	-
Thruster LAft, +X	12	21618	-26.8333	-2.4433	0.2
Thruster RPYa, +Y	13	113511	-26.0833	3.1058	0.2
Thruster RPYb, 30 Deg. off of Y	14	113585	-26.5833	3.0342	0.2
Thruster RDa, 15 Deg. off of -Z	15	113509	-26.0833	2.9333	0.6
Thruster RDb, 15 Deg. off of -Z	16	113591	-26.5833	2.8600	0.6
Thruster RUa, +Z	17	113538	-26.0833	1.9708	-
Thruster RUb, +Z	18	113661	-26.5833	1.9717	-
Thruster RAft, +X	19	121618	-26.8333	2.4433	0.2
LEFT FLAP CENTER	20	60243	-19.2583	-4.5083	1.8
LEFT INBOARD FLAP HINGE LINE	21	84001	-18.7000	-2.075	1.8
LEFT OUTBOARD FLAP HINGE LINE	22	60008	-18.7000	-6.1800	1.8
RIGHT FLAP CENTER	23	160243	-19.2583	4.5083	1.8
RIGHT INBOARD FLAP HINGE LINE	24	184001	-18.7000	2.075	1.8
RIGHT OUTBOARD FLAP HINGE LINE	25	160008	-18.7000	6.1800	1.8
LEFT RUDDER CENTER	26	81677	-26.5500	-3.9075	-
LEFT RUDDER HINGE LINE POINT	27	81441	-25.3333	-3.3950	-
RIGHT RUDDER CENTER	28	181677	-26.5500	3.9075	-
RIGHT RUDDER HINGE LINE POINT	29	181441	-25.3333	3.3950	-
BODY FLAP CENTER POINT	30	70298	-27.8667	0.0000	1.9
BODY FLAP HINGE (ENGINE GIMBAL)	31	70270	-27.1750	0.0000	2.1

Node Description,   Node Number,   Nastran ID,   Location (X, Y, Z)

Table of Vehicle Structure FEM Nodes

You must now identify some points on the finite element model that correspont to the important locations on the vehicle (as specified in the vehicle data) where the forces are being applied and the motion is being sensed. Such as TVC gimbals, gyros, etc.

Select a Location (Node) for Control Surface : 4   OK

Description	#	Nastran ID	X	Y	Z
Thruster FDb, 40 Deg. off of -Z	4	110208	-2.0492	1.3108	
Thruster FUb, 40 Deg. off of +Z	5	110166	-1.5092	1.0175	0.3
Thruster LNYa, -Y	6	13511	-26.0833	-3.1058	0.2
Thruster LNYb, 30 Deg. off of -Y	7	13585	-26.5833	-3.0342	0.2
Thruster LDa, 15 Deg. off of -Z	8	13509	-26.0833	-2.9333	0.6
Thruster LDb, 15 Deg. off of -Z	9	13591	-26.5833	-2.8600	0.6
Thruster LUa, +Z	10	13538	-26.0833	-1.9708	-1.
Thruster LUb, +Z	11	13661	-26.5833	-1.9717	-1.
Thruster LAft, +X	12	21618	-26.8333	-2.4433	0.2
Thruster RPYa, +Y	13	113511	-26.0833	3.1058	0.2
Thruster RPYb, 30 Deg. off of Y	14	113585	-26.5833	3.0342	0.2
Thruster RDa, 15 Deg. off of -Z	15	113509	-26.0833	2.9333	0.6
Thruster RDb, 15 Deg. off of -Z	16	113591	-26.5833	2.8600	0.6
Thruster RUa, +Z	17	113538	-26.0833	1.9708	-1.
Thruster RUb, +Z	18	113661	-26.5833	1.9717	-1.
Thruster RAft, +X	19	121618	-26.8333	2.4433	0.2
LEFT FLAP CENTER	20	60243	-19.2583	-4.5083	1.8
LEFT INBOARD FLAP HINGE LINE	21	84001	-18.7000	-2.075	1.8
LEFT OUTBOARD FLAP HINGE LINE	22	60008	-18.7000	-6.1800	1.8
RIGHT FLAP CENTER	23	160243	-19.2583	4.5083	1.8
RIGHT INBOARD FLAP HINGE LINE	24	184001	-18.7000	2.075	1.8
RIGHT OUTBOARD FLAP HINGE LINE	25	160008	-18.7000	6.1800	1.8
LEFT RUDDER CENTER	26	81677	-26.5500	-3.9075	-2.
LEFT RUDDER HINGE LINE POINT	27	81441	-25.3333	-3.3950	-1.
RIGHT RUDDER CENTER	28	181677	-26.5500	3.9075	-2.
RIGHT RUDDER HINGE LINE POINT	29	181441	-25.3333	3.3950	-1.
BODY FLAP CENTER POINT	30	70298	-27.8667	0.0000	1.9
BODY FLAP HINGE (ENGINE GIMBAL)	31	70270	-27.1750	0.0000	2.1
LEFT NAVIGATION BASE	32	22423	-8.8083	-0.7167	-0.
CENTER NAVIGATION BASE	33	22426	-8.8083	0.0000	-0.
RIGHT NAVIGATION BASE	34	122423	-8.8083	0.7167	-0.

Node Description,   Node Number,   Nastran ID,   Location (X, Y, Z)

Define Structure Nodes that Correspond to Vehicle Positions

You must define some Points on the finite element model that correspond to important vehicle locations, as specified in the Vehicle Input Data. Such as points where Forces are Applied and Motion is Sensed, ex. TVC gimbals, CMG, RCS, Gyros, Accels, etc.

Select a Location (Node) for Thruster Engine : 1   OK

Description	#	Nastran ID	X	Y	Z
Thruster FDb, 40 Deg. off of -Z	4	110208	-2.0492	1.3108	0.4
Thruster FUb, 40 Deg. off of +Z	5	110166	-1.5092	1.0175	0.3
Thruster LNYa, -Y	6	13511	-26.0833	-3.1058	0.2
Thruster LNYb, 30 Deg. off of -Y	7	13585	-26.5833	-3.0342	0.2
Thruster LDa, 15 Deg. off of -Z	8	13509	-26.0833	-2.9333	0.6
Thruster LDb, 15 Deg. off of -Z	9	13591	-26.5833	-2.8600	0.6
Thruster LUa, +Z	10	13538	-26.0833	-1.9708	-
Thruster LUb, +Z	11	13661	-26.5833	-1.9717	-
Thruster LAft, +X	12	21618	-26.8333	-2.4433	0.2
Thruster RPYa, +Y	13	113511	-26.0833	3.1058	0.2
Thruster RPYb, 30 Deg. off of Y	14	113585	-26.5833	3.0342	0.2
Thruster RDa, 15 Deg. off of -Z	15	113509	-26.0833	2.9333	0.6
Thruster RDb, 15 Deg. off of -Z	16	113591	-26.5833	2.8600	0.6
Thruster RUa, +Z	17	113538	-26.0833	1.9708	-
Thruster RUb, +Z	18	113661	-26.5833	1.9717	-
Thruster RAft, +X	19	121618	-26.8333	2.4433	0.2
LEFT FLAP CENTER	20	60243	-19.2583	-4.5083	1.8
LEFT INBOARD FLAP HINGE LINE	21	84001	-18.7000	-2.075	1.8
LEFT OUTBOARD FLAP HINGE LINE	22	60008	-18.7000	-6.1800	1.8
RIGHT FLAP CENTER	23	160243	-19.2583	4.5083	1.8
RIGHT INBOARD FLAP HINGE LINE	24	184001	-18.7000	2.075	1.8
RIGHT OUTBOARD FLAP HINGE LINE	25	160008	-18.7000	6.1800	1.8
LEFT RUDDER CENTER	26	81677	-26.5500	-3.9075	-
LEFT RUDDER HINGE LINE POINT	27	81441	-25.3333	-3.3950	-
RIGHT RUDDER CENTER	28	181677	-26.5500	3.9075	-
RIGHT RUDDER HINGE LINE POINT	29	181441	-25.3333	3.3950	-
BODY FLAP CENTER POINT	30	70298	-27.8667	0.0000	1.9
BODY FLAP HINGE (ENGINE GIMBAL)	31	70270	-27.1750	0.0000	2.1
LEFT NAVIGATION BASE	32	22423	-8.8083	-0.7167	-
CENTER NAVIGATION BASE	33	22426	-8.8083	0.0000	-
RIGHT NAVIGATION BASE	34	122423	-8.8083	0.7167	-

Node Description,   Node Number,   Nastran ID,   Location (X, Y, Z)

Define Structure Nodes that Correspond to Vehicle Positions ✕

You must define some Points on the finite element model that correspond to important vehicle locations, as specified in the Vehicle Input Data. Such as points where Forces are Applied and Motion is Sensed, ex. TVC gimbals, CMG, RCS, Gyros, Accels, etc.

Select a Location (Node) for Gyro/Rate Sensor : 1   **OK**

```
Thruster FDb, 40 Deg. off of -Z        4    110208    -2.0492    1.3108   0.4
Thruster FUb, 40 Deg. off of +Z        5    110166    -1.5092    1.0175  0.3
Thruster LNYa, -Y                      6    13511    -26.0833    -3.1058 0.2
Thruster LNYb, 30 Deg. off of -Y       7    13585    -26.5833    -3.0342 0.2
Thruster LDa, 15 Deg. off of -Z        8    13509    -26.0833    -2.9333 0.6
Thruster LDb, 15 Deg. off of -Z        9    13591    -26.5833    -2.8600 0.6
Thruster LUa, +Z                      10    13538    -26.0833    -1.9708    -
Thruster LUb, +Z                      11    13661    -26.5833    -1.9717    -
Thruster LAft, +X                     12    21618    -26.8333    -2.4433 0.2
Thruster RPYa, +Y                     13    113511   -26.0833     3.1058 0.2
Thruster RPYb, 30 Deg. off of Y       14    113585   -26.5833     3.0342 0.2
Thruster RDa, 15 Deg. off of -Z       15    113509   -26.0833     2.9333 0.6
Thruster RDb, 15 Deg. off of -Z       16    113591   -26.5833     2.8600 0.6
Thruster RUa, +Z                      17    113538   -26.0833     1.9708    -
Thruster RUb, +Z                      18    113661   -26.5833     1.9717    -
Thruster RAft, +X                     19    121618   -26.8333     2.4433 0.2
LEFT FLAP CENTER                      20    60243    -19.2583    -4.5083 1.8
LEFT INBOARD FLAP HINGE LINE          21    84001    -18.7000    -2.075  1.8
LEFT OUTBOARD FLAP HINGE LINE         22    60008    -18.7000    -6.1800 1.8
RIGHT FLAP CENTER                     23    160243   -19.2583     4.5083 1.8
RIGHT INBOARD FLAP HINGE LINE         24    184001   -18.7000     2.075  1.8
RIGHT OUTBOARD FLAP HINGE LINE        25    160008   -18.7000     6.1800 1.8
LEFT RUDDER CENTER                    26    81677    -26.5500    -3.9075    -
LEFT RUDDER HINGE LINE POINT          27    81441    -25.3333    -3.3950    -
RIGHT RUDDER CENTER                   28    181677   -26.5500     3.9075    -
RIGHT RUDDER HINGE LINE POINT         29    181441   -25.3333     3.3950    -
BODY FLAP CENTER POINT                30    70298    -27.8667     0.0000 1.9
BODY FLAP HINGE (ENGINE GIMBAL)       31    70270    -27.1750     0.0000 2.1
LEFT NAVIGATION BASE                  32    22423     -8.8083    -0.7167    -
CENTER NAVIGATION BASE                33    22426     -8.8083     0.0000    -
RIGHT NAVIGATION BASE                 34    122423    -8.8083     0.7167    -
```

Node Description,   Node Number,   Nastran ID,   Location (X, Y, Z)

Define Structure Nodes that Correspond to Vehicle Positions ✕

You must define some Points on the finite element model that correspond to important vehicle locations, as specified in the Vehicle Input Data. Such as points where Forces are Applied and Motion is Sensed, ex. TVC gimbals, CMG, RCS, Gyros, Accels, etc.

Select a Location (Node) for Accelerometer   : 2   **OK**

```
Thruster FUa, 40 Deg. off of +Z        3    10166     -1.5092    -1.0175   0.3
Thruster FDb, 40 Deg. off of -Z        4    110208    -2.0492    1.3108   0.4
Thruster FUb, 40 Deg. off of +Z        5    110166    -1.5092    1.0175  0.3
Thruster LNYa, -Y                      6    13511    -26.0833    -3.1058 0.2
Thruster LNYb, 30 Deg. off of -Y       7    13585    -26.5833    -3.0342 0.2
Thruster LDa, 15 Deg. off of -Z        8    13509    -26.0833    -2.9333 0.6
Thruster LDb, 15 Deg. off of -Z        9    13591    -26.5833    -2.8600 0.6
Thruster LUa, +Z                      10    13538    -26.0833    -1.9708    -
Thruster LUb, +Z                      11    13661    -26.5833    -1.9717    -
Thruster LAft, +X                     12    21618    -26.8333    -2.4433 0.2
Thruster RPYa, +Y                     13    113511   -26.0833     3.1058 0.2
Thruster RPYb, 30 Deg. off of Y       14    113585   -26.5833     3.0342 0.2
Thruster RDa, 15 Deg. off of -Z       15    113509   -26.0833     2.9333 0.6
Thruster RDb, 15 Deg. off of -Z       16    113591   -26.5833     2.8600 0.6
Thruster RUa, +Z                      17    113538   -26.0833     1.9708    -
Thruster RUb, +Z                      18    113661   -26.5833     1.9717    -
Thruster RAft, +X                     19    121618   -26.8333     2.4433 0.2
LEFT FLAP CENTER                      20    60243    -19.2583    -4.5083 1.8
LEFT INBOARD FLAP HINGE LINE          21    84001    -18.7000    -2.075  1.8
LEFT OUTBOARD FLAP HINGE LINE         22    60008    -18.7000    -6.1800 1.8
RIGHT FLAP CENTER                     23    160243   -19.2583     4.5083 1.8
RIGHT INBOARD FLAP HINGE LINE         24    184001   -18.7000     2.075  1.8
RIGHT OUTBOARD FLAP HINGE LINE        25    160008   -18.7000     6.1800 1.8
LEFT RUDDER CENTER                    26    81677    -26.5500    -3.9075    -
LEFT RUDDER HINGE LINE POINT          27    81441    -25.3333    -3.3950    -
RIGHT RUDDER CENTER                   28    181677   -26.5500     3.9075    -
RIGHT RUDDER HINGE LINE POINT         29    181441   -25.3333     3.3950    -
BODY FLAP CENTER POINT                30    70298    -27.8667     0.0000 1.9
BODY FLAP HINGE (ENGINE GIMBAL)       31    70270    -27.1750     0.0000 2.1
LEFT NAVIGATION BASE                  32    22423     -8.8083    -0.7167    -
CENTER NAVIGATION BASE                33    22426     -8.8083     0.0000    -
```

Node Description,   Node Number,   Nastran ID,   Location (X, Y, Z)

The program finally shows a bar-chart that compares the mode strength for each mode versus mode number in the pitch direction. The color of all bars is initially red before selection. The analyst manually selects one mode at a time from the bar-chart, to be included in the selected set, by clicking on the chosen tall bar with the mouse. When a mode is chosen, the color of the bar changes from red to green. Press the "Enter" key when the selection is complete to save the modes set. Figures 2.3 and 2.4 show two bar-charts that compare the relative mode strengths resulting from two types of mode selection cases: a pitch selection that was just described and a roll axis selection.
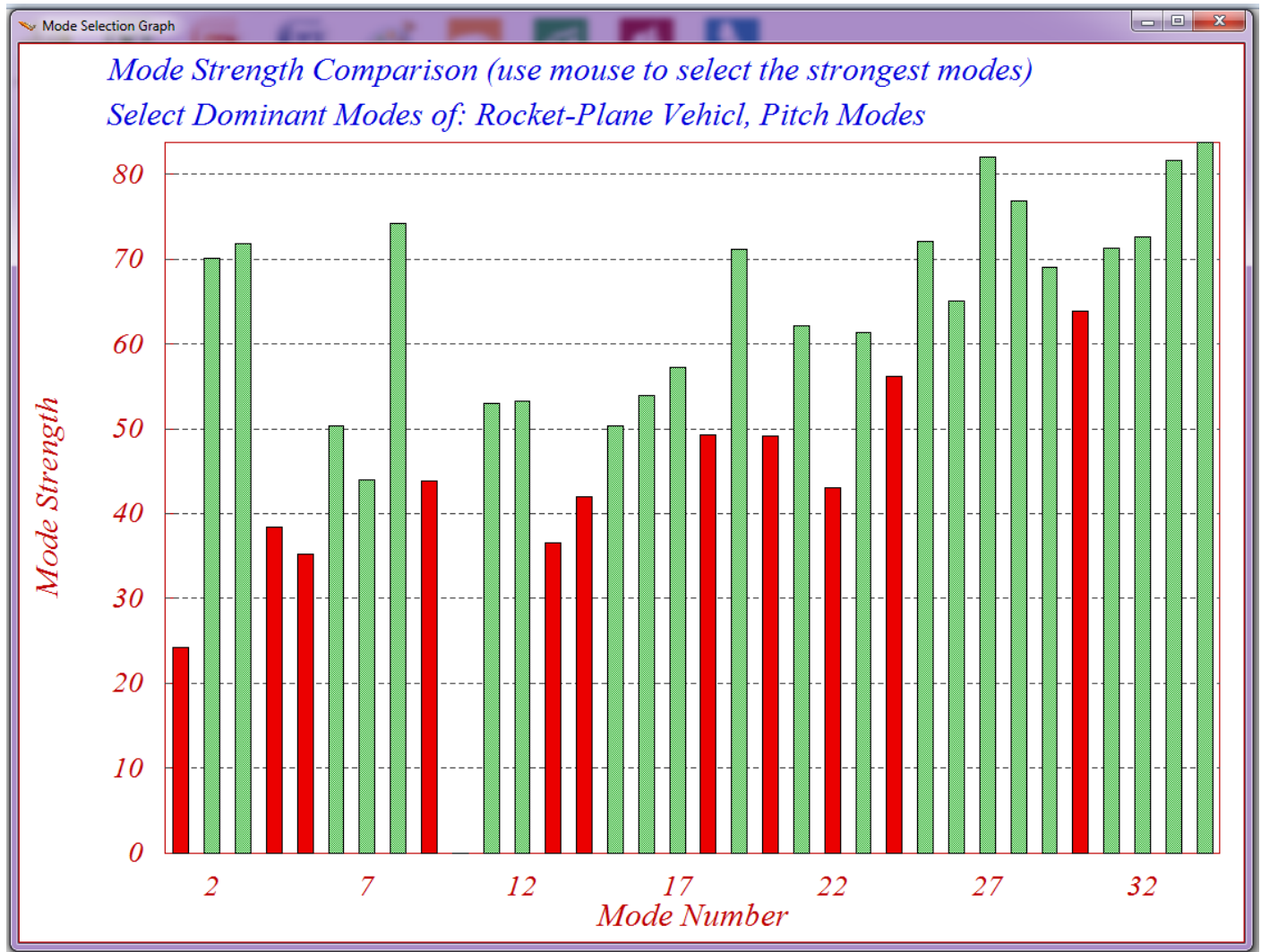
Figure 2.3 Mode Strength Comparison and Modes Selected (Green) for the Pitch Axis

In the roll mode selection case, shown in Figure 2.4, the two flaps were excited anti-symmetrically with opposite forces in the ±Z direction and also with anti-symmetric pitch torques at the hinges of the two flaps. A rotational sensor was included for measuring roll. Notice that the modes that are strong in pitch are not strong in roll, and vise-versa.
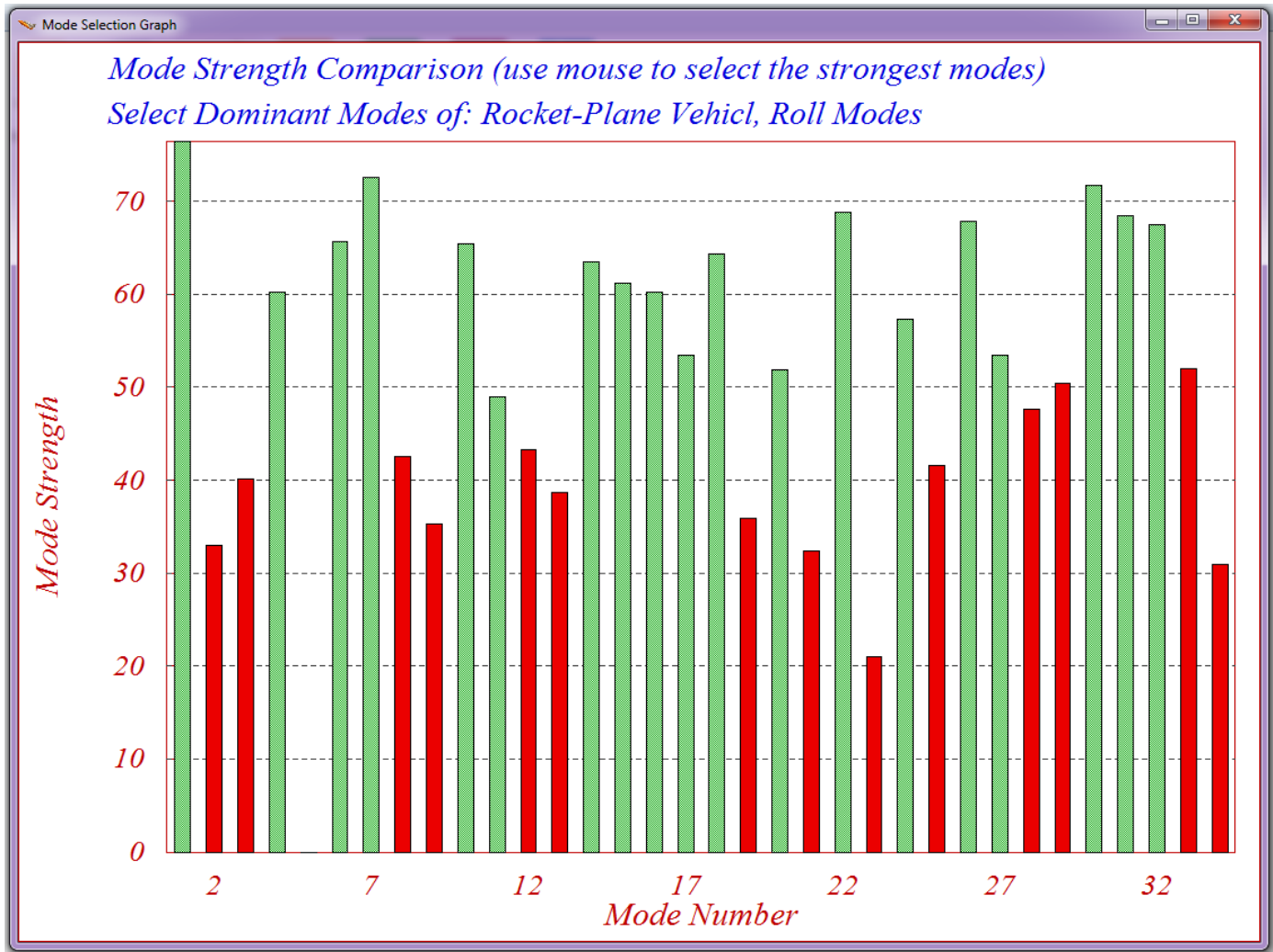
Figure 2.4 Mode Strength Comparison and Modes Selected (Green) for the Roll Axis

In the field below the user may finally write a short description that provides information about the mode selection process. Explain, for example, the rationale behind the choices made, such as, conditions, actuator and sensor locations, forcing directions, etc. The user notes will be included as comment lines below the title in the selected modes set. The selected set of mode frequencies and shapes is finally saved in file "*RocketPlane_Flx.Inp*" and ready to be processed by the vehicle modeling program, as already described in Section (2.2). The default title of the modal set was modified to: "*Rocket Plane at Mach=0.85, Q=150, Flex Model, (22 Pitch Modes)*".

2.5 Actuator Model

When analyzing the rigid-body model, and without including TWD dynamics, a simple 2nd order actuator model was sufficient in this preliminary level. With flexibility, however, and the TWD included in the aerosurfaces we will need more refined actuator models that in addition to the deflections, they also produce aerosurface rate and acceleration outputs, in order to implement the TWD and load-torque feedback dynamic effects. The position, rate, and acceleration actuator model outputs are inputs to the vehicle system. The aerosurface rotational accelerations about the hinge create the TWD reaction forces and moments on the vehicle and they also excite flexibility.

The rotation of a control surface relative to its hinge is the result of two torques which are applied to the control surface: a control torque created by the actuator which in this case is an electro-mechanical actuator shaft that pushes against the load, and also an external load-torque generated by the vehicle motion, mainly due to rotational and translational accelerations of the vehicle at the hinges. The actuator model in addition to the linear shaft dynamics and the shaft position control system, it also includes the rotational dynamics of the aerosurface load and the associated: backup, load and shaft stiffnesses. The external load-torque is also included in the actuator model and the load acceleration relative to the hinge is affected by both: the control torque and also the load-torque. The control torque is produced internally in the actuator model due to the deflection command driving the shaft motor, but the load-torque is an external input from the vehicle system. The load-torque is a mechanical feedback loop from the vehicle's hinge moment outputs to the actuator load-torque input.

The actuator models in this example are electro-mechanical type (b) and they are fully documented in the actuator modeling Section-4. Each type of aerosurface (flaps, rudders and body-flap) is driven by the corresponding actuator. The actuator parameters for each type are already saved in separate datasets in file "*RocketPlane-Flx.Inp*". Each dataset includes different actuator parameters, such as inertias, stiffnesses, geometry, etc. and they are processed by the actuator modeling program to create the actuator systems. To process the rudder actuator dataset "*Electro-Mechanical Rudder Type-B Actuator*", start the Flixan program and select the directory "*18-Rocket Plane\2-Flex Model*". From the main menu go to "*Flight Vehicle/ Spacecraft Modeling*", and then to "*Actuator State-Space Modeling*" program. From the filename selection menu select the input file "*RocketPlane_Flx.Inp*" and the systems file "*RocketPlane_Flx.Qdr*". The actuator selection menu comes up showing the titles of the actuator datasets in file.
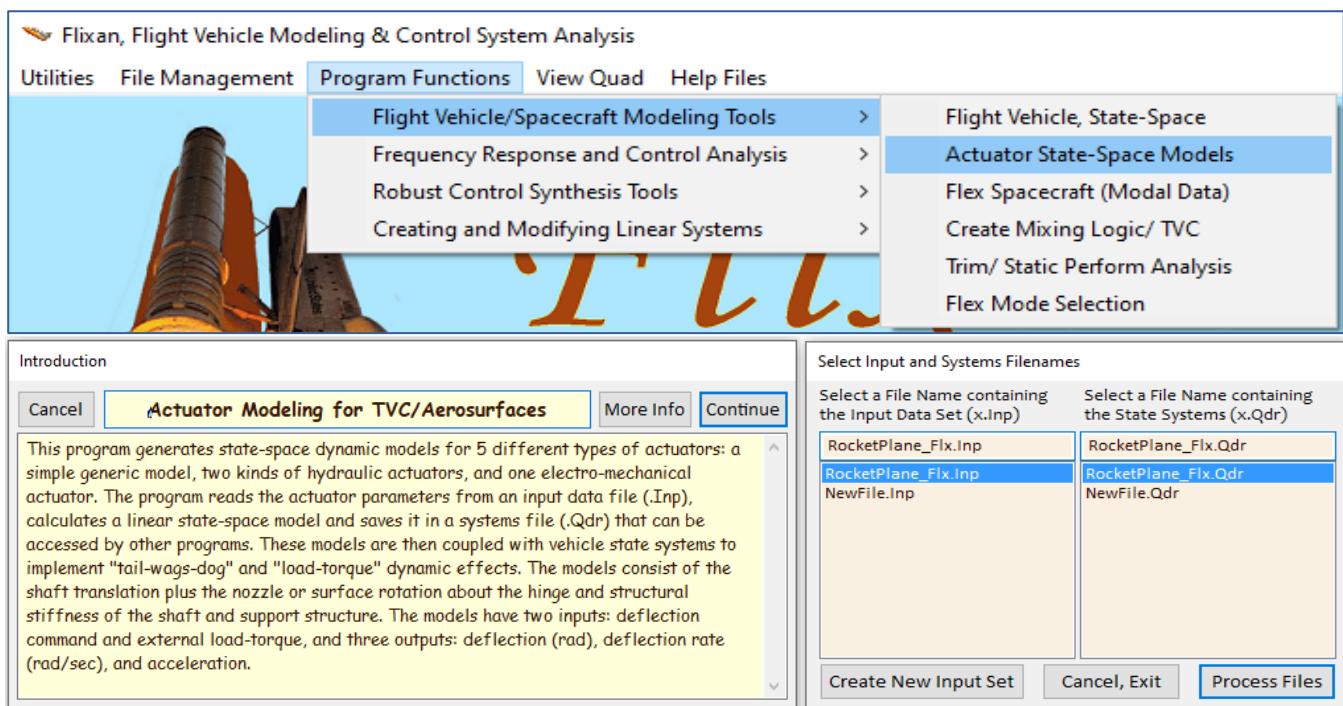
Select a Set of Input Data for "ACTUATOR" from an Input File: RocketPlane_Flx.inp | **Run Selected Input Set**

Electro-Mechanical Flap Type-B Actuator
Electro-Mechanical Rudder Type-B Actuator
Electro-Mechanical Body-Flap Type-B Actuator

Make New Set Interactively

Cancel, Exit

The input file includes 3 actuator datasets. Select the rudder actuator title from the above menu and click on "*Run Selected Input Set*". The program recognizes that the actuator is an electro-mechanical type (b) model and it opens the following actuator dialog showing the actuator parameters. Click on "Run" to process the dataset and also confirm the 1st order compensator coefficients in the next dialog. The actuator state-space system will be saved in the systems file under the same title "*Electro-Mechanical Rudder Type-B Actuator*". The final step is to convert this actuator state-space system to an m-function format that can be exported into Matlab. The name of the actuator m-file is "*rudder_ema.m*".

Electro-Mechanical Actuator, Model (B) Data

Enter Electro-Mechanical Actuator Model (B) Parameters | Exit

Electro-Mechanical Rudder Type-B Actuator | Save / Run

Parameter	Value
Position Error Loop Gain, (Kpl) in (Volt/ft)	480.0
Motor Rate Feedback Gain, (Kmr), (Volt/ft/sec)	0.3000E-02
Position Error Integral Gain, (Ki), (Volt/ft-sec)	1.200
Servo Motor Bandwidth, Wm, (rad/sec)	1200.
Motor Control Torque Gain, (Kv) in (ft-lb/ volt)	500.0
Motor Rotor Mom of Inertia, (Jm) in (ft-lb-sec^2)	0.7000E-04
Gear Ratio (Ngear), (Motor Turns/ Screw Turns)	17.00
Screw Ratio (Nscrew), (Piston Extens/Screw Turn), (ft/rad)	0.2700E-02
Motor Gear Stiffness (Kgs), (ft-lb/ rad)	4000.
Motor Gear Friction (Kmfr), (ft-lb/ rad/sec)	0.2000E-01
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)	0.1200E-02
Actuator (Piston+Electrical) Stiffness, (Kact) in (lbf/ft)	0.2400E+07
Load Stiffness, (Klod), (Surface or Nozzle), (lbf/ft)	0.3360E+07
Vehicle Backup Structure Stiffness, (Kbck) in (lb/ft)	0.6000E+07
Moment Arm (R), Actuator Rod to Gimbal dist. in (feet)	0.3000
Effectr Load Mom of Inertia about Hinge, (Je), (ft-lb-sec^2)	4.000
Effector Hinge Viscous Damping (Be) in (ft-lb-sec)	80.00
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   ○ Second 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

Select One of Three Options

This System Title is already Saved in systems file RocketPlane_Flx.qdr You may Replace the Old System, Save it under Different Title, or Keep the Old

Replace the Old System with this New System Using the Same Title ◉ ✔

Save the New System with a Different Title and still Keep the Old System ○ ✗

Do Not Save this New System but Keep the Old System ○ ✗ | OK

2.6 Closed-Loop Simulation Model with Structural Flexibility

The Simulink model with flexibility and TWD is in file "*Closed_Loop_Flx.Slx*", shown in Figure 2.5. It consists of 5 control loops: roll and yaw loops, the pitch control loop that controls altitude by commanding alpha, the axial acceleration loop that controls speed by throttling the engine, and the heading direction control loop that controls heading by banking. It is similar to the rigid-body simulation model described in Section 1 but with some improvements. The vehicle subsystem "*Rocket Plane at Mach=0.85, Q=150, Flex Model*" which is loaded into Matlab from file "*vehi_30flx.m*", includes the 30 flex modes and the tail-wags-dog effects of the 5 aerosurfaces. The vehicle block is shown in detail in Figure 2.6. It includes the (6x4) mixing logic matrix "K4axmix" that converts the roll, pitch, yaw, and axial acceleration demands into effector commands.
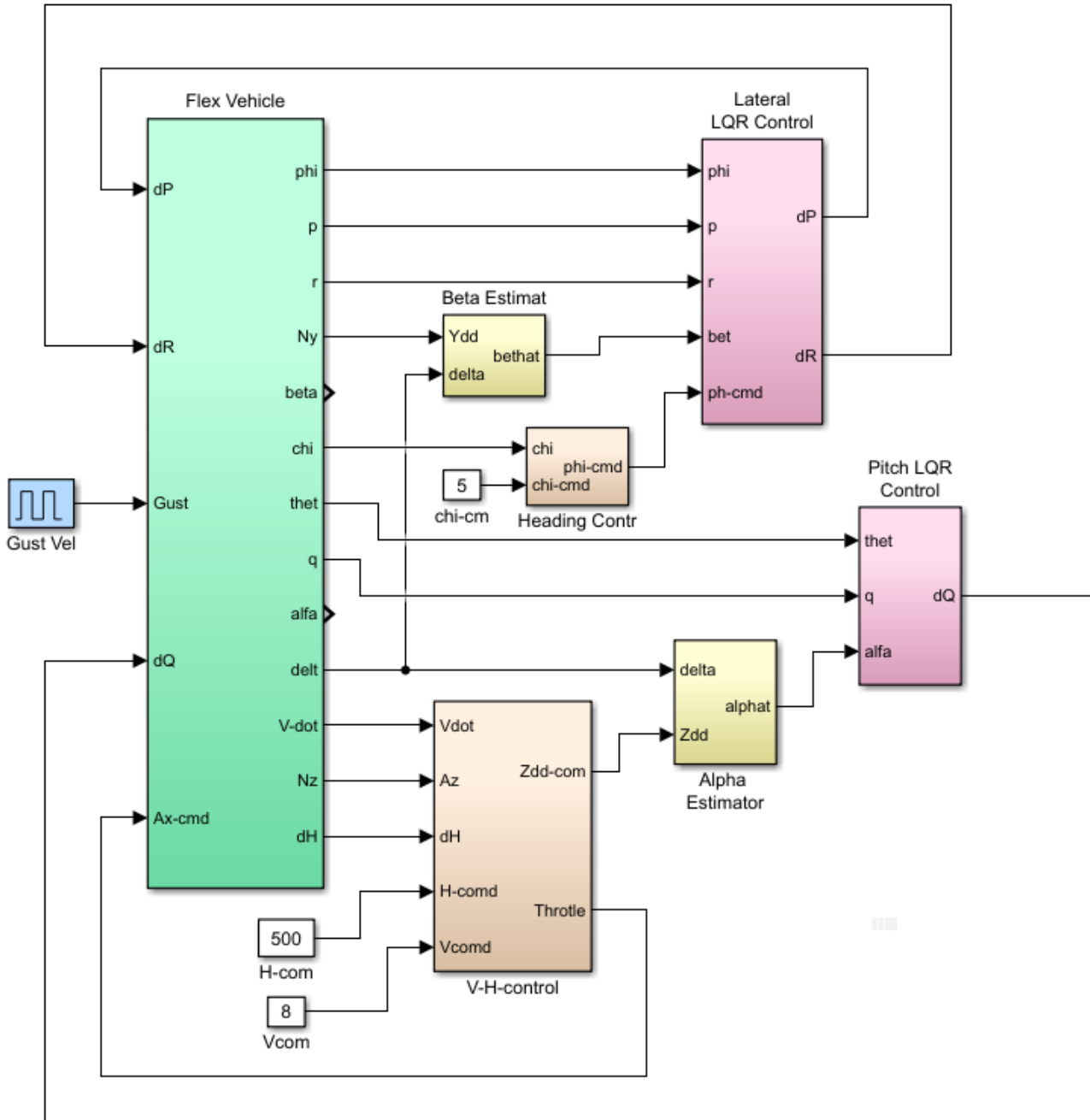
Figure 2.5 Closed-Loop Simulation Model with Flexibility "Closed_Loop_Flx.Mdl"

