

Space Shuttle Ascent, First Stage



In this example we are going to model the Space Shuttle vehicle during first stage and analyze the flight control system stability and performance at a flight condition where the dynamic pressure is maximum. During first stage the Shuttle propulsion system consists of three Space Shuttle main engines, (SSME) and two solid rocket boosters, (SRB). The vehicle attitude and direction is controlled by gimballing the five engines in pitch and yaw. The vehicle attitude, rate, and acceleration are measured by an IMU, rate gyros, and accelerometer sensors which are located at the top section of the SRBs. Roll attitude and rate are measured by sensors which are located in the orbiter vehicle. Inside the orange external tank (ET) there are two large tanks containing the propulsion fuel, a liquid oxygen (LOX) tank located in the front section, and a liquid hydrogen (LH2) tank in the aft section of the ET. During Max-Q the tanks are partially filled and fuel sloshing is a potential problem. If not properly controlled it may destabilize the vehicle by creating oscillatory disturbance forces. The control surfaces are not used during ascent but they are scheduled open-loop to minimize loading on the aero-surface actuators. Structural flexibility generated by engine gimballing is significant and it is included in the analysis. Aero-elasticity, however, is not as significant during ascent and it was not included in this analysis. It is included in the entry analysis.

The analysis is separated in three sections. In the first section we develop the pitch vehicle model and include 18 symmetric (pitch) structural modes. Fuel sloshing dynamics is also included (along z) for the two tanks which excite the vehicle in the pitch direction. The pitch Shuttle model is then discretized and combined with the digital flight control system to create control analysis models in the

z-domain and the models are used to evaluate the control system stability and performance using Matlab/ Simulink. In the second section we develop dynamic models that include both pitch and lateral dynamics. In addition, 29 flex modes are also included in the dynamic model which are both symmetric (pitch) and anti-symmetric (roll/ yaw). The sloshing of the two propellant tanks is also included in the dynamic model. It is represented by two masses oscillating in two directions perpendicular to the vehicle acceleration vector. The spring-mass analogy is used where the slosh masses are oscillating about the center of the tank, along the y and z directions. The analysis consists of stability analysis in the frequency domain to determine the phase and gain margins, sensitivity to wind gusts, and also time domain simulations of the vehicle in response to attitude commands from guidance and also responses to wind gusts. In the third section we shall redesign the Shuttle Ascent flight control system at Max-Q and attempt to improve the vehicle sensitivity to wind-gust disturbances. The original classical control design demonstrated poor wind-gust sensitivity performance with an undesirable resonance in the range of the disturbance frequencies. We will use the H-infinity method because it has the capability to reduce the vehicle sensitivity to disturbances.

The data files for this analysis are located in directory "C:\Flixan\Examples\Shuttle Ascent". This directory contains the files used for creating the Shuttle vehicle models and for analyzing its performance in Matlab. There are three subfolders corresponding to the three sections. "*Pitch Analysis*", and "*Coupled Vehicle*" where the pitch and lateral stability analysis and simulations are performed using Matlab and Simulink. The folders contain structural flexibility data files (*.Mod, *.Nod), vehicle input data (*.Inp), and system files (*.Qdr). The third subdirectory is "*Hinfinity Design*" which corresponds to Section 3.

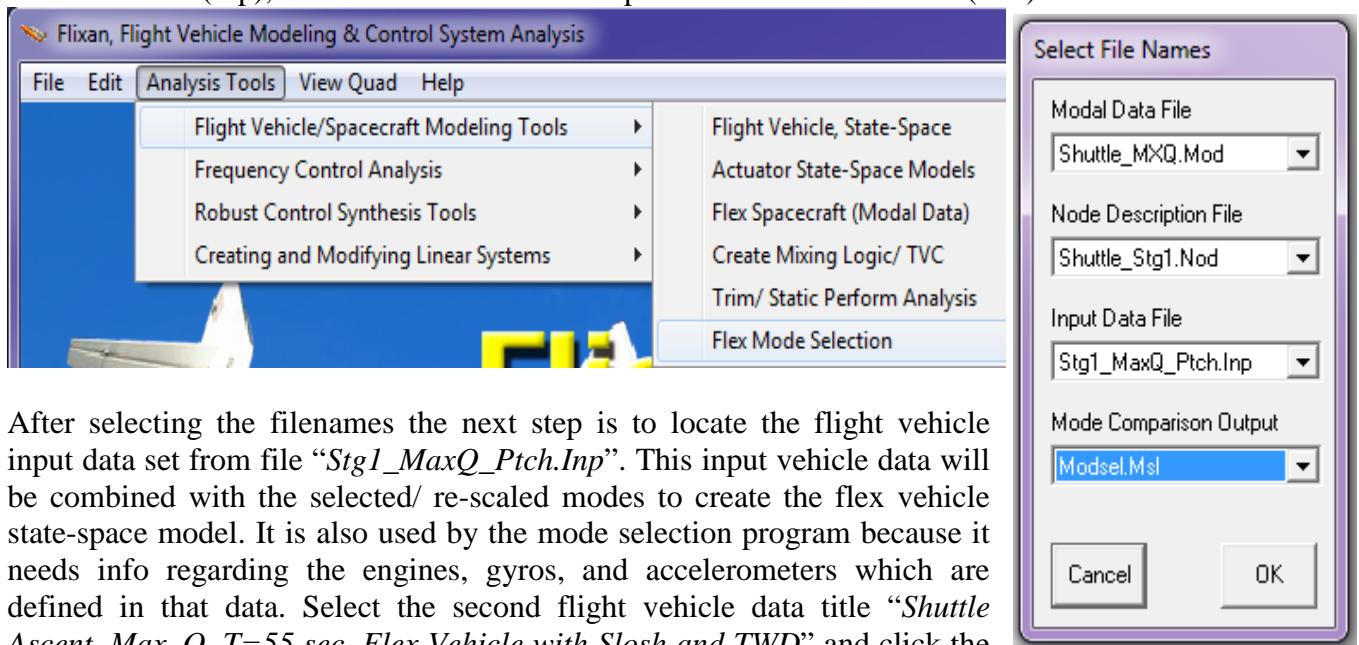
1.0 Pitch Axis Vehicle Modeling and Analysis

In the first part of the analysis we generate the pitch Shuttle model. We will use the flight vehicle modeling program to generate the vehicle state-space models using the vehicle parameters during max-Q which are already saved in the input file "*Stg1_MaxQ-Ptch.Inp*". The vehicle parameters during max-Q are obtained from six-dof simulations. Two pitch state-space systems are created for this analysis: a simple rigid-body, and a high order system that includes slosh and bending. The titles of two system generated by the modeling program are: "*Shuttle Ascent, Max_Q, T=55 sec (Rigid Body)*" and "*Shuttle Ascent, Max_Q, T=55 sec, Flex Vehicle with Slosh and TWD*". The second system contains 18 symmetric structural modes that have already been selected from the modal data file "*Shuttle_MXQ.Mod*". The set of the 18 selected symmetric modes are also included in the input data file and the title of the set is "*Shuttle Ascent, Max_Q, T=55 sec, Rigid Body with Slosh/ TWD, Pitch Modes*". The input file is processed by Flixan and the state-space systems used in pitch analysis are saved in the systems file "*Stg1_MaxQ_Ptch.Qdr*". The Shuttle state-space systems created by the vehicle modeling program include both pitch and lateral dynamics. The pitch flexible system is extracted from the coupled system using the systems extraction and modification utility. The reduced system title is "*Shuttle Ascent, Max_Q, T=55 sec, Flex Pitch Vehicle with Slosh and TWD*". But before we get to the analysis let us describe how the modes were selected from the modal data file.

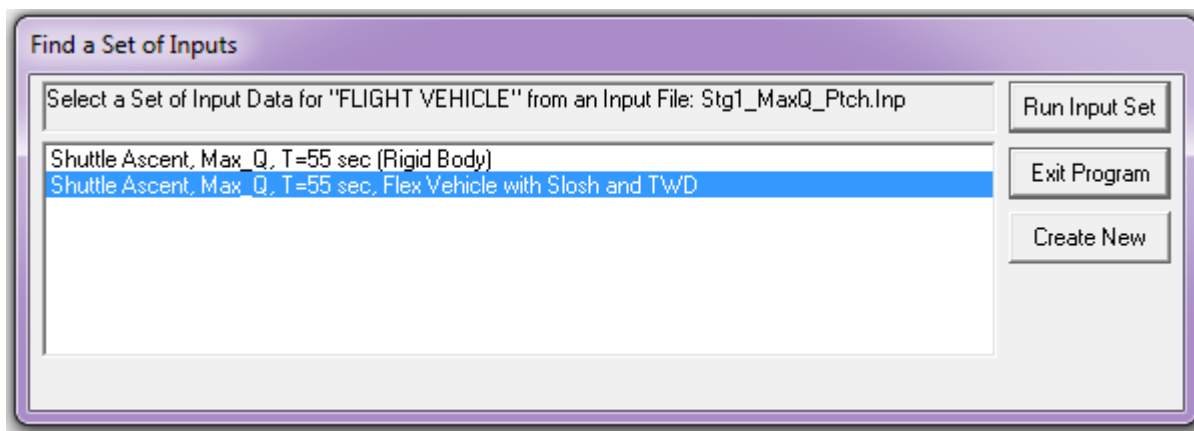
1.1 Pitch Mode Selection

The file that contains the finite element structural modes is “*Shuttle_MXQ.Mod*”. It is a Nastran output that contains the mode shapes and slopes for 95 modes, at 14 vehicle location (also known as nodes). This file is extracted from a big finite element model (FEM) file that includes several hundred modes and many vehicle locations. It is more manageable because it includes fewer modes (only the first 95 modes) and fewer locations (only 14 relevant to control analysis) and it is formatted to be recognizable and readable by the mode selection program. An intermediate program was used (not shown here) to convert the huge Nastran output to this smaller file. This modal data file contains frames of data at each mode frequency. Each frame consists of the mode frequency in (rad/sec), the modal damping coefficient (ζ) which are all set to $\zeta=0.005$, the generalized mass (all set to 10,000 in this case), followed by the mode shapes and slopes at the 14 vehicle locations (3 translations x, y, z, and 3 rotations about x, y, z). The locations which are important for flight control analysis are the engine gimbals, the sensors, and the slosh mass locations. The vehicle locations (nodes) are defined in a separate file “*Shuttle_Stg1.Nod*”, known as the map. This file contains a description for each node, the node numbers (in this case 1 to 14), a node identification number (that is the node number used in Nastran), and the node location in vehicle coordinates (which is only for reference and not used by the program).

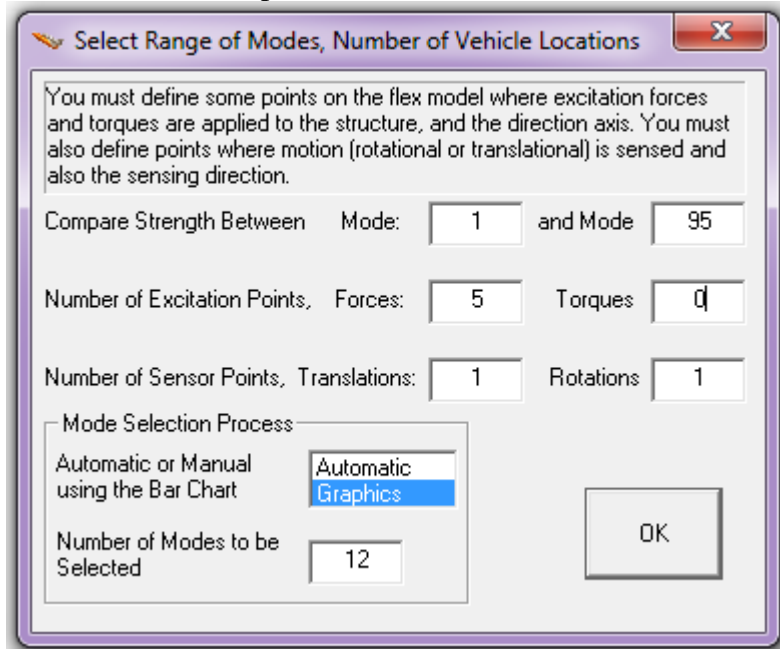
The mode selection is a Flixan process by which we select an even smaller number of modes (18 dominant modes in this case) to be combined with the rigid vehicle model. The mode shapes are also scaled during this process in order to be compatible with the rigid-body model. The flex mode selection program is under the “*Flight Vehicle/ Spacecraft Modeling*” group, as shown below. It begins with a small filenames selection menu where the user selects the modal data file, the nodes file, the flight vehicle input data file, and an output filename (Modsel.Msl by default) that shows the relative mode strength at the completion of the mode selection, see below. The modal data input filenames must have an extension (Mod). The node filenames must have an extension (Nod), the vehicle input data filenames (Inp), and the mode selection output filenames extension is (Msl).



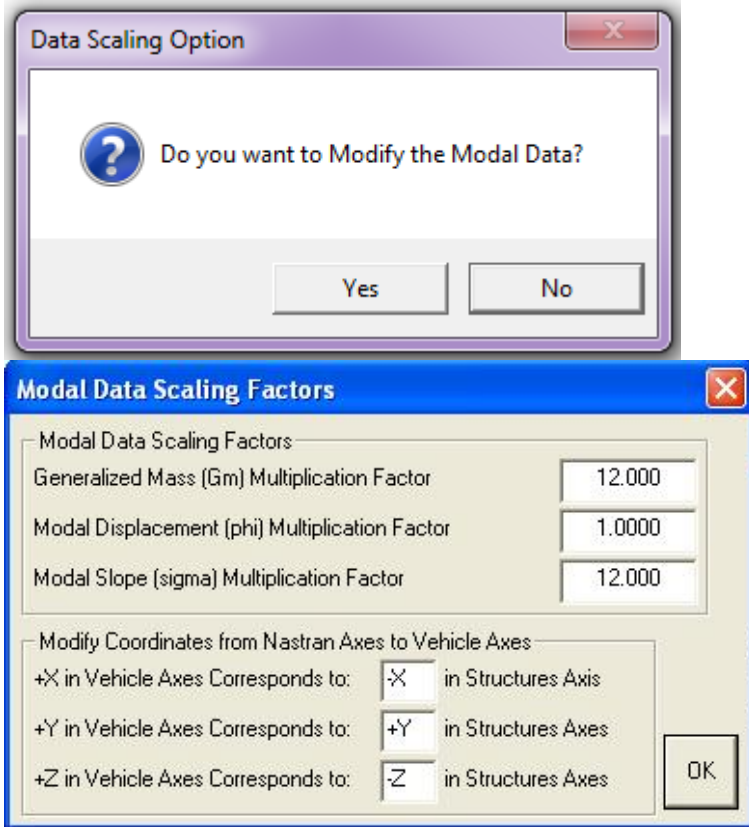
After selecting the filenames the next step is to locate the flight vehicle input data set from file “*Stg1_MaxQ_Ptch.Inp*”. This input vehicle data will be combined with the selected/ re-scaled modes to create the flex vehicle state-space model. It is also used by the mode selection program because it needs info regarding the engines, gyros, and accelerometers which are defined in that data. Select the second flight vehicle data title “*Shuttle Ascent, Max_Q, T=55 sec, Flex Vehicle with Slosh and TWD*” and click the “*Run Input Set*” button.



The mode strength comparison is performed between a selected set of excitation and sensor points. The user must select those points via menus that display the nodes map. From the following menu the user must define the number of excitation points and the number of sensors used for mode selection. These points do not have to be the same and equal to the number of vehicle effectors and sensors. They are only used for mode selection purposes. We must also define the range of mode selection in case we want to limit the range (1 to 95 modes in this case). We must remember, however, to not select the first 6 modes because they are rigid body modes and only include structural modes in the flex model. We also select the number of excitation forces (to be 5 in this case because we will use the 5 engine gimbals as excitation points). There are zero torque excitation points. We will also select one rotational sensor for the pitch gyro, and one translational sensor for the (Nz) accelerometer. We will also select the graphic mode selection option where the user selects the modes from a chart using the mouse. The number of modes to be selected does not apply in this case. The user may try different number of actuator and sensor points to see how the mode selection results may change.



The following menu is used for unit conversions and axis transformation. This is because the units and directions used in GN&C models are usually different from those used by typical FEM such as Nastran. In a typical GN&C analysis model the x-axis is forward (in the direction of the velocity vector), and the z-axis is down towards the floor. The Nastran models, almost always, they point the x axis aft toward the back of the vehicle and the z-axis up towards the ceiling of the airplane. The y-axis is the same in both models. The modal mass from Nastran needs also to be scaled up by a factor of 12 because Nastran uses (snails) while GN&C uses (slugs). The modal rotations (slopes) also need to be scaled up by a factor of 12 because in Nastran they are (rad/inch) and they need to be converted to (rad/ft). The modal displacements do not require scaling because their units change from (inches/inch) to (feet/foot). The conversion dialog below is used for scaling the modal data. It has the default conversion parameters described but the scaling values, signs, and axes can be modified as needed to make the modal data compatible with the vehicle input data.



The next step is to identify the nodes for the 5 excitation points (which are the 5 engine gimbals), the node for one gyro sensor, and the node for one accelerometer sensor. Remember, these locations are only for mode selection purposes and they do not have to be the same as the actual locations of the gimbals and the flight control sensors that will be defined later. We could have picked, for example, 2 gimbals and one sensor for mode selection. In this case, however, the mode selection is calculated between the 5 excitation points and the 2 sensor points.

The nodes map, which is in file "*Shuttle_Stg1.Nod*" is shown in a dialog/menu and it helps the user selecting the proper nodes and in identifying the excitation and sensor locations in the modal data file. The program locates the mode shapes of the engine gimbals and sensor points from the modal data file, and calculates the modal strength for each mode between the excitation and sensor points. For example, in the following case the program needs to identify a node for the force excitation point #1, and also the direction of force which is along +Z.

Table of Vehicle Structure FEM Nodes

In mode selection, in order to calculate the relative mode strength of a number of modes in a specified direction you must define some node points in the Nastran model where the excitation forces or torques will be applied and also the forcing directions.

Similarly, you must also define the sensor points (translations or rotations) and the sensing directions.

Select a Location (Node) for Force Excitation : 1

LOX SLOSH Mass	1	238	142.0	0.0
LH2 SLOSH Mass	2	239	86.0	0.0
Shuttle Main Engine # 1	3	2088	19.0	0.0
Shuttle Main Engine # 2 (left)	4	2254	17.0	-4.5
Shuttle Main Engine # 3 (right)	5	2091	17.0	4.5
Solid Rocket Booster # 4 (left)	6	1367	0.0	-21.0
Solid Rocket Booster # 5 (right)	7	367	0.0	21.0
IMU/ Accelerometer (right)	8	2322	108.3	1.0
IMU/ Accelerometer (left)	9	2323	108.3	-1.0
Aft Payload Gyro (a)	10	2179	-166.72	0.0
Aft Payload Gyro (b)	11	2183	-166.72	0.0
Booster Gyro (right)	12	372	-166.72	0.0
Booster Gyro (left)	13	1372	-166.72	0.0
Forward Payload Gyro	14	1502	0.0	0.0

Axis

Along-X
Along-Y
Along-Z

Direction

+ (positive)
- (negative)

OK
Cancel

The 5 excitation points are selected sequentially (one at a time) using the above menu with the force direction in the positive Z direction in order to excite the symmetric modes. The force excitation point #1 is the SSME Engine #1, node #3, Along Z, and in the positive direction, and click OK. The last excitation point #5 is the SRB Engine #5, node #7, Along Z, +ve, and click OK.

The single gyro sensor #1 used for flight control feedback in this example is the right booster gyro, node #12, in the positive pitch direction. Similarly, the single translation sensor #1 used for accelerometer feedback is the right IMU/ Accelerometer, node #8, in the positive Z direction, and click OK.

Table of Vehicle Structure FEM Nodes

In mode selection, in order to calculate the relative mode strength of a number of modes in a specified direction you must define some node points in the Nastran model where the excitation forces or torques will be applied and also the forcing directions.

Similarly, you must also define the sensor points (translations or rotations) and the sensing directions.

Select a Location (Node) for Translation Sensor 1

LOX SLOSH Mass	1	238	142.0	0.0
LH2 SLOSH Mass	2	239	86.0	0.0
Shuttle Main Engine # 1	3	2088	19.0	0.0
Shuttle Main Engine # 2 (left)	4	2254	17.0	-4.5
Shuttle Main Engine # 3 (right)	5	2091	17.0	4.5
Solid Rocket Booster # 4 (left)	6	1367	0.0	-21.0
Solid Rocket Booster # 5 (right)	7	367	0.0	21.0
IMU/ Accelerometer (right)	8	2322	108.3	1.0
IMU/ Accelerometer (left)	9	2323	108.3	-1.0
Aft Payload Gyro (a)	10	2179	-166.72	0.0
Aft Payload Gyro (b)	11	2183	-166.72	0.0
Booster Gyro (right)	12	372	-166.72	0.0
Booster Gyro (left)	13	1372	-166.72	0.0
Forward Payload Gyro	14	1502	0.0	0.0

Axis

Along-X
Along-Y
Along-Z

Direction

+ (positive)
- (negative)

OK
Cancel

Table of Vehicle Structure FEM Nodes

In mode selection, in order to calculate the relative mode strength of a number of modes in a specified direction you must define some node points in the Nastran model where the excitation forces or torques will be applied and also the forcing directions.

Similarly, you must also define the sensor points (translations or rotations) and the sensing directions.

Select a Location (Node) for Rotational Sensor: 1

LOX SLOSH Mass	1	238	142.0	0.0
LH2 SLOSH Mass	2	239	86.0	0.0
Shuttle Main Engine # 1	3	2088	19.0	0.0
Shuttle Main Engine # 2 (left)	4	2254	17.0	-4.5
Shuttle Main Engine # 3 (right)	5	2091	17.0	4.5
Solid Rocket Booster # 4 (left)	6	1367	0.0	-21.0
Solid Rocket Booster # 5 (right)	7	367	0.0	21.0
IMU/ Accelerometer (right)	8	2322	108.3	1.0
IMU/ Accelerometer (left)	9	2323	108.3	-1.0
Aft Payload Gyro (a)	10	2179	-166.72	0.0
Aft Payload Gyro (b)	11	2183	-166.72	0.0
Booster Gyro (right)	12	372	-166.72	0.0
Booster Gyro (left)	13	1372	-166.72	0.0
Forward Payload Gyro	14	1502	0.0	0.0

OK

Cancel

Axis

Roll

Pitch

Yaw

Direction

+ (positive)

- (negative)

At this point we have identified all the excitation and sensor points and directions for the mode comparison and mode selection process which is mainly in the pitch direction. The modal strength for each mode is determined by the values of the mode shapes at the nodes where the forces are being applied in the force direction, and also by the values of the mode shapes at the sensors in the directions measured. High mode shape values at the excitation and sensor points imply strong contribution from that mode. The mode selection program calculates the mode strength for each mode and saves it in file "Modsel.Msl", from where the user can select the dominant modes graphically.

The selection process, however, is not finished yet because the program needs additional information before allowing the user to select which modes to retain from the modal data file. The mode selection program will create a much smaller subset of the original modal data set and it will save it in the input data file "Stg1-MaxQ-Ptch.Inp" under a separate title. The selected modal data set will contain only the selected few dominant modes and modal shapes at only a few locations that play an important role in the flight vehicle model such as the engine gimbals, the sensors, a disturbance point, and the slosh mass locations. The important vehicle locations (gimbals, sensors, etc) are identified automatically by the mode selection program from the vehicle input data. These locations are matched with the corresponding nodes in the nodes map. The mapping between structural nodes and the vehicle locations in the input data is performed by the user using menus similar to the previous location selection menus but this time it is for a different purpose. The program expects the user to identify nodes for the 5 engines, the 3 gyros (roll, pitch, and yaw), the 2 accelerometers (Ny and Nz), the 2 slosh masses (LOX and LH2), and one disturbance point (not used).

Table of Vehicle Structure FEM Nodes

You must now identify some points on the finite element model that correspond 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 Thruster Engine : 2 OK

LOX Slosh Mass	1	238	142.0	0.0	-0
LH2 Slosh Mass	2	239	86.0	0.0	-0
Shuttle Main Engine # 1	3	2088	19.0	0.0	-3
Shuttle Main Engine # 2 (left)	4	2254	17.0	-4.5	-2
Shuttle Main Engine # 3 (right)	5	2091	17.0	4.5	-2
Solid Rocket Booster # 4 (left)	6	1367	0.0	-21.0	0
Solid Rocket Booster # 5 (right)	7	367	0.0	21.0	0
IMU/ Accelerometer (right)	8	2322	108.3	1.0	-2
IMU/ Accelerometer (left)	9	2323	108.3	-1.0	-2
Aft Payload Gyro (a)	10	2179	-166.72	0.0	-0
Aft Payload Gyro (b)	11	2183	-166.72	0.0	-0
Booster Gyro (right)	12	372	-166.72	0.0	-0
Booster Gyro (left)	13	1372	-166.72	0.0	-0
Forward Payload Gyro	14	1502	0.0	0.0	0

Table of Vehicle Structure FEM Nodes

You must now identify some points on the finite element model that correspond 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 Thruster Engine : 5 OK

LOX Slosh Mass	1	238	142.0	0.0	-0
LH2 Slosh Mass	2	239	86.0	0.0	-0
Shuttle Main Engine # 1	3	2088	19.0	0.0	-3
Shuttle Main Engine # 2 (left)	4	2254	17.0	-4.5	-2
Shuttle Main Engine # 3 (right)	5	2091	17.0	4.5	-2
Solid Rocket Booster # 4 (left)	6	1367	0.0	-21.0	0
Solid Rocket Booster # 5 (right)	7	367	0.0	21.0	0
IMU/ Accelerometer (right)	8	2322	108.3	1.0	-2
IMU/ Accelerometer (left)	9	2323	108.3	-1.0	-2
Aft Payload Gyro (a)	10	2179	-166.72	0.0	-0
Aft Payload Gyro (b)	11	2183	-166.72	0.0	-0
Booster Gyro (right)	12	372	-166.72	0.0	-0
Booster Gyro (left)	13	1372	-166.72	0.0	-0
Forward Payload Gyro	14	1502	0.0	0.0	0

Notice, that each sensor in the flight vehicle input data measures only one direction. If you want a measurement in 3 axes you must define 3 separate sensors. For the three (roll, pitch, yaw) gyros we must select node #12 three times, and for the two (Ny and Nz) accelerometers we select node #8 twice. We also choose nodes #1 and #2 for the LOX and the LH2 slosh masses respectively, and one disturbance point that we are not using in this example.