Vehicle Dynamics/ Actuators/ Mixing Logic

Outputs

1. Roll Attitude (phi-body) (radians)
2. Roll Rate (p-body) (rad/sec)
3. Pitch Attitude (thet-body) (radians)
4. Pitch Rate (q-body) (radians)
5. Yaw Attitude (psi-body) (radians)
6. Yaw Rate (r-body) (rad/sec)
7. Angle of attack, alfa, (radians)
8. Angle of sideslip, beta, (radian)
9. Change in Altitude, delta-h, (feet)
10. Forward Acceleration (V-dot) (ft/sec)
11. Cross Range Velocity (Vcr) (ft/sec)
12. Rate-Gyro # 1, Roll Rate (Body) (rad/sec)
13. Rate-Gyro # 2, Pitch Rate (Body) (rad/sec)
14. Rate-Gyro # 3, Yaw Rate (Body) (rad/sec)
15. Accelerom # 1, (along Y), (ft/sec^2) Translat. Acceler
16. Accelerom # 2, (along Z), (ft/sec^2) Translat. Acceler
17. Hinge Moment for Aero Surface # 1, (ft-lb)
18. Hinge Moment for Aero Surface # 2, (ft-lb)
19. Hinge Moment for Aero Surface # 3, (ft-lb)
20. Hinge Moment for Aero Surface # 4, (ft-lb)
21. Hinge Moment for Aero Surface # 5, (ft-lb)

Inputs

1. Throttle Input dTh/Th for Engine No 1 (-)
2. Left Flap Deflection (radians)
3. Right Flap Deflection (radians)
4. Left Rudder Deflection (radians)
5. Right Rudder Deflection (radians)
6. Body Flap Deflection (radians)
7. Left Flap Velocity (rad/sec)
8. Right Flap Velocity (rad/sec)
9. Left Rudder Velocity (rad/sec)
10. Right Rudder Velocity (rad/sec)
11. Body Flap Velocity (rad/sec)
12. Left Flap Acceleration (rad/s^2)
13. Right Flap Acceleration (rad/s^2)
14. Left Rudder Acceleration (rad/s^2)
15. Right Rudder Acceleration (rad/s^2)
16. Body Flap Acceleration (rad/s^2)
17. Wind Gust Azim, Elev Angles=(45.0 90.0) (deg)

The file "*init.m*" below initializes the simulation by loading the flex vehicle, the 3 actuators, the effectors mixing logic matrix K4axmix, the pitch and lateral LQR gain matrices Kq and Kpr, and the (α, β) estimator parameters into Matlab.

```
% Initialization File
d2r=pi/180; r2d=180/pi;
[Avf, Bvf, Cvf, Dvf] =vehi_30flx;          % Load Flex Vehicle Model
[Ardr,Brdr,Crdr,Drdr]=rudder_ema;          % Load Rudder Electro-Mechan Actuator
[Afla,Bfla,Cfla,Dfla]=flap_ema;            % Load Flap    Electro-Mechan Actuator
[Abfp,Bbfp,Cbfp,Dbfp]=bodyflap_ema;        % Load Rudder Electro-Mechan Actuator
load K4axmix.mat K4axmix -ascii             % Engine + AeroSurface Mixing Logic
load Kq.mat  Kq  -ascii                     % Pitch    LQR Gains
load Kpr.mat Kpr -ascii                     % lateral LQR Gains

% Alpha-Beta Estimator Parameters
Qbar=150; Mass=198.32; Sref=79.069; V0=822.8;
Cza=-0.073; Cyb=-0.0245;
Cydel= [-0.24668,0.24668, 0.47413,-0.47413,0]/100;    % Cy due to surf deflect
Czdel= [0.51664,0.51664,0.60478,0.60478,0.06]/100;    % Cz due to contrl surface
```
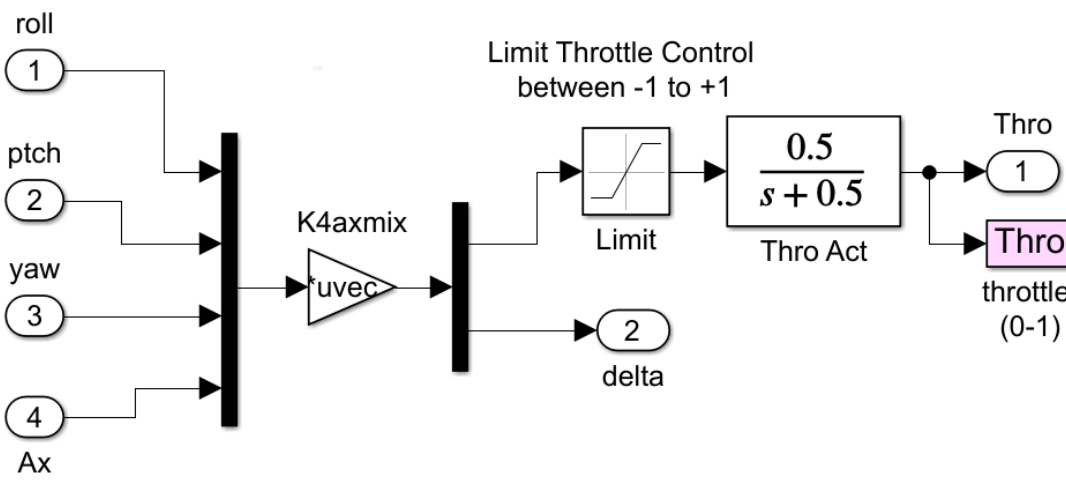

Figure 2.7 Mixing Logic that Combines Throttle Control and Aero-Surface Deflections

The Mixing-Logic matrix converts the roll, pitch, yaw, and axial acceleration demands to thrust variations and 5 aero-surface deflections. The engine throttle control is the first vehicle input that varies between (-1 to +1), with zero corresponding to the nominal thrust of 2000 (lbf), (-1) corresponding zero thrust, and (+1) corresponding to the maximum 4000 (lbf) thrust. Five separate actuators are used, one for each aerosurface. They are combined to an actuator subsystem in Figure 2.8. The 5 position, 5 velocity, and 5 acceleration outputs from the actuators are driving the corresponding inputs in the flexible vehicle model.

The vehicle system in Figure 2.6 has five additional outputs which are the hinge moments at the five aerosurfaces. These are the external load-torques that we talked about representing the mechanical external loading on the actuators caused by the vehicle acceleration. The direction of a hinge moment is defined to be positive when the torque is in the clockwise direction about the hinge vector. The hinge moments are fed-back to the actuator hinge moment inputs. The last input to the vehicle model is the wind-gust disturbance. A gust filter is included in the vehicle gust input to smooth out the rectangular wind-gust velocity impulse and make it more realistic.
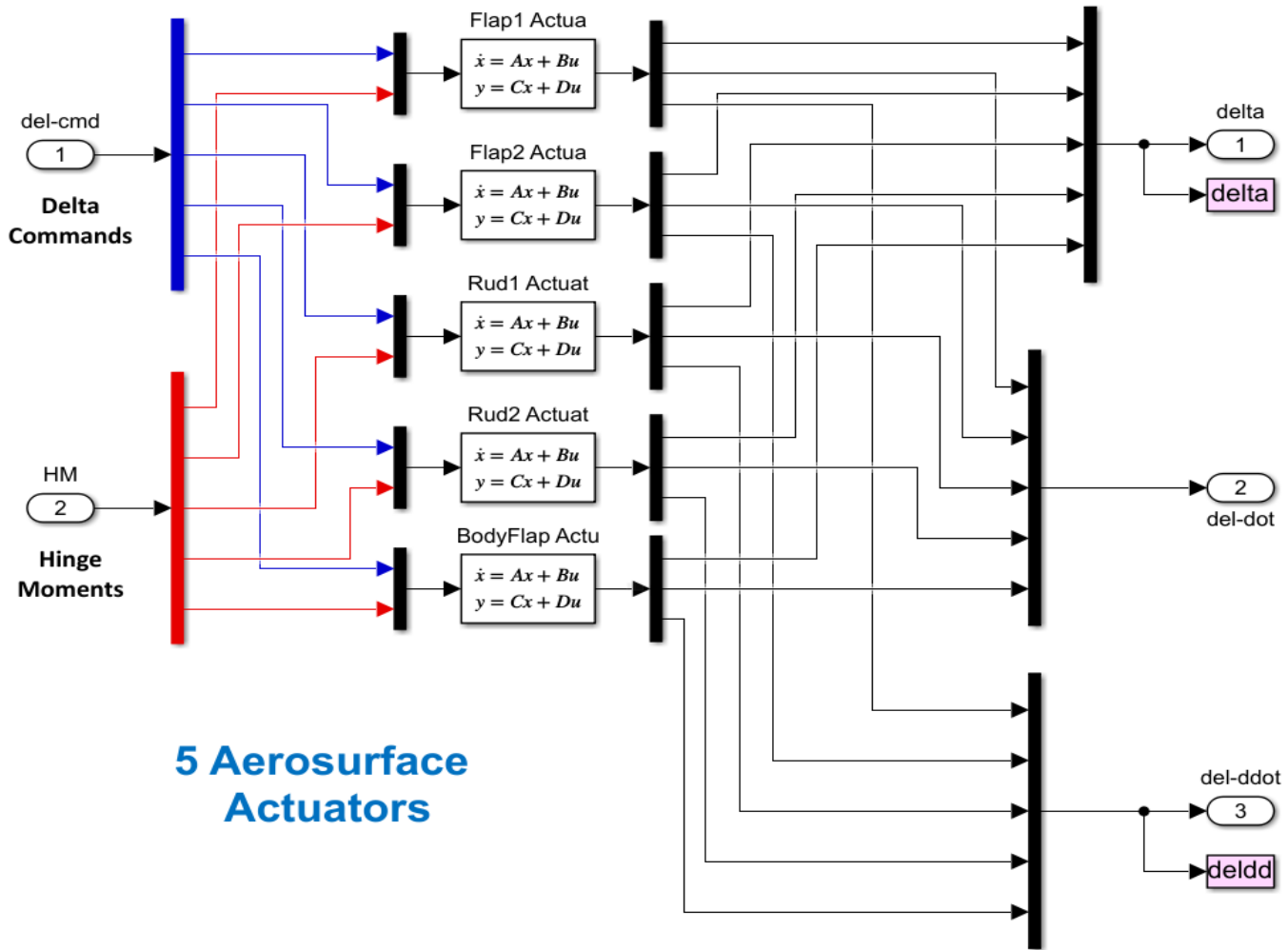
Figure 2.8 System of 5 Aero-Surface Actuators

The remaining of the flexible Simulink model is very similar to the rigid-body model. The cross-range velocity (V_{cr}) is divided by the total ground speed in order to calculate the heading direction angle (chi) which needs to be controlled by roll maneuvers. The heading direction controller is part of the lateral control system. It receives a change in heading direction command (chi-cmd) and commands a momentary change in bank angle to achieve the required change in the heading direction. The bank angle returns to zero after the change in heading direction is achieved. The V-dot integrator which calculates the vehicle speed is initialized at the nominal vehicle speed which is 823 (ft/sec).

Several notch and low-pass filters were included in the control systems to prevent flex mode instabilities. The initialization file loads also the alpha & beta estimator parameters, because the estimated alpha and beta replace the real alpha and beta angles required by the LQR controller.

Altitude Control

2 Az → Filters → K- Kf → K- Kr2=0.25 → 1/s Int2

Kh=0.05

dH **3** → (+ −) → 1/s Int3 → K- Khi=0.0025

4 H-comd

Zdd-com **1**

Ground Speed Control

Vgr

1/s Int1 → K- Ki=0.007

Vdot **1** → 1/s Int → (+ −) → K- Kp=0.07

5 Vcomd

Kr=0.04 → K-

Throtle **2**

Limit Throtle Control between -1 to +1

Lateral State-Feedback Controller

Roll Notch

2 p → In Ot

Yaw Notch

3 r → In Ot

4 bet

1 phi → (+ −)

5 ph-cmd

State Feedback Kpr → K*uvec

Roll Low Pass

$$\frac{40^2}{s^2 + 1.4 * 40s + 40^2}$$

dP **1**

Yaw Low Pass

$$\frac{20^2}{s^2 + 1.3 * 20s + 20^2}$$

2 dR

Pitch LQR Controller with Filter

1 thet

Notch Filters

2 q → in ou Notch

3 alfa

1/s Int

State-Feedback Matrix

-Kq → K*u

$$\frac{30^2}{s^2 + 1.3 * 30s + 30^2}$$
Filt

1 dQ

Figure 2.9 The Flight Control System is now Modified to Include Filters

2.7 Simulation Results

The Simulink model "*Closed_Loop_Flx.Mdl*" in Figure 2.5 is now used to simulate the system's response to commands and to the wind-gust, similar to Section-1. This time the vehicle model includes flexibility and "tail-wag-dog" dynamics that can be noticed in the accelerations. The gust impulse is applied at 5 (sec) and its duration is shortened to excite flexibility. Two additional plots are included showing the control surface accelerations (from the actuator outputs) and the hinge moments due to vehicle motion. The Matlab file "pl.m" is used to plot the simulation data.
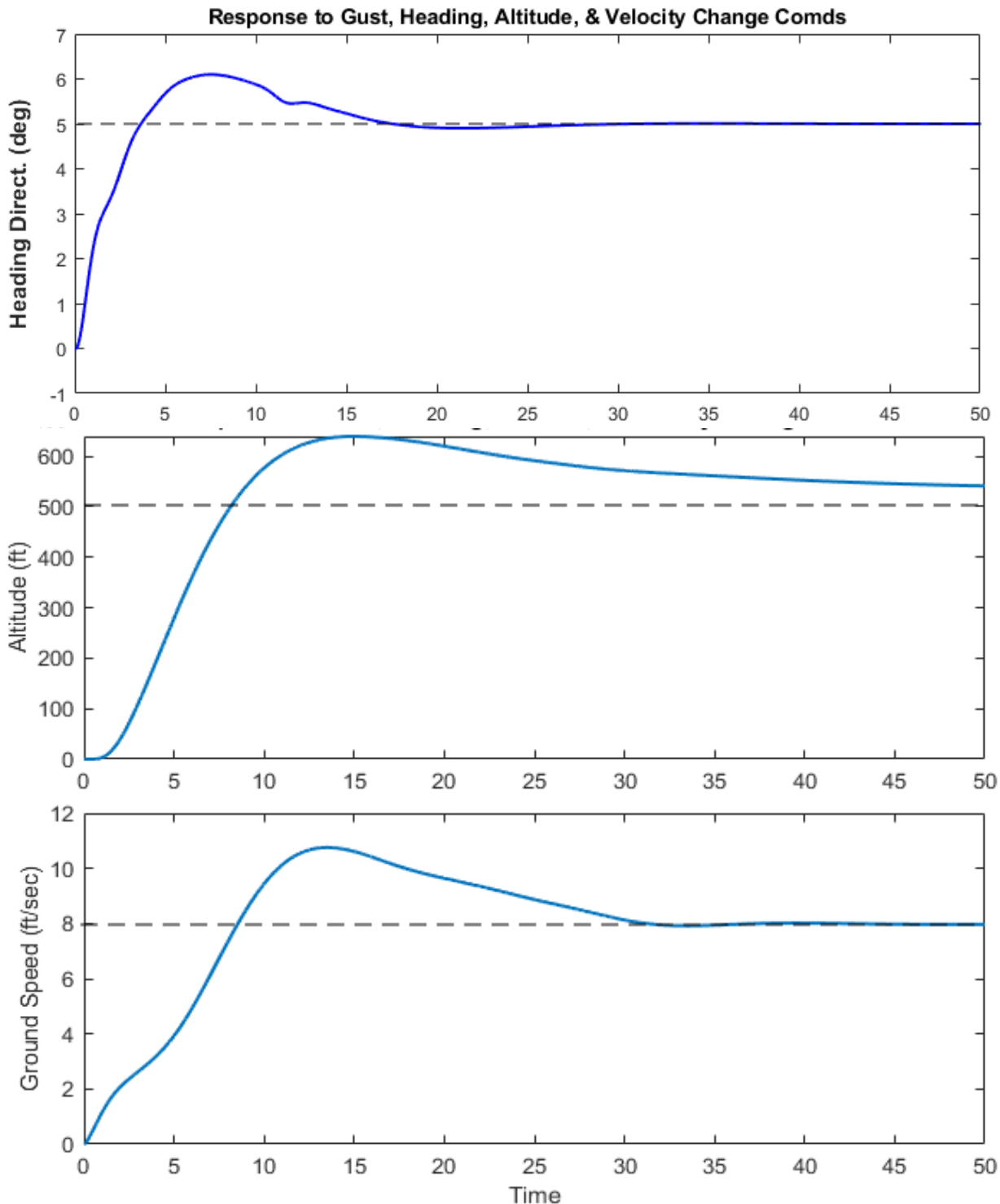
Figure 2.10 Change in Heading Direction, Altitude and Speed due to Commands
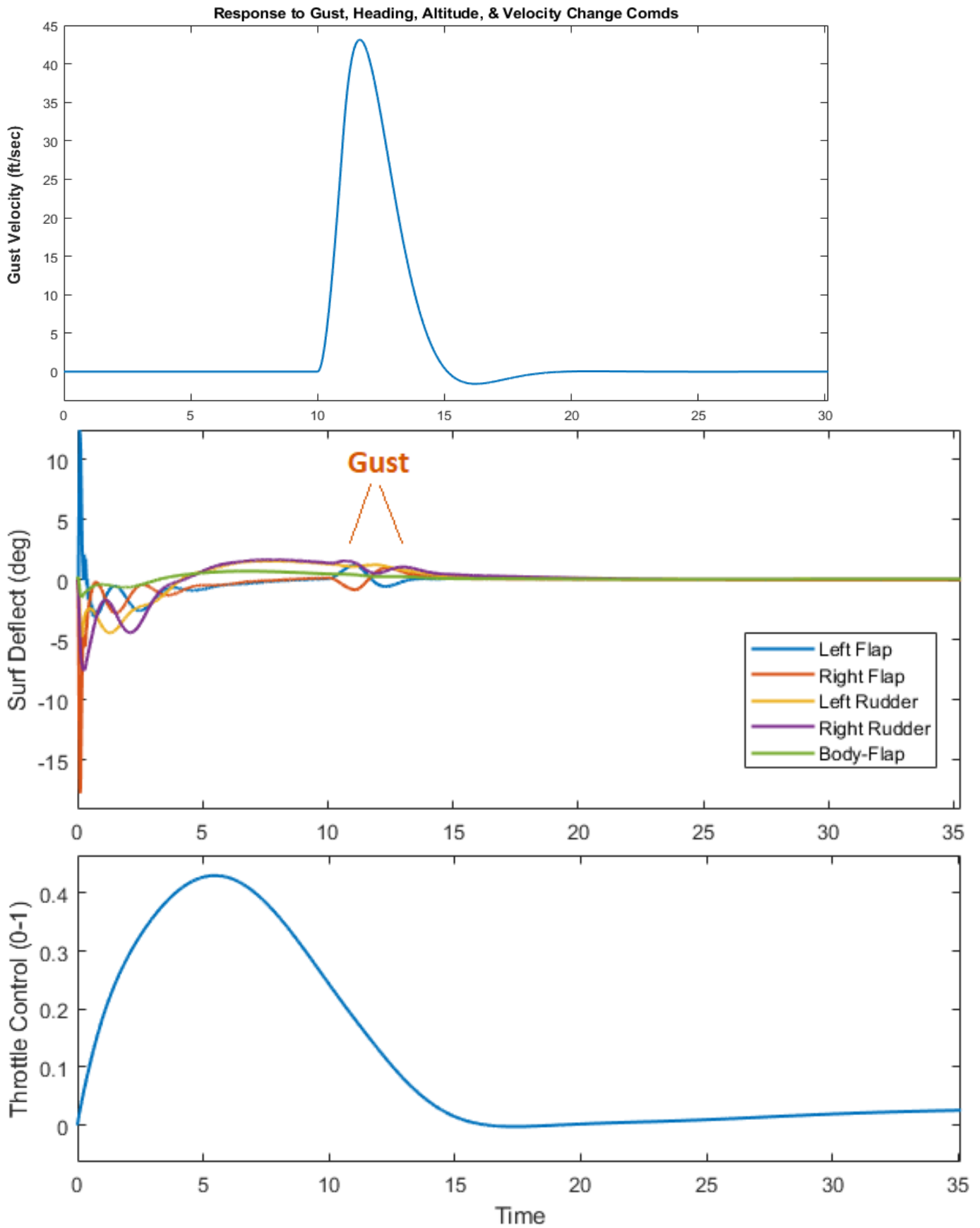
Figure 2.11 Engine Throttle and Aerosurfaces Response to Commands and Gust
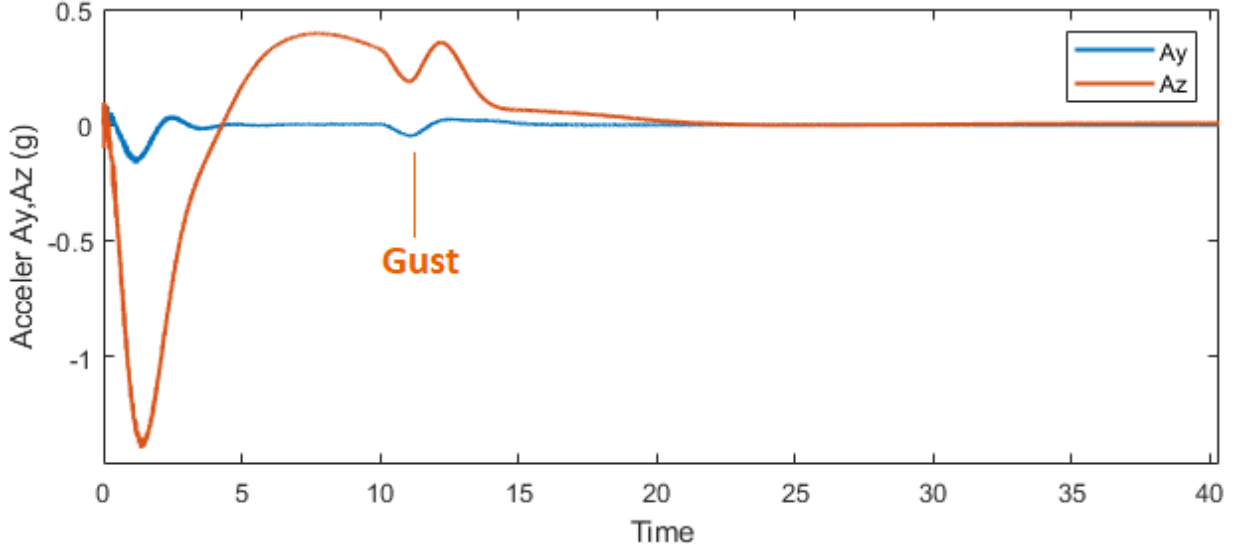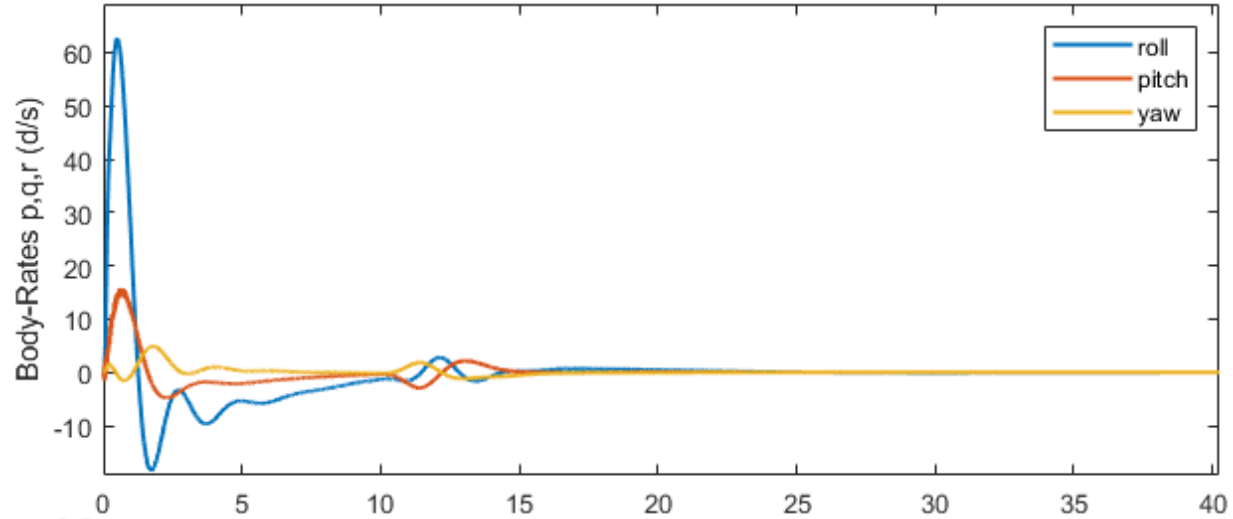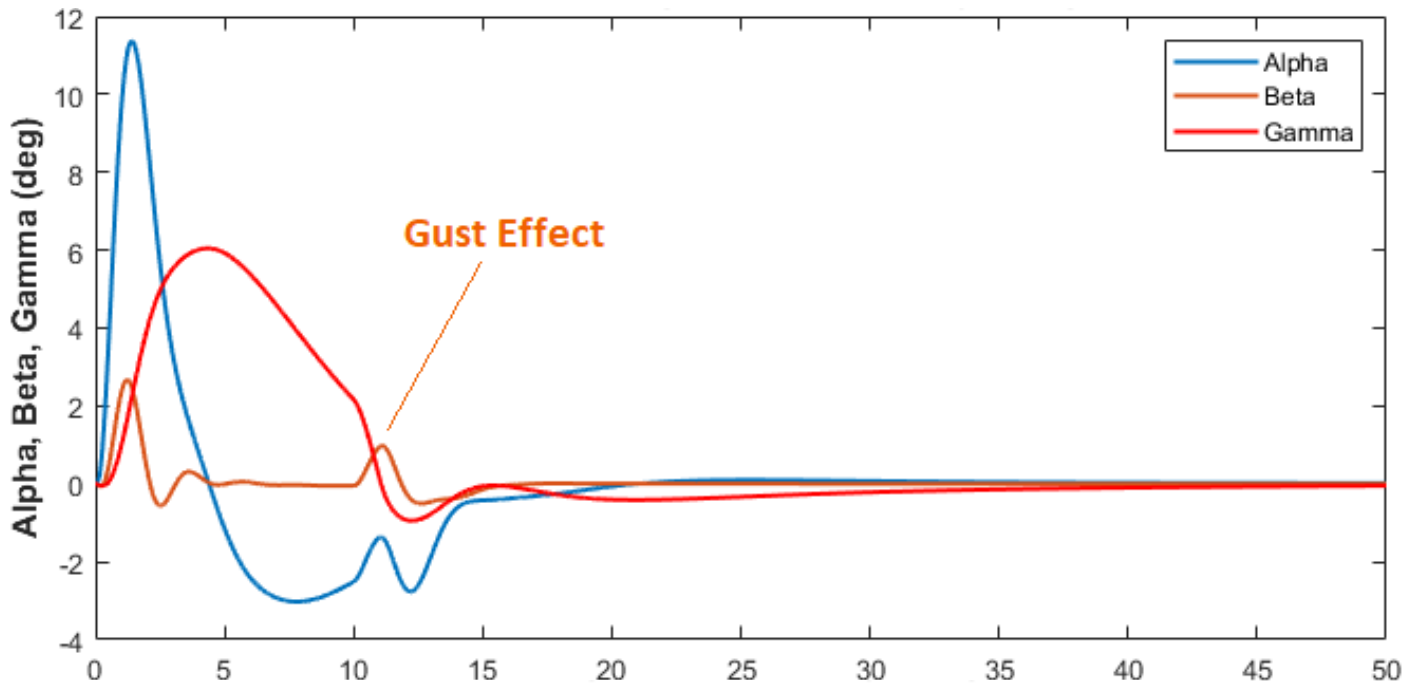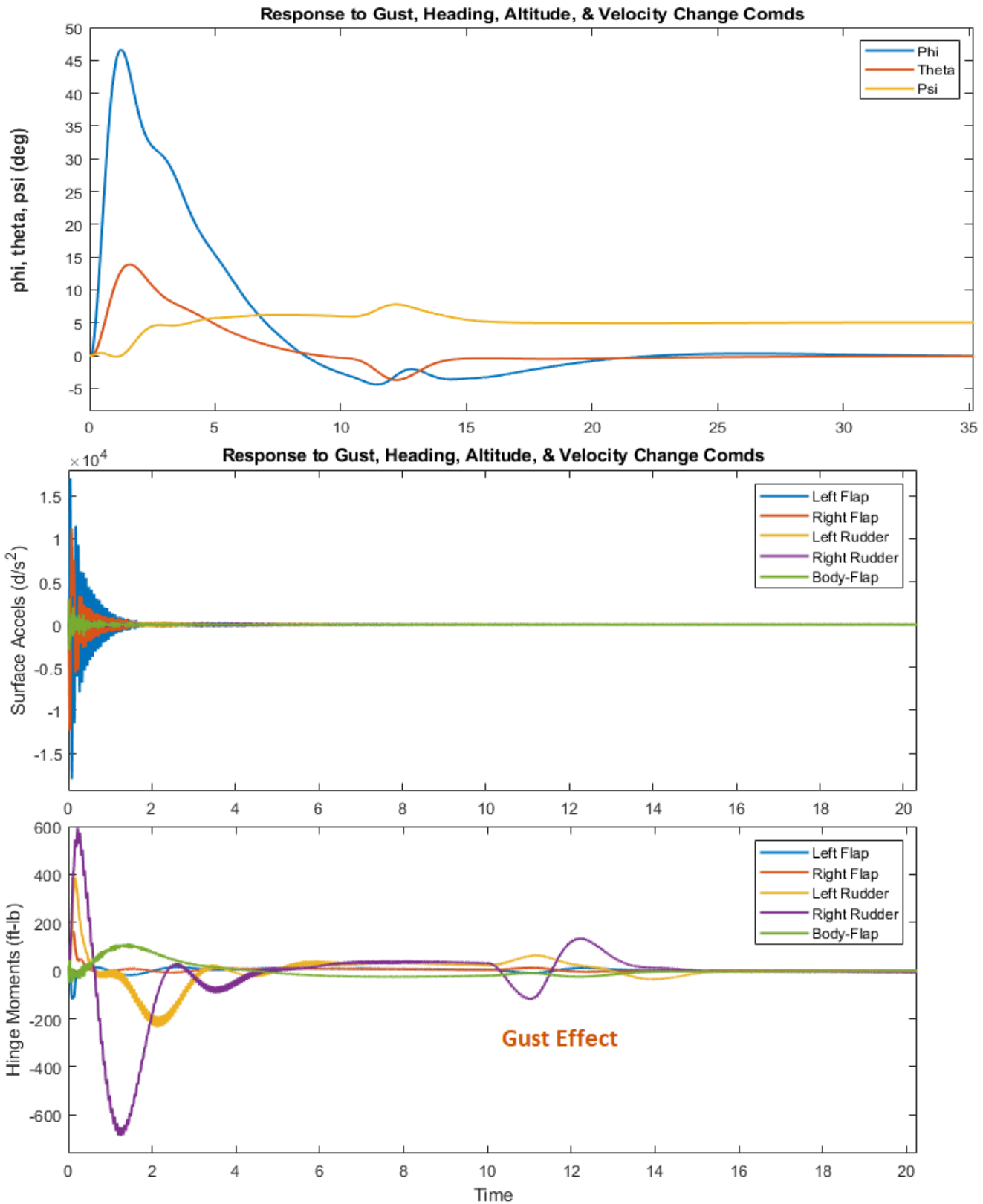
Figure 2.12 The Vehicle Rolls 45 (deg) to the Right to Change Direction and it Returns to Zero Roll

The effects of structural flexibility are visible in the aerosurface accelerations and in the hinge moments. Flex modes are excited at the surface hinges mainly due to flap deflections. The change in the hinge moments are mainly due to aerodynamic loading of the aerosurfaces. The gust also produces a transient in the hinge moments.