Table of Vehicle Structure FEM Nodes

You must now identify some points on the finite element model that correspond 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 Gyro/Rate Sensor : 1

OK

LOX SLOSH Mass	1	238	142.0	0.0	-0
LH2 SLOSH Mass	2	239	86.0	0.0	-0
Shuttle Main Engine # 1	3	2088	19.0	0.0	-3
Shuttle Main Engine # 2 (left)	4	2254	17.0	-4.5	-2
Shuttle Main Engine # 3 (right)	5	2091	17.0	4.5	-2
Solid Rocket Booster # 4 (left)	6	1367	0.0	-21.0	0
Solid Rocket Booster # 5 (right)	7	367	0.0	21.0	0
IMU/ Accelerometer (right)	8	2322	108.3	1.0	-2
IMU/ Accelerometer (left)	9	2323	108.3	-1.0	-2
Aft Payload Gyro (a)	10	2179	-166.72	0.0	-0
Aft Payload Gyro (b)	11	2183	-166.72	0.0	-0
Booster Gyro (right)	12	372	-166.72	0.0	-0
Booster Gyro (left)	13	1372	-166.72	0.0	-0
Forward Payload Gyro	14	1502	0.0	0.0	0

Table of Vehicle Structure FEM Nodes

You must now identify some points on the finite element model that correspond 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 Accelerometer : 1

OK

LOX SLOSH Mass	1	238	142.0	0.0	-0
LH2 SLOSH Mass	2	239	86.0	0.0	-0
Shuttle Main Engine # 1	3	2088	19.0	0.0	-3
Shuttle Main Engine # 2 (left)	4	2254	17.0	-4.5	-2
Shuttle Main Engine # 3 (right)	5	2091	17.0	4.5	-2
Solid Rocket Booster # 4 (left)	6	1367	0.0	-21.0	0
Solid Rocket Booster # 5 (right)	7	367	0.0	21.0	0
IMU/ Accelerometer (right)	8	2322	108.3	1.0	-2
IMU/ Accelerometer (left)	9	2323	108.3	-1.0	-2
Aft Payload Gyro (a)	10	2179	-166.72	0.0	-0
Aft Payload Gyro (b)	11	2183	-166.72	0.0	-0
Booster Gyro (right)	12	372	-166.72	0.0	-0
Booster Gyro (left)	13	1372	-166.72	0.0	-0
Forward Payload Gyro	14	1502	0.0	0.0	0

Table of Vehicle Structure FEM Nodes

You must now identify some points on the finite element model that correspond 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 SLOSH Mass Locat.: 1

OK

LOX SLOSH Mass	1	238	142.0	0.0	-0
LH2 SLOSH Mass	2	239	86.0	0.0	-0
Shuttle Main Engine # 1	3	2088	19.0	0.0	-3
Shuttle Main Engine # 2 (left)	4	2254	17.0	-4.5	-2
Shuttle Main Engine # 3 (right)	5	2091	17.0	4.5	-2
Solid Rocket Booster # 4 (left)	6	1367	0.0	-21.0	0
Solid Rocket Booster # 5 (right)	7	367	0.0	21.0	0
IMU/ Accelerometer (right)	8	2322	108.3	1.0	-2
IMU/ Accelerometer (left)	9	2323	108.3	-1.0	-2
Aft Payload Gyro (a)	10	2179	-166.72	0.0	-0
Aft Payload Gyro (b)	11	2183	-166.72	0.0	-0
Booster Gyro (right)	12	372	-166.72	0.0	-0
Booster Gyro (left)	13	1372	-166.72	0.0	-0
Forward Payload Gyro	14	1502	0.0	0.0	0

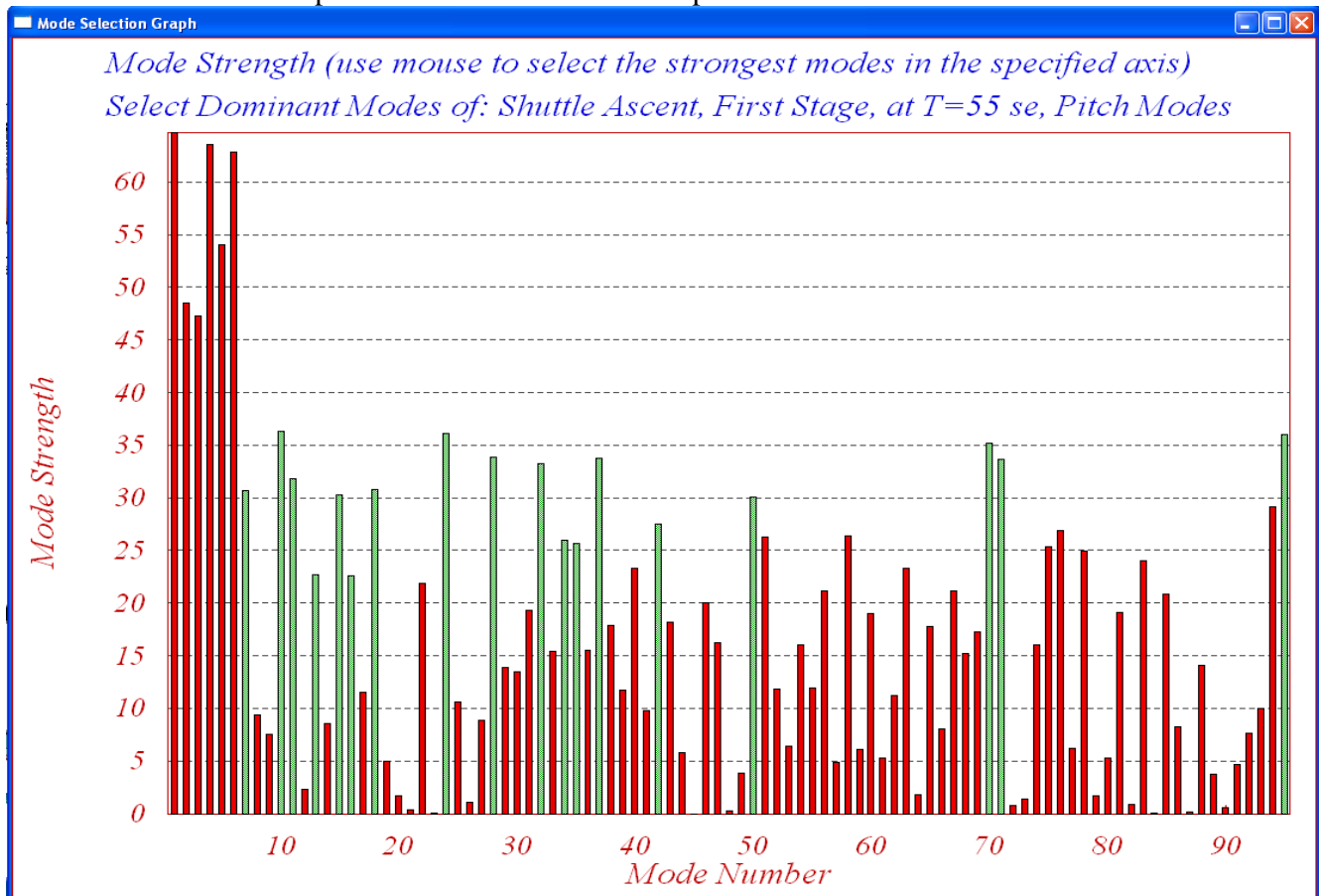
The user must also enter a short label to be included in the title of the selected modes set. For example, to identify the type of modes.

Insert a Short Description to the Title (10 char)

OK

Pitch Modes

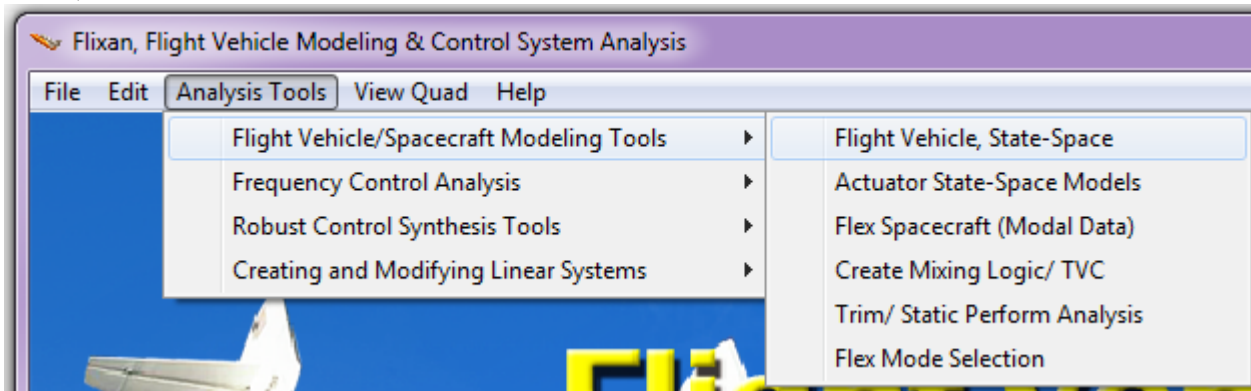
At this point a bar chart comes up used for selecting the dominant modes. It is showing the modal strengths by means of vertical red bars. The height of each bar is logarithmically proportional to the relative mode strength. The strong modes are tall and the weak modes are short. The modal strength is not a physical number but it is measured relative to the weakest mode. The user manually selects some of the strongest modes by pointing the mouse cursor at the bar and clicking the mouse. The modes change color from red to green when they are selected. Notice, that the first six modes, although strong, they were not selected because they are rigid-body modes. The rigid-body dynamics are already included in the vehicle model. We select 18 flex modes and press the "enter" button to complete the mode selection.



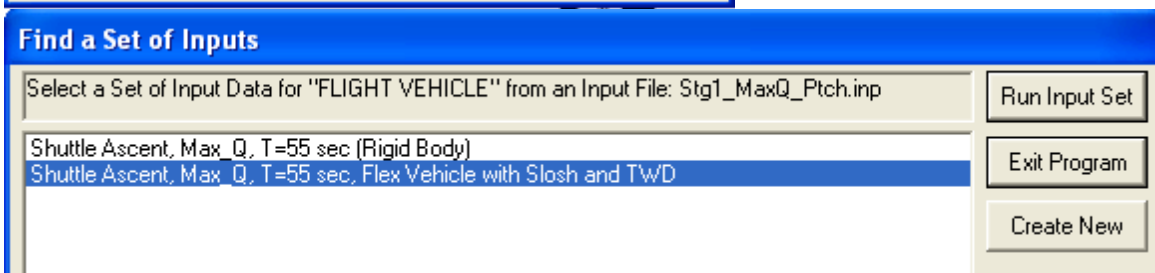
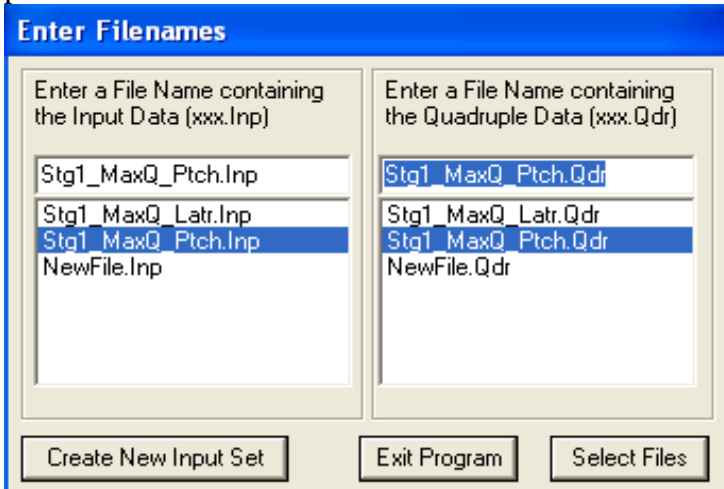
The final step before exiting the mode selection is to type-in some additional reference notes regarding the mode selection process by using a dialog. The notes describe, for example, information regarding what kind of modes were selected and the conditions of mode selection, the excitation and measurement points, directions, etc. This information will be included as comments below the title in the selected modes set, which is saved in the input data file "Stg1_MaxQ_Ptch.Inp". The title of the selected modes set is "Shuttle Ascent, Max_Q, T=55 sec, Rigid Body with Slosh/TWD, Pitch Modes". It contains the frequencies and mode shapes of the selected pitch modes at vehicle locations that correspond to the locations defined in the vehicle data. The title of the selected modes set must also be included at the bottom of the flexible vehicle input data set (below the number of flex modes). This is how the flight vehicle modeling program will associate the flex modes with the vehicle input data.