2.8 Stability Analysis

The Simulink model "*Open_Loop_Flx.slx*" is used for stability analysis in the frequency domain. It is a single-input-single-output system for classical control analysis similar to the model that was used for rigid-body analysis. It contains the same subsystem blocks as the closed-loop system but the loop to be analyzed is opened, while the other three loops must remain closed. The Matlab file "frequ.m" calculates the frequency response across the open-loop and plots the Bode and Nichols charts which are used to analyze the system stability. To check, for example, the yaw axis stability we must open the yaw loop (as shown in Figure 2.13) with the roll, pitch, and throttle loops closed, and calculate the frequency response across the opened yaw loop. The (-1) gain in the open loop output is included in order to set the phase correctly for classical control analysis. The system has acceptable phase and gain margins in all four loops with a control system bandwidth of approximately 3.5 (rad/sec). The throttle control loop is slower with only 0.5 (rad/sec) bandwidth.
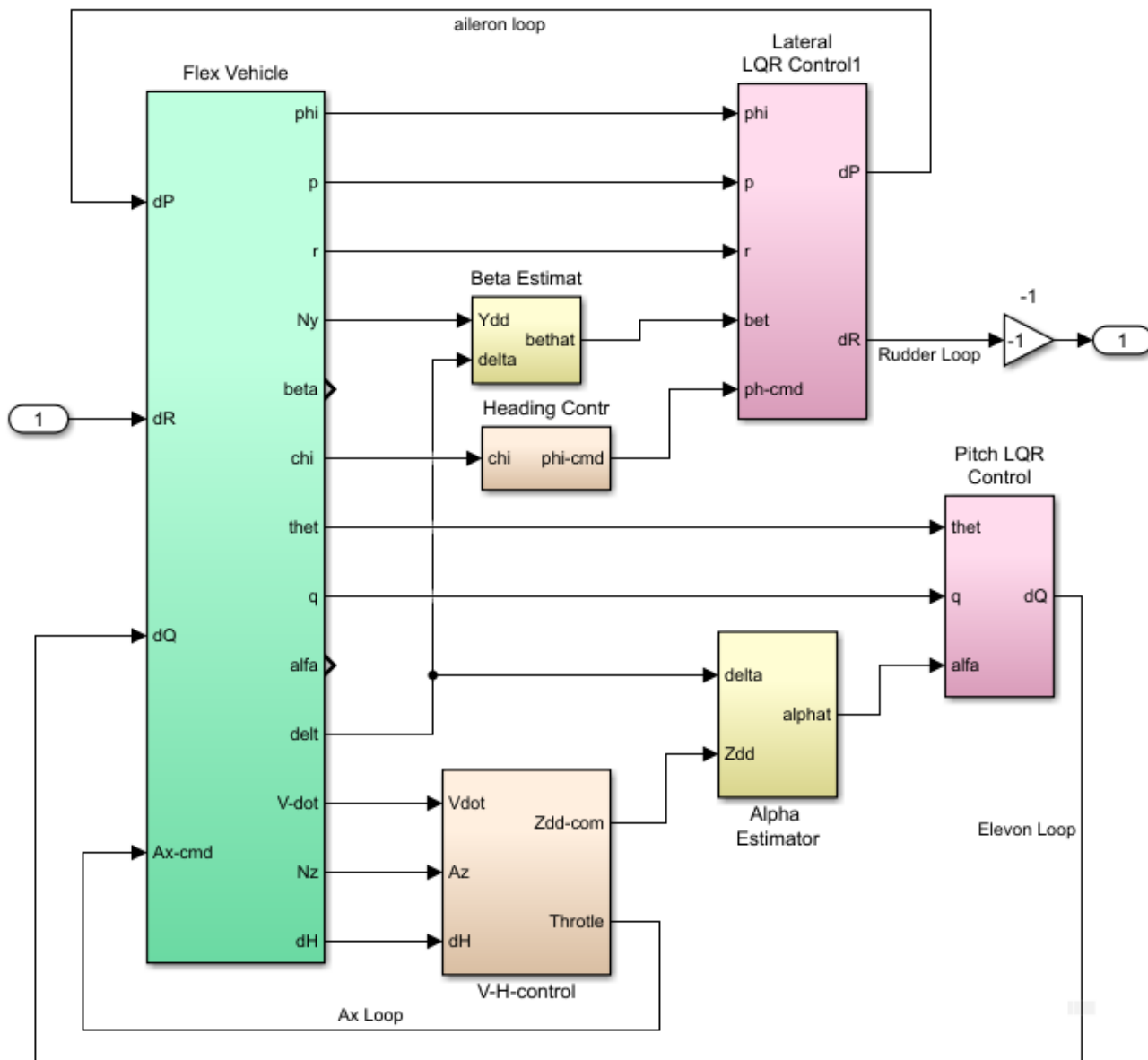
Figure 2.13 Simulink Model "Open_Loop_Flx.slx" Configured for Analyzing Yaw Stability

Yaw Axis Open-Loop Frequency Response
(Other Loops are Closed)

Cross-Over
Frequ: 3.2 r/s

Flex Modes

Nichols Chart

Yaw Axis Stability

Margins
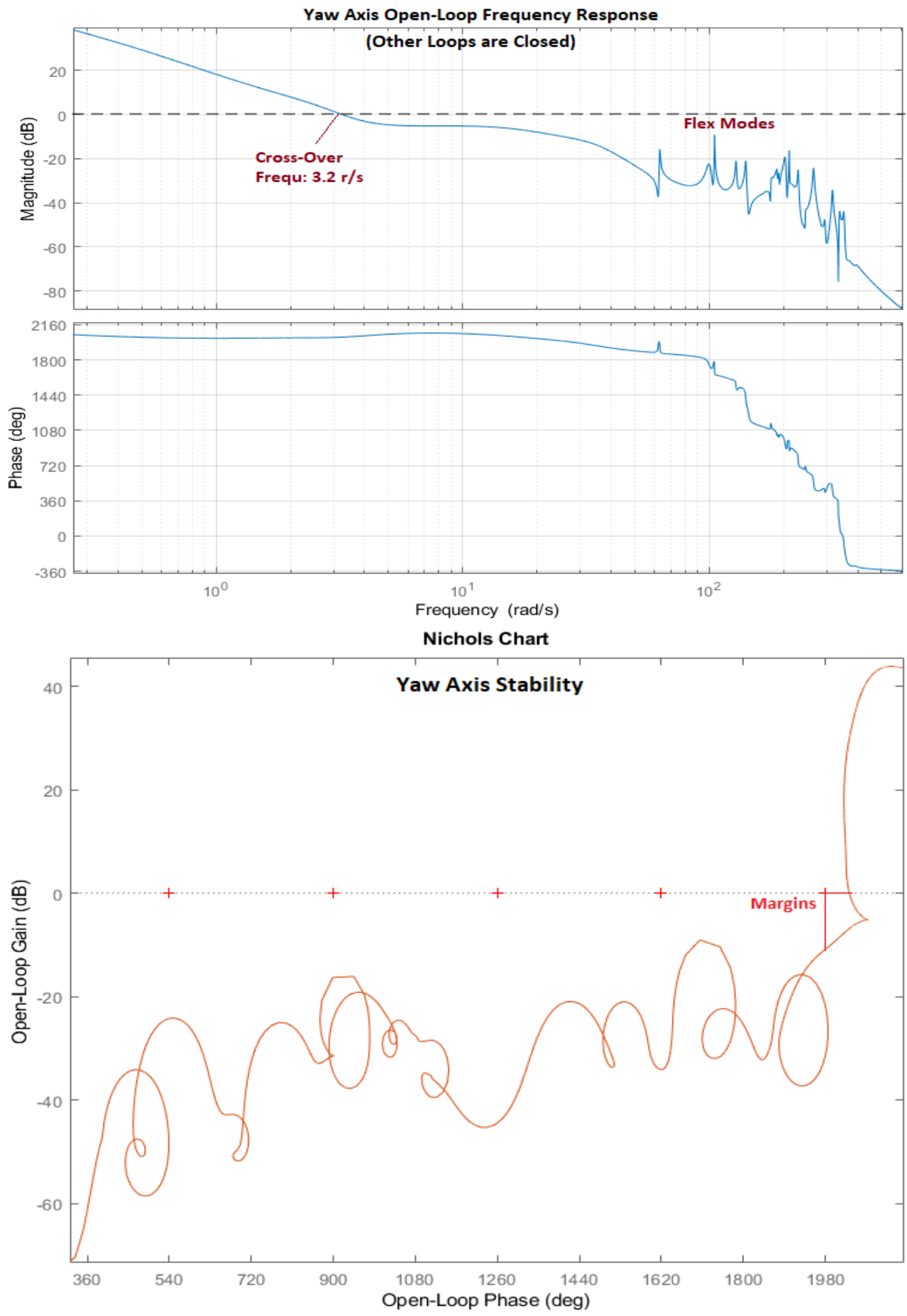
Figure 2.14 Stability of the Yaw Axis Loop
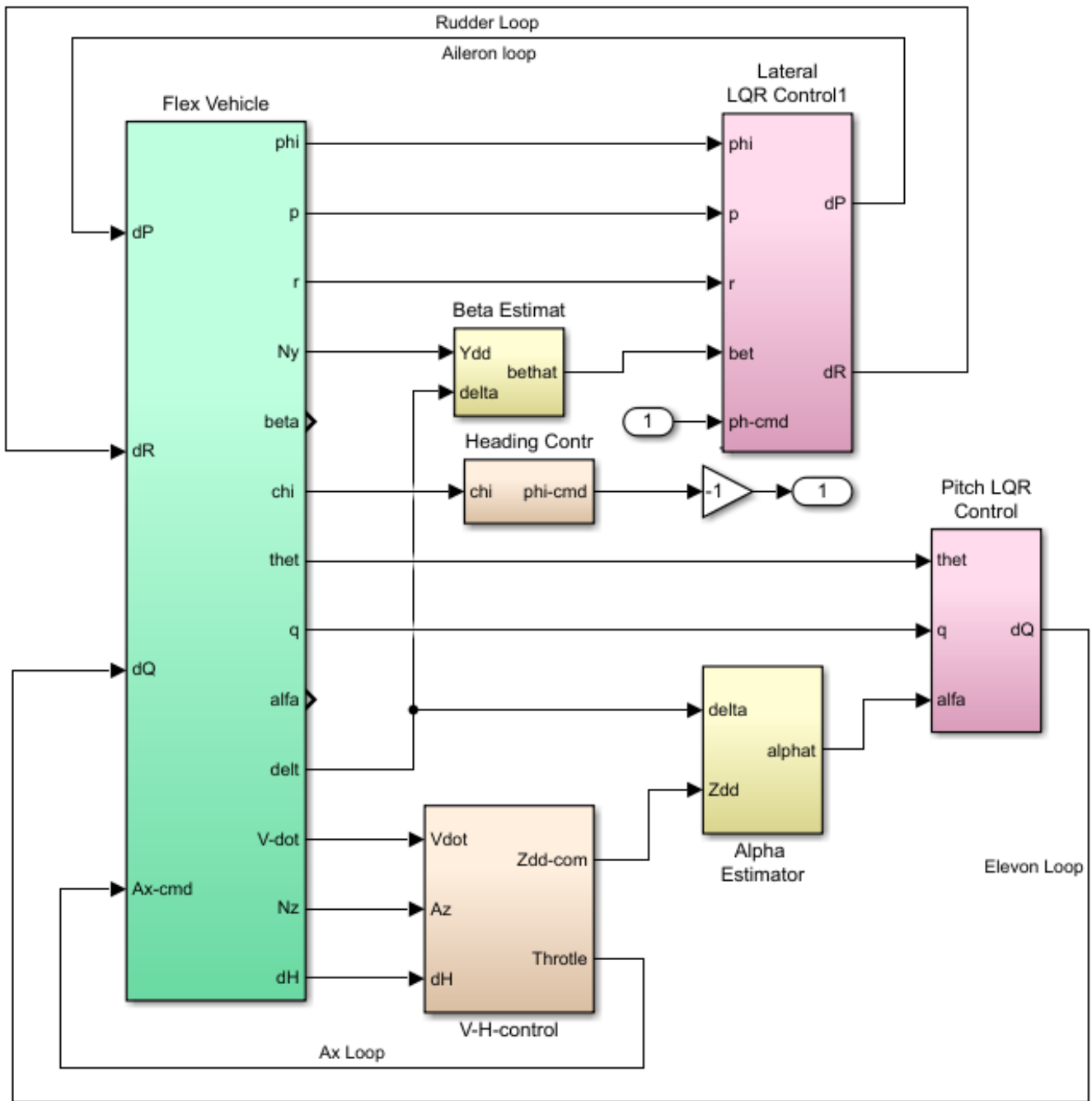
Figure 2.15 Simulink Model "Open_Loop_Flx.slx" Configured to Analyze Stability of the Heading Control Loop which is Opened at the Phi-Command
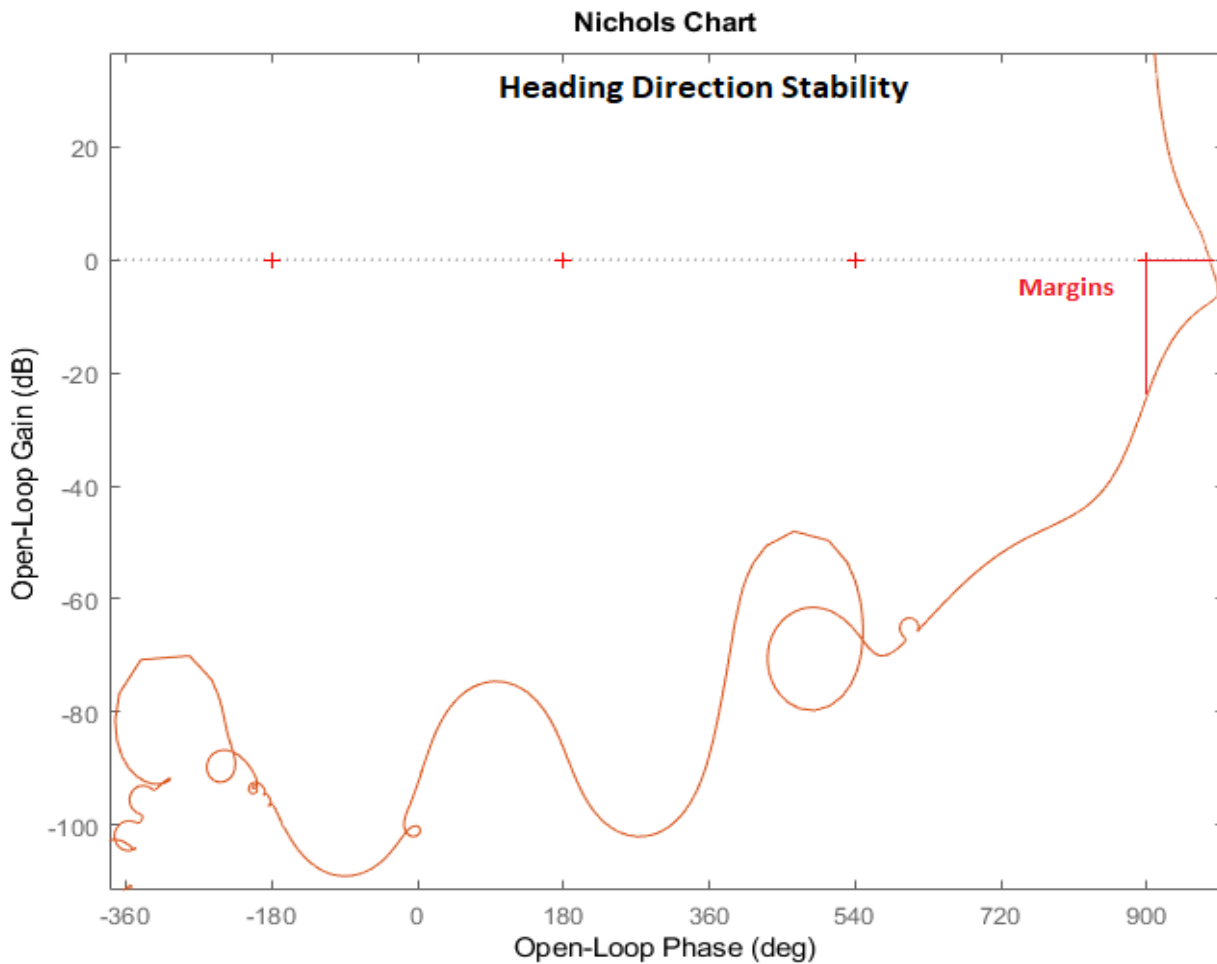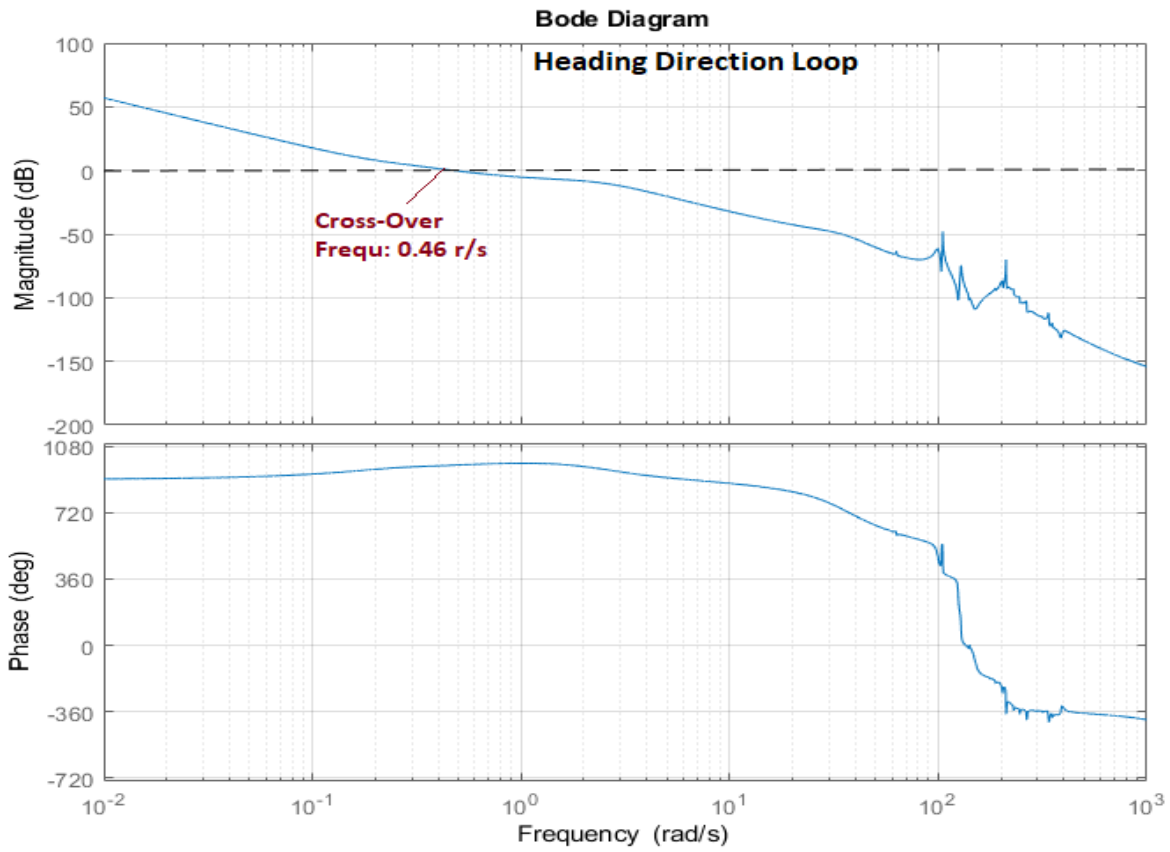
Figure 2.16 Stability of the Heading Control Loop

Roll Axis Open-Loop Frequency Response (other loops closed)

Bode Diagram
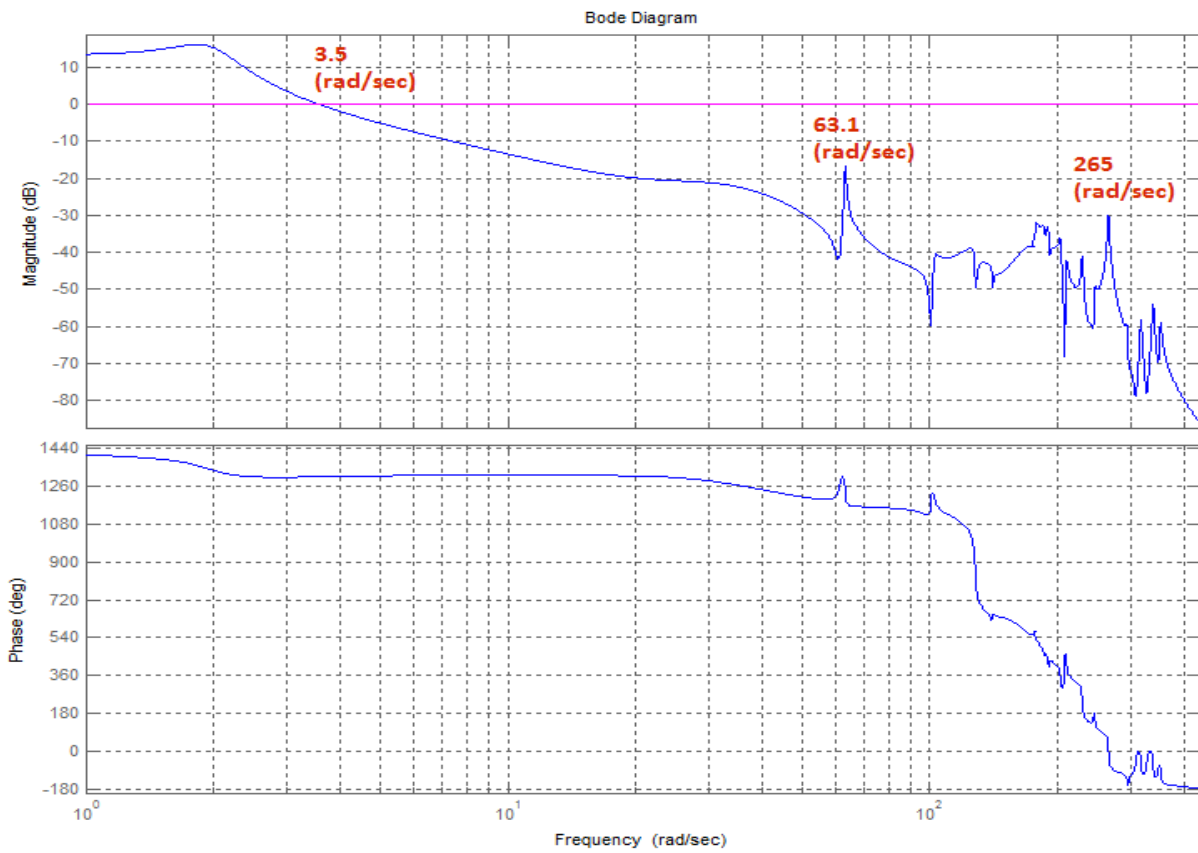
Roll Axis Stability (all other loops closed)
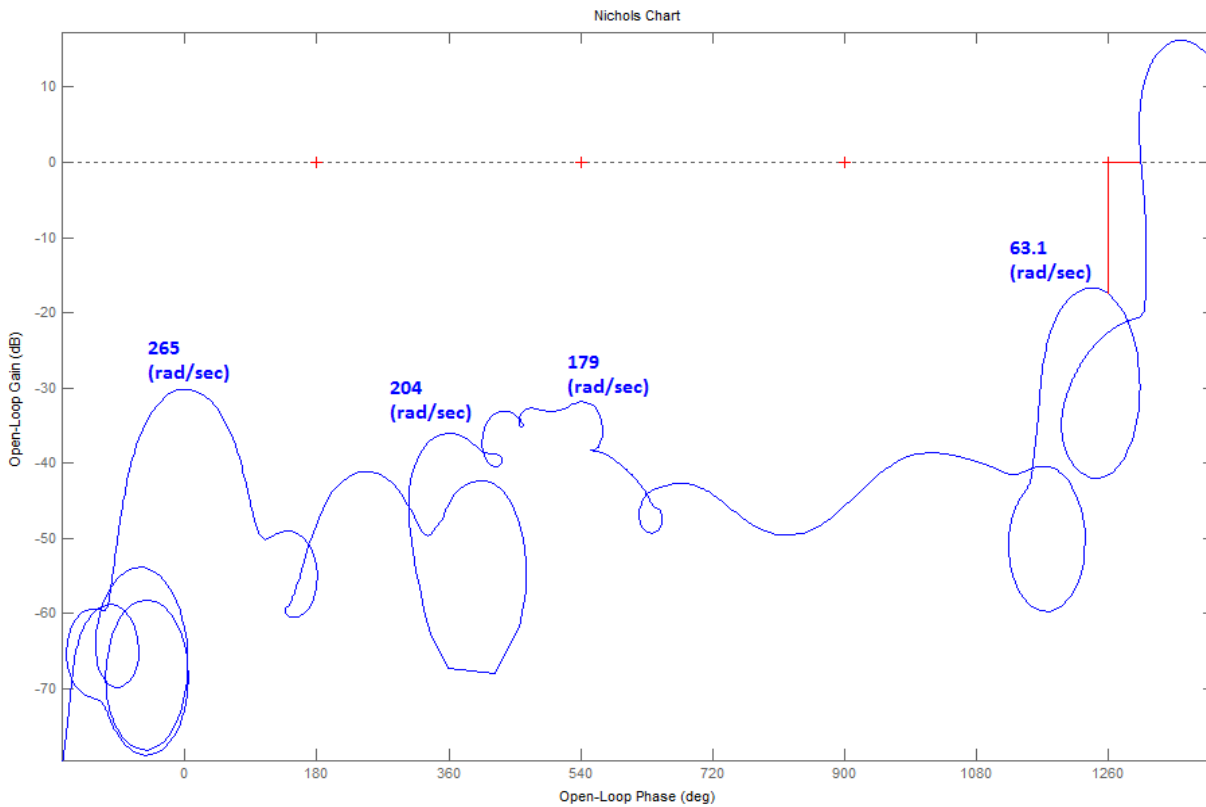
Nichols Chart

Figure 2.17 Stability of the Roll Axis Loop

Pitch Axis Open-Loop Frequency Response

Rigid-Body Aero Mode: 2 r/s

Cross-Over Frequ: 3.4 r/s

Flex Modes

Nichols Chart

Pitch Axis Stability

Margins
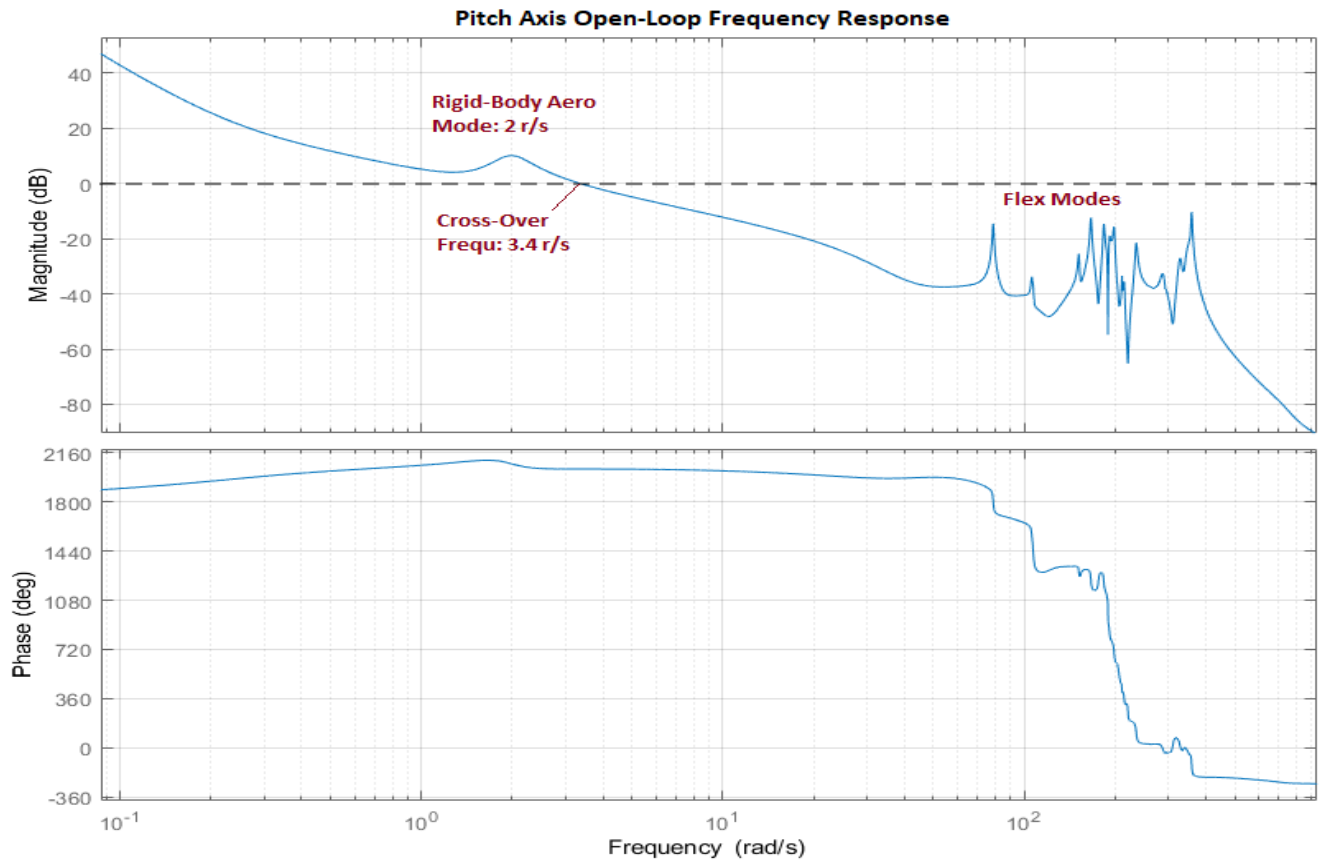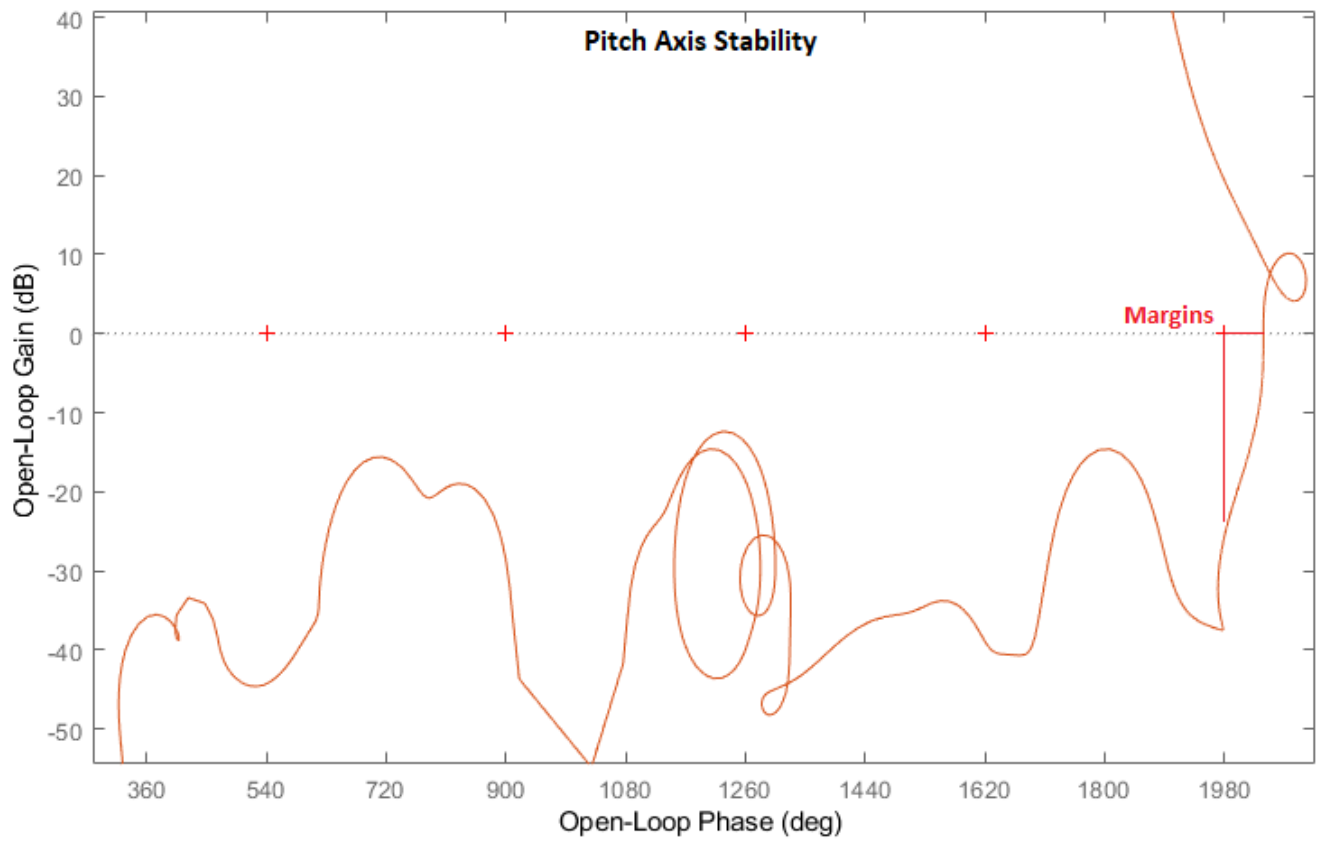
Figure 2.18 Stability of the Pitch Axis Loop
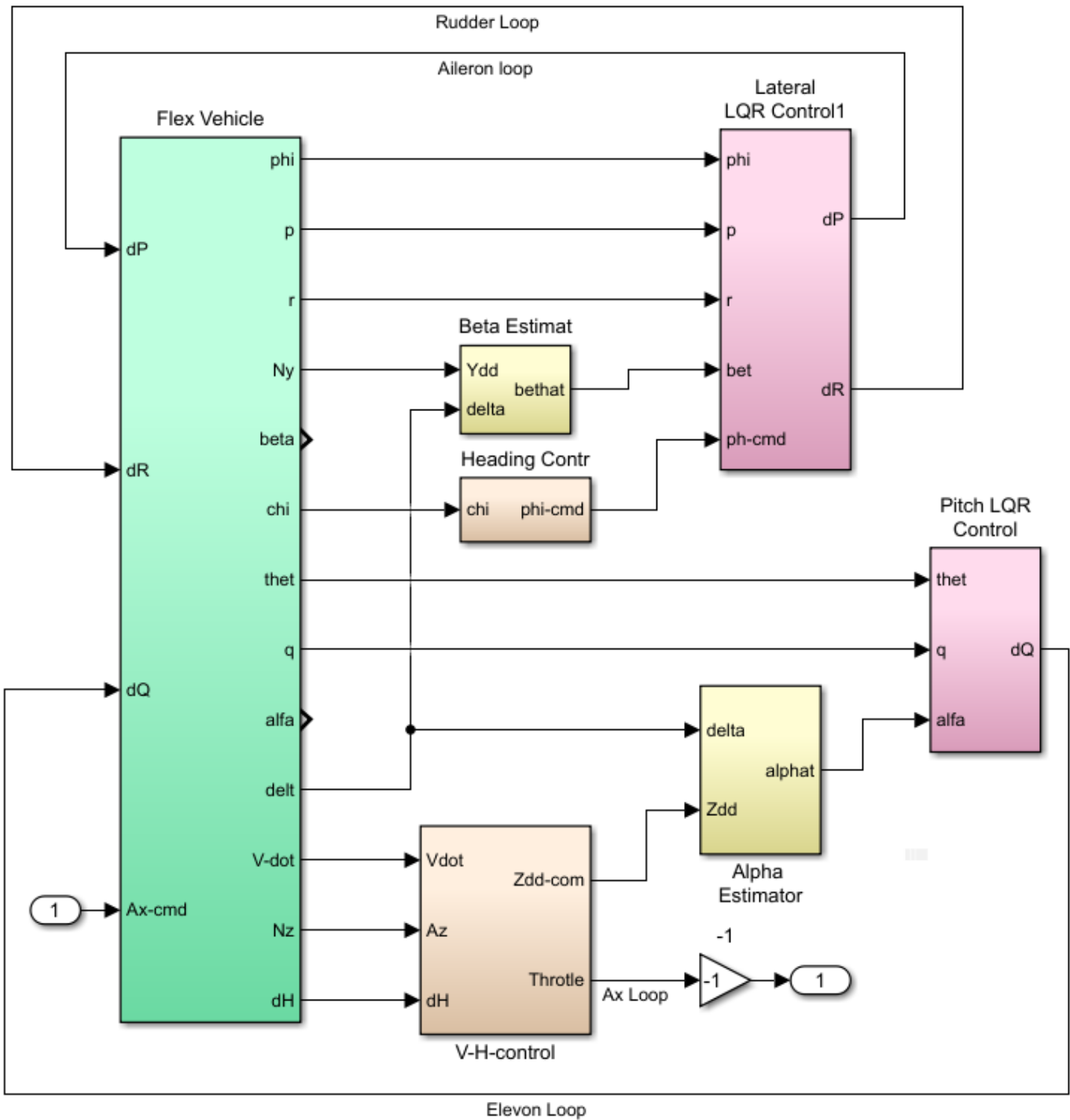
Figure 2.19 Simulink Model "Open_Loop_Flx.slx" Configured for Analyzing Stability of the Throttle Control Loop that Controls Speed and it is Opened at the Throttle Acceleration Command

Bode Diagram

Throttle Control Loop

Cross-Over
Frequ: 0.51 r/s

Nichols Chart

Velocity Control Loop Stability

Margins
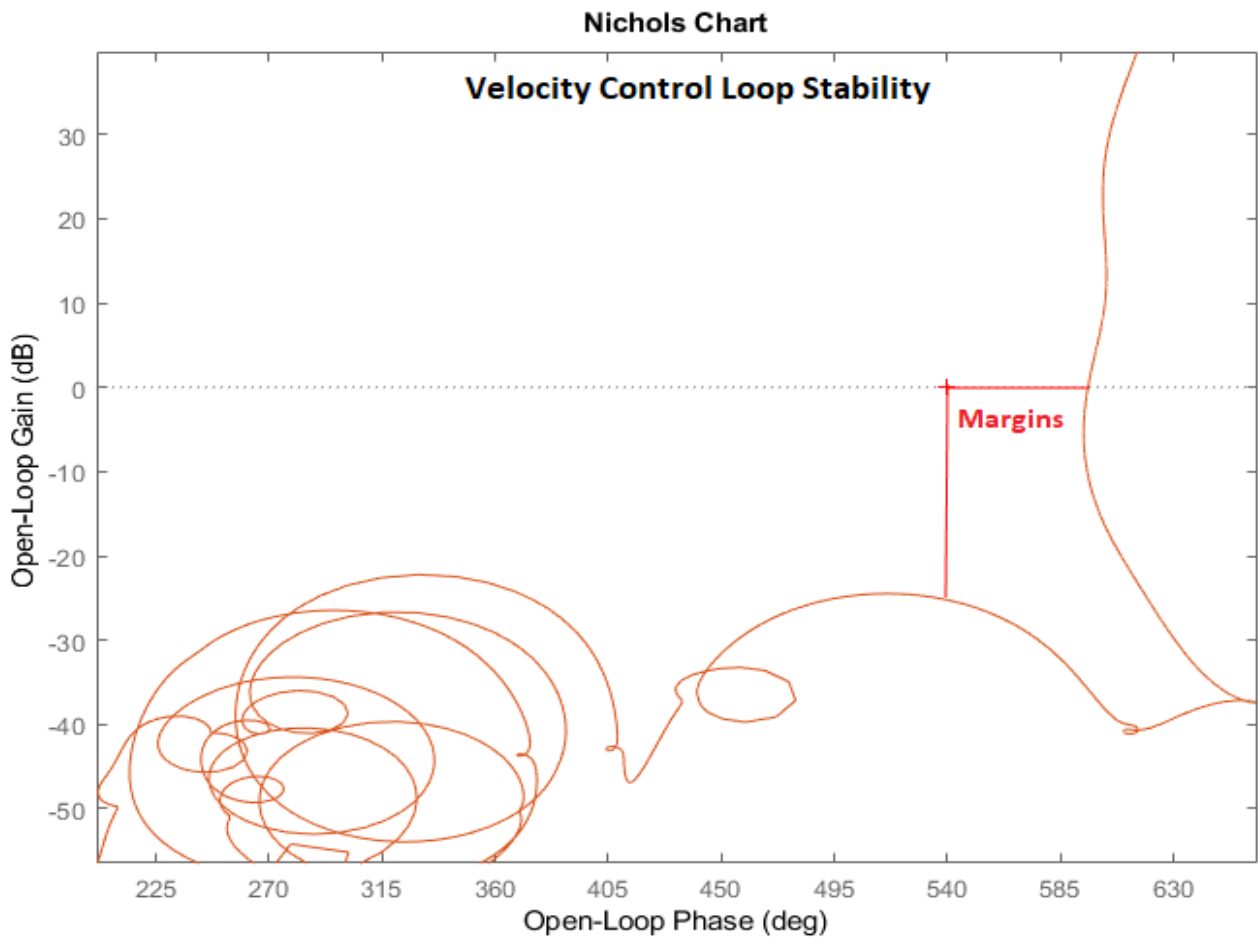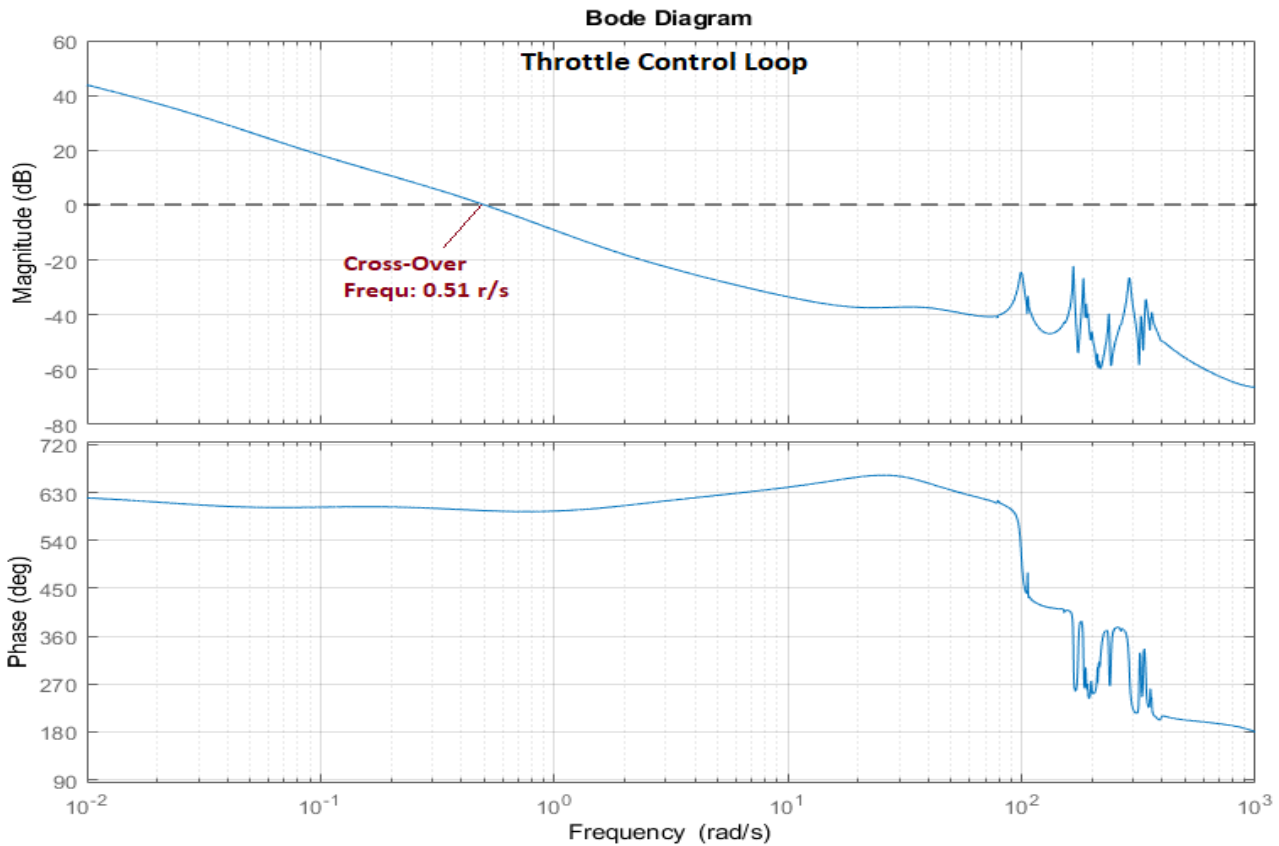
Figure 2.20 Stability of the Throttle Control Loop Used for Speed Control

3.0 Flexible Vehicle Analysis Using Aero-Elasticity Coefficients

We will now go one step further in analyzing the vehicle flexibility by introducing the aero-elasticity coefficients that couple aerodynamics with the flex modes. The aero-elastic coefficients are also known as Generalized Aerodynamic Force Derivatives (GAFD). We will also include inertial coupling coefficients that couple the aerosurface accelerations with flexibility. These additional coefficients are generated from the finite elements model. They will be combined with the vehicle parameters to create a more accurate structural flexibility model. The GAFD coefficients define how the aerodynamic forces and moments vary as a function of the modal excitations (η_i), surface deflections (δ_{as}) and deflection rates. They also define how the bending modes are excited by the variations in (α, β) relative to wind, and the body rates (p, q, r), and how they couple with other bending modes. There are also coefficients that define how the moment at an aerosurface hinge varies as a function of angles of attack, sideslip, body rates, accelerations, modal displacements, modal rates, and also by the interactions with other control surface deflections and rates. The mode selection process presented in Section 2 will not be repeated because the previously selected set of flex modes will also be used in this section. In addition to the mode shapes and frequencies, the program will read the GAFD data file. It will combine it with the vehicle data and create the flexible vehicle model which is the same size as the previous model but it includes the aero-elastic coupling effects which is a more accurate representation than the previous model in Section 2. The hinge moment calculations are also more accurate because they are based on a better CFD model that produced those coupling coefficients. We will conclude by repeating the analysis that was described in Section 2 using the aero-elastic coefficients and compare the results between the two flex models.

3.1 Generalized Aerodynamic Force Derivatives (GAFD)

The Generalized Aerodynamic Force Derivatives (GAFD) are used to model the dynamic coupling between structure and aerodynamics on a flight vehicle. They are created by combining results from FEM and CFD models and they consist of the following sets of coefficients.

- The first set of coefficients define how the vehicle basic aerodynamic forces and moments, such as C_Z, C_m, C_n, etc. are affected by the modal displacements (η_i), and the modal rates ($\dot{\eta}_j$).

- The second set coefficients describe how the modal displacement (η_i) of a flex mode (j), is excited by the vehicle motion, such as, changes in angle of attack α, sideslip β, body rates p, q, r, accelerations, aerosurface deflections, rates, and also by modal displacements, rates, and accelerations of other modes.

- The third set of coefficients are hinge moment coefficients. They define how the moment at the hinge of an aerosurface is affected by changes in the vehicle angles of attack, sideslip, body rates, accelerations, modal displacements, modal rates, and also by the interactions with other aerosurface deflections and rates.

- The original GAFD output includes the rigid-body aerodynamic force and moment derivatives produced by changes in angle of attack, sideslip, body rates, accelerations, control surface deflections, and surface rates. They are created from the CFD model. These coefficients, however, are not included in the GAFD file and they will not be used by the modeling program. More accurate wind-tunnel aero derivatives will be used instead which are included in the vehicle input data.

Even though the preparation of aero-elastic data is beyond the scope of this document, in the following paragraph we will present a brief description on the GAFD derivation in order to point the user in the right direction and understand what kind of information is needed. The GAFD data are obtained by post processing the generalized aerodynamic forces [Qij] which is a mass matrix obtained from the "Doublet Lattice" program, which is included in the finite elements modeling tools. The Qij terms can be used for flutter analysis, loads, and for control system analysis. The generalized aerodynamic forces are complex and are a function of Mach number and a reduced frequency. For each Mach number and reduced frequency, a complex generalized force matrix is generated. In the flutter analysis, a Mach number and reduced frequency is assumed and the flutter solution is calculated. If the solution indicates that the flutter frequency is at a different frequency than the assumed reduced frequency, then that solution is invalid. The flutter analysis is then repeated until the flutter frequency equals the assumed reduced frequency. This iterative process is not used in the control system analysis. A complex generalized aerodynamic force matrix is constructed which is independent of reduced frequency. The real part of this complex matrix consists of displacement coefficients and the imaginary part consists of the velocity coefficients. The inputs to the Doublet Lattice program are the Modal Data (mode shapes and mode frequencies) obtained from the finite elements model. The aerodynamic shape of the vehicle is modeled by means of flat plates in the Doublet Lattice program, and it computes the aerodynamic coefficients at different Mach numbers. The program finally combines the NASTRAN model with the aerodynamic model and produces the Generalized Aerodynamic Forces, the Qij matrix. The finite-elements-model includes the aerosurfaces with the hinges locked. The hinges are then released in the equations by the introduction of the inertial coupling coefficients (also known as h-parameters).

The GAFD data at a given Mach number consists of a pair of two matrices: a displacements matrix and a velocities matrix. The displacements matrix describes how the coefficients are affected by changes in $\{\beta, \alpha, p, q, r, \eta_i, \delta_j\}$. The rates matrix describes how the coefficients are affected by the derivatives of: $\{\beta, \alpha, p, q, r, \eta_i, \delta_j\}$. The matrix pairs are calculated at different frequencies, the 6 rigid body frequencies and at each bending mode. The Displacements matrix for (i) number of flex modes and for (j) aero-surfaces has the following form:

$$
\begin{Bmatrix} C_Y \\ C_Z \\ C_l \\ C_m \\ C_n \\ C_{\eta 1} \\ C_{\eta 2} \\ C_{\eta i} \\ C_{h1} \\ C_{hj} \end{Bmatrix} =
\begin{bmatrix}
C_{Y\beta} & C_{Y\alpha} & C_{Yp} & C_{Yq} & C_{Yr} & C_{Y\eta_1} & C_{Y\eta_2} & C_{Y\eta_i} & C_{Y\delta_1} & C_{Y\delta_j} \\
C_{Z\beta} & C_{Z\alpha} & C_{Zp} & C_{Zq} & C_{Zr} & C_{Z\eta_1} & C_{Z\eta_2} & C_{Z\eta_i} & C_{Z\delta_1} & C_{Z\delta_j} \\
C_{l\beta} & C_{l\alpha} & C_{lp} & C_{lq} & C_{lr} & C_{l\eta_1} & C_{l\eta_2} & C_{l\eta_i} & C_{l\delta_1} & C_{l\delta_j} \\
C_{m\beta} & C_{m\alpha} & C_{mp} & C_{mq} & C_{mr} & C_{m\eta_1} & C_{m\eta_2} & C_{m\eta_i} & C_{m\delta_1} & C_{m\delta_j} \\
C_{n\beta} & C_{n\alpha} & C_{np} & C_{nq} & C_{nr} & C_{n\eta_1} & C_{n\eta_2} & C_{n\eta_i} & C_{n\delta_1} & C_{n\delta_j} \\
C_{\eta 1\beta} & C_{\eta 1\alpha} & C_{\eta 1p} & C_{\eta 1q} & C_{\eta 1r} & C_{\eta 1\eta_1} & C_{\eta 1\eta_2} & C_{\eta 1\eta_i} & C_{\eta 1\delta_1} & C_{\eta 1\delta_j} \\
C_{\eta 2\beta} & C_{\eta 2\alpha} & C_{\eta 2p} & C_{\eta 2q} & C_{\eta 2r} & C_{\eta 2\eta_1} & C_{\eta 2\eta_2} & C_{\eta 2\eta_i} & C_{\eta 2\delta_1} & C_{\eta 2\delta_j} \\
C_{\eta_i\beta} & C_{\eta_i\alpha} & C_{\eta_i p} & C_{\eta_i q} & C_{\eta_i r} & C_{\eta_i\eta_1} & C_{\eta_i\eta_2} & C_{\eta_i\eta_i} & C_{\eta_i\delta_1} & C_{\eta_i\delta_j} \\
C_{h_1\beta} & C_{h_1\alpha} & C_{h_1 p} & C_{h_1 q} & C_{h_1 r} & C_{h_1\eta_1} & C_{h_1\eta_2} & C_{h_1\eta_i} & C_{h_1\delta_1} & C_{h_1\delta_j} \\
C_{h_j\beta} & C_{h_j\alpha} & C_{h_j p} & C_{h_j q} & C_{h_j r} & C_{h_j\eta_1} & C_{h_j\eta_2} & C_{h_j\eta_i} & C_{h_j\delta_1} & C_{h_j\delta_j}
\end{bmatrix}
\begin{Bmatrix} \beta \\ \alpha \\ p \\ q \\ r \\ \eta_1 \\ \eta_2 \\ \eta_i \\ \delta_1 \\ \delta_j \end{Bmatrix}
$$

The Velocities matrix for (i) number of flex modes and for (j) aero-surfaces is:

$$
\begin{pmatrix} C_Y \\ C_Z \\ C_l \\ C_m \\ C_n \\ C_{\eta 1} \\ C_{\eta 2} \\ C_{\eta i} \\ C_{h1} \\ C_{hj} \end{pmatrix}
=
\begin{bmatrix}
C_{Y\dot\beta} & C_{Y\dot\alpha} & C_{Y\dot p} & C_{Y\dot q} & C_{Y\dot r} & C_{Y\dot\eta_1} & C_{Y\dot\eta_2} & C_{Y\dot\eta_i} & C_{Y\dot\delta_1} & C_{Y\dot\delta_j} \\
C_{Z\dot\beta} & C_{Z\dot\alpha} & C_{Z\dot p} & C_{Z\dot q} & C_{Zr} & C_{Z\eta_1} & C_{Z\eta_2} & C_{Z\eta_i} & C_{Z\delta_1} & C_{Z\delta_j} \\
C_{l\dot\beta} & C_{l\dot\alpha} & C_{l\dot p} & C_{l\dot q} & C_{lr} & C_{l\eta_1} & C_{l\eta_2} & C_{l\dot\eta_i} & C_{l\dot\delta_1} & C_{l\delta_j} \\
C_{m\dot\beta} & C_{m\alpha} & C_{m\dot p} & C_{m\dot q} & C_{mr} & C_{m\dot\eta_1} & C_{m\dot\eta_2} & C_{m\dot\eta_i} & C_{m\delta_1} & C_{m\dot\delta_j} \\
C_{n\beta} & C_{n\dot\alpha} & C_{n\dot p} & C_{n\dot q} & C_{n\dot r} & C_{n\eta_1} & C_{n\eta_2} & C_{n\eta_i} & C_{n\delta_1} & C_{n\dot\delta_j} \\
C_{\eta 1\dot\beta} & C_{\eta 1\dot\alpha} & C_{\eta 1p} & C_{\eta 1q} & C_{\eta 1\dot r} & C_{\eta 1\dot\eta_1} & C_{\eta 1\dot\eta_2} & C_{\eta 1\eta_i} & C_{\eta 1\delta_1} & C_{\eta 1\delta_j} \\
C_{\eta 2\beta} & C_{\eta 2\alpha} & C_{\eta 2\dot p} & C_{\eta 2\dot q} & C_{\eta 2\dot r} & C_{\eta 2\dot\eta_1} & C_{\eta 2\dot\eta_2} & C_{\eta 2\dot\eta_i} & C_{\eta 2\dot\delta_1} & C_{\eta 2\dot\delta_j} \\
C_{\eta_i\dot\beta} & C_{\eta_i\dot\alpha} & C_{\eta_i p} & C_{\eta_i q} & C_{\eta_i r} & C_{\eta_i\dot\eta_1} & C_{\eta_i\dot\eta_2} & C_{\eta_i\dot\eta_i} & C_{\eta_i\dot\delta_1} & C_{\eta_i\dot\delta_j} \\
C_{h_1\dot\beta} & C_{h_1\dot\alpha} & C_{h_1\dot p} & C_{h_1\dot q} & C_{h_1\dot r} & C_{h_1\dot\eta_1} & C_{h_1\dot\eta_2} & C_{h_1\dot\eta_i} & C_{h_1\dot\delta_1} & C_{h_1\dot\delta_j} \\
C_{h_j\dot\beta} & C_{h_j\dot\alpha} & C_{h_j\dot p} & C_{h_j\dot q} & C_{h_j\dot r} & C_{h_j\dot\eta_1} & C_{h_j\dot\eta_2} & C_{h_j\eta_i} & C_{h_j\dot\delta_1} & C_{h_j\dot\delta_j}
\end{bmatrix}
\begin{Bmatrix} \dot\beta \\ \dot\alpha \\ \dot p \\ \dot q \\ \dot r \\ \dot\eta_1 \\ \dot\eta_2 \\ \dot\eta_i \\ \dot\delta_1 \\ \dot\delta_j \end{Bmatrix}
$$

The data files used in this vehicle aero-elastic model analysis are in directory *"C:\Flixan\Examples\18-Rocket Plane\3-Flex Model with Gafd"*. The GAFD file "*RocketPlane.Gaf*", partially shown below, contains inertial coupling coefficients (h-parameters) and the aero-elastic matrix coefficients. It was prepared (not shown details) by post-processing the double-lattice output which is a much bigger data file, after rescaling it to be compatible with the vehicle data and reformatting it to be accessible by the vehicle modeling program. It contains the coefficients described for 34 frequencies and the 5 aerosurfaces. The GAFD frequencies correspond to the 34 modes in the modal data file "*RocketPlane.Mod*". The order of the aerosurfaces is the same as in the vehicle data (left and right flaps, left and right rudders, and body-flap). It also contains the aerosurfaces moments of inertia about the hinges, the GAFD frequencies in (rad/sec), the vehicle reference length and reference area, the reference chords and the reference areas for each aerosurface, the inertial coupling coefficients that couple the modal equations with the aerosurface accelerations, and the GAFD coefficients. The inertial coupling coefficients, or h-parameters $h_s(k,j)$, define the excitation of a mode (j) due to the control surface (k) accelerations. They also define the hinge moment variation at a surface (k) due to a mode (j) displacement. They are included in the same GAFD data file. The modal equations with inertial coupling and aero-elastic coefficients are described in the vehicle equations of motion, Section 2.7, and the hinge moment equations are in Section 2.10.

The vehicle input dataset is "*Rocket Plane at Mach=0.85, Q=150, Aero-Elastic Model with GAFD*", in file *"RocketPlane-Gafd.Inp"*. It is almost identical to the flex vehicle model in Section 2, except that in this case the "*Include GAFD*" flag in the flags line is turned-on to include the additional GAFD data file. The flags line is below the vehicle title and comments. When the GAFD flag is set, the program attempts to read and use the GAFD file. Otherwise, if it cannot find the file "*RocketPlane.Gaf*" or if the flag is set to "*Without GAFD*", the vehicle modeling program uses only the modal data. It is approximating the aeroelastic effects with aerodynamic forces and torques applied at the hinge nodes as a result of the aerosurface deflections and accelerations as it was implemented in Section 2. There is another identical vehicle dataset in the input file to be used for batch processing. Its title is "*Rocket Plane at Mach=0.85, Q=150, Aero-Elastic Model with GAFD (Batch)*". It is identical to the first dataset except that it is conveniently processed in batch mode because it includes the selected GAFD frequency numbers and the selected GAFD aerosurface numbers at the bottom of the data-set.

GENERALIZED AERO FORCE DERIVATIVES (GAFD) and INERTIAL COUPLING PARAMETERS (H-param) Data for the Rocket Plane Vehicle: Mach 0.85, Q=150 (psf)
```
Number of: Rigid Body Vehicle Degrees of Freedom, Flexible Modes, Control Surfaces=   5          34          5
Mach No, Velocity (ft/sec), Vehicle Reference Area (ft^2), Aerodynamic Chord (ft) =   0.85000E+00 0.94898E+03 79.0        6.1
Control Surface Reference Areas in (ft^2)  {2 flaps, 2 rudders, body flap}     =   5.55        5.55        10.36       10.36       5.8
Control Surface Reference Chords in (feet) {2 flaps, 2 rudders, body flap}     =   1.207       1.207       2.28        2.28        1.68
Moments of Inertia of the Control Surfaces about the Hinge, (ft-lb-sec^2)      =   0.287       0.287       3.914       3.914       1.2
Modal Frequencies in (radian/sec)                                             =   0.63169E+02 0.80048E+02 0.10621E+03 0.11776E+03 0.13108E+03

INERTIAL COUPLING PARAMETERS in (lb-sec^2-ft)
Inertial Coupling (H-param) for Surface (   1), for Modes (j=1,2,Nmode), .......... -0.86029E-01  0.68432E-01  0.31973E+00 -0.22637E+00 -0.30744E-02
Inertial Coupling (H-param) for Surface (   2), for Modes (j=1,2,Nmode), ..........  0.86513E-01  0.69159E-01  0.31289E+00  0.24183E+00 -0.32765E-02
Inertial Coupling (H-param) for Surface (   3), for Modes (j=1,2,Nmode), .......... -0.66851E+00 -0.66782E+00 -0.13457E+00  0.27968E+01 -0.46936E+01
Inertial Coupling (H-param) for Surface (   4), for Modes (j=1,2,Nmode), ..........  0.67299E+00 -0.65977E+00 -0.70748E-01 -0.28348E+01 -0.46012E+01
Inertial Coupling (H-param) for Surface (   5), for Modes (j=1,2,Nmode), ..........  0.59991E-03 -0.27464E+00  0.63212E-02 -0.21172E-02  0.71388E-01


FORCE/ MOMENT COEFFICIENTS DUE TO MODAL DISPLACEMENTS (ETA) - (1/feet)
Cy due to Generalized Displacement eta(j), {Cy_eta(j)}, where (j=1,2,3,,,Nmode)     0.48471E-01 -0.56448E-03 -0.32820E-02  0.33106E+00 -0.60205E-02
Cz due to Generalized Displacement eta(j), {Cz_eta(j)}, where (j=1,2,3,,,Nmode)    -0.23842E-03  0.28122E+00 -0.10046E+00  0.40608E-03  0.63277E+00
Cl (roll) due to Generalized Displacement eta(j), {Cl_eta(j)}, where (j=1,2,3,Nmode) -0.13694E-01 -0.38372E-03 -0.25397E-02  0.26169E+00 -0.55124E-02
Cm (ptch) due to Generalized Displacement eta(j), {Cm_eta(j)}, where (j=1,2,3,Nmode)  0.57100E-03  0.31409E+00  0.30840E-02  0.46856E-02  0.11182E+01
Cn (yaw)  due to Generalized Displacement eta(j), {Cn_eta(j)}, where (j=1,2,3,Nmode) -0.59780E-01  0.95394E-03  0.62141E-02 -0.59678E+00  0.10691E-01
MODAL EXCITATION COEFFIC. DUE TO VEHICLE ROTATION: (alpha, beta, p,q,r)
Ceta(j) due to change in alpha, (Ceta(j)_alpha), (1/rad), where (j=1,2,.. n modes)... -0.77735E-03 -0.27782E+00 -0.10914E+01 -0.18654E-01  0.11526E+01
Ceta(j) due to change in beta,  (Ceta(j)_beta),  (1/rad), where (j=1,2,.. n modes)... -0.33324E+00  0.76823E-04 -0.17690E-01  0.10142E+01 -0.10522E+01
Ceta(j) due to roll rate (p),   (Ceta(j)_p),   (1/rad/sec), where (j=1,2,.. n modes)... -0.60219E+00 -0.63664E+02  0.21458E+02  0.36298E+00 -0.20475E+00
Ceta(j) due to pitch rate (q),  (Ceta(j)_q),   (1/rad/sec), where (j=1,2,.. n modes)... -0.24726E-01 -0.35844E+00 -0.98438E+00  0.42506E-02  0.40954E+01
Ceta(j) due to yaw rate (r),    (Ceta(j)_r),   (1/rad/sec), where (j=1,2,.. n modes)...  0.10781E+01  0.26752E-02  0.34750E-01 -0.28113E+01  0.48096E-01
MODAL EXCITATION COEFFICIENTS DUE TO OTHER MODAL DISPLACEMENTS (Etas) - DIMENSIONLESS
Ceta(  1) due to Mode eta(j), {Ceta(i)_eta(j)}, for (j=1,2,.. n modes).............  0.23101E-02  0.23065E-04 -0.85295E-04  0.88919E-02 -0.99044E-04
Ceta(  2) due to Mode eta(j), {Ceta(i)_eta(j)}, for (j=1,2,.. n modes)............. -0.27415E-05  0.27510E-02 -0.45511E-02 -0.13867E-03 -0.19056E-01
Ceta(  3) due to Mode eta(j), {Ceta(i)_eta(j)}, for (j=1,2,.. n modes).............  0.42837E-04  0.28959E-02 -0.34305E-02  0.25472E-02 -0.30481E-02
Ceta(  4) due to Mode eta(j), {Ceta(i)_eta(j)}, for (j=1,2,.. n modes)............. -0.17805E-02  0.40002E-04  0.15631E-03 -0.26143E-01  0.10871E-03
Ceta(  5) due to Mode eta(j), {Ceta(i)_eta(j)}, for (j=1,2,.. n modes).............  0.29634E-04 -0.10598E-01 -0.21049E-02  0.91526E-04 -0.75524E-01
Ceta(  6) due to Mode eta(j), {Ceta(i)_eta(j)}, for (j=1,2,.. n modes)............. -0.38106E-03  0.19156E-03 -0.24050E-03  0.16006E-01  0.33805E-03
MODAL EXCITATION DUE TO CONTROL SURFACE DISPLACEMENTS Delta(k) in (rad) - DIMENSIONLESS
Ceta(  1) due to Surface delta(j), {Ceta(i)_delt(j)}, (1/rad), for (j=1,2,Nsurface)  0.69359E-01 -0.70535E-01 -0.14630E+00  0.14763E+00 -0.54672E-03
Ceta(  2) due to Surface delta(j), {Ceta(i)_delt(j)}, (1/rad), for (j=1,2,Nsurface) -0.16056E+00 -0.16179E+00 -0.15309E+00 -0.15181E+00  0.13232E+00
Ceta(  3) due to Surface delta(j), {Ceta(i)_delt(j)}, (1/rad), for (j=1,2,Nsurface) -0.38369E+00 -0.37358E+00 -0.24456E-01 -0.13756E+00  0.18909E+00
Ceta(  4) due to Surface delta(j), {Ceta(i)_delt(j)}, (1/rad), for (j=1,2,Nsurface)  0.30356E+00 -0.32160E+00  0.41388E+00 -0.42018E+00  0.96871E-03
Ceta(  5) due to Surface delta(j), {Ceta(i)_delt(j)}, (1/rad), for (j=1,2,Nsurface) -0.37282E-02 -0.29142E-02 -0.63619E+00 -0.62411E+00 -0.26556E-01
Ceta(  6) due to Surface delta(j), {Ceta(i)_delt(j)}, (1/rad), for (j=1,2,Nsurface) -0.10580E-01  0.78601E-01 -0.23740E+00  0.24810E+00  0.27144E-02
HINGE MOMENT COEFFICIENTS DUE TO VEHICLE MOTION (Change in alpha,beta, p,q,r) - DIMENSIONLESS
Hinge Moment at Surf(  1) due to (alfa,beta,p,q,r), {Ch_alfa,Ch_beta,Ch_p,Ch_q,Ch_r} -0.38351E+00 -0.30457E-01  0.32496E+00  0.23788E+01 -0.49980E+00
Hinge Moment at Surf(  2) due to (alfa,beta,p,q,r), {Ch_alfa,Ch_beta,Ch_p,Ch_q,Ch_r} -0.38354E+00  0.30472E-01 -0.32493E+00  0.23792E+01  0.49989E+00
Hinge Moment at Surf(  3) due to (alfa,beta,p,q,r), {Ch_alfa,Ch_beta,Ch_p,Ch_q,Ch_r}  0.11678E+01 -0.12033E+01 -0.20401E+01  0.62035E+01  0.53232E+01
Hinge Moment at Surf(  4) due to (alfa,beta,p,q,r), {Ch_alfa,Ch_beta,Ch_p,Ch_q,Ch_r}  0.11678E+01  0.12033E+01  0.20401E+01  0.62035E+01 -0.53232E+01
Hinge Moment at Surf(  5) due to (alfa,beta,p,q,r), {Ch_alfa,Ch_beta,Ch_p,Ch_q,Ch_r} -0.99814E-01 -0.14009E-06 -0.38161E-06  0.21220E+01  0.34970E-04
HINGE MOMENTS COEFFICIENTS DUE TO MODAL DISPLACEMENTS (Eta) - DIMENSIONLESS
Hinge Moment at Surface (i=   1), due to Modes (j=1,2,3,,,Nmode),  {Ch(i)_eta(j)}   -0.18374E-02  0.59316E-02  0.41956E-02 -0.67208E-02 -0.15245E-02
Hinge Moment at Surface (i=   2), due to Modes (j=1,2,3,,,Nmode),  {Ch(i)_eta(j)}    0.18648E-02  0.59150E-02  0.40524E-02  0.70655E-02 -0.15391E-02
Hinge Moment at Surface (i=   3), due to Modes (j=1,2,3,,,Nmode),  {Ch(i)_eta(j)}    0.93461E-03 -0.10786E-01 -0.28837E-02  0.38733E-01 -0.81103E-01
Hinge Moment at Surface (i=   4), due to Modes (j=1,2,3,,,Nmode),  {Ch(i)_eta(j)}   -0.90886E-03 -0.10700E-01 -0.21266E-02 -0.39377E-01 -0.79619E-01
Hinge Moment at Surface (i=   5), due to Modes (j=1,2,3,,,Nmode),  {Ch(i)_eta(j)}    0.15674E-05  0.90747E-03 -0.17689E-03  0.38216E-04  0.67400E-02
HINGE MOMENTS COEFFICIENTS DUE TO SURFACE DEFLECTIONS Delta(j) in (rad) - DIMENSIONLESS
Hinge Moment at Surface (i=   1) due Surf. Deflect(j=1,2,3,,,Nsurf), {Ch(i)_delt(j)} -0.90253E+00 -0.31909E-01 -0.14313E+00  0.47703E-01  0.72469E-02
Hinge Moment at Surface (i=   2) due Surf. Deflect(j=1,2,3,,,Nsurf), {Ch(i)_delt(j)} -0.31907E-01 -0.90252E+00  0.47703E-01 -0.14313E+00  0.72469E-02
Hinge Moment at Surface (i=   3) due Surf. Deflect(j=1,2,3,,,Nsurf), {Ch(i)_delt(j)}  0.67770E-02  0.69683E-02 -0.13766E+01 -0.73547E-01  0.36888E-01
Hinge Moment at Surface (i=   4) due Surf. Deflect(j=1,2,3,,,Nsurf), {Ch(i)_delt(j)}  0.69682E-02  0.67772E-02 -0.73547E-01 -0.13766E+01  0.36888E-01
Hinge Moment at Surface (i=   5) due Surf. Deflect(j=1,2,3,,,Nsurf), {Ch(i)_delt(j)} -0.54242E-02 -0.54244E-02  0.65454E-01  0.65454E-01 -0.91850E+00


FORCE/ MOMENT COEFFICIENTS DUE TO MODAL RATES (Eta_Dot) - (1/feet/sec)
Cy due to Modal Displacement Rate eta_dot, {Cy_eta(j)_dot}, where (j=1,2,3,,, Nmode) -0.10271E+01 -0.44769E-02 -0.17799E+00  0.11899E+02 -0.14263E+00
Cz due to Modal Displacement Rate eta_dot, {Cz_eta(j)_dot}, where (j=1,2,3,,, Nmode) -0.13732E+00 -0.27772E+01 -0.18597E+02 -0.44913E+00 -0.14631E+02
Cl (roll) due to Modal Displ Rate eta_dot, {Cl_eta(j)_dot}, where (j=1,2,3,,, Nmode) -0.79142E+01 -0.22764E-01 -0.41719E+01  0.39561E+01 -0.18023E+00
Cm (ptch) due to Modal Displ Rate eta_dot, {Cm_eta(j)_dot}, where (j=1,2,3,,, Nmode) -0.59188E-02  0.32984E+02 -0.13570E+02 -0.20314E+00  0.11894E+01
Cn (yaw)  due to Modal Displ Rate eta_dot, {Cn_eta(j)_dot}, where (j=1,2,3,,, Nmode)  0.19684E+01  0.35216E-01  0.43389E+00 -0.28118E+02  0.29442E+00
MODAL EXCITATION COEFFIC. DUE TO VEHICLE RATES: (alpha_dot, beta_dot, p_dot, q_dot, r_dot)
Ceta(j) due to alpha_dot, (Ceta(j)_alpha_dot), (1/rad/sec), for (j=1,2,.. n modes)... -0.49448E-02  0.65015E-01  0.15863E+00  0.65777E-02 -0.29761E+00
Ceta(j) due to beta_dot,  (Ceta(j)_beta_dot),  (1/rad/sec), for (j=1,2,.. n modes)... -0.14500E+00  0.48190E-02 -0.65521E-02 -0.11003E+00  0.13372E-03
Ceta(j) due to roll accelerat (p_dot), (Ceta(j)_pdot), (1/rad/sec2), (j=1,2,n modes). -0.49144E+00 -0.58579E-02 -0.11919E+02  0.34732E+00 -0.11192E+01
Ceta(j) due to pitch accelerat (q_dot), (Ceta(j)_qdot) (1/rad/sec2), (j=1,2,n modes). -0.92449E-02  0.16303E+01  0.91145E+00  0.12965E-01 -0.26301E+01
Ceta(j) due to yaw accelerat (r_dot), (Ceta(j)_rdot), (1/rad/sec2), (j=1,2,n modes). -0.17018E+00 -0.32814E-02 -0.18356E-01  0.86922E+00 -0.50692E-03
MODAL EXCITATION COEFFICIENTS DUE TO MODAL RATES (Eta_dot) - DIMENTIONLESS
Ceta(  1) due to Mode Rate eta(j)_dot, {Ceta(i)_eta(j)_dot}, for (j=1,2,.. Nmodes).. -0.19107E+00  0.13767E-02 -0.57383E-02  0.25356E+00 -0.62742E-02
Ceta(  2) due to Mode Rate eta(j)_dot, {Ceta(i)_eta(j)_dot}, for (j=1,2,.. Nmodes).. -0.32859E-02 -0.59009E+00 -0.29394E+00 -0.10137E-01 -0.30360E+00
Ceta(  3) due to Mode Rate eta(j)_dot, {Ceta(i)_eta(j)_dot}, for (j=1,2,.. Nmodes).. -0.32683E-03 -0.33994E+00 -0.89756E+00  0.24040E-02  0.26421E+00
Ceta(  4) due to Mode Rate eta(j)_dot, {Ceta(i)_eta(j)_dot}, for (j=1,2,.. Nmodes)..  0.10087E+00 -0.89064E-02  0.31738E-02 -0.19531E+01  0.14679E-01
Ceta(  5) due to Mode Rate eta(j)_dot, {Ceta(i)_eta(j)_dot}, for (j=1,2,.. Nmodes).. -0.25342E-02 -0.34034E+00 -0.44640E-01  0.10188E-01 -0.33761E+00
Ceta(  6) due to Mode Rate eta(j)_dot, {Ceta(i)_eta(j)_dot}, for (j=1,2,.. Nmodes).. -0.26120E+00 -0.38901E-02 -0.41548E-01  0.11125E+01  0.22579E-01
MODAL EXCITATION COEFFICIENTS DUE TO CONTROL SURFACE RATES (Delta_dot) in (rad/sec) - DIMENSIONLESS
Ceta(  1) due to Surface Rate delta(j)_dot, {Ceta(i)_delt(j)_dot}, (1/rad/sec)......  0.59383E+00 -0.59595E+00 -0.22182E+00  0.22050E+00  0.10308E-02
Ceta(  2) due to Surface Rate delta(j)_dot, {Ceta(i)_delt(j)_dot}, (1/rad/sec)......  0.11278E+01  0.11242E+01 -0.65251E-01 -0.62089E-01  0.56986E-02
Ceta(  3) due to Surface Rate delta(j)_dot, {Ceta(i)_delt(j)_dot}, (1/rad/sec)......  0.16815E+00  0.15046E+00  0.96643E-02  0.32555E-01 -0.80349E-01
Ceta(  4) due to Surface Rate delta(j)_dot, {Ceta(i)_delt(j)_dot}, (1/rad/sec)...... -0.53396E+00  0.54589E+00  0.10235E+01 -0.10297E+01 -0.25726E-02
Ceta(  5) due to Surface Rate delta(j)_dot, {Ceta(i)_delt(j)_dot}, (1/rad/sec)......  0.44352E+00  0.42314E+00 -0.13804E+01 -0.13469E+01 -0.46608E+00
Ceta(  6) due to Surface Rate delta(j)_dot, {Ceta(i)_delt(j)_dot}, (1/rad/sec)......  0.25712E+00 -0.26069E+00 -0.75612E+00  0.79172E+00  0.72931E-02
HINGE MOMENT COEFFICIENTS DUE TO VEHICLE RATES (Rates of alpha,beta, p,q,r) - DIMENSIONLESS
Hinge Moment at Surface (   1), due to Rate of alpha,beta,p,q,r, Ch_alpha_dot, etc. -0.56878E+01 -0.10190E+00  0.62024E+01 -0.49919E+01  0.65995E+00
Hinge Moment at Surface (   2), due to Rate of alpha,beta,p,q,r, Ch_alpha_dot, etc. -0.56884E+01  0.10191E+00 -0.62030E+01 -0.49958E+01 -0.66165E+00
Hinge Moment at Surface (   3), due to Rate of alpha,beta,p,q,r, Ch_alpha_dot, etc. -0.11290E+01  0.30371E+00 -0.71830E+01  0.76569E+01  0.39444E+01
Hinge Moment at Surface (   4), due to Rate of alpha,beta,p,q,r, Ch_alpha_dot, etc. -0.11291E+01 -0.30372E+00  0.71829E+01  0.76568E+01 -0.39623E+01
Hinge Moment at Surface (   5), due to Rate of alpha,beta,p,q,r, Ch_alpha_dot, etc. -0.49973E+01  0.37576E-04  0.49564E-05 -0.22557E+02  0.98186E-02
HINGE MOMENTS COEFFICIENTS DUE TO MODAL RATES (Eta_dot) - DIMENSIONLESS
Hinge Moment at Surface (i=   1), due to Modal Rates (j=1,2,3..), {Ch(i)_eta(j)_dot}  0.18145E+00  0.18181E+00 -0.78487E+00  0.43709E+00  0.51729E-01
Hinge Moment at Surface (i=   2), due to Modal Rates (j=1,2,3..), {Ch(i)_eta(j)_dot} -0.18285E+00  0.18027E+00 -0.77402E+00 -0.47619E+00  0.53285E-01
Hinge Moment at Surface (i=   3), due to Modal Rates (j=1,2,3..), {Ch(i)_eta(j)_dot} -0.49419E+00 -0.68649E+00 -0.10283E+01  0.29652E+01 -0.48042E+01
Hinge Moment at Surface (i=   4), due to Modal Rates (j=1,2,3..), {Ch(i)_eta(j)_dot}  0.49874E+00 -0.67922E+00 -0.37318E-01 -0.30004E+01 -0.46992E+01
Hinge Moment at Surface (i=   5), due to Modal Rates (j=1,2,3..), {Ch(i)_eta(j)_dot} -0.44585E-03  0.58365E+00 -0.83568E-01  0.38348E-02  0.40230E-02
HINGE MOMENTS COEFFICIENTS DUE TO SURFACE RATES Delta_dot(k) in (rad/sec) - DIMENSIONLESS
Hinge Moment at Surface (i=   1) due to Surf. Rates (j=1,2,3..), {Ch(i)_delt(j)_dot} -0.65476E+01  0.26048E-01  0.21981E+01 -0.94193E+00 -0.14477E+00
Hinge Moment at Surface (i=   2) due to Surf. Rates (j=1,2,3..), {Ch(i)_delt(j)_dot}  0.26030E-01 -0.65477E+01 -0.94192E+00  0.21981E+01 -0.14476E+00
Hinge Moment at Surface (i=   3) due to Surf. Rates (j=1,2,3..), {Ch(i)_delt(j)_dot} -0.12980E+00 -0.14242E+00 -0.42140E+01  0.44442E+00  0.14506E+00
Hinge Moment at Surface (i=   4) due to Surf. Rates (j=1,2,3..), {Ch(i)_delt(j)_dot} -0.14242E+00 -0.12981E+00  0.44442E+00 -0.42140E+01  0.14506E+00
Hinge Moment at Surface (i=   5) due to Surf. Rates (j=1,2,3..), {Ch(i)_delt(j)_dot}  0.15761E+00  0.15761E+00 -0.79702E+00 -0.79702E+00 -0.59120E+01
```