1.2 Creating the Pitch Vehicle Model

The Shuttle vehicle input data are already saved in the input data file “*Stg1_MaxQ_Ptch.Inp*”, so we don’t have to type-in the data in Flixan from scratch using the utility dialogs. If you look inside this file, there are two sets of flight vehicle data. The first set is for building a simple rigid-body model using the title: “*Shuttle Ascent, Max_Q, T=55 sec (Rigid Body)*”, and a second set is for a high order vehicle model that includes slosh and structural bending using the title: “*Shuttle Ascent, Max_Q, T=55 sec, Flex Vehicle with Slosh and TWD*”. The Shuttle state-space systems are generated from the vehicle input data by running the flight vehicle state-space modeling program from the Flixan main menu, as shown below.



From the filenames selection menu you must select the input data file “*Stg1_MaxQ_Ptch.Inp*”, and the systems filename “*Stg1_MaxQ_Ptch.Qdr*” where the state-space systems will be saved by the program. The program will scan the input data file and locate the two data sets containing flight vehicle data. It will then open another menu, shown below, where the user selects one of the flight vehicle titles. In this case we select the second title which includes flexibility and slosh, and click on “*Run Input Set*” to process the data.



Flight Vehicle Parameters

Vehicle System Title
Shuttle Ascent, Max_Q, T=55 sec, Flex Vehicle with Slosh and TWD

Number of Vehicle Effectors
 Gimbal Engines or Jets: 5 **WITH TWD**
 Include Tail-Wags-Dog? **WITHOUT TWD**
 Rotating Control Surfaces: 0 **WITH TWD**
 Include Tail-Wags-Dog? **WITHOUT TWD**
 Reaction Wheels? 0 **Momentum Control Devices**
 Single Gimbal CMGs? 0 Include a 3-axes Stabilized Double Gimbal CMG System? Yes No

Number of Sensors
 Gyros: 3
 Acceleromet: 2
 Aero Vanes: 0
 External Torques: 0

Modeling Options (Flags)
 Output Rates in: **Body Axes**
 Stability Axes
 Turn Coordination?: **Include Turn Coordination**
 Without Turn Coordination
 Aero-Elasticity Options: **Include GAFD, H-param**
 Flex Coupl. data only
 Neither Gafid nor Hpar
 Attitude Angles: **Euler Angles**
 Integrals of Rates
 LVLH Attitude

Number of Modes
 Structure Bending: 18
 Fuel Sloshing: 2

Reaction/Wheels | Single Gimbal CMGs | Double Gimbal CMG 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 | Control Surfaces | Gimbal Engines/ RCS | External Torques

This Vehicle has 5 Thruster Engines **Engine No: 2** **Left SSME** Engine/ Thruster Jet Definition

Thrust in (lb)
 Nominal Thrust: 275000.0
 Maximum Thrust: 275000.0

Maximum Deflections (deg)
 Pitch, Delta_Y max: 10.00000
 Yaw, Delta_Z max: 10.00000

Nominal Position Angles (deg)
 Azimuth, Delta_Zo: 0.000000
 Elevation, Delta_Yo: -10.000000
 Engine Orientation Angles with respect to the vehicle X axis

Engine Mass Properties
 Engine Mass in (Slugs): 210.0000
 Moment of Inertia about the Gimbal (slug-ft²): 4032.000
 Moment Arm (ft), Engine CG to Gimbal: 3.000000

Location of Engine Gimbal (feet)
 X_gimbal: 17.00000
 Y_gimbal: -4.500000
 Z_gimbal: -23.000000

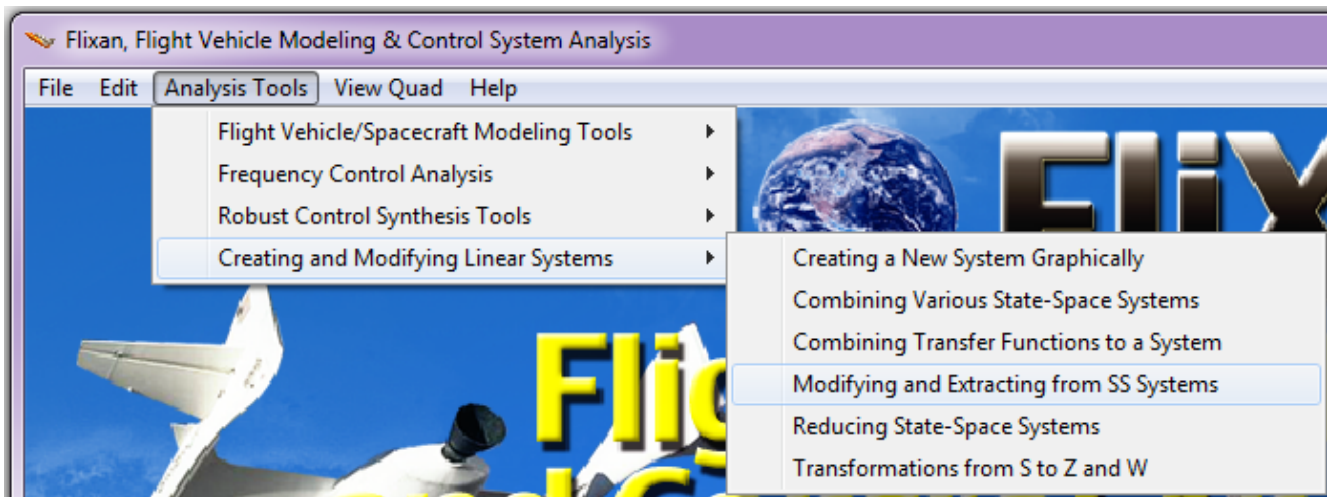
Gimbaling or Throttling?
 Is the Engine Gimbaling? Yes No
 Can it Vary its Thrust like a Jet? Yes No

Next Engine

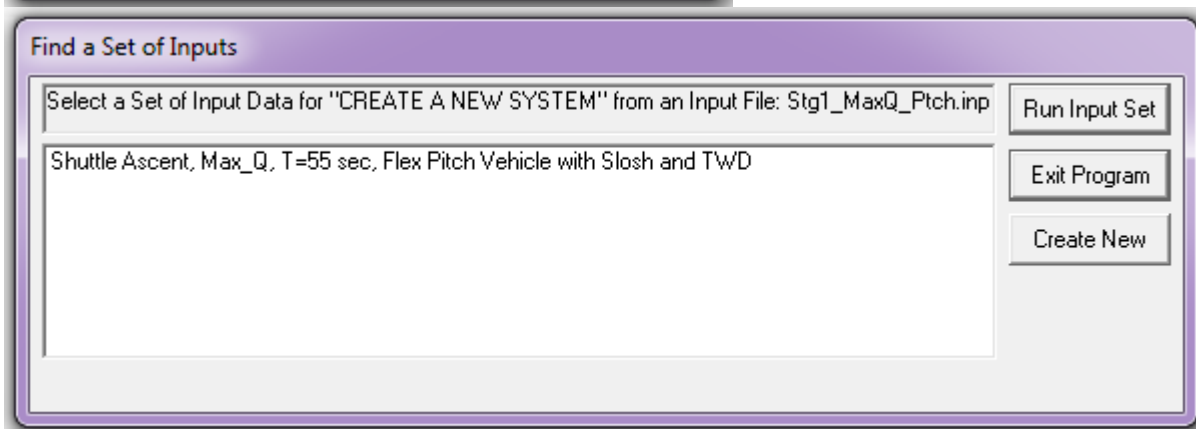
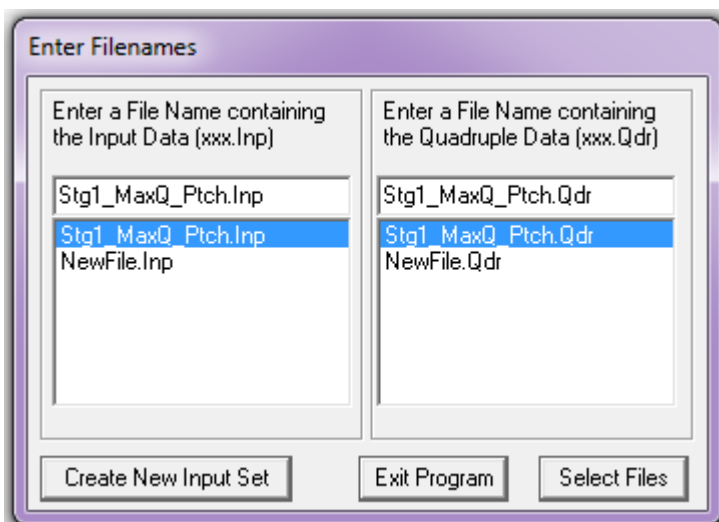
The program continues by opening the above dialog from where the user is able to view the vehicle input parameters, modify the data if necessary, and process the data. In this case we will not modify the data. Press the “Run” button to process it. The Shuttle vehicle state-space system will be saved in file “*Stg1_MaxQ_Pitch.Qdr*” under the same title as the input data. A similar model generation process can be applied also for the rigid-body system. These systems, however, contain both, pitch and lateral dynamics. The high order system also contains pitch and yaw sloshing in addition to pitch flexibility, since only pitch modes were included. It is a good practice to truncate the extraneous lateral system state-space variables since they are not needed for longitudinal analysis.

1.3 Extracting the Pitch State-Space Model from the Coupled System

Since in this case we are only analyzing the pitch axis we will, therefore, truncate the lateral state-space model variables and extract only the pitch axis system. We would like to eliminate variables such as yaw and roll attitude and rates, sloshing in the y direction, gimbaling in the yaw direction, lateral acceleration, sideslip angle, etc, and retain only variables that relate in the longitudinal directions. Flixan has a utility program created for this purpose and it is located in the “*Creating and Modifying Linear Systems*” group. It will process a set of data that defines which state-variables will be retained in the new pitch model. The remaining variables will be truncated. In order to run this system modification utility from the Flixan main menu click on “*Modifying and Extracting from a State-Space System*”, as shown below.



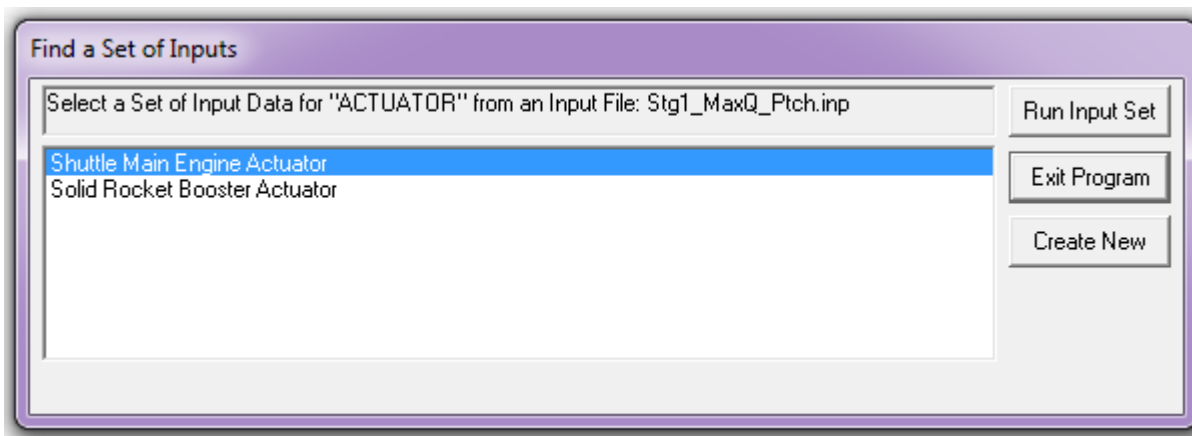
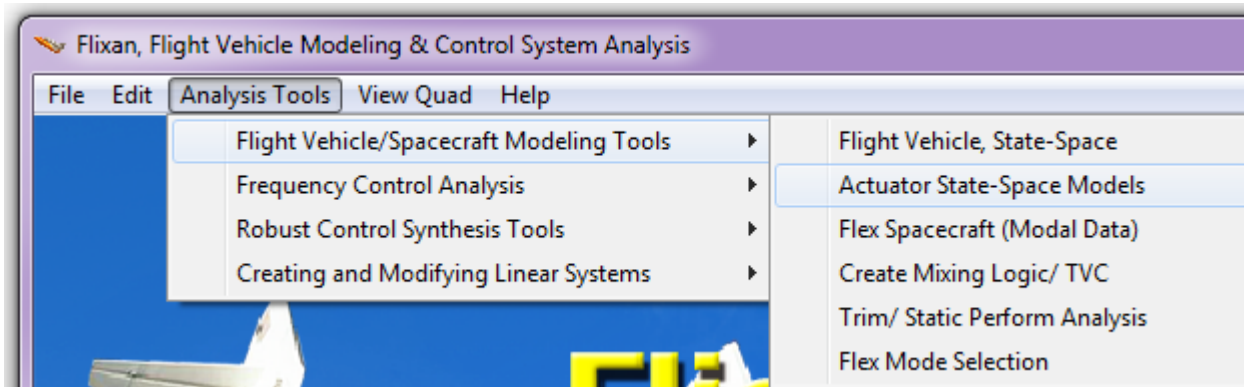
The first step is to select the two filenames, the input data and system files: “*Stg1-MaxQ-Ptch.Inp*” and “*Stg1-MaxQ-Ptch.Qdr*” from the filename selection menu. An input data set for extracting the pitch variables from the coupled system has already been created and saved in the input data file so we won't have to enter the model extraction from scratch. The program locates the one and only system modification data-set in file “*Stg1-MaxQ-Ptch.Inp*”, the user selects it and clicks on “*Run Input Set*” to process it.



The system modification utility retains the pitch gimbal deflection inputs, the pitch attitude and rate, and angle of attack states, the slosh states in the z direction, and all the flex modes because they are all symmetric and dominant in pitch. The same logic is used for the system outputs by selecting the pitch rate gyro and normal (Nz) accelerometer. The extracted state-space system is: “*Shuttle Ascent, Max_Q, T=55 sec, Flex Pitch Vehicle with Slosh and TWD*” and it is saved in the systems file “*Stg1-MaxQ-Ptch.Qdr*”. This system must be combined with the actuators and the flight control system to perform the pitch analysis.

1.4 Modeling the Actuators and Flight Control System

The input data file contains also two actuator data-sets which are processed by Flixan to generate actuator models and they are saved in the state-space systems file “*Stg1_MaxQ_Ptch.Qdr*”. The two actuator state-space subsystems correspond to the Shuttle main engine (SSME) and the solid rocket booster (SRB) actuators. They are both hydraulic types and their models are documented in the actuator modeling section of the Flixan program. They are processed by the Flixan actuator state-space modeling program as shown below. The user selects the title of the actuator data-set and the actuator program generates the actuator dynamic model.



1.5 Combining the Vehicle with the Actuators

The next step is to combine the vehicle model with the actuators and the flight control system. There are many ways to combine the subsystems together and we will consider two options: (a) combining all the individual subsystems together using Simulink, and (b) use the Flixan systems interconnection utility to combine all the continuous (s-plane) subsystems together in order to create a continuous state-space plant model and then complete the system combination using Simulink by connecting the continuous plant model with the discrete flight control system and to create simulation models in Simulink. We did it both ways, but in this section we shall describe how to combine the pitch vehicle with the two actuators together using Flixan.

The interconnection of the vehicle with the actuator models is not as simple as connecting the actuator output to the deflection input of the vehicle model. There is additional dynamics involved that makes the actuator/ vehicle interconnection a little more complex. There is the tail-wag-dog dynamics, which is a reaction torque on the vehicle caused by the slewing acceleration of the nozzle. The vehicle model in addition to nozzle deflection inputs it also has gimbal acceleration inputs for modeling the tail-wag-dog (TWD) dynamics. There is also the load-torque feedback which is a disturbance torque applied on the actuator gimbal and is attempting to rotate the nozzle against the actuator control torque. It is caused by the vehicle acceleration, both rotational and translational. On the Shuttle and most launch vehicles the load-torque effects are not as significant than the TWD, that usually creates a complex pair of zeros in the transfer function near the $j\omega$ axis. This causes a sharp notch in the open-loop frequency response amplitude of $\{q(\omega)/\delta(\omega)\}$ and a 180° phase reversal at the tail-wags-dog frequency. This happens only if the engine cg is below the gimbal, otherwise, the TWD zeros are on the real axis of the complex plane. In order to model the TWD dynamics two things are needed, an actuator that provides a gimbal acceleration output, that is, in addition to the gimbal output angle, and a flight vehicle state-space model that includes gimbal acceleration inputs. In the vehicle/ actuator interconnection, the gimbal angle outputs from the actuator connect to the gimbal angle inputs of the vehicle model, and the gimbal acceleration outputs from the actuator go to the gimbal acceleration inputs of the vehicle model. This takes care of the tail-wags-dog modeling.

For the load-torque feedback modeling, the actuator in addition to the (δ -com) it must also have a load-torque input, which is a mechanical reaction torque in (ft-lb) on the nozzle gimbal caused by the vehicle motion. The load-torque attempts to rotate the nozzle in a direction that may be against the actuator control torque. In order to model the TVC load-torques correctly a separate actuator model must be included for each engine gimbaling direction. In this case, however the model can be simplified and instead of using 5 separate actuators directly connecting to the 5 vehicle pitch gimbal deflection and acceleration inputs, we lump the 3 SSME actuators in a single SSME model and the two SRB actuators in a single SRB actuator. A single SSME actuator deflection output drives all 3 SSME deflection inputs in the vehicle model via the TVC gains, and the actuator acceleration output drives all 3 SSME acceleration inputs via the same TVC gains. The same applies for the single SRB actuator output deflection driving the two SRB deflection inputs in the vehicle model, and the acceleration output driving the two acceleration inputs. It is mathematically equivalent to the actual physical system and it uses fewer states. The load-torque feedback outputs from the vehicle system are also connected to actuator load-torque inputs. The 3 load-torque outputs from the SSME are averaged to a single signal (Tly_ssme) that goes to the SSME actuator, and also the 2 SRB load-torque outputs are averaged to a single signal (Tly-srb) that goes into the SRB actuator load-torque input. The flight vehicle modeling program creates the additional inputs and outputs required to implement the TWD and the load-torque feedback dynamics when the TWD flag is turned-on in the TVC engines “With TWD”, in the vehicle input data.

Shuttle Stage-1 at Max-Q, Closed-Loop Simulation

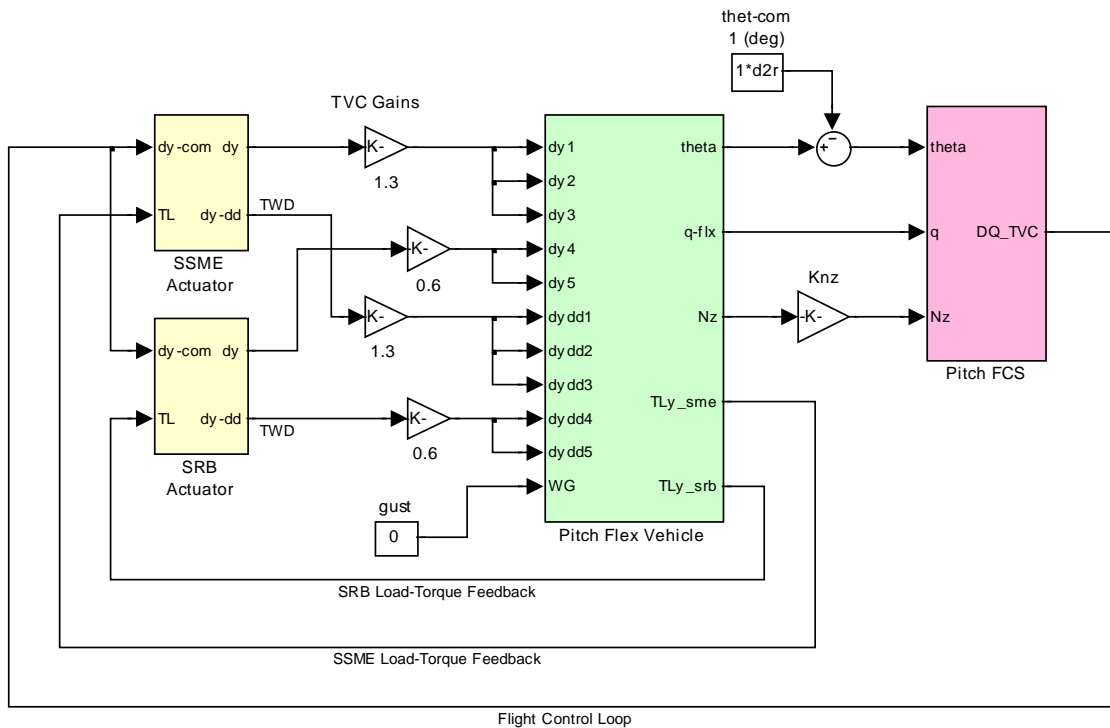
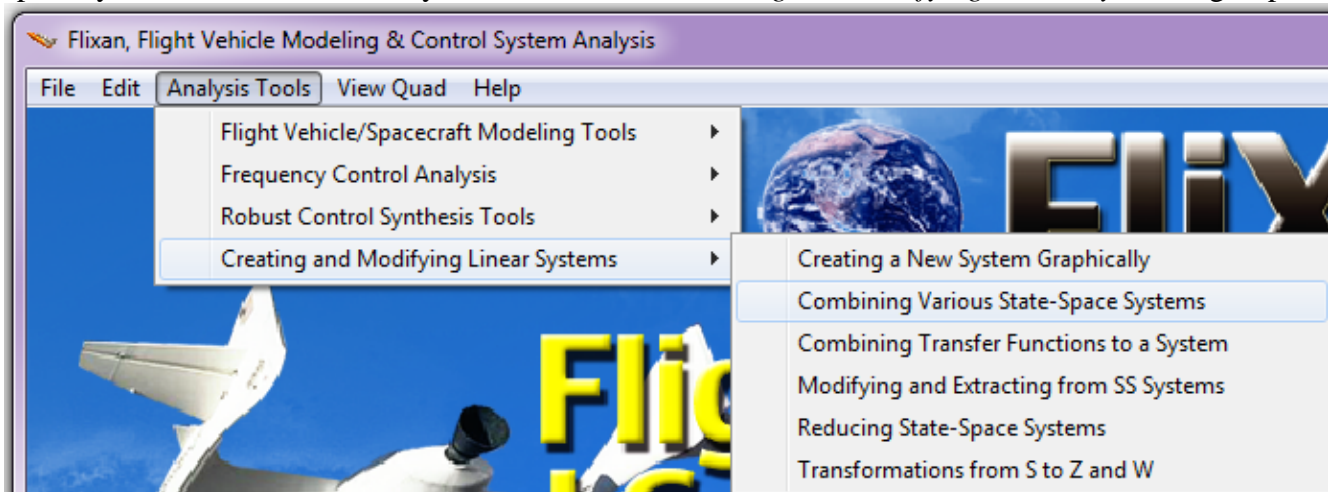
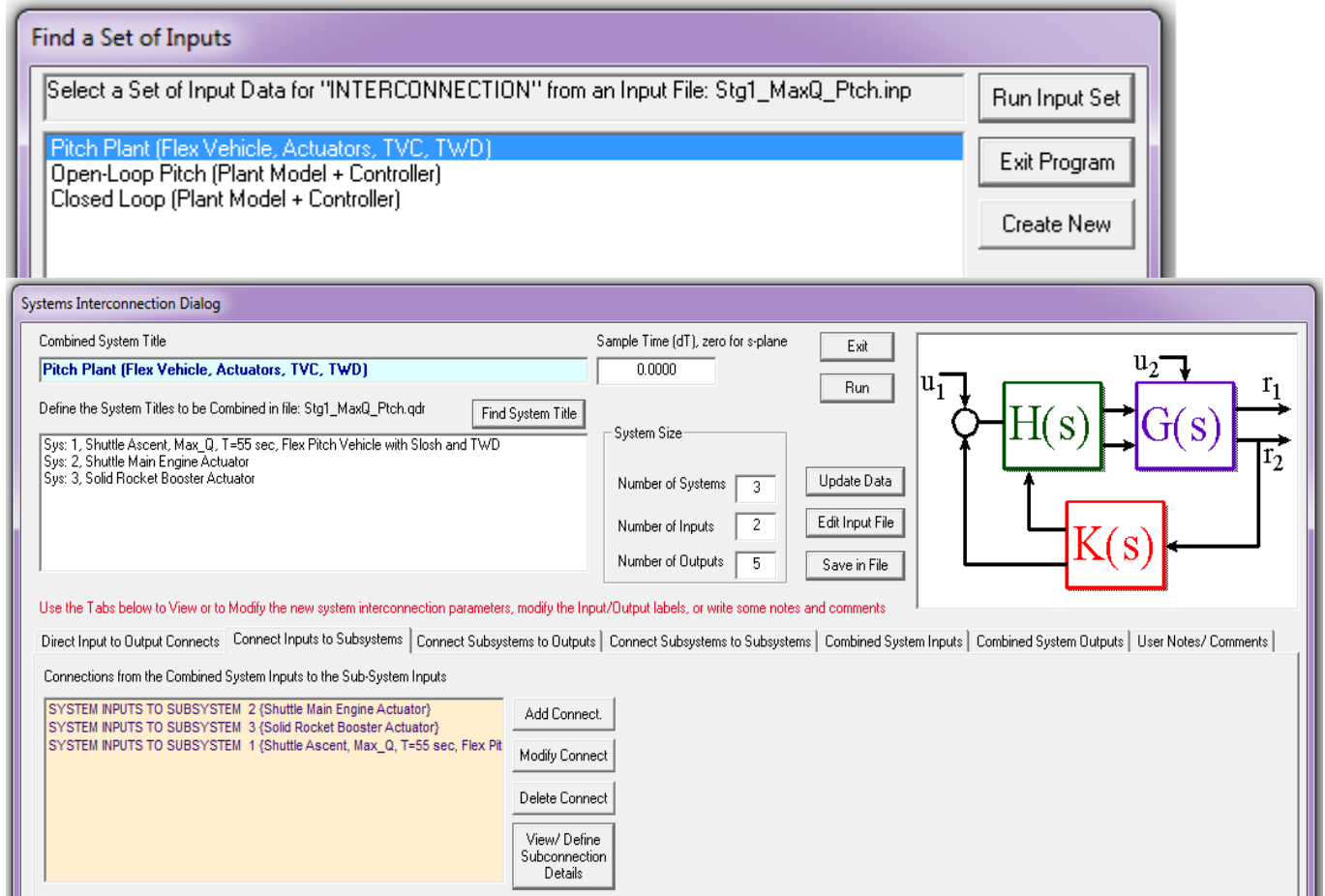