The number of modes to be included is also set to 30 in the vehicle datasets and the selected modes title is included in the next line. The selected set of 30 mixed modes, same as the ones used in Section 2, is also included in the input file *"RocketPlane-Gafd.Inp"*. Actually, there are two sets of selected modes in the input file. A set of 22 pitch modes and a set of 30 mixed modes. The selected set of modes that will be used in this model are located under the title "SELECTED MODAL DATA AND LOCATIONS FOR MIXED AXES MODES", followed by the title of the modes set: *"Rocket Plane at Mach=0.85, Q=150, Flex Model, (30 Mixed Modes)"*. The title of the selected modes set also appears in the vehicle dataset, below the line *"Number of Bending Modes: 30"*.

3.2 Processing the Vehicle Data with GAFD Interactively

Having described the input data files we are now ready to process the first vehicle dataset interactively, including the aero-elastic coefficients, using the flight vehicle modeling program. Start the Flixan program and select the directory: *"Flixan\Examples\18-Rocket Plane\3-Flex Model With Gafd"*. From the Flixan main menu go to *"Program Functions"*, *"Flight Vehicle/ Spacecraft Modeling Tools"*, and then *"Flight Vehicle State-Space Modeling"*. From the filenames selection menu select the vehicle input and the system filenames *"RocketPlane_Gafd.Inp"* and *"RocketPlane-Gafd.Qdr"*. From the flight vehicle data selection menu, select the first title: *"Rocket Plane at Mach=0.85, Q=150, Aero-Elastic Model with GAFD"*, and click on *"Run Selected Input Set"* to process the data set.
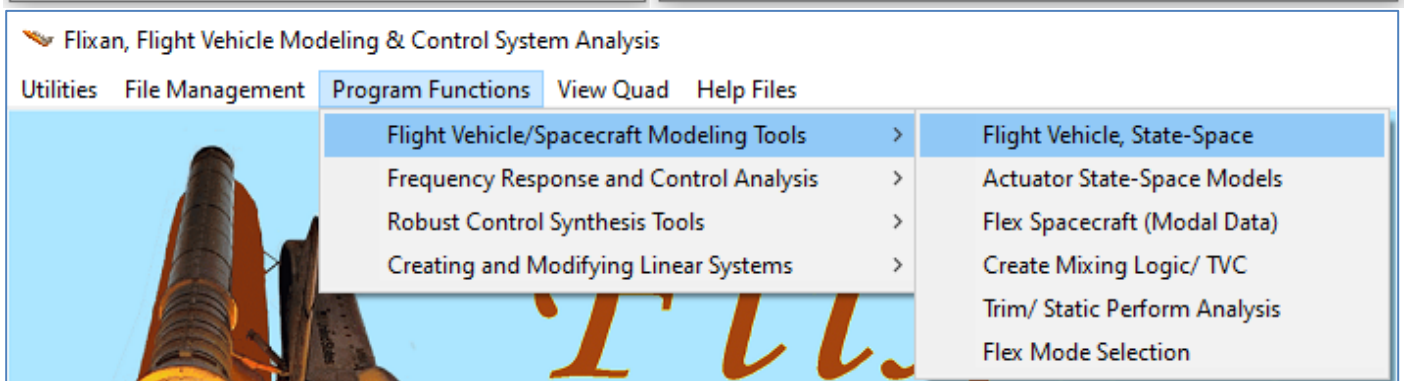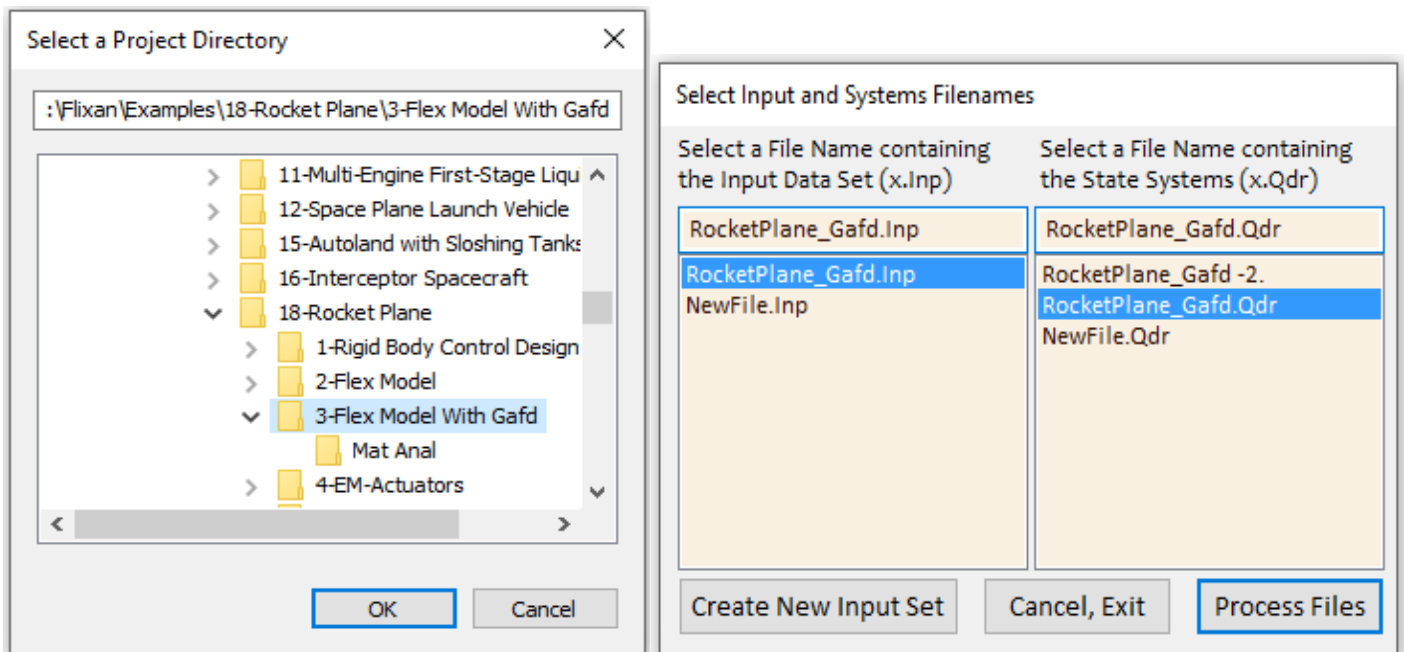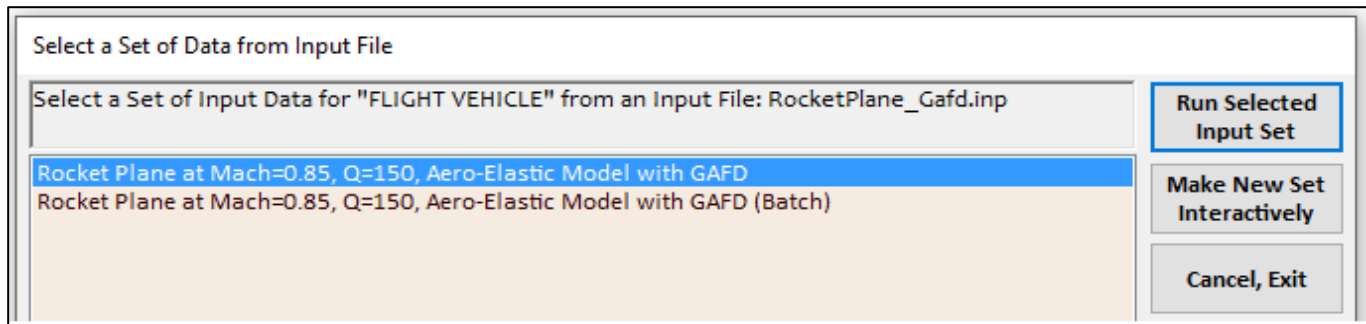
The FV modeling program opens up a dialog that shows the vehicle parameters read from the vehicle data set. Notice that the "Include GAFD Data" and the "WITH TWD" flags are set. The vehicle parameters are in tabs and the user can only see one tab at a time. You may click on some of the tabs to make sure that the data in the input file are correct. The "Control Surfaces" tab will show you the aerosurfaces data. You may also click on the "Flex Modes" tab which includes some additional menus. Make sure that the second set of modes (30 mixed modes) is selected from the top menu. Select also the file "*RocketPlane.Gaf*" from the GAFD filename selection menu.

Click on the "*Run*" button for the program to read and process the data files. The GAFD file includes data at many frequencies that may be more than the selected modes and they must be matched with the selected modes. Also, the user may want to choose fewer than the 5 aerosurfaces. The following dialog comes up for the user to select the GAFD frequencies and the aerosurfaces from menus. The cyan display on the left shows the frequencies of the selected 30 modes which are in file "*RocketPlane-Gafd.Inp*", and the white menu on its right shows the frequencies read from the GAFD file. The user must select a set of frequencies from the white GAFD frequencies menu that match the selected mode frequencies in the cyan menu. The mode frequencies on the left are only a display and not for being selected. The GAFD coefficients are calculated at frequencies close to the modal frequencies but not necessarily exactly and the user must make the selection manually. The GAFD file must include all the selected mode frequencies and, obviously, the menu should contain more frequencies than the cyan display on the left. Using the mouse, highlight the frequencies on the GAFD frequencies menu that correspond to the selected mode frequencies on the left. Most of them are selected, except of four.

The second pair of menus on the right side of the dialog is similar to the pair on the left side and it is used in the same manner for selecting GAFD data for the five control surfaces which are defined in the vehicle data. In this case all 5 are selected. The GAFD data for the five control surfaces must be ordered in the same sequence as in the vehicle data. Select all five aero-surfaces from the GAFD file using the white menu on the right, that is: left and right flaps, left and right rudders, and body-flap. The display on its left just shows the aerosurfaces as they are defined in the vehicle dataset in the input data file. Finally, click on "*Exit and Process Data*" button and the program will process the data to create the state-space model of the vehicle with 30 flex modes and aero-elasticity. It will save it in the systems file "*RocketPlane_Gafd.Qdr*" under the same title "*Rocket Plane at Mach=0.85, Q=150, Aero-Elastic Model with GAFD*".

The flex vehicle system must also be converted to a Matlab function m-file using the "*Export to Matlab*" utility, as demonstrated in Section 1. The system filename is "*vehi_gafd_30flx.m*". Repeat the exporting to Matlab conversions also for the actuator systems and for the mixing logic matrix "*K4axmix.mat*".

Flight Vehicle Parameters

Vehicle System Title

Rocket Plane at Mach=0.85, Q=150, Aero-Elastic Model with GAFD

Edit Input File | Exit
Update Data | Run
Save in File

Number of Vehicle Effectors

Gimbaling Engines or Jets. Include Tail-Wags-Dog? `1` WITH TWD / WITHOUT TWD

Rotating Control Surfaces. Include Tail-Wags-Dog? `5` WITH TWD / WITHOUT TWD

Reaction Wheels? `0`   **Momentum Control Devices**

Single Gimbal CMGs? `0` Include a Centralized, 3-Axes Momentum Control System? Yes / No

Number of Sensors

Gyros `3`
Accelerometers `2`
Aero Probes `0`
External Torques `0`

Modeling Options (Flags)

Output Rates in: Body Axes / Stability Axes

Turn Coordination ? Include Turn Coordina / Without Turn Coordin

Aero-Elasticity Options: Include GAFD, H-param / Flex Coupl. data only / Neither Gafd nor Hpar

Attitude Angles: Euler Angles / Integrals of Rates / LVLH Attitude

Number of Modes
Structure Bending `30`
Propellant Sloshing: `0`

Tabs: Single Gimbal CMGs | Momentum Control System | Slewing Appendages | Gyros | Accelerometer | Aero Sensors | Fuel Slosh | Flex Modes | User Notes
Mass Properties | Trajectory Data | Gust/ Aero Paramet. | Aero Force Coeffs | Aero Moment Coeffs | Aero-Surfaces | Gimbal Engines/ RCS | External Torques | Reaction Wheels

This Vehicle has 5 Control Surfaces   **Control Surface No: 1   Left Flap**   Surface Definition   Next Surface

Surface Rotation Angles

Surface Trim Position (deg) `0.000000`
Largest Positive Deflection from Trim (deg) `30.00000`
Largest Negative Deflection from Trim (deg) `-30.00000`

Surface Location (ft) and Hinge Orientation Angles (deg)

Xcs `-18.70000`
Ycs `-2.640000`   Phi_cs `2.000000`
Zcs `2.073300`   Lambda_cs `0.000000`

Control Surface Mass Properties

Contol Surface Mass in (Slugs) `1.185000`
Moment of Inertia about Hinge (slug-ft^2) `0.4000000`
Moment Arm (feet), Surface CG to Hinge `0.2830000`
Control Surface Chord (feet) `1.207000`
Control Surface Reference Area (ft^2) `5.553000`

Aero Force Derivatives

Ca_delta `0.4543200E-03`   Ca_delta_dot `0.000000`
Cy_delta `-0.2466800E-02`   Cy_delta_dot `0.000000`
Cz_delta `-0.6047800E-02`   Cz_delta_dot `0.000000`

Control Force Derivatives due to Surface Deflection (1/deg) and Control Force Derivatives due to Surface Rate (1/deg/sec)

Aero Moment Derivatives

Cl_delta `0.1189300E-02`   Cl_delta_dot `0.000000`
Cm_delta `-0.2662500E-02`   Cm_delta_dot `0.000000`
Cn_delta `0.8151500E-03`   Cn_delta_dot `0.000000`

Control Moment Derivatives due to Surface Deflection (1/deg) and Control Moment Derivatives due to Surface Rate (1/deg/sec)

Hinge Moment Derivatives

Chm_Alpha `-0.4700000E-02`
Chm_Beta `-0.5500000E-03`
Chm_Delta `-0.9700000E-02`
Chm_Mach `0.000000`

Hinge Moment Derivatives with respect to Changes in: Alpha, Beta, Surf Deflection (1/deg) and changes in Mach Number

---

Flight Vehicle Parameters

Vehicle System Title

Rocket Plane at Mach=0.85, Q=150, Aero-Elastic Model with GAFD

Edit Input File | Exit
Update Data | Run
Save in File

Number of Vehicle Effectors

Gimbaling Engines or Jets. Include Tail-Wags-Dog? `1` WITH TWD / WITHOUT TWD

Rotating Control Surfaces. Include Tail-Wags-Dog? `5` WITH TWD / WITHOUT TWD

Reaction Wheels? `0`   **Momentum Control Devices**

Single Gimbal CMGs? `0` Include a Centralized, 3-Axes Momentum Control System? Yes / No

Number of Sensors

Gyros `3`
Accelerometers `2`
Aero Probes `0`
External Torques `0`

Modeling Options (Flags)

Output Rates in: Body Axes / Stability Axes

Turn Coordination ? Include Turn Coordina / Without Turn Coordin

Aero-Elasticity Options: Include GAFD, H-param / Flex Coupl. data only / Neither Gafd nor Hpar

Attitude Angles: Euler Angles / Integrals of Rates / LVLH Attitude

Number of Modes
Structure Bending `30`
Propellant Sloshing: `0`

Tabs: Mass Properties | Trajectory Data | Gust/ Aero Paramet. | Aero Force Coeffs | Aero Moment Coeffs | Aero-Surfaces | Gimbal Engines/ RCS | External Torques | Reaction Wheels
Single Gimbal CMGs | Momentum Control System | Slewing Appendages | Gyros | Accelerometer | Aero Sensors | Fuel Slosh | Flex Modes | User Notes

This Vehicle has 30 Bending Modes

Select a set of Modal Data to be combined with the flight vehicle parameters

Rocket Plane at Mach=0.85, Q=150, Flex Model, (22 Pitch Modes)
Rocket Plane at Mach=0.85, Q=150, Flex Model, (30 Mixed Modes)

Additional data files to be included in the flex model

Aero-Elastic (GAFD) data and Control Surface Coupling Coefficients (.Gaf)

Appendages Coupling Coefficients and Moments of Inertia Matrix (.Hpr)

RocketPlane.Gaf

3.3 Batch Processing

However, there is a much faster way of processing the data and creating the systems required in this analysis. The input file *"RocketPlane_Gafd.Inp"* includes a batch set on the top "*Batch for the Flexible Rocket Plane with GAFD*". This batch will process the datasets faster and create the systems required for the analysis.

3.4 Input File "RocketPlane_Gafd.Inp"

```
BATCH MODE INSTRUCTIONS ...............
Batch for the Flexible Rocket Plane with GAFD
! This batch creates a flexible model for the rocket plane including 30 modes from all directions.
! In addition to the modal data this vehicle also reads GAFD data from file: RocketPlane.Gaf
! It creates also electro-mechanical actuator models for the flaps, rudders and body-flap aerosurfaces
! It preserves the previously calculated effectors mixing logic for the five aero-surfaces and
! the engine throttle control.
!
Retain Matrix      : Coupled axes Mixing Matrix for Rocket-Plane, K4axmix
Flight Vehicle     : Rocket Plane at Mach=0.85, Q=150, Aero-Elastic Model with GAFD (Batch)
Actuator Model     : Electro-Mechanical Flap Type-B Actuator
Actuator Model     : Electro-Mechanical Rudder Type-B Actuator
Actuator Model     : Electro-Mechanical Body-Flap Type-B Actuator
!
!                    Save Systems and Matrices for Matlab
To Matlab Format : Rocket Plane at Mach=0.85, Q=150, Aero-Elastic Model with GAFD (Batch)
To Matlab Format : Electro-Mechanical Flap Type-B Actuator
To Matlab Format : Electro-Mechanical Rudder Type-B Actuator
To Matlab Format : Electro-Mechanical Body-Flap Type-B Actuator
To Matlab Format : Coupled axes Mixing Matrix for Rocket-Plane, K4axmix
-----------------------------------------------------------------------------------------------
FLIGHT VEHICLE INPUT DATA ......
Rocket Plane at Mach=0.85, Q=150, Aero-Elastic Model with GAFD
! This Vehicle is a Rocket Plane that has five control surfaces: 2 flaps, 2 rudders, and
! a body-flap. It also has a fixed throttling engine.
! The "Include GAFD" is On, and also "tail-wags-dog" option on the aerosurfaces is turned on.
! This version does not run in Batch mode because it does not have the Selected GAFD frequency
! numbers and the selected surface numbers at the bottom of the set.
! It can only run interactively.
!
Body Axes Output, Attitude=Euler Angles, Include GAFD, No Turn Coordination


---------------------------------------------------------------------------------------
          3 ELECTRO-MECHANICAL ACTUATOR MODELS (2-Flaps, 2-Rudders and Body-Flap)
---------------------------------------------------------------------------------------
ACTUATOR INPUT DATA ............ ELECTROMECHANICAL TYPE B
Electro-Mechanical Flap Type-B Actuator
! This EMA system includes a PID Controller with a Second Order Compensator
! Input-1 is the Deflection command in (rad)
! Input-2 is the Load-Torque in (foot pounds)
! The Outputs are in radians
!
Symbol       Parameter Description                (Units)        Value
C(s)    Order of Compensat:(0,1,2), Coefficients   (---)        2, 1.2,2000.0, 0.6,250.0
Kpl     Position Error Loop Gain                  (Volt/ft)     60.0
Krf     Rate Feedback Gain                    (Volt/ft/sec)     0.00045
Ki      Position Error Integral Gain           (Volt/ft-sec)    10.0
Wm      Servo Motor Bandwidth,                   (rad/sec)      1200.0
Kv      Servo Motor Torque Gain                (ft-lb/volt)     100.0
Jm      Motor Rotor Moment of Inertia         (ft-lb-sec^2)     2.0e-5
Ngr     Gear Ratio (Motor Turns/ Screw Turns)     ( - )        10.25
Nscr    Screw Ratio (Piston Extension/Screw Turns) (ft/rad)    0.0026
Kgs     Motor Gear Stiffness                    (ft-lb/rad)     350.0
Kmfr    Motor/ Gear Friction                 (ft-lb/rad/sec)    0.03
Kdmp    Shaft Damping Friction               (ft-lb/rad/sec)    0.004
Keff    Gear Effectiveness Coefficient            ( - )        0.8
Ja      Gear plus Screw Inertia               (ft-lb-sec^2)     4.6e-4
Kact    Actuator Stiffness (Piston+Electric).... (lb/ft)       2.0e+6
Klod    Load Stiffness,(Con. Surface or Nozzle)  (lb/ft)       0.5e+6
Kbck    Vehicle Backup Structure Stiffness ..... (lb/ft)       0.5e+6
R       Moment Arm of Actuator Shaft from Gimbal.. (feet)      0.4
Je      Load Inertia about the Gimbal ....... (ft-lb-sec^2)    0.4
Be      Aero-Surface Bearing Viscous Damping   (ft-lb-sec)     30.0
Kg      Aero-Surface Bearing Spring Constant   (ft-lb/rad)     0.0
---------------------------------------------------------------------------------------
```

The Batch set on the top is used for fast processing the datasets. The 3 actuator datasets are the same as those used in Section 2. The interactively processed vehicle version is identical to the batch version, but it's missing the GAFD numbers at the bottom.

```
FLIGHT VEHICLE INPUT DATA ......
Rocket Plane at Mach=0.85, Q=150, Aero-Elastic Model with GAFD (Batch)
! This Vehicle is a Rocket Plane that has five control surfaces: 2 flaps, 2 rudders, and
! a body-flap. It also has a fixed throttling engine.
! The "Include GAFD" is on, and also "tail-wags-dog" option on the aerosurfaces is turned on.
! This version can run in Batch mode because it includes the selected GAFD frequencies and
! the corresponding aerosurface numbers at the bottom of the set.
!
Body Axes Output, Attitude=Euler Angles, Include GAFD, No Turn Coordination

Vehicle Mass (lb-sec^2/ft), Gravity Accelerat. (g) (ft/sec^2), Earth Radius (Re) (ft)   :  198.32       32.17        0.20896E+08
Moments and products of Inertias Ixx, Iyy, Izz, Ixy, Ixz, Iyz, in (lb-sec^2-ft)         :  1098.0       10933.       11290.       0.0000       123.75
CG location with respect to the Vehicle Reference Point, Xcg, Ycg, Zcg, in (feet)       : -15.167       0.0000       0.467
Vehicle Mach Number, Velocity Vo (ft/sec), Dynamic Pressure (psf), Altitude (feet)      :  0.85000      822.80       150.13       45880.
Inertial Acceleration Vo_dot, Sensed Body Axes Accelerations Ax,Ay,Az (ft/sec^2)        : -0.81        -1.14         0.0000      -32.15
Angles of Attack and Sideslip (deg), alpha, beta rates (deg/sec)                        :  2.0          0.0          1.76         0.0000
Vehicle Attitude Euler Angles, Phi_o,Thet_o,Psi_o (deg), Body Rates Po,Qo,Ro (deg/sec)  : -0.16079      2.0000       0.0000       0.0000       0.0000
Wind Gust Vel wrt Vehi (Azim & Elev) angles (deg), or Force(lb), Torque(ft-lb), locat:xyz:  Gust         45.0         90.0
Surface Reference Area (feet^2), Mean Aerodynamic Chord (ft), Wing Span in (feet)       :  79.0         6.1          15.0
Aero Moment Reference Center (Xmrc,Ymrc,Zmrc) Location in (ft), {Partial_rho/ Partial_H} : -14.792       0.0000       0.54000      0.0000
Aero Force Coef/Deriv (1/deg), Along -X, {Cao,Ca_alf,PCa/PV,PCa/Ph,Ca_alfdot,Ca_q,Ca_bet}:  0.143,      -0.0039,      0.0004, 0.0,      0.0,        -0.244,   0.0
Aero Force Coeffic/Derivat (1/deg), Along Y, {Cyo,Cy_bet,Cy_r,Cy_alf,Cy_p,Cy_betdot,Cy_V}:  0.0,        -0.0245,      1.77,   0.0,      0.00838, 0.0,       0.0
Aero Force Coeff/Deriv (1/deg), Along Z, {Czo,Cz_alf,Cz_q,Cz_bet,PCz/Ph,Cz_alfdot,PCz/PV}: -0.14,       -0.073,      -9.93,   0.0,      0.0,         0.0,      0.00093
Aero Moment Coeffic/Derivat (1/deg), Roll: {Clo, Cl_beta, Cl_betdot, Cl_p, Cl_r, Cl_alfa}:  0.0,        -0.00212,     0.0,   -0.393,   0.427,       0.0
Aero Moment Coeff/Deriv (1/deg), Pitch: {Cmo,Cm_alfa,Cm_alfdot,Cm_bet,Cm_q,PCm/PV,PCm/Ph}: -0.0838, -0.015,         0.0,    0.0,     -12.83,       0.0004, 0.0
Aero Moment Coeffic/Derivat (1/deg), Yaw : {Cno, Cn_beta, Cn_betdot, Cn_p, Cn_r, Cn_alfa}:  0.0,         0.001,       0.0,    0.184,  -1.49,        0.0


Number of Control Surfaces, With or No TWD (Tail-Wags-Dog and Hinge Moment Dynamics) ?   :  5   WITH TWD

Control Surface No:  1                                                           Left Flap
Trim Angle, Max/Min Deflection Angles from Trim, Hinge Line Angles: phi_h, lamda_h  (deg):  0.0          30.000      -30.000      +2.0000      0.000
Surface Mass, Inertia about Hinge, Moment Arm (Hinge to Surface CG), Surface Chord, Area :  1.185        0.4          0.283        1.2070       5.5530
Hinge Moment Derivatives (1/deg), { Chm_Alpha, Chm_Beta, Chm_Delta, Chm_Mach }          : -0.0047       -0.00055     -0.0097       0.0000
Location of the Hinge Line Center with respect to Vehicle Reference (feet), {Xcs,Ycs,Zcs}: -18.7        -2.64         2.0733
Forces (-x,y,z) due to Deflect. and Rates {Ca_del,Cy_del,Cz_del, Ca_deld,Cy_deld,Cz_deld}:  0.45432E-03 -0.24668E-02 -0.60478E-02  0.0000       0.0000
Moments due to Deflections and Rates {Cl_del,Cm_del,Cn_del,Cl_deldot,Cm_deldot,Cn_deldot}:  0.11893E-02 -0.26625E-02  0.81515E-03  0.0000       0.0000
Control Surface No:  2                                                           Right Flap
Trim Angle, Max/Min Deflection Angles from Trim, Hinge Line Angles: phi_cs,lamda_cs (deg):  0.0          30.000      -30.000      -2.0000      0.000
Surface Mass, Inertia about Hinge, Moment Arm (Hinge to Surface CG), Surface Chord, Area :  1.185        0.4          0.283        1.2070       5.5530
Hinge Moment Derivatives (1/deg), { Chm_Alpha, Chm_Beta, Chm_Delta, Chm_Mach }          : -0.0047        0.00055     -0.0097       0.0000
Location of the Hinge Line Center with respect to Vehicle Reference (feet), {Xcs,Ycs,Zcs}: -18.7         2.64         2.0733
Forces (-x,y,z) due to Deflect. and Rates {Ca_del,Cy_del,Cz_del, Ca_deld,Cy_deld,Cz_deld}:  0.45432E-03  0.24668E-02 -0.60478E-02  0.0000       0.0000
Moments due to Deflections and Rates {Cl_del,Cm_del,Cn_del,Cl_deldot,Cm_deldot,Cn_deldot}: -0.11893E-02 -0.26625E-02 -0.81515E-03  0.0000       0.0000
Control Surface No:   3                                                          Left Rudder
Trim Angle, Max/Min Deflection Angles from Trim, Hinge Line Angles: phi_cs,lamda_cs (deg): -1.2          30.000      -30.000      48.000       0.000
Surface Mass, Inertia about Hinge, Moment Arm (Hinge to Surface CG), Surface Chord, Area :  2.19         4.0          0.833        2.2830       10.382
Hinge Moment Derivatives (1/deg), { Chm_Alpha, Chm_Beta, Chm_Delta, Chm_Mach }          : -0.019         0.0229      -0.0236       0.0000
Location of the Hinge Line Center with respect to Vehicle Reference (feet), {Xcs,Ycs,Zcs}: -25.3333      -3.395       -1.6242
Forces (-x,y,z) due to Deflect. and Rates {Ca_del,Cy_del,Cz_del, Ca_deld,Cy_deld,Cz_deld}:  0.46197E-03  0.47413E-02 -0.51664E-02  0.0000       0.0000
Moments due to Deflections and Rates {Cl_del,Cm_del,Cn_del,Cl_deldot,Cm_deldot,Cn_deldot}:  0.17964E-02 -0.98720E-02 -0.35668E-02  0.0000       0.0000
Control Surface No:   4                                                          Right Rudder
Trim Angle, Max/Min Deflection Angles from Trim, Hinge Line Angles: phi_cs,lamda_cs (deg): -1.2          30.000      -30.000      -48.000      0.000
Surface Mass, Inertia about Hinge, Moment Arm (Hinge to Surface CG), Surface Chord, Area :  2.19         4.0          0.833        2.2830       10.382
Hinge Moment Derivatives (1/deg), { Chm_Alpha, Chm_Beta, Chm_Delta, Chm_Mach }          : -0.019        -0.0229      -0.0236       0.0000
Location of the Hinge Line Center with respect to Vehicle Reference (feet), {Xcs,Ycs,Zcs}: -25.3333       3.395       -1.6242
Forces (-x,y,z) due to Deflect. and Rates {Ca_del,Cy_del,Cz_del, Ca_deld,Cy_deld,Cz_deld}:  0.46197E-03 -0.47413E-02 -0.51664E-02  0.0000       0.0000
Moments due to Deflections and Rates {Cl_del,Cm_del,Cn_del,Cl_deldot,Cm_deldot,Cn_deldot}: -0.17964E-02 -0.98720E-02  0.35668E-02  0.0000       0.0000
Control Surface No:  5                                                           Body Flap
Trim Angle, Max/Min Deflection Angles from Trim, Hinge Line Angles: phi_cs,lamda_cs (deg): -10.0         40.000      -40.000      0.0000       0.0000
Surface Mass, Inertia about Hinge, Moment Arm (hinge to surface CG), Surface Chord & Area:  1.8          2.2          0.6          1.6670       5.7430
Hinge Moment Derivatives (1/deg), { Chm_Alpha, Chm_Beta, Chm_Delta, Chm_Mach }          : -0.1e-03       0.0000      -0.10E-03     0.0000
Location of the Hinge Line Center with respect to Vehicle Reference (feet), {Xcs,Ycs,Zcs}: -25.8         0.0000       0.80000
Forces (-x,y,z) due to Deflect. and Rates {Ca_del,Cy_del,Cz_del, Ca_deld,Cy_deld,Cz_deld}: -0.83830E-05  0.0000      -0.59235E-03  0.0000       0.0000
Moments due to Deflections and Rates {Cl_del,Cm_del,Cn_del,Cl_deldot,Cm_deldot,Cn_deldot}:  0.0000      -0.15765E-02  0.0000       0.0000       0.0000


Number of Thruster Engines, Include or Not the Tail-Wags-Dog and Load-Torque Dynamics ?  :  1

TVC Engine No: 1                              (Gimbaling  Throttling   Single_Gimbal) : Engine Throtl    Throttling
Engine Nominal Thrust, and Maximum Thrust in (lb)   (for throttling)                  : 2000.0           4000.0
Mounting Angles wrt Vehicle (Dyn,Dzn), Maximum Deflections from Mount (Dymax,Dzmax) (deg): -1.3           0.0          0.0          0.0
Eng Mass (slug), Inertia about Gimbal (lb-sec^2-ft), Moment Arm, engine CG to gimbal (ft):  2.00          65.0         0.8
Gimbal location with respect to the Vehicle Reference Axes, Xgimb, Ygimb, Zgimb, in (ft) : -26.5          0.0          0.0


Number of Gyros, (Attitude and Rate)                                             :  3
Gyro No 1 Axis:(Pitch,Yaw,Roll), (Attitude or Rate), Location in Vehicle Axes  (feet)   :  Roll Rate                  -8.8, 0.0, -0.19
Gyro No 2 Axis:(Pitch,Yaw,Roll), (Attitude or Rate), Location in Vehicle Axes  (feet)   :  Pitch Rate                 -8.8, 0.0, -0.19
Gyro No 3 Axis:(Pitch,Yaw,Roll), (Attitude or Rate), Location in Vehicle Axes  (feet)   :  Yaw Rate                   -8.8, 0.0, -0.19


Number of Accelerometers, (x,y,z)                                                :  2
Acceleromet No 1 Axis:(X,Y,Z), (Acceleration,Flex_Posit,Flex_Veloc,Flex_Accel), Locat(ft):  Y-axis Acceleration       -8.8, 0.0, -0.19
Acceleromet No 2 Axis:(X,Y,Z), (Acceleration,Flex_Posit,Flex_Veloc,Flex_Accel), Locat(ft):  Z-axis Acceleration       -8.8, 0.0, -0.19


Number of Bending Modes                                                          : 30
Rocket Plane at Mach=0.85, Q=150, Flex Model, (30 Mixed Modes)
Selected GAFD Mode Numbers from GAFD File                                        :  1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20
Selected GAFD Surface Numbers from GAFD File                                     :  1  2  3  4  5
-----------------------------------------------------------------------------------------------------------
```

The bottom of the vehicle dataset includes the title of the selected modal dataset with 30 modes, the numbers of the mode frequencies in the GAFD file that correspond to the 30 selected modes, and the numbers of the aerosurfaces in the GAFD file that correspond to the 5 aerosurfaces which are defined in the vehicle data. They are converted to files that can be loaded into Matlab.

```
CONVERT TO MATLAB FORMAT .......        (TITLE, SYSTEM/MATRIX, M-FILENAME)
Rocket Plane at Mach=0.85, Q=150, Aero-Elastic Model with GAFD (Batch)
System
Vehi_Gafd_30flx
-----------------------------------------------------------------------------
CONVERT TO MATLAB FORMAT ........       (Title, System/Matrix, m-filename)
Electro-Mechanical Flap Type-B Actuator
System
flap_ema
-----------------------------------------------------------------------------
CONVERT TO MATLAB FORMAT ........       (Title, System/Matrix, m-filename)
Electro-Mechanical Rudder Type-B Actuator
System
rudder_ema
-----------------------------------------------------------------------------
CONVERT TO MATLAB FORMAT ........       (Title, System/Matrix, m-filename)
Electro-Mechanical Body-Flap Type-B Actuator
System
bodyflap_ema
-----------------------------------------------------------------------------
CONVERT TO MATLAB FORMAT ........       (TITLE, SYSTEM/MATRIX, M-FILENAME)
Coupled axes Mixing Matrix for Rocket-Plane, K4axmix
Matrix K4axmix
-----------------------------------------------------------------------------
```

3.5 Closed-Loop Simulation Model of the Flexible Vehicle with Aero-Elasticity

The simulation model used in the aero-elastic analysis is "*Closed-Loop-Gafd.mdl*" and it is located used in directory "*Examples\18-Rocket Plane\3-Flex Model With Gafd*". It is shown in Figure 3.1 and is almost identical to the simulation model used in Section 2. It consists of the same four control loops. The vehicle system, however, contains the flexible vehicle system with GAFD, title: " *Rocket Plane at Mach=0.85, Q=150, Aero-Elastic Model with GAFD* " which is loaded into Matlab from file "*vehi_gafd_30flx.m*".

The green vehicle block is very similar to the one described in Section 2. It comprises of the flexible vehicle, the (6x4) mixing logic matrix "K4axmix.mat" that transforms the roll, pitch, yaw, and axial acceleration demands into control surface and throttle commands, and the actuators of the 3 aerosurfaces. The LQR state-feedback gain matrices Kq and Kpr are the same as before and most of the notch filters. A notch at 62.7 (rad/sec) was included because the mode at that frequency is a lot stronger with the aero-elastic coupling coefficients than it was in Section 2.

The initialization m-file "init.m" loads the flex vehicle, actuators, mixing logic, and the control system into Matlab. It loads also the alpha & beta estimator parameters, because the estimated alpha and beta replace the real alpha and beta angles required by the LQR controller. A similar 6-dof simulation is performed using the flexible vehicle system with the GAFD data. Figures 3.2 to 3.4 show the simulation results to the commanded changes in speed, altitude, heading direction and to the wind-gust excitation. A short duration, intentionally strong, wind-gust is applied at 8 (sec) to excite the structure. The altitude is commanded to increase 500 (feet), the heading direction to change 5°, and the ground speed to increase 8 (ft/sec). The Matlab script file "pl.m" is used to plot the simulation data. The angle of attack and the engine thrust initially increase in order for the vehicle to gain altitude. The flight-path angle γ starts from level flight, it increases as it gains altitude and eventually stabilizes back to zero (level flight). The gust creates a momentary disturbance to the system at 8 sec but then it calms down as the vehicle responds.
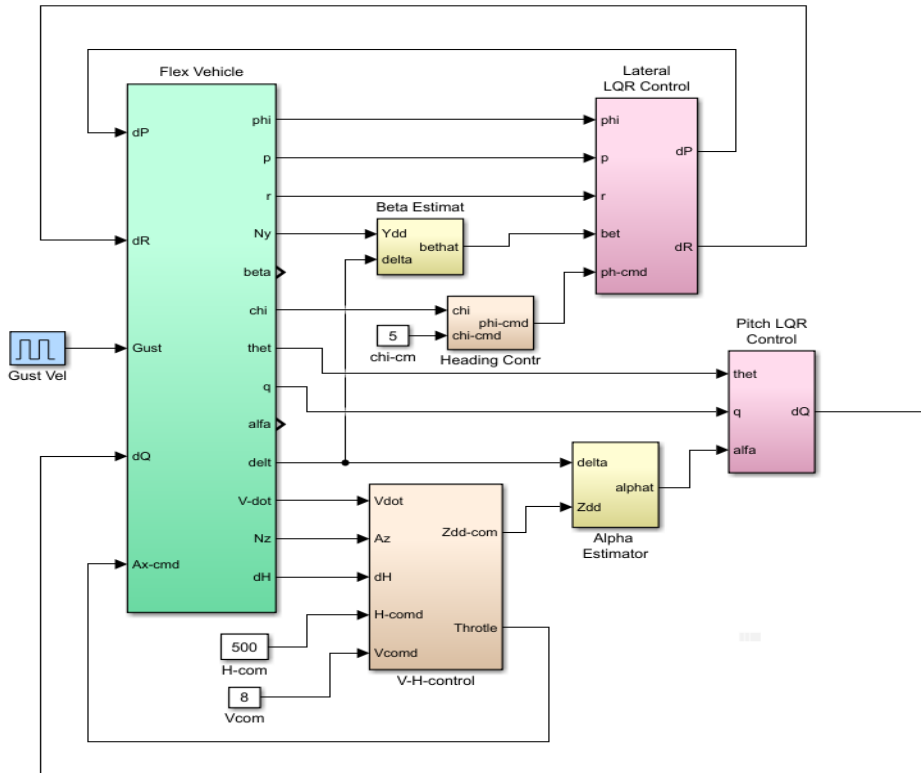
Figure 3.1 Closed-Loop Simulation Model with Aeroelastic Coefficients "Closed_Loop_Gafd.Mdl"
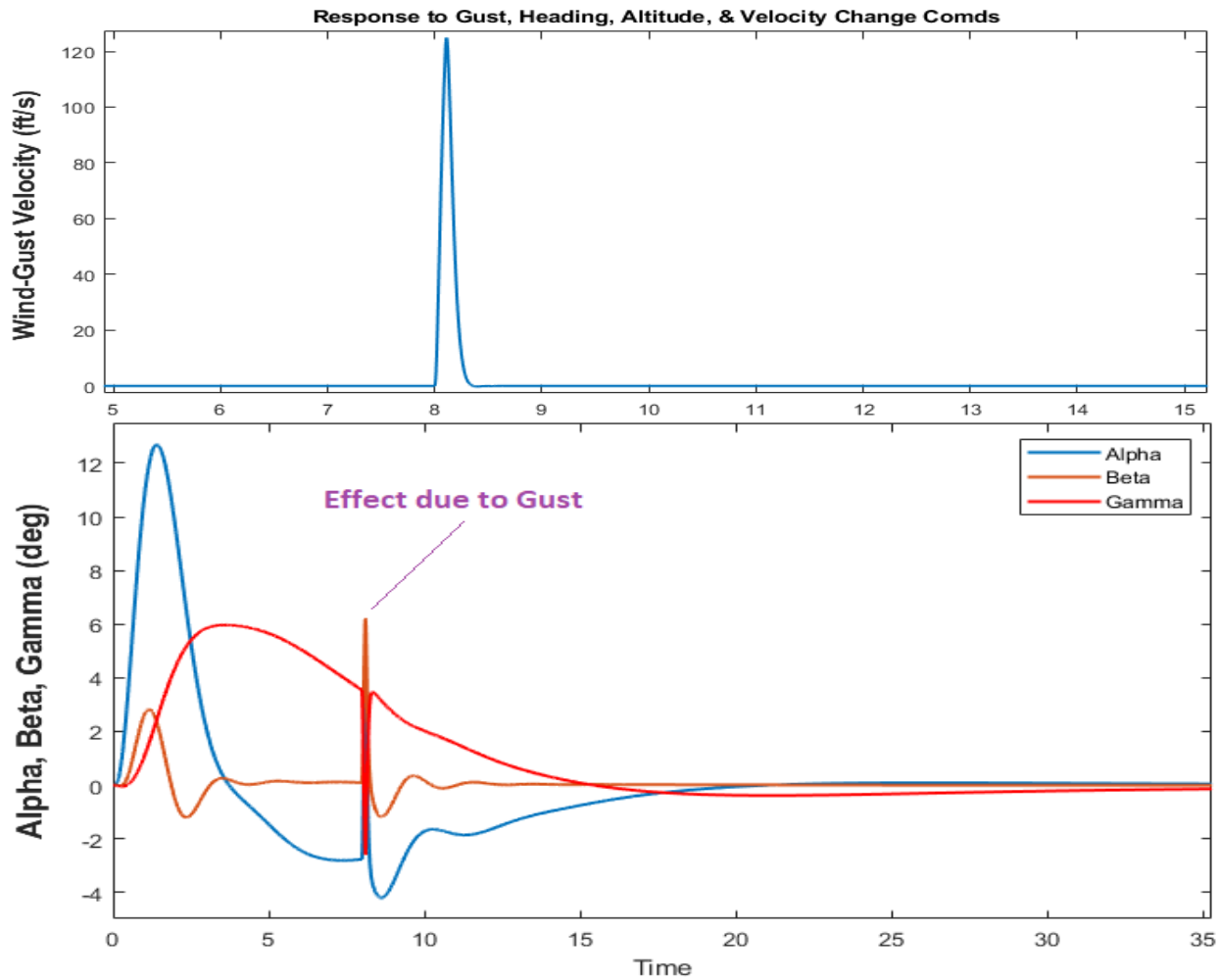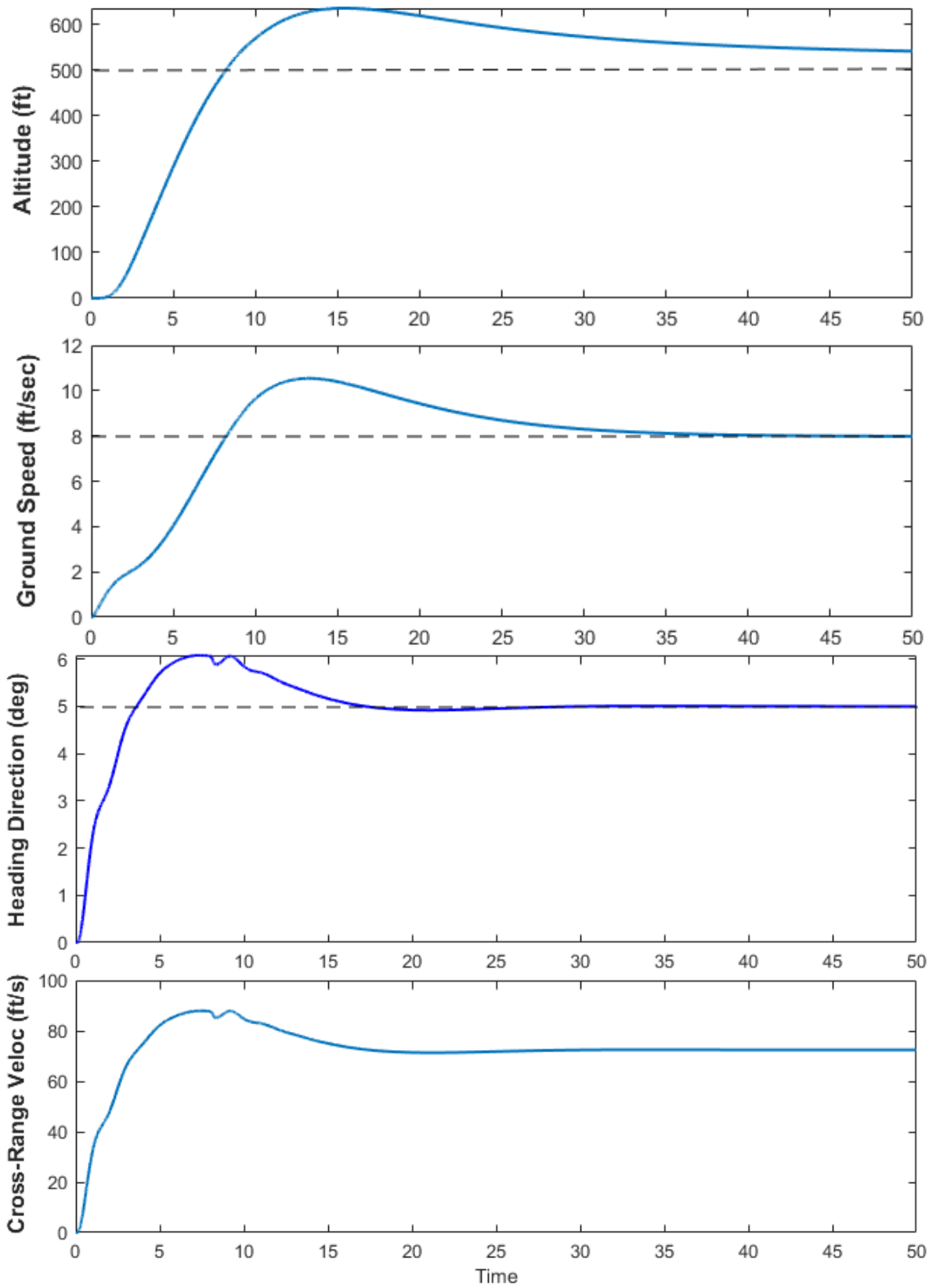
Figure 3.2 A Change in Heading Direction of 5° is attained by Rolling. The Speed achieves the 8 (ft/sec) commanded increase by momentarily throttling up the engine. The Altitude approaches the commanded 500 (feet) Altitude increase. The Cross-Range Velocity is perpendicular and relative to the original heading direction.
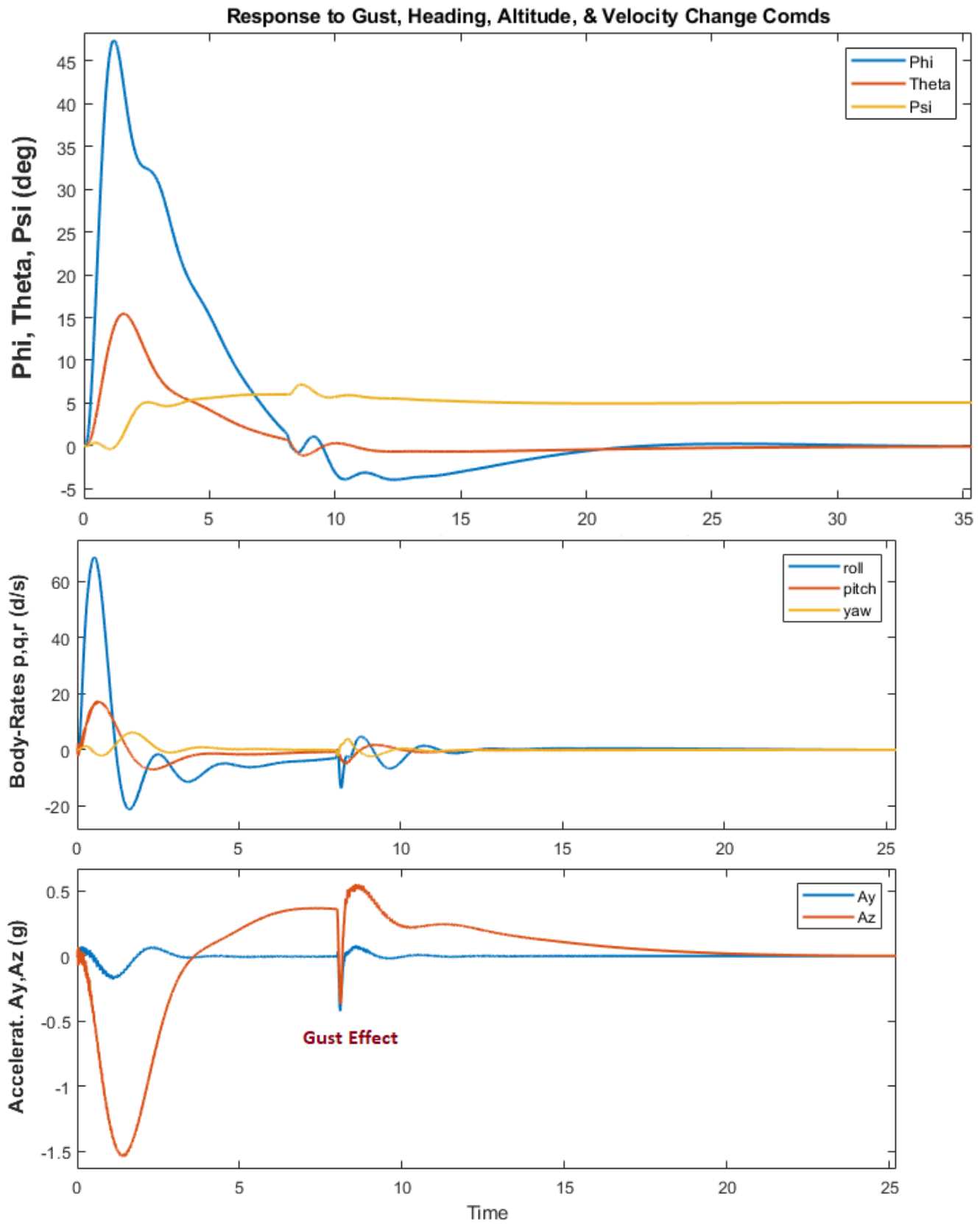
Figure 3.3 The Vehicle initially rolls towards the right to change direction and it returns back to zero roll angle. It initially experiences negative acceleration because it is gaining altitude. The Gust produces Normal and Lateral Accelerations (Az & Ay). It has a bigger effect on Az because of the Wings and V-Tail. Flexibility is noticeable in the accelerations.
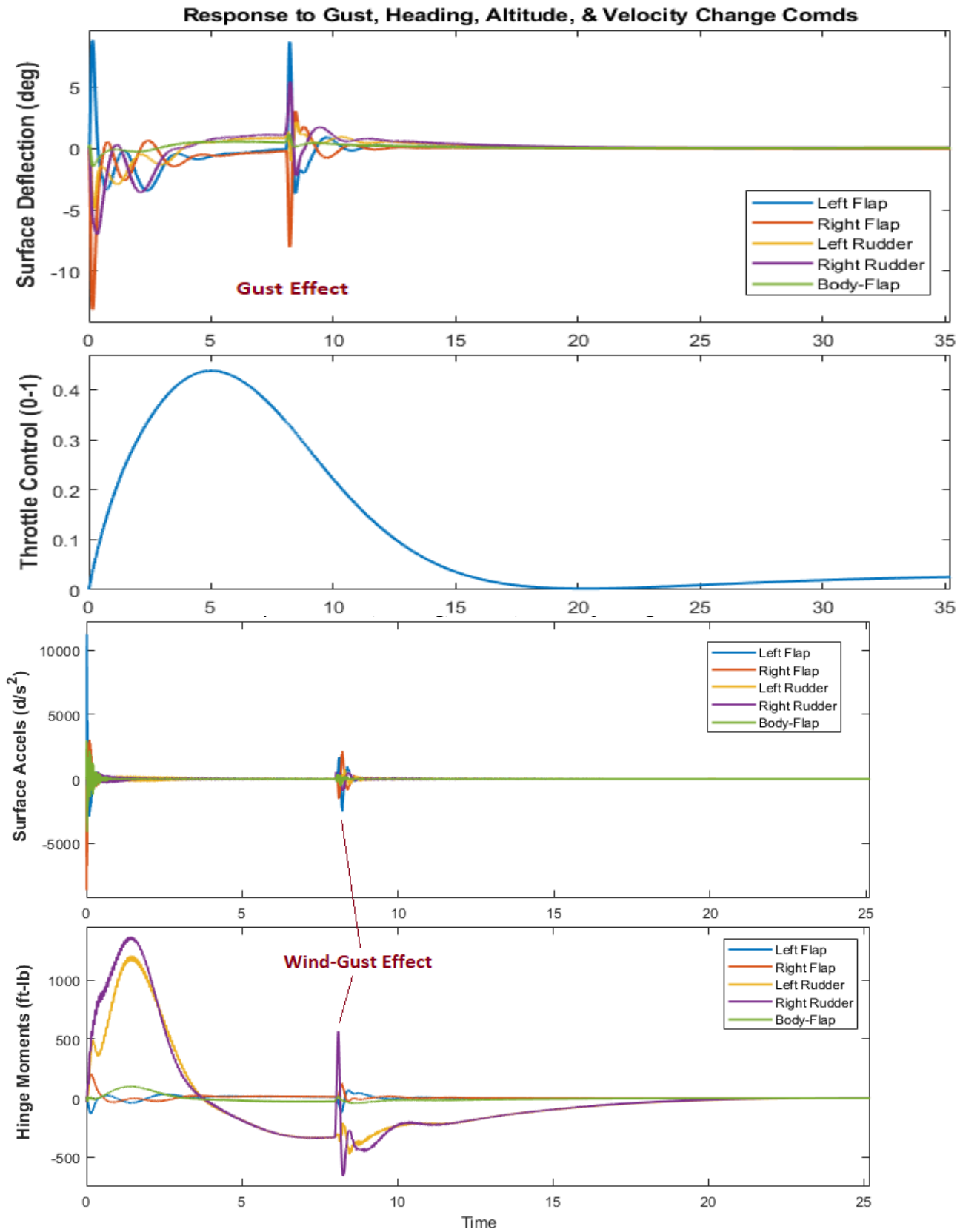
Figure 3.4 The Engine Throttles Up to increase Altitude and Speed and then it drops down to Just above nominal. The flaps deflect differentially to begin the Roll Maneuver and they deflect again to counteract the Gust. Both Hinge Moments are Positive when Initiating the Roll Maneuver because the Hinge Directions are Defined Opposite. The Right Rudder experiences bigger Hinge Moment because the Wind-Gust is Head-On towards it. Flexibility is noticeable in the Hinge Moments and Aerosurface Acceleration. In general, the GAFD model predicts more hinge moment than the previous flex model.

3.6 Open-Loop Stability Analysis

The Simulink model "*Open_Loop_Gafd.slx*" in Figure 3.5 is used for frequency response stability analysis of the open-loop system. It is configured as a single-input-single-output system for classical control analysis similar to the open-loop model used in Section 2. Only one loop is opened at a time while the other 4 loops are closed. It comprises of the same elements as the closed-loop model with aero-elasticity described in Section 3.5. The Matlab file "*frequ.m*" calculates the frequency response of the open-loop system and plots the Bode and Nichols charts which are used to analyze the system's characteristics. In Figure 3.5 it is configured for analyzing the stability of the heading loop where the heading control loop is opened at the ϕ_{cmd}. The results indicate that more flex activity was present in comparison with the model of Section-2 and additional flex filters were included to attenuate the flex modes. The system still has acceptable phase and gain margins in all four loops with a control system bandwidth of approximately 3.5 (rad/sec).
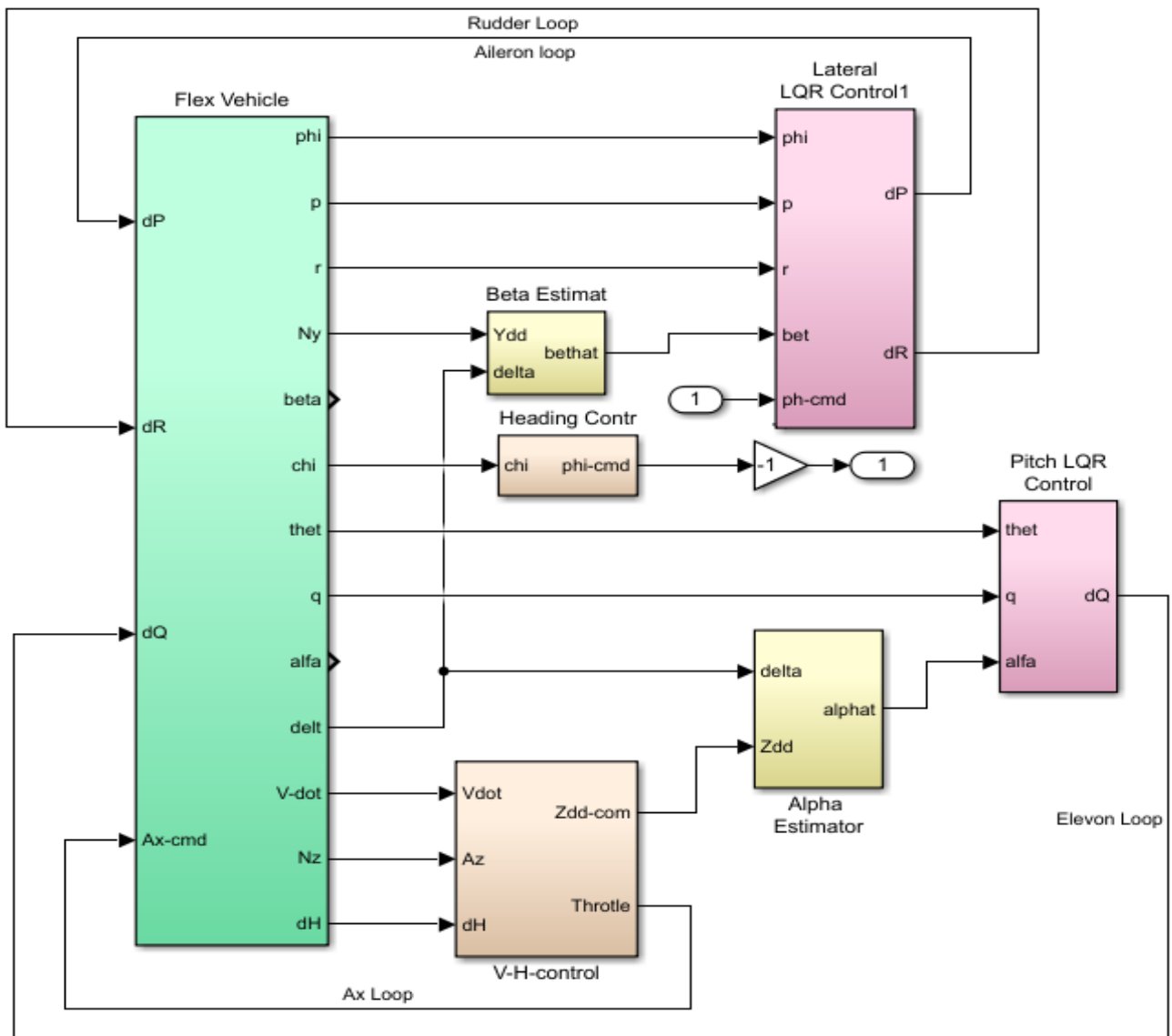
Figure 3.5 Simulink Model "Open_Loop_Gafd.slx" Configured for Frequency Response Analysis of the Heading Control Loop
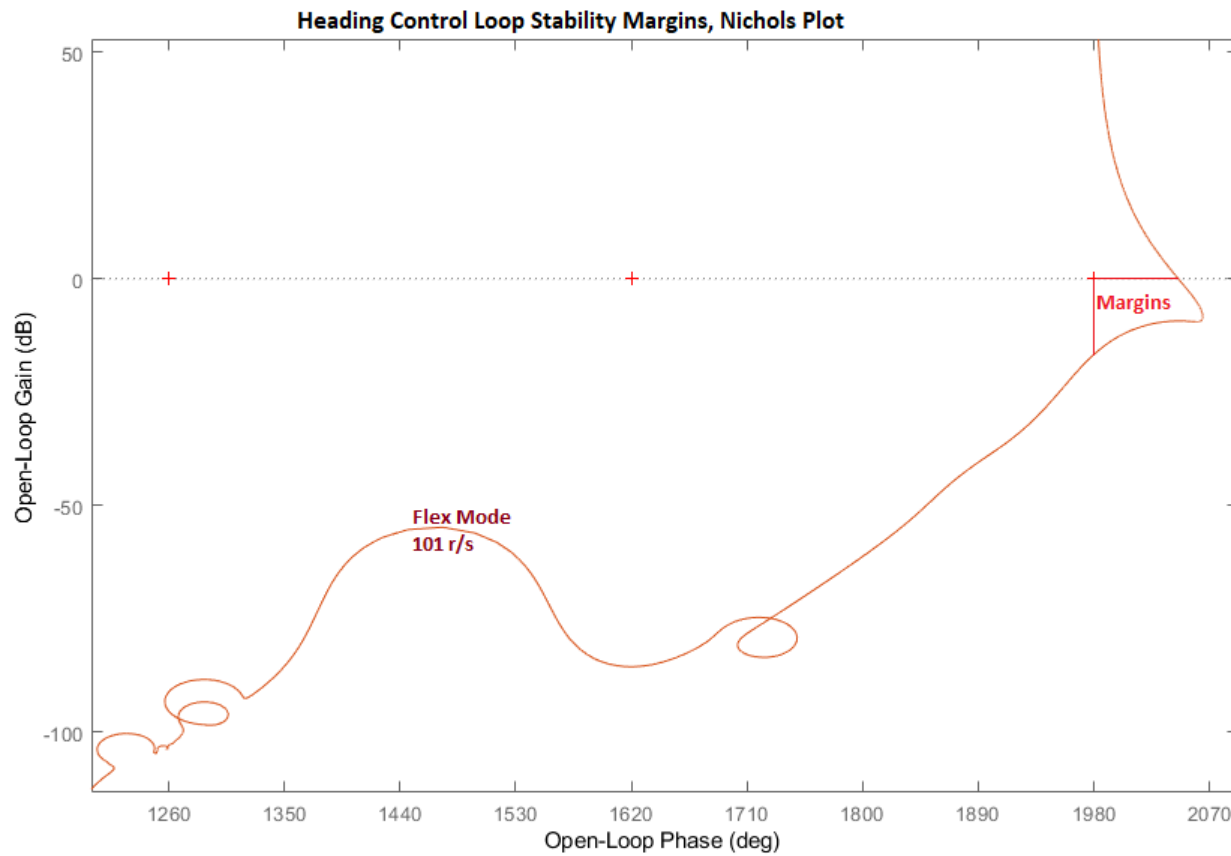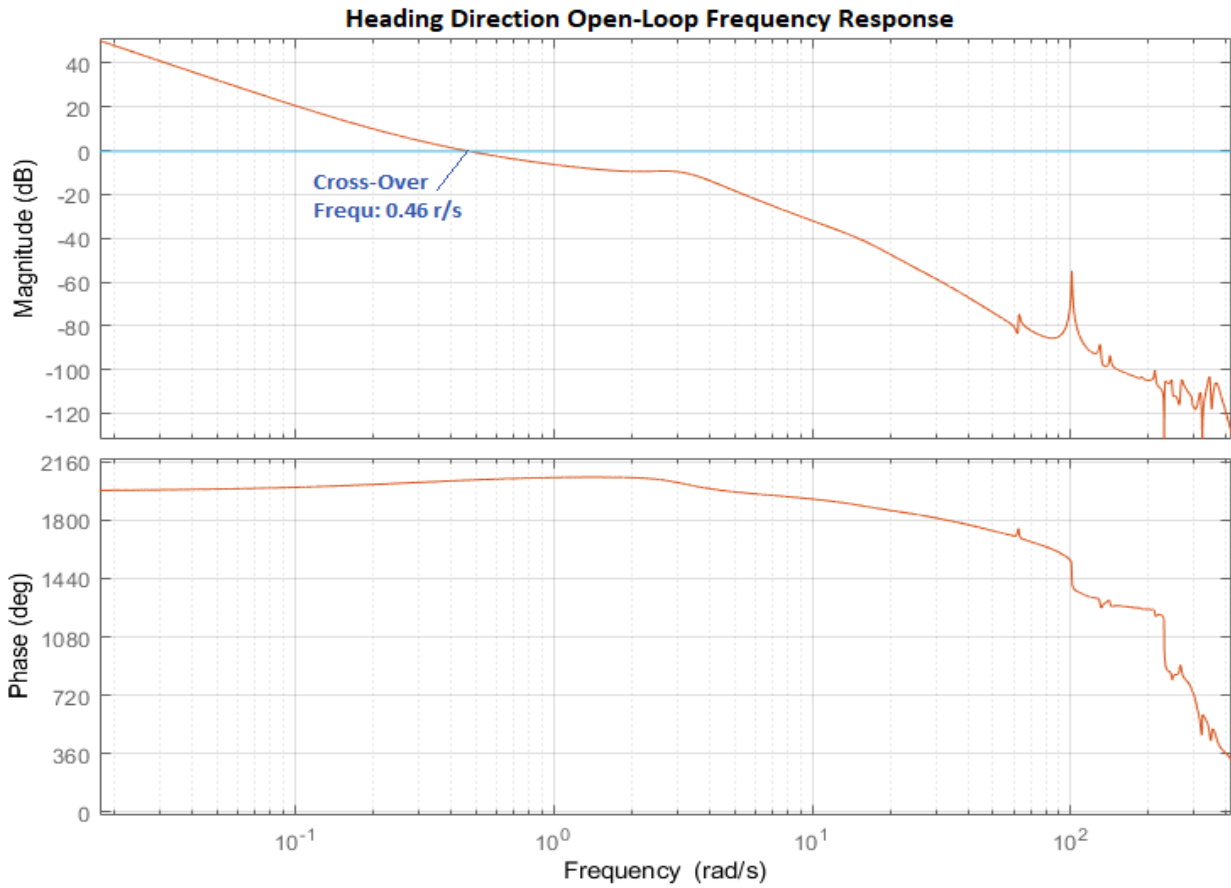
Figure 3.6 Bode and Nichols Plots Showing Stability Margins of the Heading Control Loop

Pitch Axis Open-Loop Frequency Response

Rigid Aero
Mode: 1.8 r/s

Cross-Over
Frequ: 3.3 r/s

Flex Modes

Magnitude (dB)

Phase (deg)

Frequency (rad/s)

Pitch Axis Open-Loop Stability, Nichols Plot

Open-Loop Gain (dB)