Figure (1.5.1) Pitch Vehicle and Actuators Interconnection

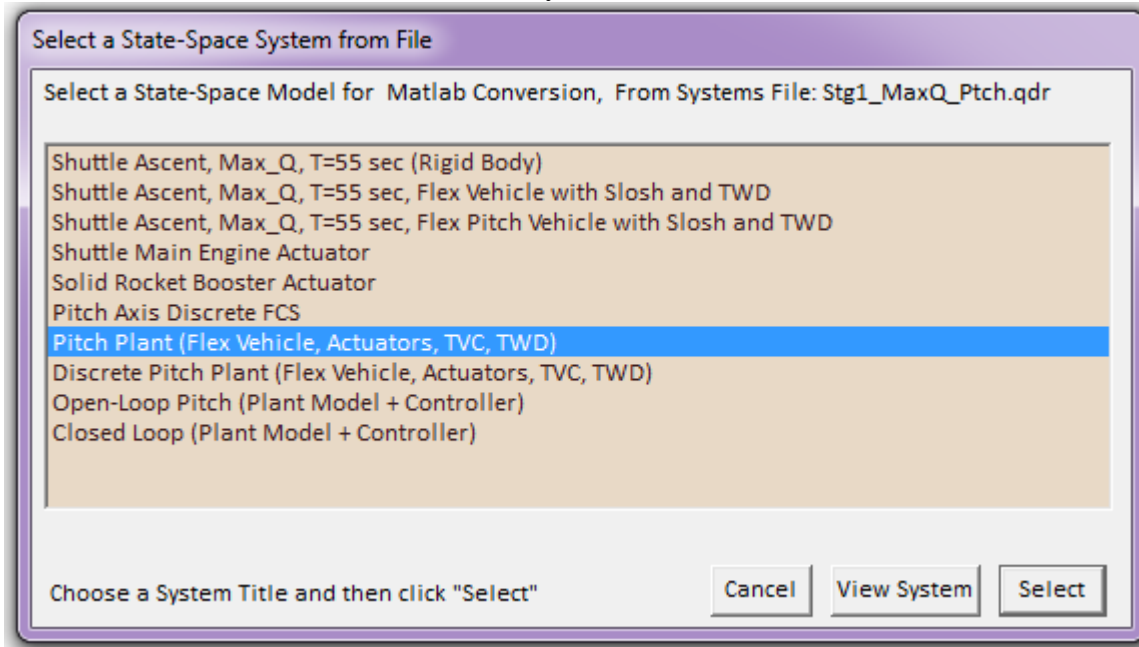
The pitch vehicle and the actuators interconnection is shown in Figure (1.5.1). We use the systems interconnection utility to combine them as shown. The systems interconnection data is in file “*Stg1_MaxQ_Ptch.Inp*”. Its title is “*Pitch Plant (Flex Vehicle, Actuators, TVC, TWD)*”. The state-space systems combination utility is also under the “*Creating and Modifying Linear Systems*” group.



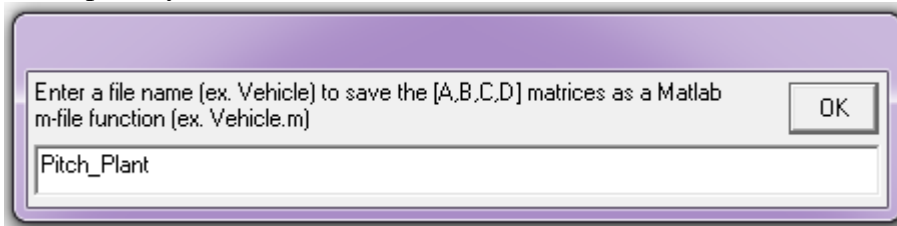
From the filename selection menu select the same input data and system filenames “*Stg1_MaxQ_Ptch.Inp*” and “*Stg1_MaxQ_Ptch.Qdr*”. From the systems interconnection menu select the title: “*Pitch Plant (Flex Vehicle, Actuators, TVC, TWD)*”. The systems combination dialog appears showing the system inter-connections, as in Figure (1.5.1). Press the “Run” button to execute the systems inter-connection. The new combination system will be saved in the systems file using the same title as the interconnection instructions: “*Pitch Plant (Flex Vehicle, Actuators, TVC, TWD)*”.



The pitch plant system is also needed in Matlab to perform analysis and simulations. It should, therefore, be converted to Matlab format. The Matlab conversion data-sets are already created and included in file “*Stg1_MaxQ_Ptch.Inp*”. From the Flixan main menu, go to “*Matlab Conversions*” and then go to “*Export to Matlab*”. Select the systems file “*Stg1-MaxQ-Ptch.Qdr*”. Select a directory where the converted system will be saved. The Matlab analysis will be performed in “... \ *Examples\ Shuttle Ascent\ Pitch Analysis*”. Choose the output to be a system, and an m-file. From the systems selection menu (shown below) select the system title to be converted.



Enter also the name of the Matlab file “*Pitch_Plant_s*” (without the .m) which will contain the plant state-space system.



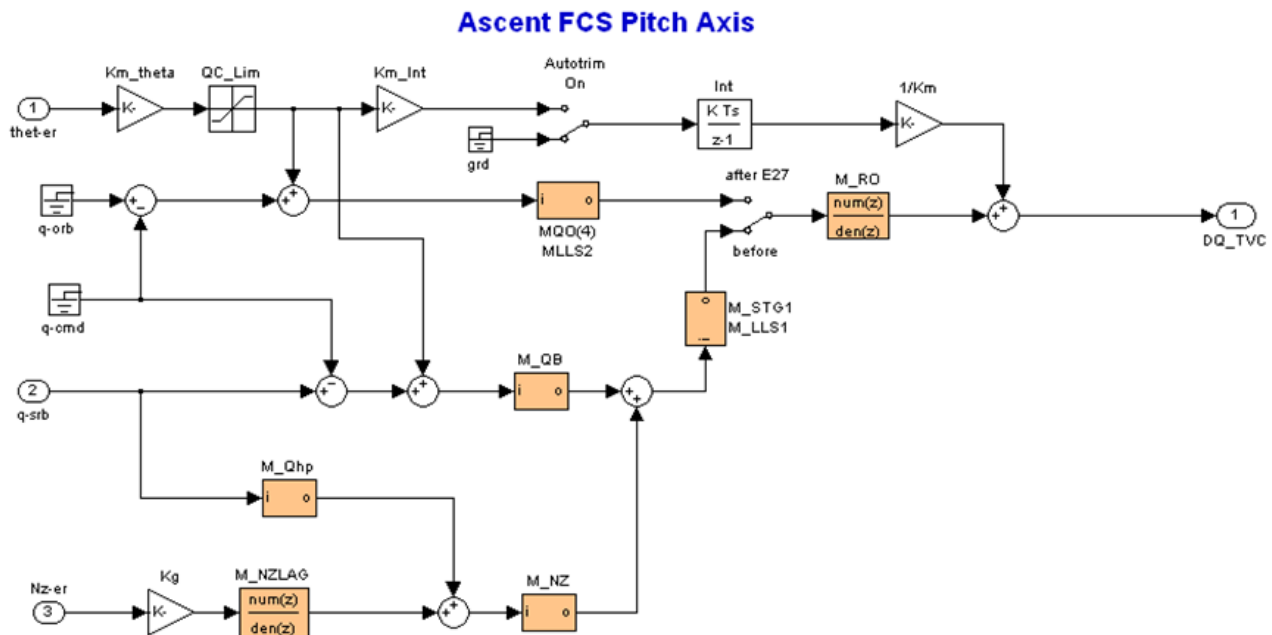
This will create the state-space function file “*Pitch_Plant_s.m*” containing the plant state-space system as an m-file function. It will be located in the “\Examples\ Shuttle Ascent\ Pitch Analysis” directory. To load it into Matlab workspace you must type:

```
[Ap1, Bp1, Cp1, Dp1]= pitch_plant_s;
```

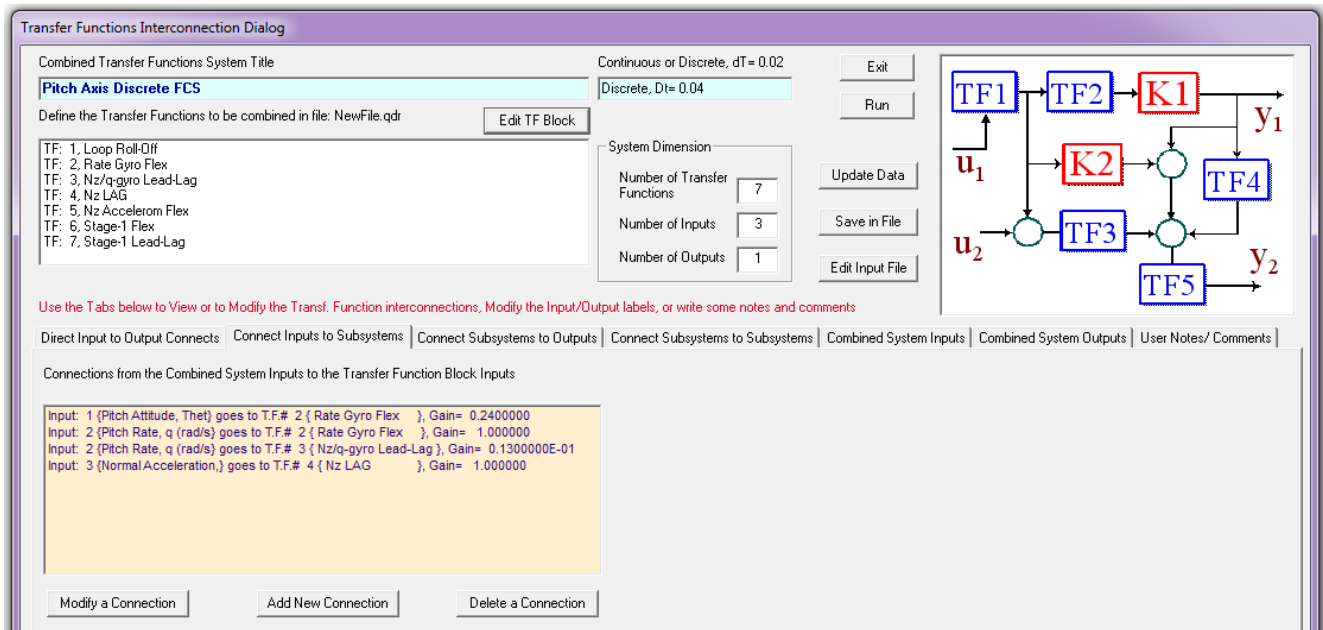
1.6 Pitch Axis Discrete Flight Control System

The pitch flight control system of the Space Shuttle during ascent is defined by a combination of discrete transfer functions in the z-domain. The inputs are: vehicle pitch attitude error (Θ) in (radians), pitch rate (q) in (rad/sec), and normal acceleration (N_z) in (ft/sec²). The output DQ_TVC is the command that drives the pitch actuators via the TVC. The gains and filters are designed strictly for the Max-Q flight condition. In this example we are not emphasizing in the flight control system description and design, but only in the overall vehicle modeling and performance analysis. The pitch flight control system is also included in the input data file “*Stg1_MaxQ_Ptch.Inp*” together with the other data related with this analysis. It is defined in transfer functions form. The transfer functions interconnection title is: “*Pitch Axis Discrete FCS*”, and its sampling rate is 40 (msec). In order to be able to combine this transfer-function defined FCS with the other vehicle subsystems we must convert it to a discrete state-space system. The Flixan transfer functions interconnection utility will be used to create the discrete state-space FCS and will save it in the systems file together with the other systems.