Margins

101

Open-Loop Phase (deg)
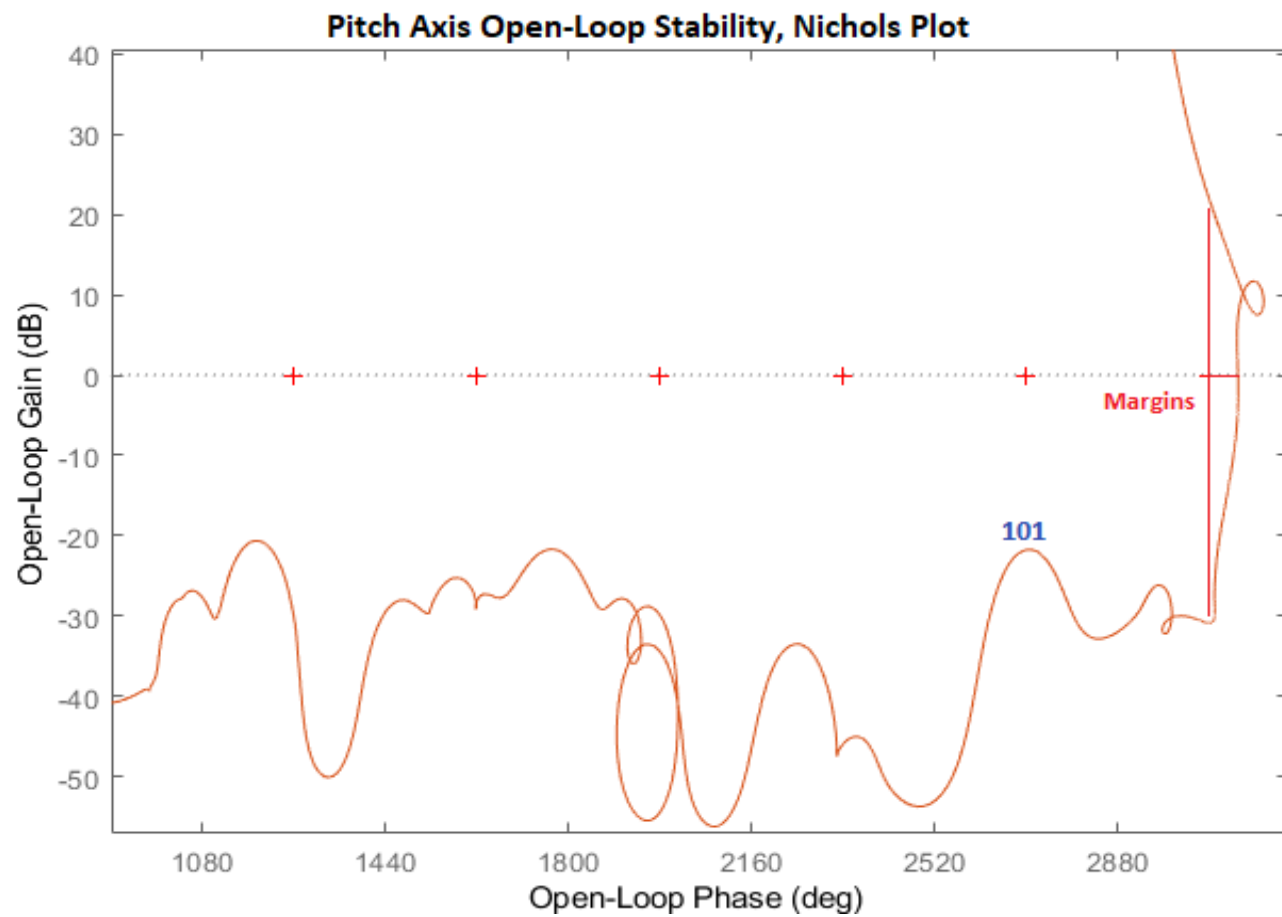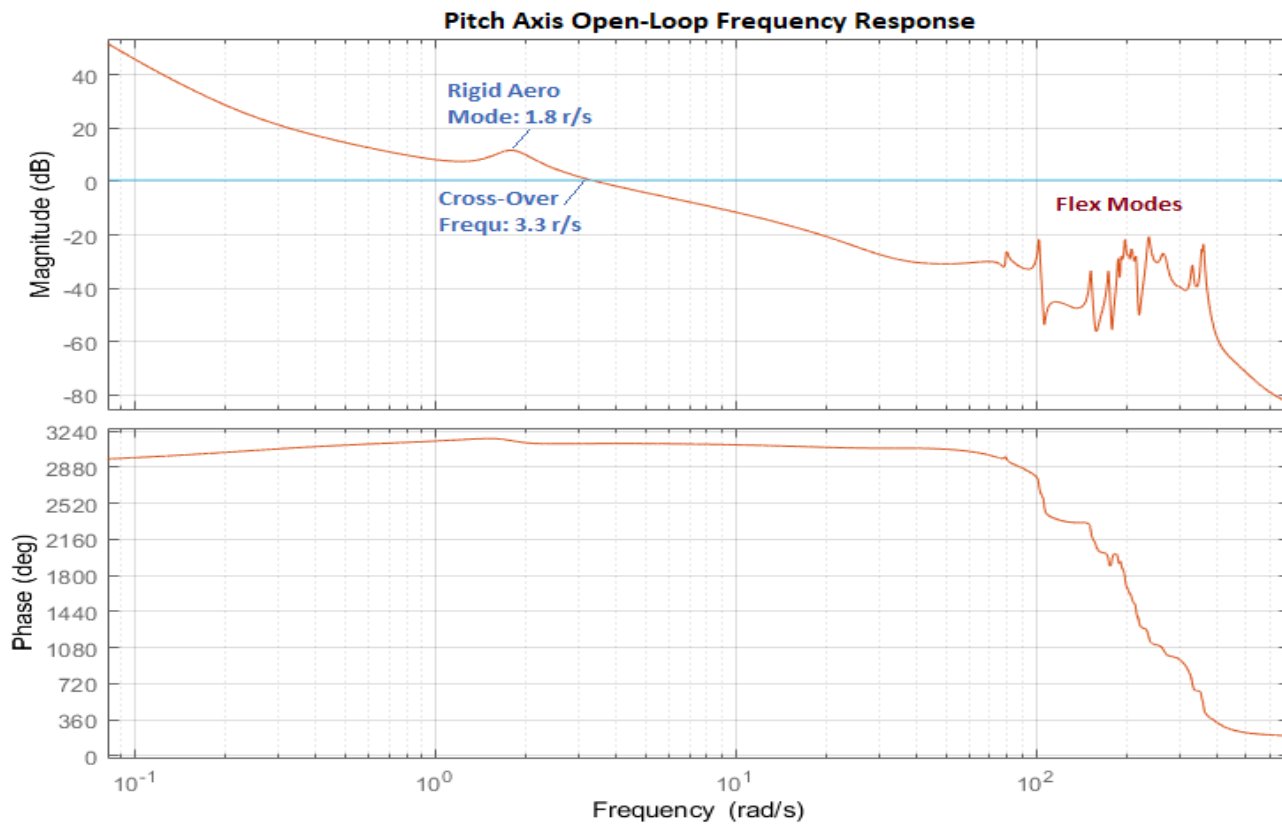
Figure 3.7 Pitch Axis Bode and Nichols Plots Showing Stability Margins
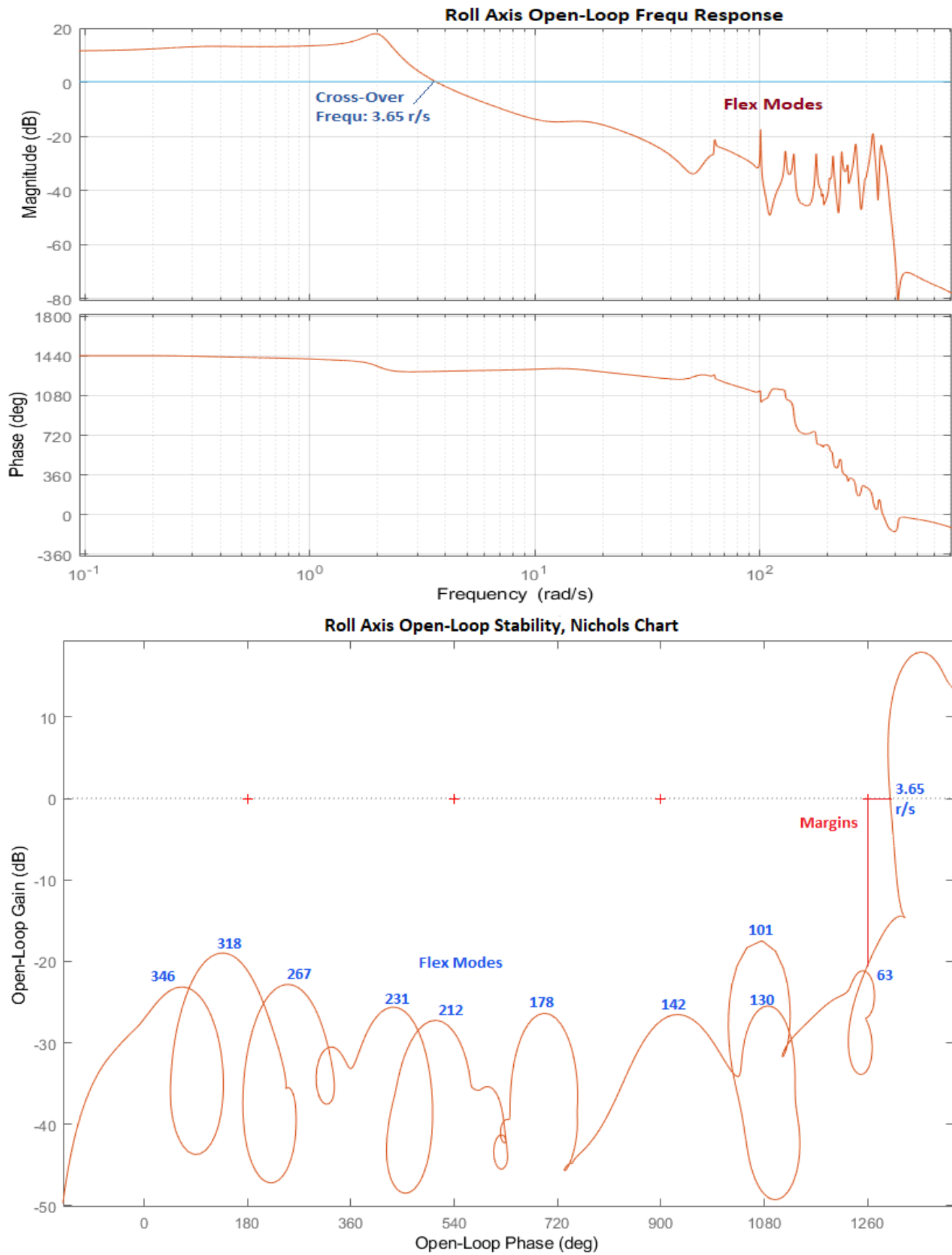
Figure 3.8 Roll Axis Bode and Nichols Plots Showing Stability Margins
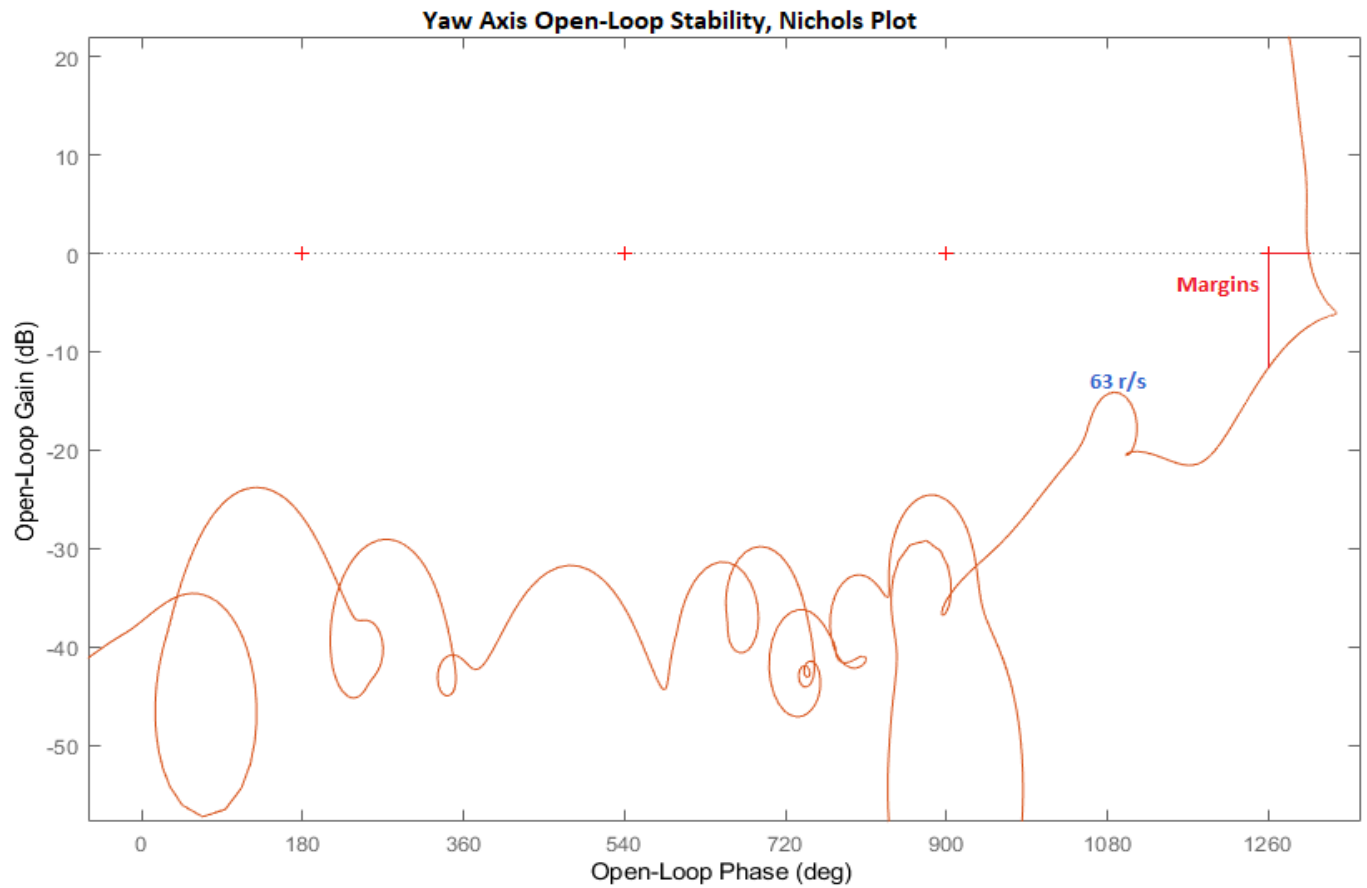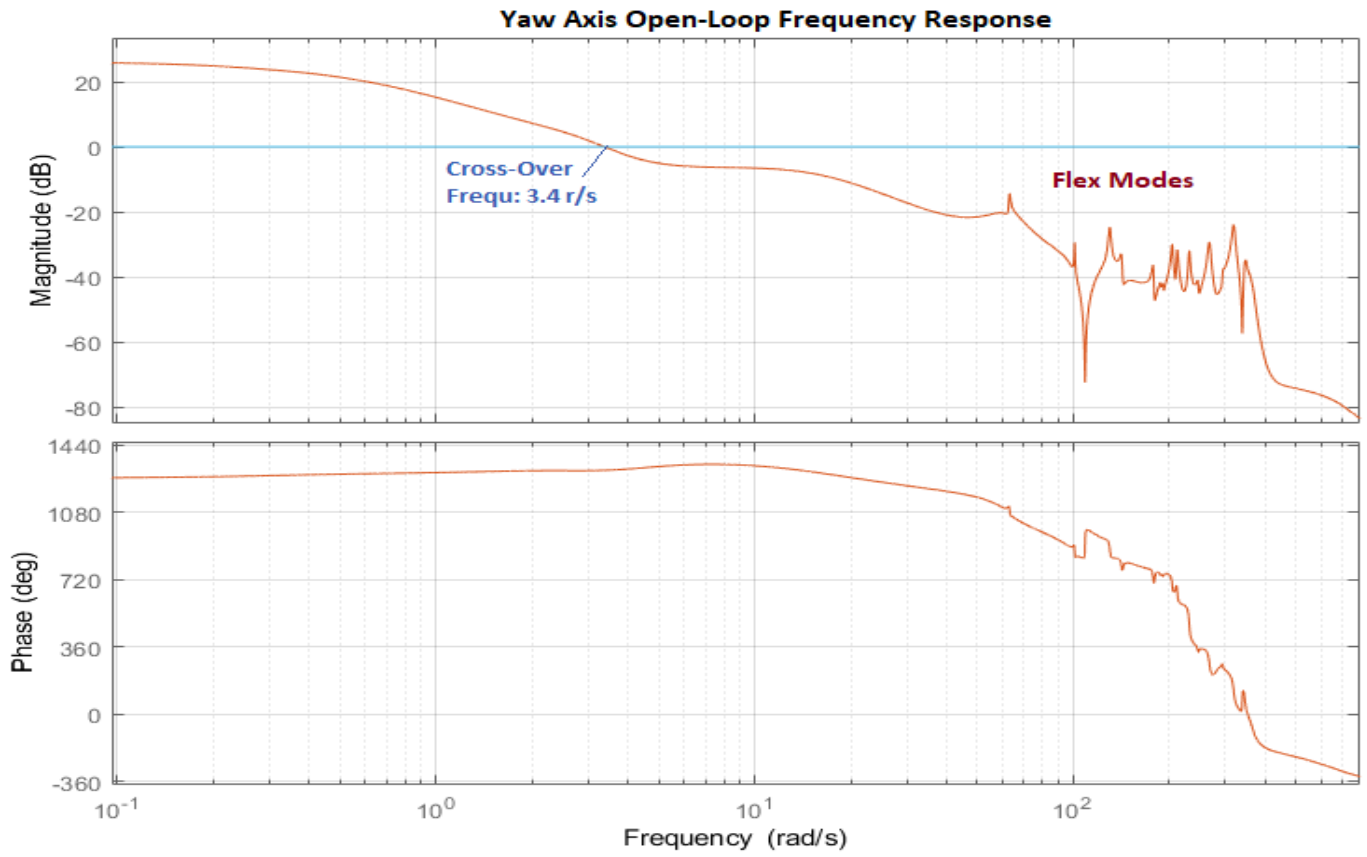
Figure 3.9 Yaw Axis Bode and Nichols Plots Showing Stability Margins

4.0 Actuators Analysis

In this Section we will examine the three aerosurface actuators alone, separate from the vehicle. The EM-Actuator model is shown in Figure 4.1. It uses a spinning motor that is controlled by dc voltage via a current amplifier and it provides the power to drive the load. The motor torque is transferred from the rotor to a spiral screw that is rotating via a gear mechanism, a small gear driving a bigger gear, and it produces a higher torque. The rotation of the screw converts the rotational motion to translational that extends or retracts the shaft. The end of the shaft is connected to the aerosurface via a linkage mechanism and it is pushing against the load that rotates about a hinge in order to control the vehicle. The other side of the actuator is attached to a stiff point on the vehicle structure. The EMA system uses two gear ratios. The first gear ratio Ngear represents the number of motor spins for one rotation of the screw gear and the second gear ratio Nscrew is the number of screw rotations per unit length extension of the shaft. The detailed description of the Electro-Mechanical type-B model is given in the Actuators Section 4.3.5.
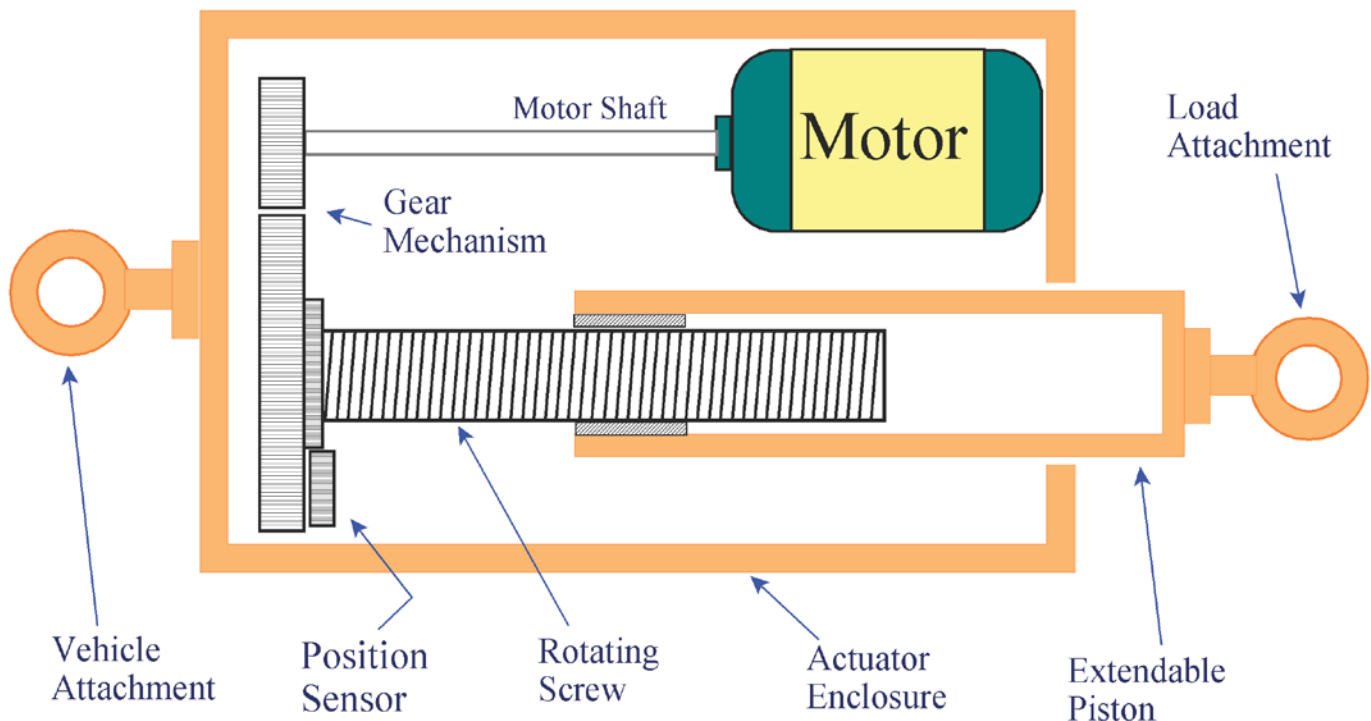
Figure 4.1 Electro-Mechanical Actuator

We will analyze stability and step responses of each actuator system attached to the load, including the local mechanical stiffness at the hinge which is a combination of backup stiffness, load and shaft stiffnesses. We will use linear models to analyze open loop stability and to calculate the closed-loop frequency responses (δ/δ_{comd}). We will also use non-linear models to calculate the step responses to deflection commands and plot the actuator internal variables. The actuator analysis files of this example are in directory "*Examples\18-Rocket Plane\4-EM-Actuators*". It includes separate and similar subdirectories for each aerosurface actuator.

4.1 Non-Linear Simulation Model

The simulation model is shown in Figure 4.2 and it consists of four subsystem blocks shown in detail in Figures 4.3 and 4.4. The total stiffness Kt consists of 3 stiffnesses (backup, load, and shaft) which are combined in series, and it produces the force F_L that pushes against the load and rotates the aerosurface.
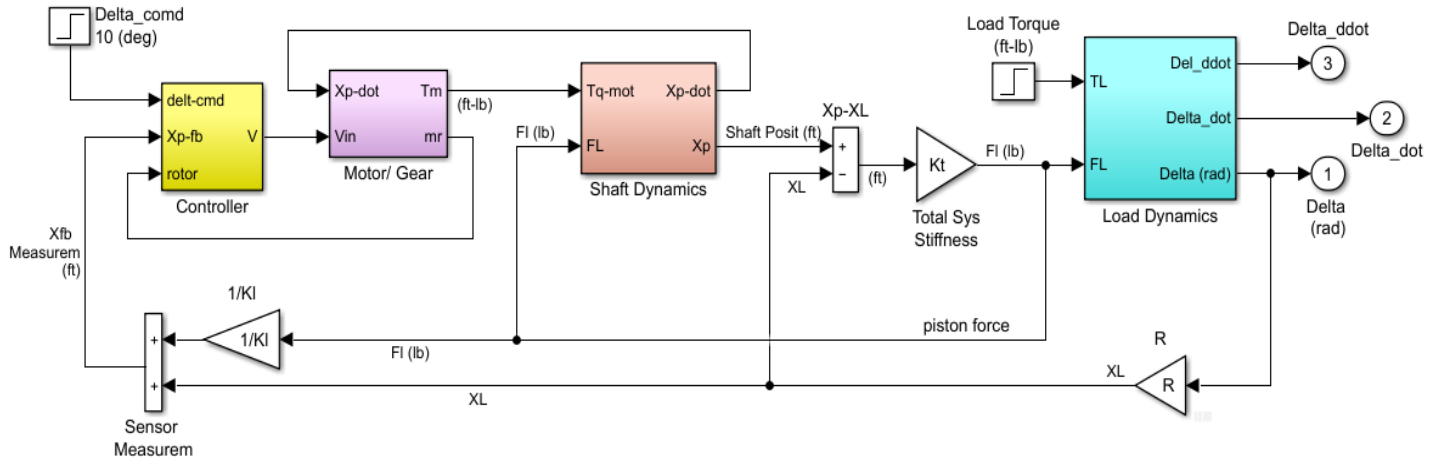
Figure 4.2 Closed-Loop Simulation Model "Flap_EMAB.slx"
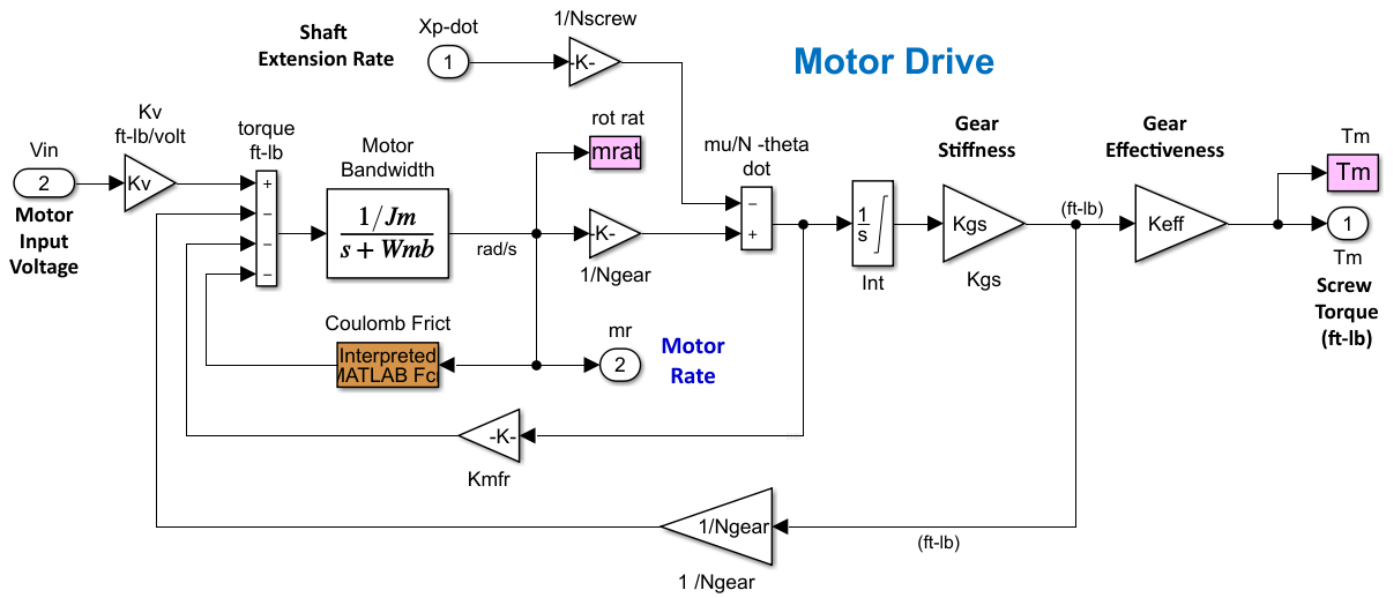

Figure 4.3 PID Control System Block
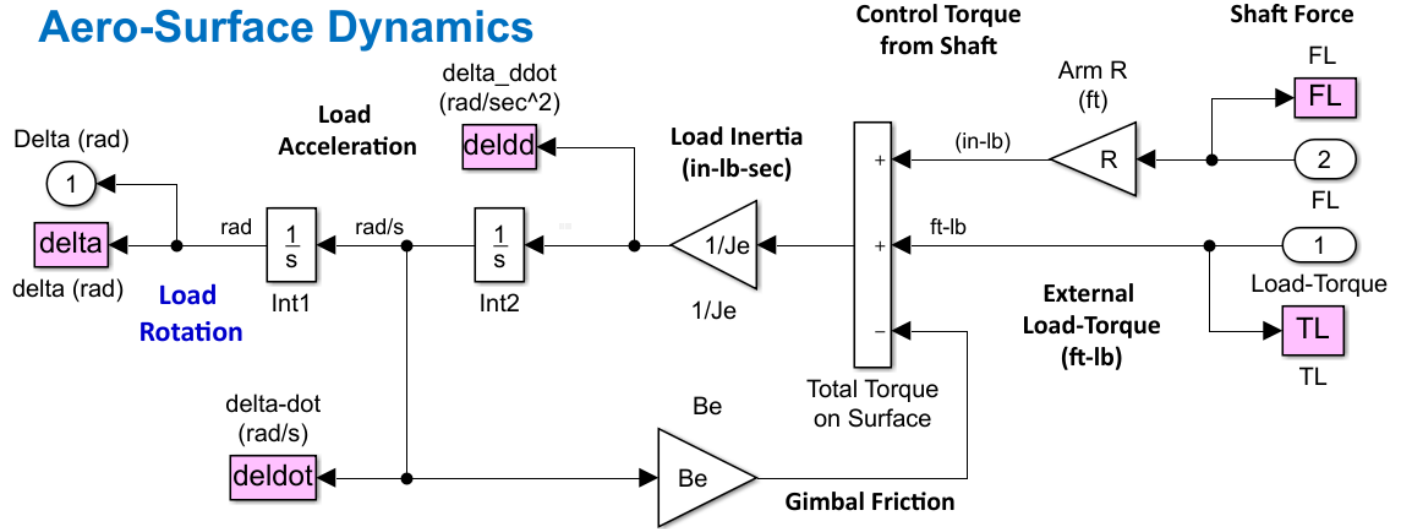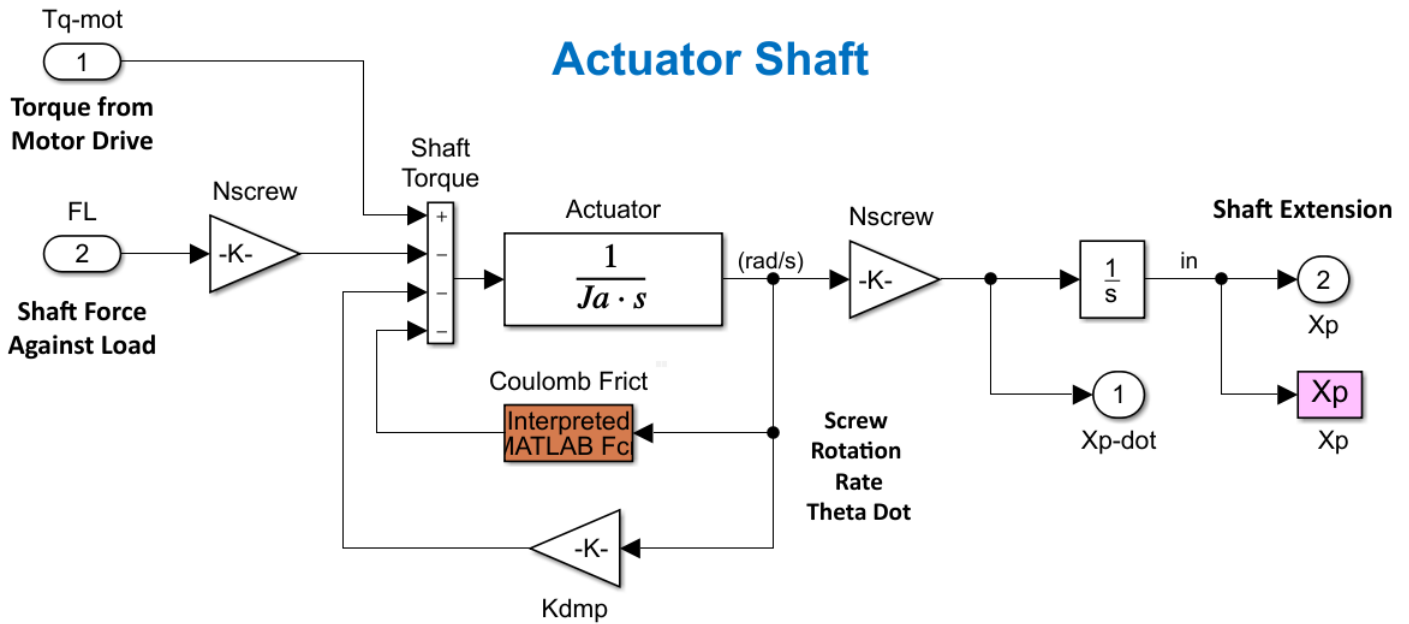
Figure 4.4 Motor, Shaft and Aerosurface Load Dynamics