Pitch Flight Control System



The transfer-function data processing utility in Flixan is selected from “*Combining Transfer-Functions to System*” option which is under the “*Creating and Modifying Linear Systems*” group and it is similar to the systems interconnection option. In the filename selection menu you must select the same input data and systems filenames already used in this project. In the transfer functions interconnection selection menu select “*Pitch Axis Discrete FCS*”. Run the selected set and the transfer function interconnections dialog appears showing the interconnection info.



Click on “Run” to execute the set. The program transforms the pitch FCS transfer function interconnection data to a state-space system and saves it in file “*Stg1_MaxQ_Ptch.Qdr*”, under the same title: “*Pitch Axis Discrete FCS*”. The discrete FCS is also exported to Matlab as a state-space system m-file “*pitch_fcs.m*” in directory “*\Shuttle Ascent\Pitch Analysis*”. It will also be combined with the vehicle and actuators to perform stability analysis and simulations.

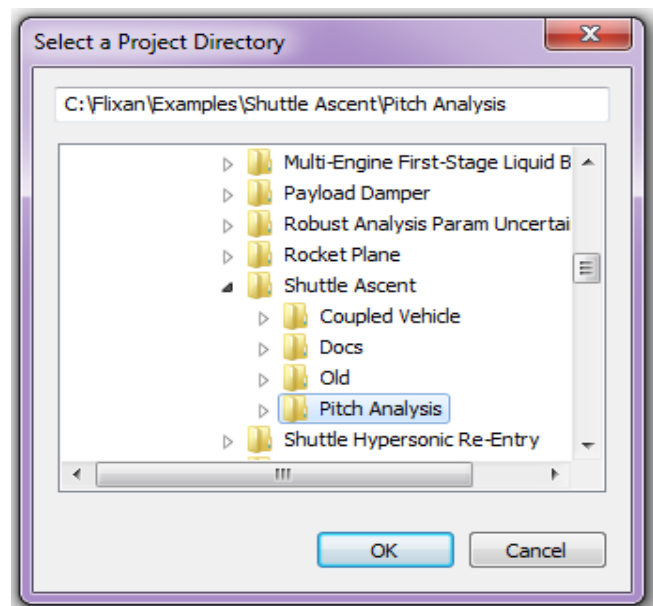
1.7 Processing the Input Data in Batch Mode

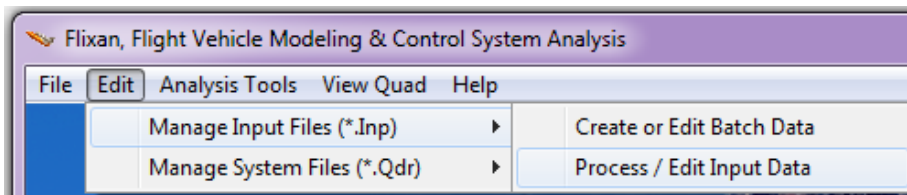
The dynamic model development described in sections (1.2 to 1.6) is for an initial setup and it takes longer to process. When the input file: “*Stg1_MaxQ_Ptch.Inp*” is already prepared there is a much faster way to process it using Flixan in batch mode. Batch processing requires a batch data-set that is usually located at the top of the input data file. Let us take a look in the input file: “*Stg1_MaxQ_Ptch.Inp*”.

1. The first set of data in this file is a batch for processing the remaining data-sets in batch mode. This is faster because it processes them all together, instead of processing each set interactively. Its title is “*Batch for preparing the Shuttle Ascent, First Stage Max-Q, Longitudinal Axis Models*”. Below the title there are comment lines describing the models created by this file and batch, followed by the batch instruction lines. Each batch instruction line corresponds to a data-set in the file that will be processed by Flixan.
2. The next two data-sets below the batch generate two vehicle models in the same max-Q flight condition. The first one is a rigid-body model and its title is “*Shuttle Ascent, Max_Q, T=55 sec (Rigid Body)*”. The second one is a high order model that includes flexibility, slosh, and tail-wag-dog dynamics. Its title is “*Shuttle Ascent, Max_Q, T=55 sec, Flex Vehicle with Slosh and TWD*”.
3. The next data-set is a set of selected pitch modes which are combined with the second vehicle model and introduce flexibility in the model. This set of modes was created and described in section (1.1) using the mode-selection process. The modal data title is “*Shuttle Ascent, Max_Q, T=55 sec, Rigid Body with Slosh/TWD, Pitch Modes*” and it is also included in the vehicle data.

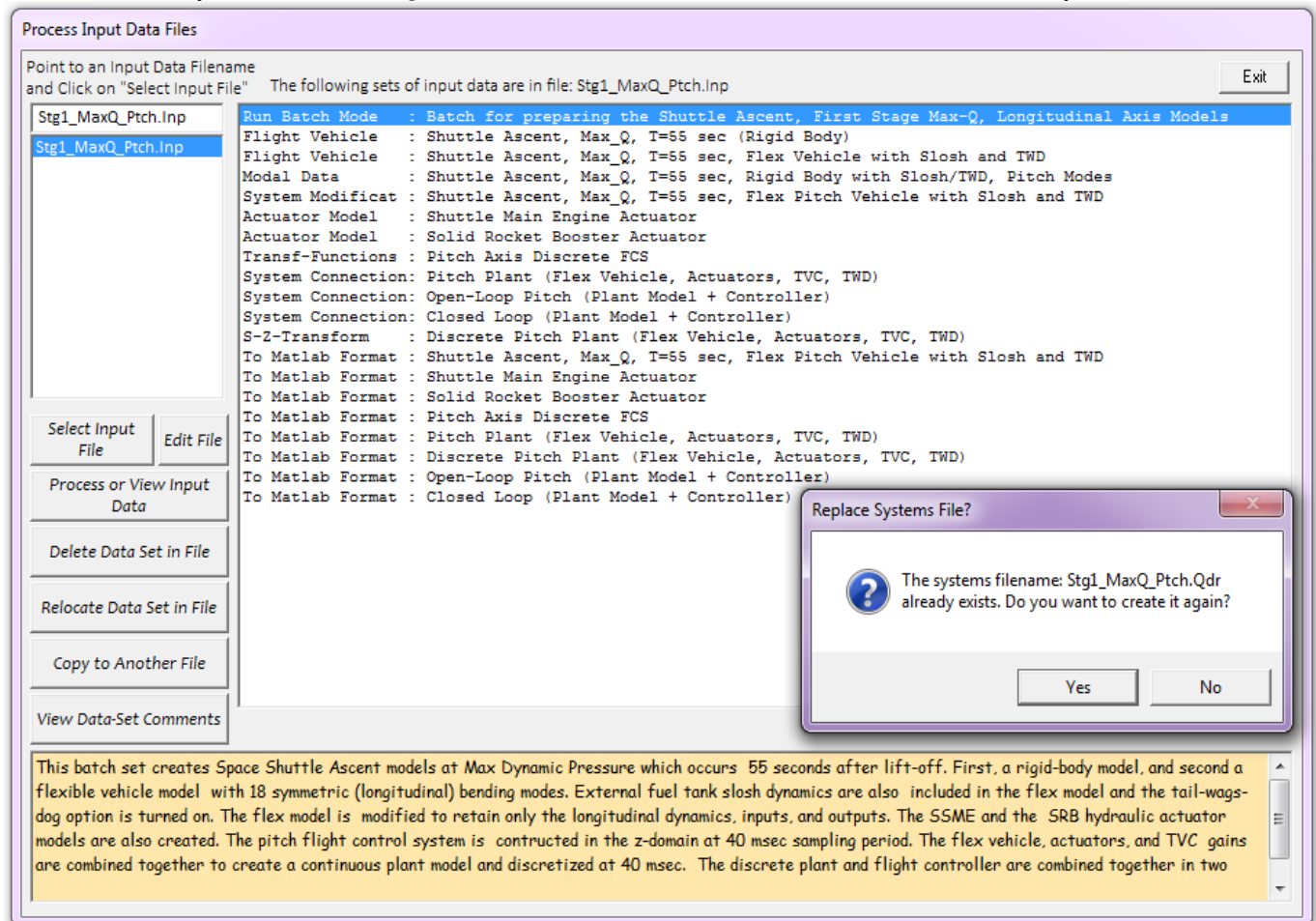
4. The next data-set is a system modification set that extracts only the longitudinal axis variables from the coupled state-space model with flex. The reduced pitch system includes all flex modes and its title is "*Shuttle Ascent, Max_Q, T=55 sec, Flex Pitch Vehicle with Slosh and TWD*". This system is also saved in file "*Pitch_Vehi_Flex.m*" for Matlab analysis.
5. The next two data-sets are actuator data used to generate actuator models for the Shuttle main engines and for the rocket booster nozzles. Their titles are: "*Shuttle Main Engine Actuator*" and "*Solid Rocket Booster Actuator*" respectively. These two systems are also saved in files "*SSME_Actuator.m*" and "*SRB_Actuator.m*" for Matlab analysis.
6. The next data-set is a transfer-function system that defines the Shuttle discrete flight control system at max-Q. The sampling rate is 40 (msec). Its title is "*Pitch Axis Discrete FCS*". Flixan will convert this transfer-function interconnection data to a state-space system. This system is also saved in file "*Pitch_FCS.m*" for Matlab analysis.
7. The next data-set is a systems interconnection set that combines the flexible pitch vehicle model with the SSME and the SRB actuators. The interconnection includes tail-wag-dog and load-torque feedback dynamics as already described. Its title is "*Pitch Plant (Flex Vehicle, Actuators, TVC, TWD)*". This system is discretized at 40 (msec) using the s to z conversion utility. The discrete system's title is "*Discrete Pitch Plant (Flex Vehicle, Actuators, TVC, TWD)*". These two systems are also saved in files "*Pitch_Plant_s.m*" and "*Pitch_Plant_z.m*" for Matlab analysis.
8. The next two data-set are systems interconnections that combine the discrete pitch plant model created in step-7 with the pitch flight control system created in step-6. Two discrete systems are created, an open-loop system used for stability analysis "*Open-Loop Pitch (Plant Model + Controller)*" and a closed-loop system used for time-domain simulations "*Closed Loop (Plant Model + Controller)*". These two systems are also saved in files "*open_loop.m*" and "*closed_loop.m*" for Matlab analysis.
9. The remaining data-sets are used to convert the systems from file "*Stg1_MaxQ_Ptch.Qdr*" to Matlab format and they will be loaded in Matlab to perform system analysis.

Now let us process this input file using Flixan. Start the Flixan program and select the project folder "*C:\Flixan\Examples\Shuttle Ascent\Pitch Analysis*". Then go to "*Edit*", "*Manage Input Files (.Inp)*", and "*Process/ Edit Input Data*", as shown.





The following dialog is used for editing and processing Flixan input files. The left menu shows the only input file in the project directory, which is "Stg1_MaxQ_Ptch.Inp". Select it and click on "Select Input File". The menu on the right side shows the data-sets which are included in file "Stg1_MaxQ_Ptch.Inp". They can be processed individually, but select the batch set on the top to process them all together, and click on "Process or View Input Data". Flixan will process the input file and create the systems in file "Stg1_MaxQ_Ptch.Qdr". It will also create the Matlab system files.