Non-Linear Simulation of the Flap Actuator
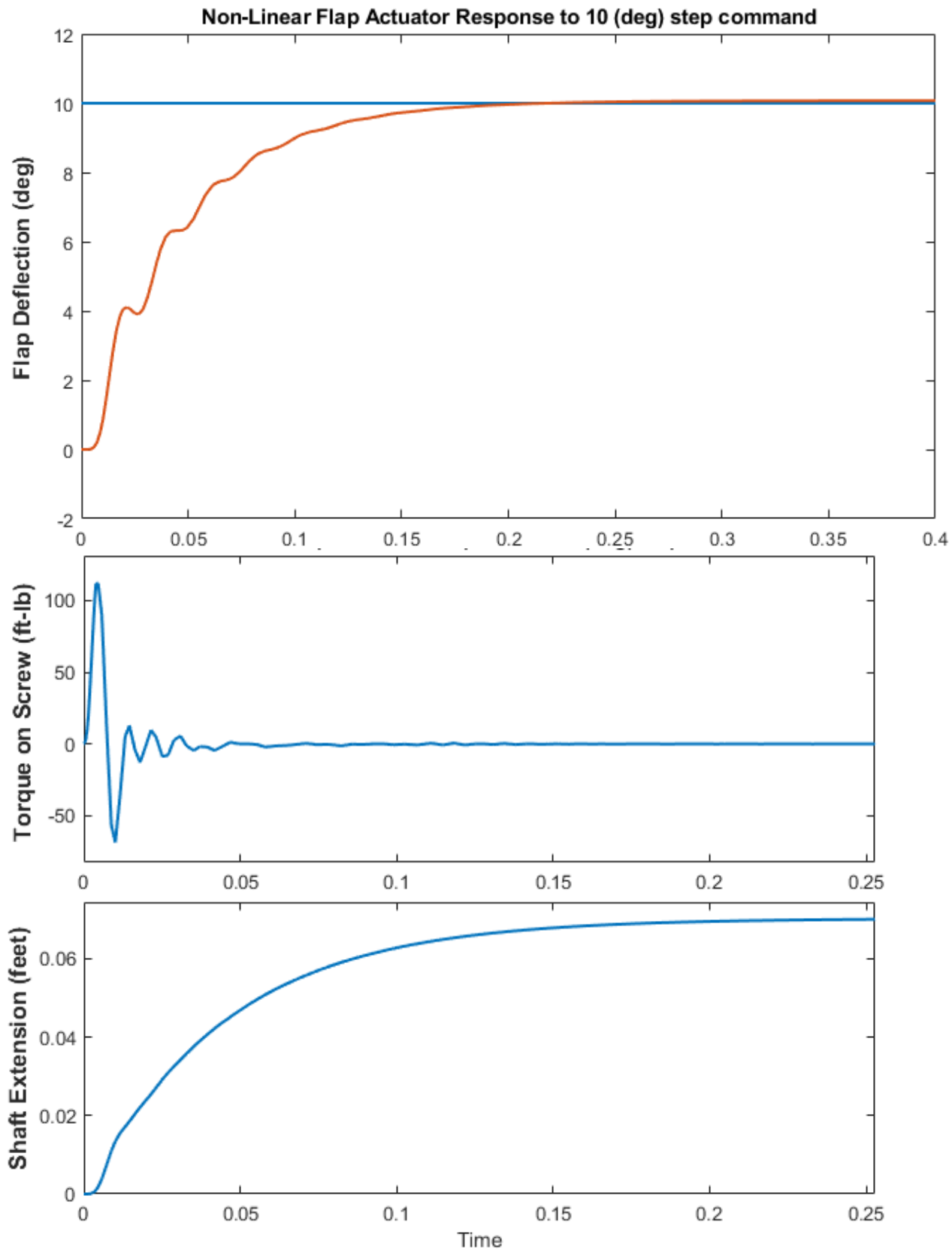
Figure 4.5 Flap Deflection to 10 (deg) Command, Shaft Extension (feet), the Screw Torque is Limited
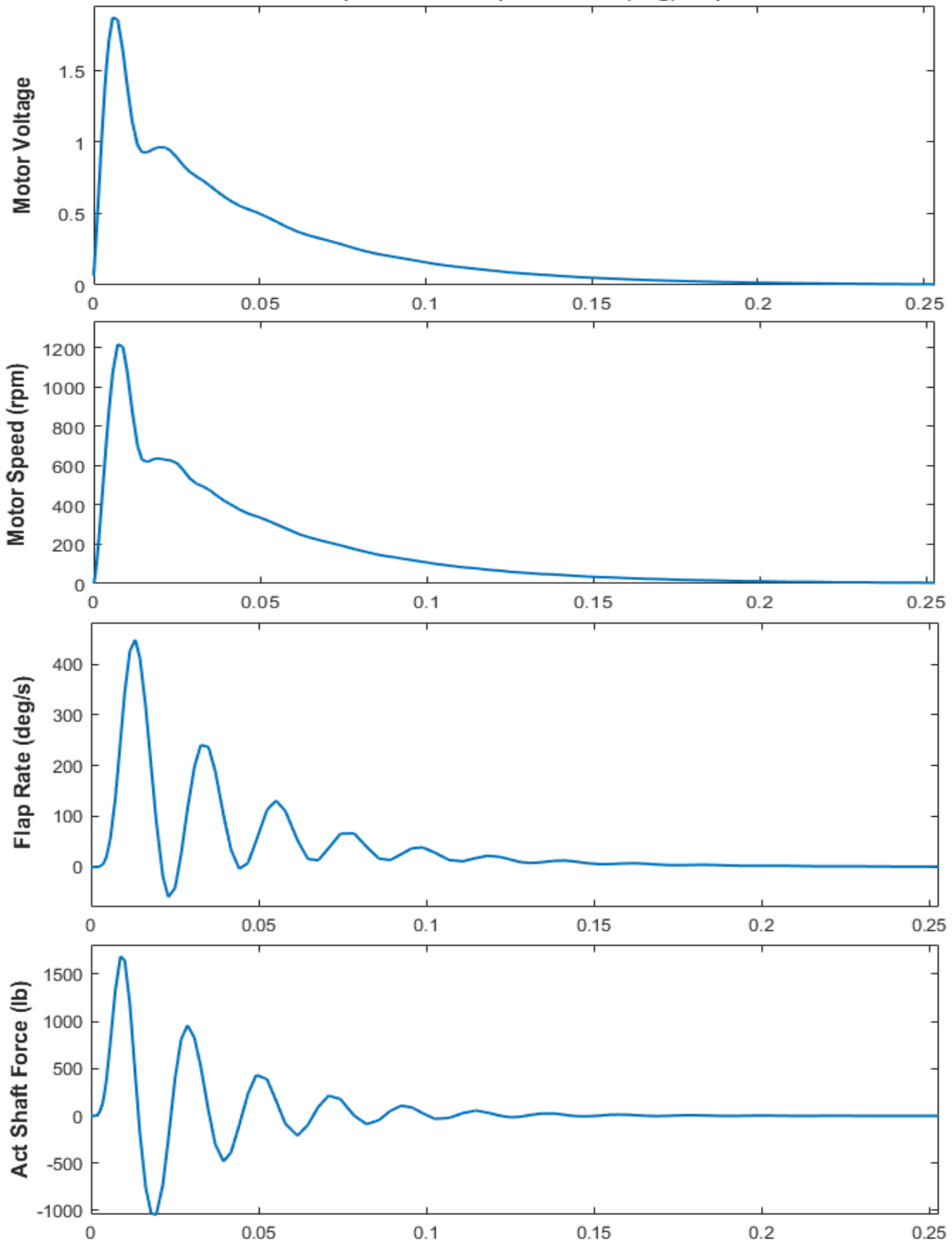
Figure 4.6 Motor Voltage, Speed, Flap Rate and Force Against the Shaft

Rudder Non-Linear Simulation
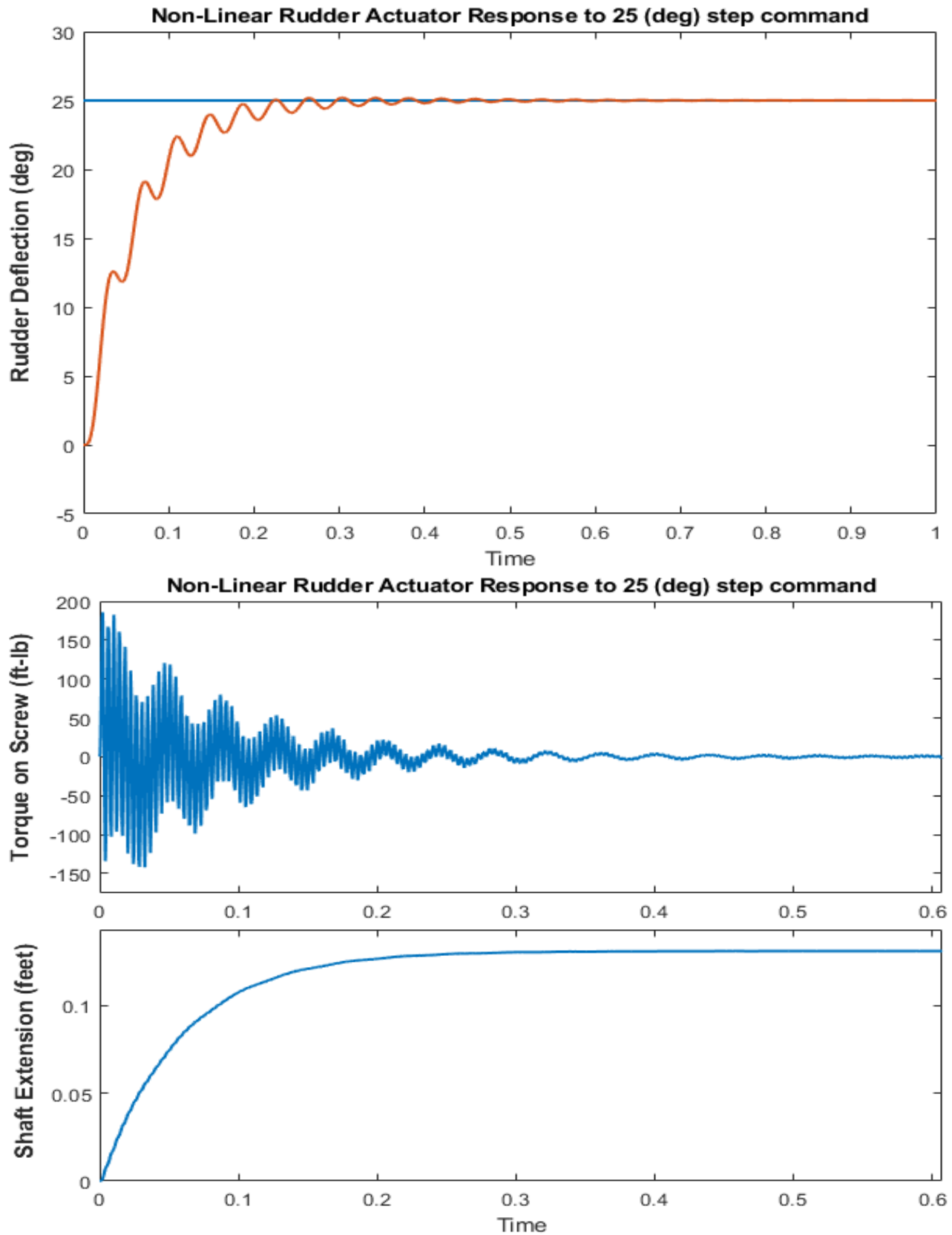
Figure 4.7 Rudder Deflection, Shaft Extension (feet) and Screw Torque, in Response to 25° Command
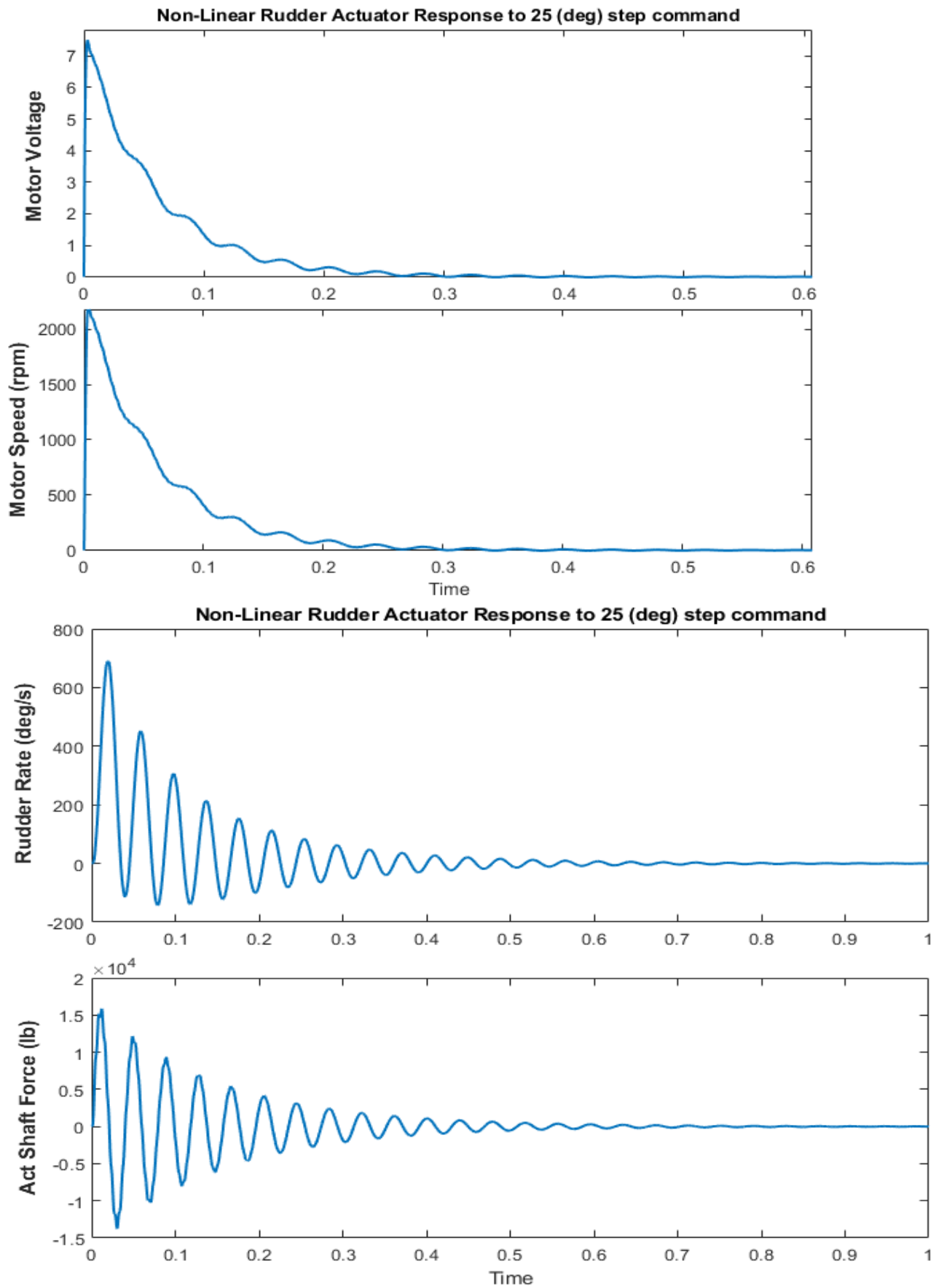
Figure 4.8 Motor Voltage, Speed (rpm), Flap Rate and Force Against the Shaft

4.2 Closed-Loop Frequency Responses

The frequency response (δ/δ_{com}) is calculated using the linear closed loop model in Figure 4.9. It includes the same blocks as the simulation model but without the non-linearities.
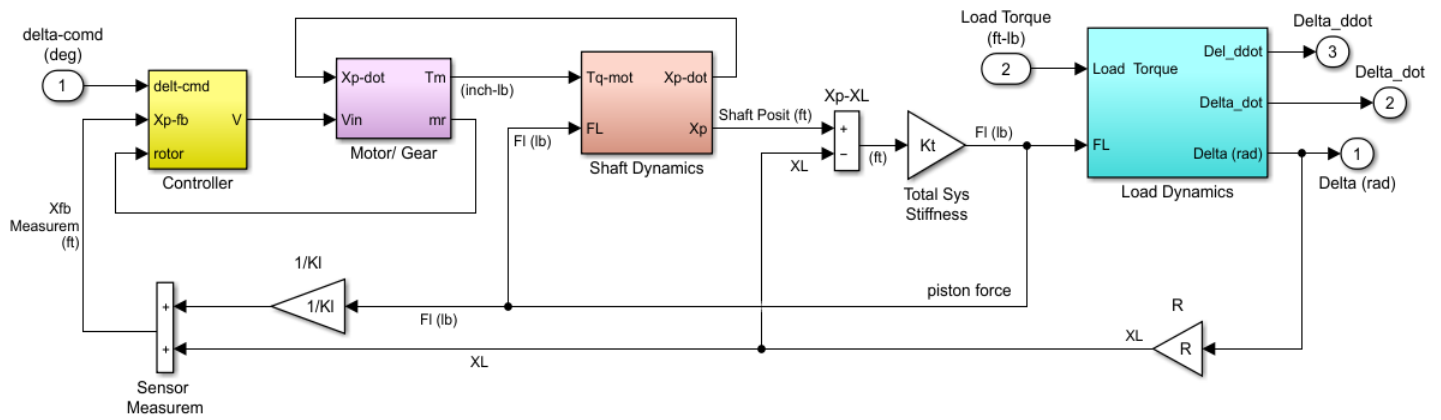
Figure 4.9 Closed-Loop Model "Flap_EMAB_Anal.slx" that Calculates the Flap Actuator Frequency Response
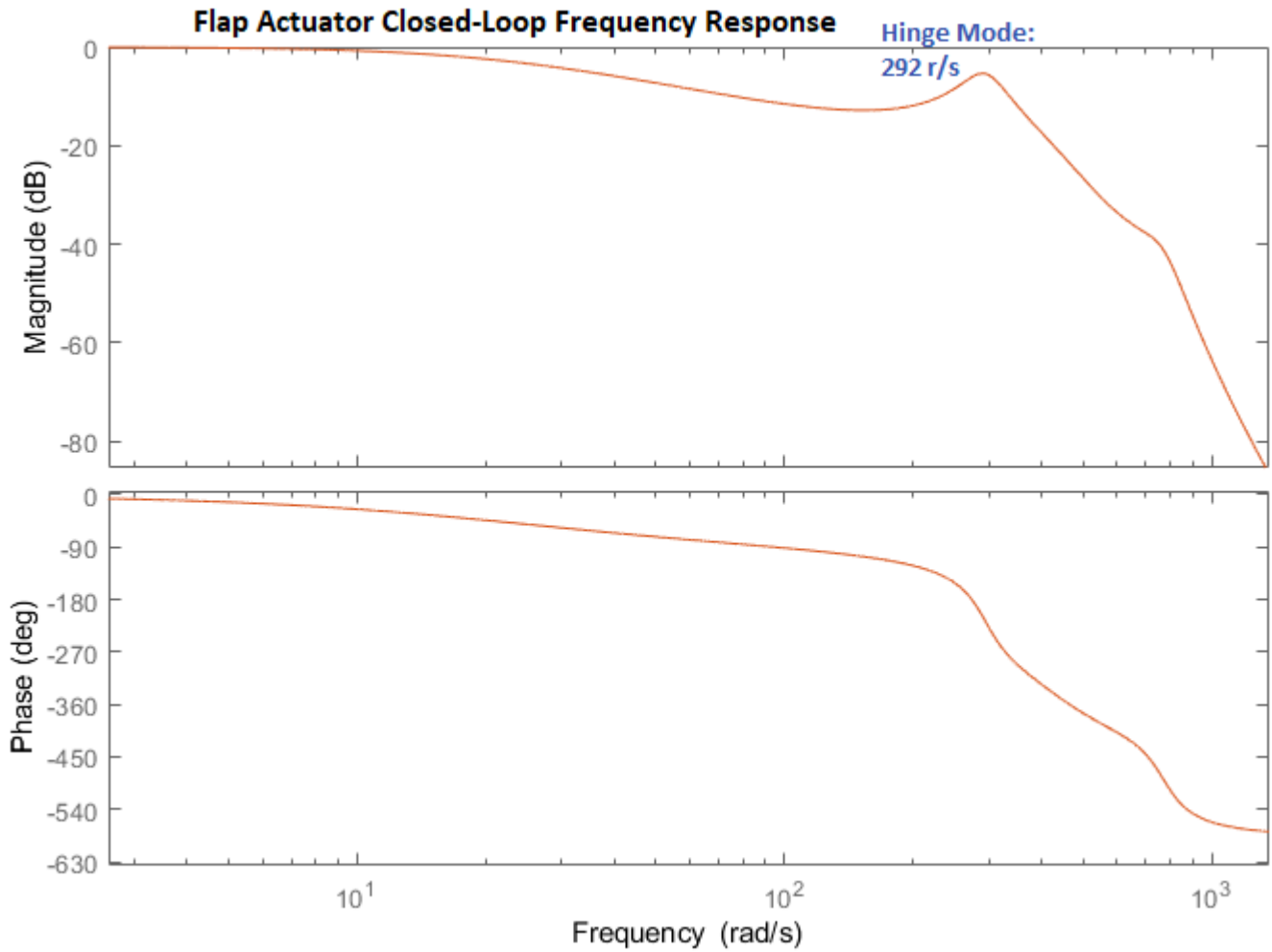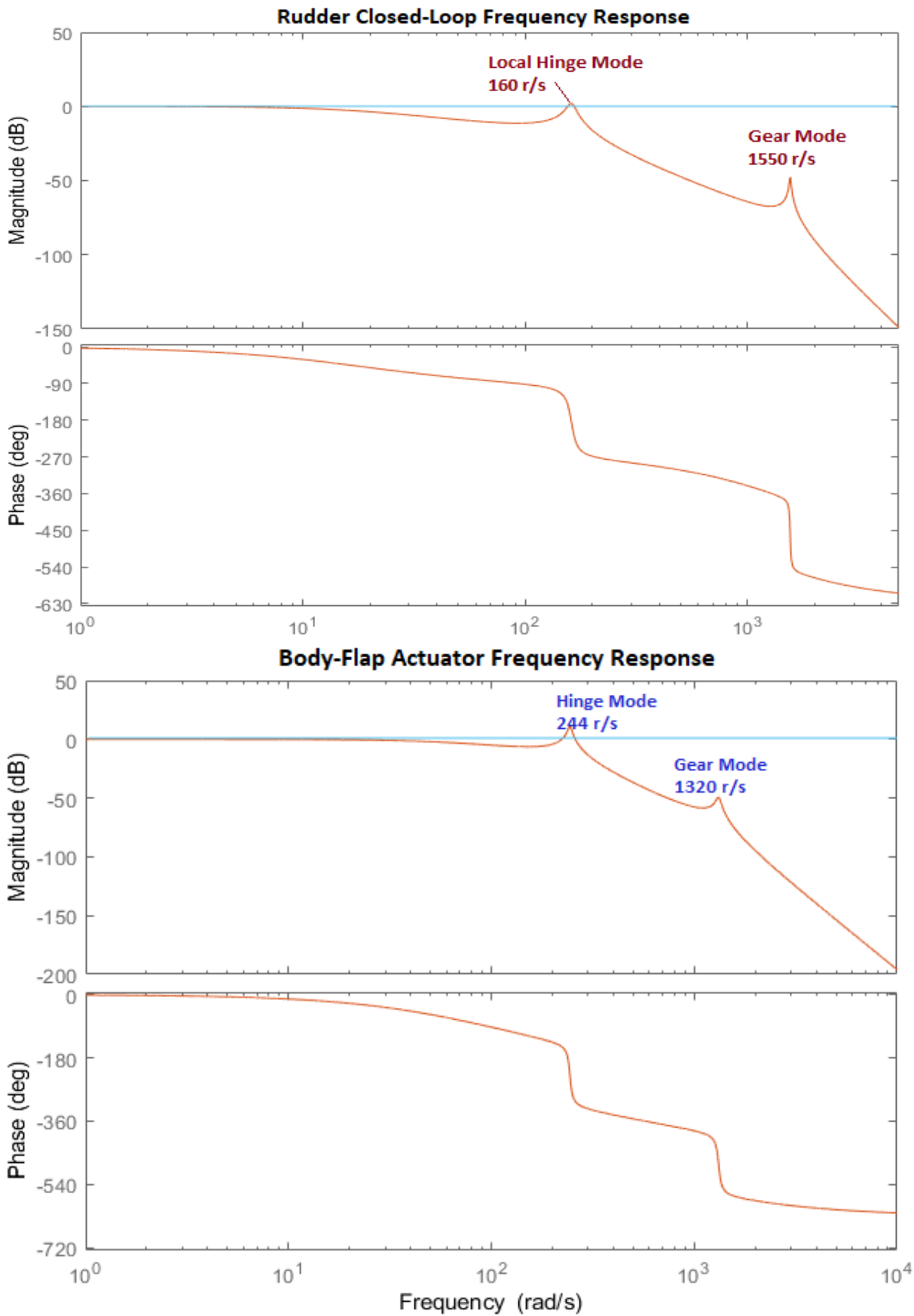

Figure 4.10 Flap Actuator Closed-Loop Frequency Response

Figure 4.11 Rudder and Body-Flap Actuators Closed-Loop Frequency Responses

4.3 Stability Analysis

The open-loop model for analyzing stability is shown in Figure 4.12. It includes the same blocks as the closed-loop model and it has the loop opened at controller output voltage. Figures 4.13 and 4.14 show the Nichols plot with the Phase and Gain Margins.
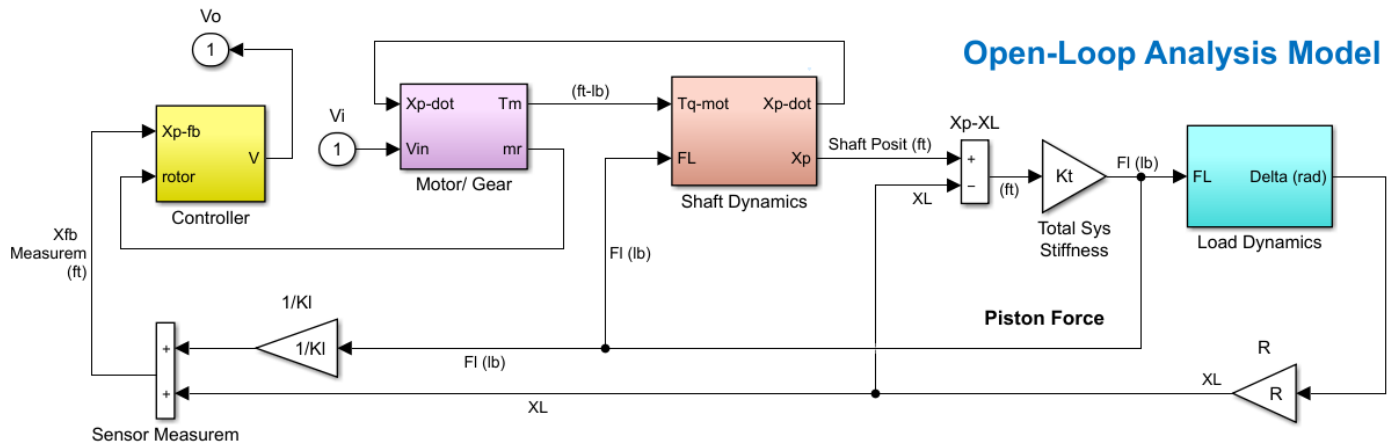

Figure 4.12 Open-Loop Model "Flap_EMAB_OpenLp.slx" Used for the Flap Actuator Stability Analysis
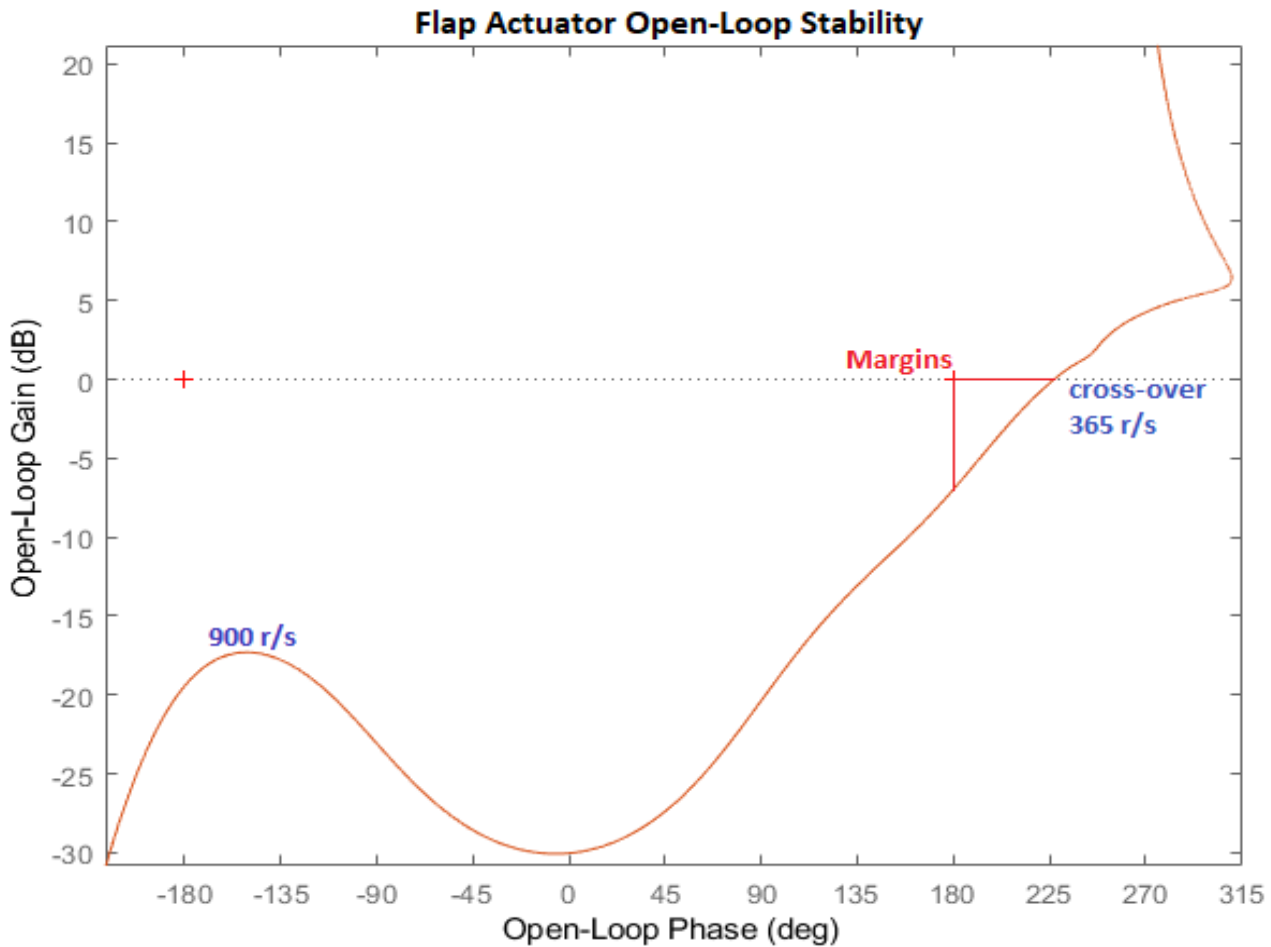

Figure 4.13 Flap Actuator Open-Loop Stability

Nichols Chart

Rudder Actuator Open-Loop Stability

186

cross-over
707 r/s

Margins

1600 r/s

Nichols Chart
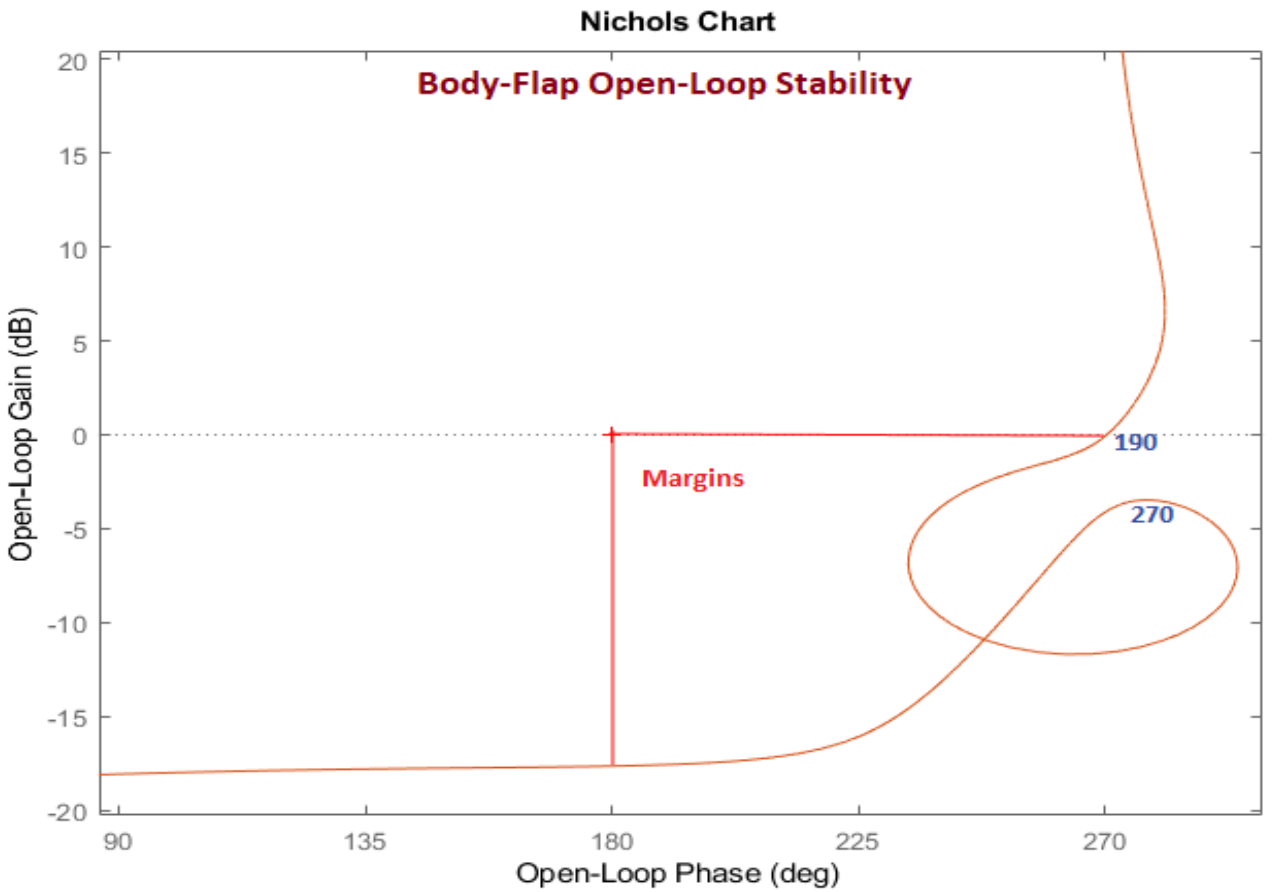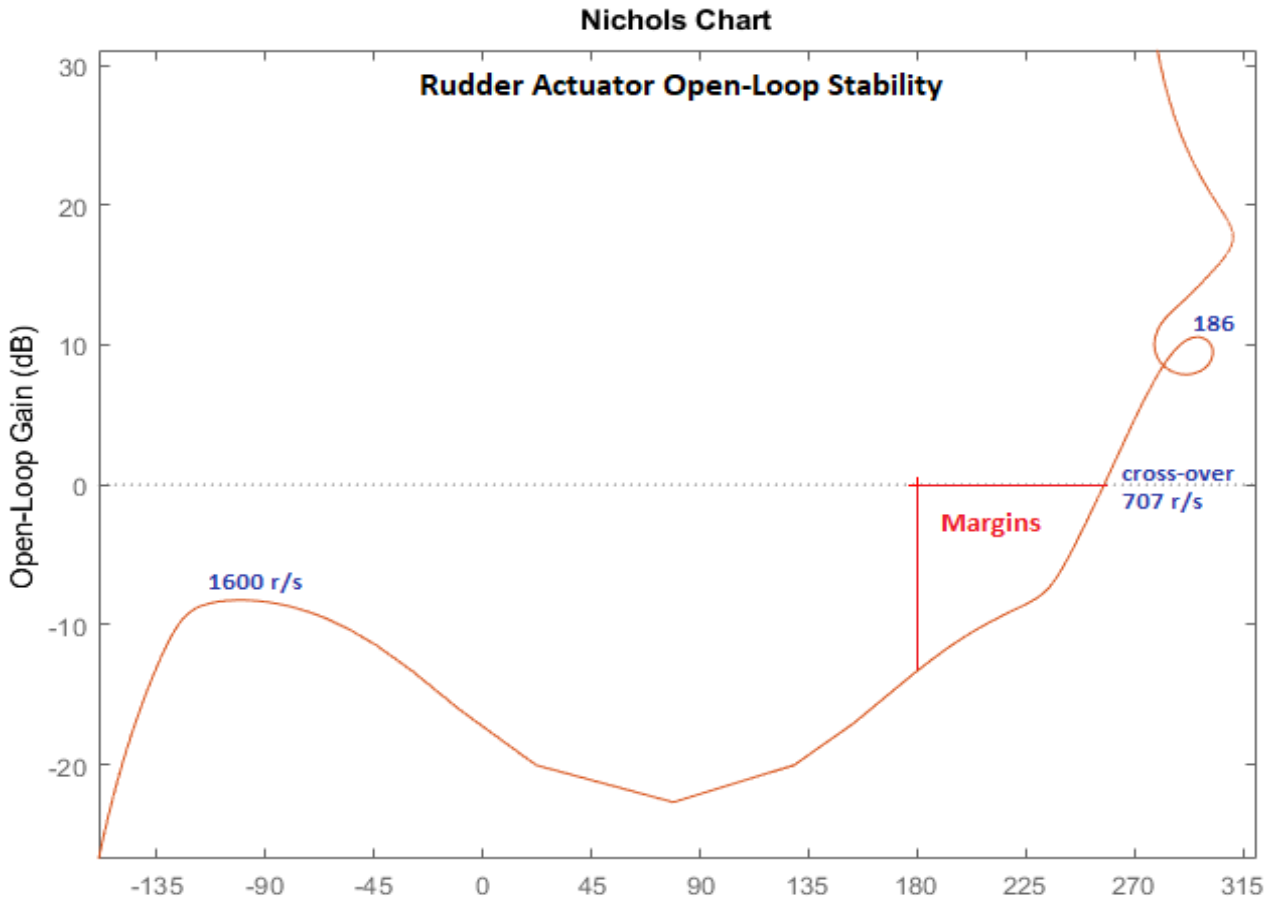
Body-Flap Open-Loop Stability

190

270

Margins

Figure 4.14 Rudder and Body-Flap Actuators Open-Loop Stability