1.8 Pitch Axis Stability Analysis Using Matlab

In the previous section we have created several models that can be used to analyze open-loop stability using frequency response analysis in Matlab. The following Matlab script file "run.m" loads the Flixan generated models to Matlab and performs frequency response analysis. An open-loop model is already created by Flixan and it is saved in file "open-loop.m". However, in this case we will use Simulink to connect the subsystems together open-loop and to perform the linear analysis.

```
% File: run.m
r2d= 180/pi; d2r=1/r2d; Ts=0.04;

% Load Systems from Flixan
[Apf,Bpf,Cpf,Dpf]= pitch_vehi_flex;
[Aac,Bac,Cac,Dac]= ssme_actuator;
[Asb,Bsb,Csb,Dsb]= srb_actuator;
[Afc,Bfc,Cfc,Dfc]= pitch_fcs;
[Apl,Bpl,Cpl,Dpl]= pitch_plant_s;
[Apz,Bpz,Cpz,Dpz]= pitch_plant_z;
[Aol,Bol,Col,Dol]= open_loop;
[Acl,Bcl,Ccl,Dcl]= closed_loop;

% Titles in file "Stg1_MaxQ_Ptch.Inp"
% Shuttle Ascent, Max_Q, T=55 sec, Flex Pitch Vehicle with Slosh
% Shuttle Main Engine Actuator
% Solid Rocket Booster Actuator
% Pitch Axis Discrete FCS
% Pitch Plant (Flex Vehicle, Actuators, TVC, TWD)
% Pitch Plant Discrete
% Open-Loop Pitch (Plant Model + Controller)
% Closed Loop (Plant Model + Controller)

[Ao,Bo,Co,Do]= dlinmod('Pitch_Open_Flex',0.04); % Linearize Open-Loop Simulink model that uses separate blocks
%[Ao,Bo,Co,Do]= dlinmod('Pitch_Open_Flex2',0.04); % Linearize Open-Loop Simulink model that uses combined plant
sys= SS(Ao,Bo,Co,Do,0.04); % Create SS System
%sys= SS(Aol,Bol,Col,Dol,0.04); % Create SS System using the pre-combined z-system "open_loop.m"
w=logspace(-2.4, 2, 24000); % Define Frequ Range
figure(1); Nichols(sys,w) % Plot Nichol's Chart
figure(2); Bode(sys,w) % Plot Bode
figure(3); Nyquist(sys,w) % Plot Nyquist
```

The open-loop Simulink interconnection file "*Pitch_Open_Flex.Mdl*", shown in Figure (1.7.1), has the loop opened at the FCS output. It is used to calculate the frequency response and the stability margins.

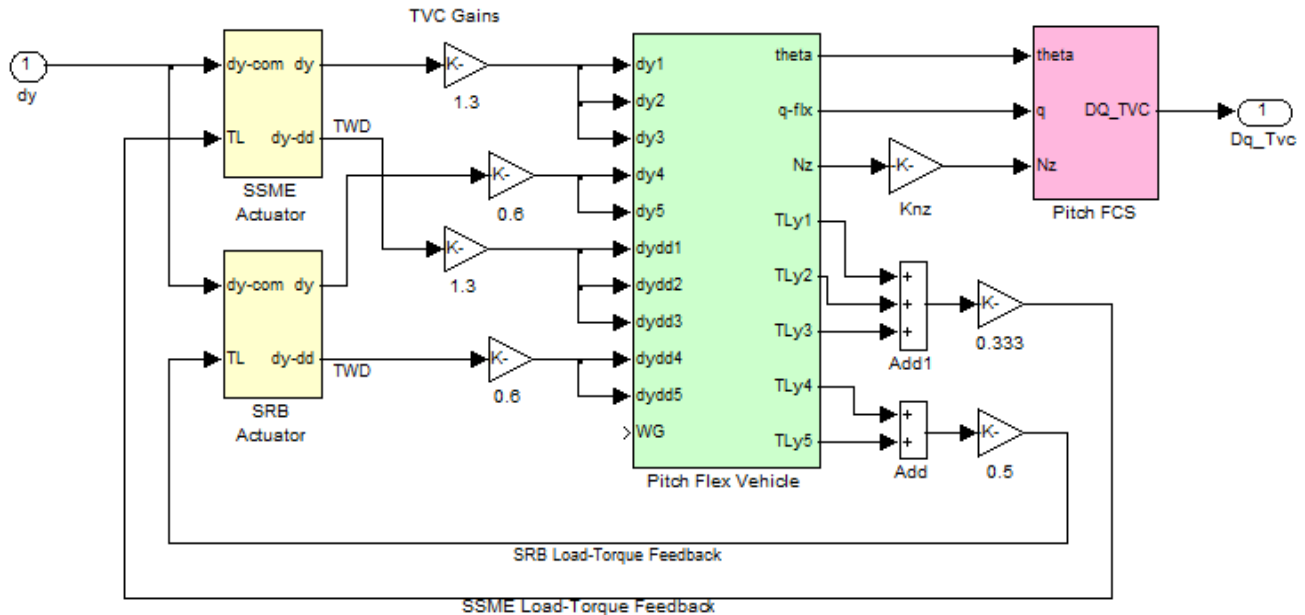


Figure (1.7.1) Open-Loop Analysis Model "Pitch_Open_Flex.Mdl" with the Loop Opened at the FCS Output

This system consists of the continuous pitch flex vehicle from file "*pitch_vehi_flex.m*", the two actuator (SSME and SRB) subsystems, and the TVC gains in series with the discretized flight control system "*pitch_fcs.m*", sampled at 0.04 sec. Matlab calculates the frequency response and plots the Bode, Nichols, and Nyquist diagrams to show the gain and phase margins.

We also have a second open-loop implementation in Simulink file "*Pitch_Open_Flex2.Mdl*", shown in figure (1.7.2) below, and used for tutorial purposes. This implementation connects the FCS with the combined vehicle/ actuator/ TVC plant system: "*Pitch Plant (Flex Vehicle, Actuators, TVC, TWD)*" that was connected together using Flixan, and it was loaded in Matlab from file "*pitch_plant_s.m*". A third implementation uses the open-loop system "*Open-Loop Pitch (Plant Model + Controller)*" generated by Flixan, loaded in Matlab from file "*open_loop.m*". This consists of all subsystems including the FCS. The frequency response results from all three systems are very similar and they are presented in all three: Bode, Nyquist, and Nichols flavors.

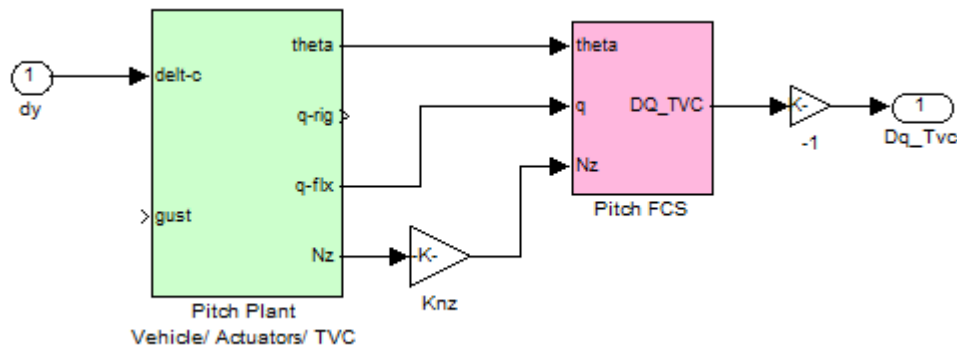
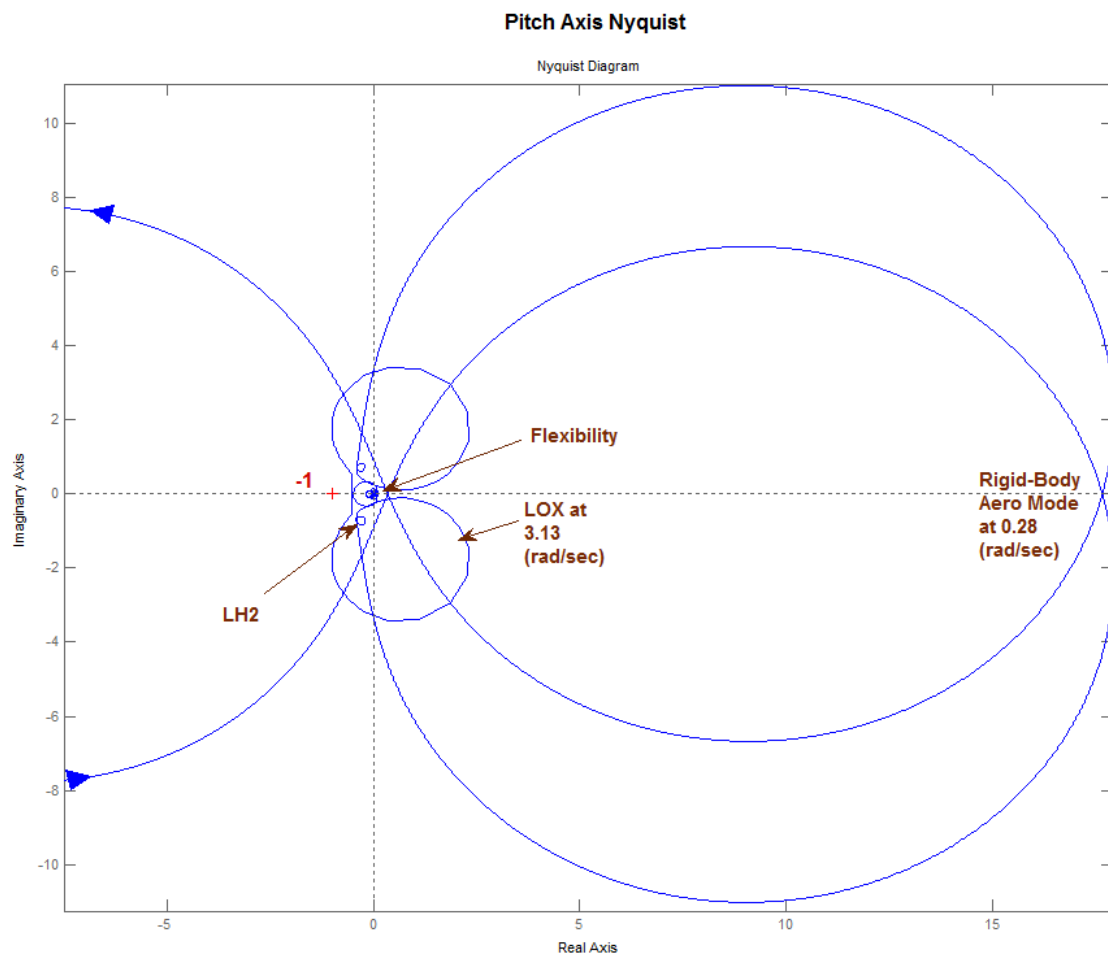
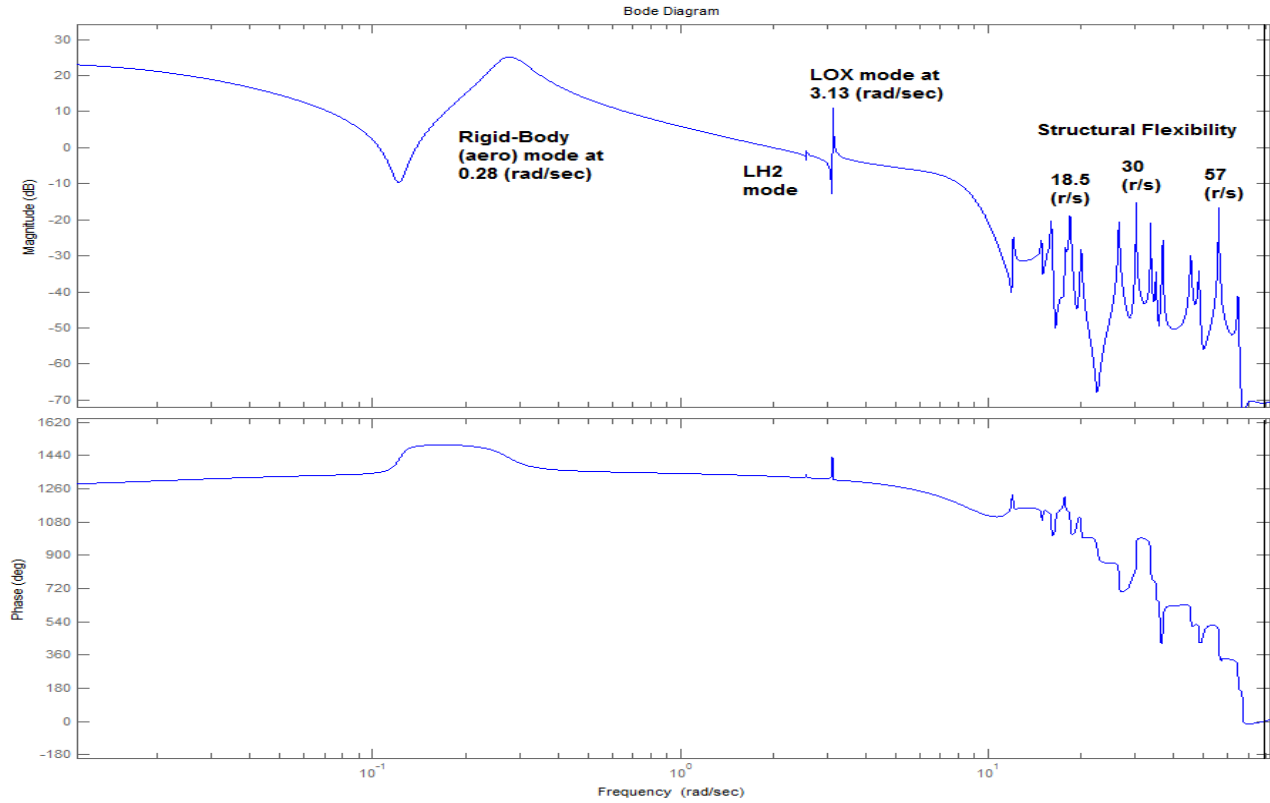


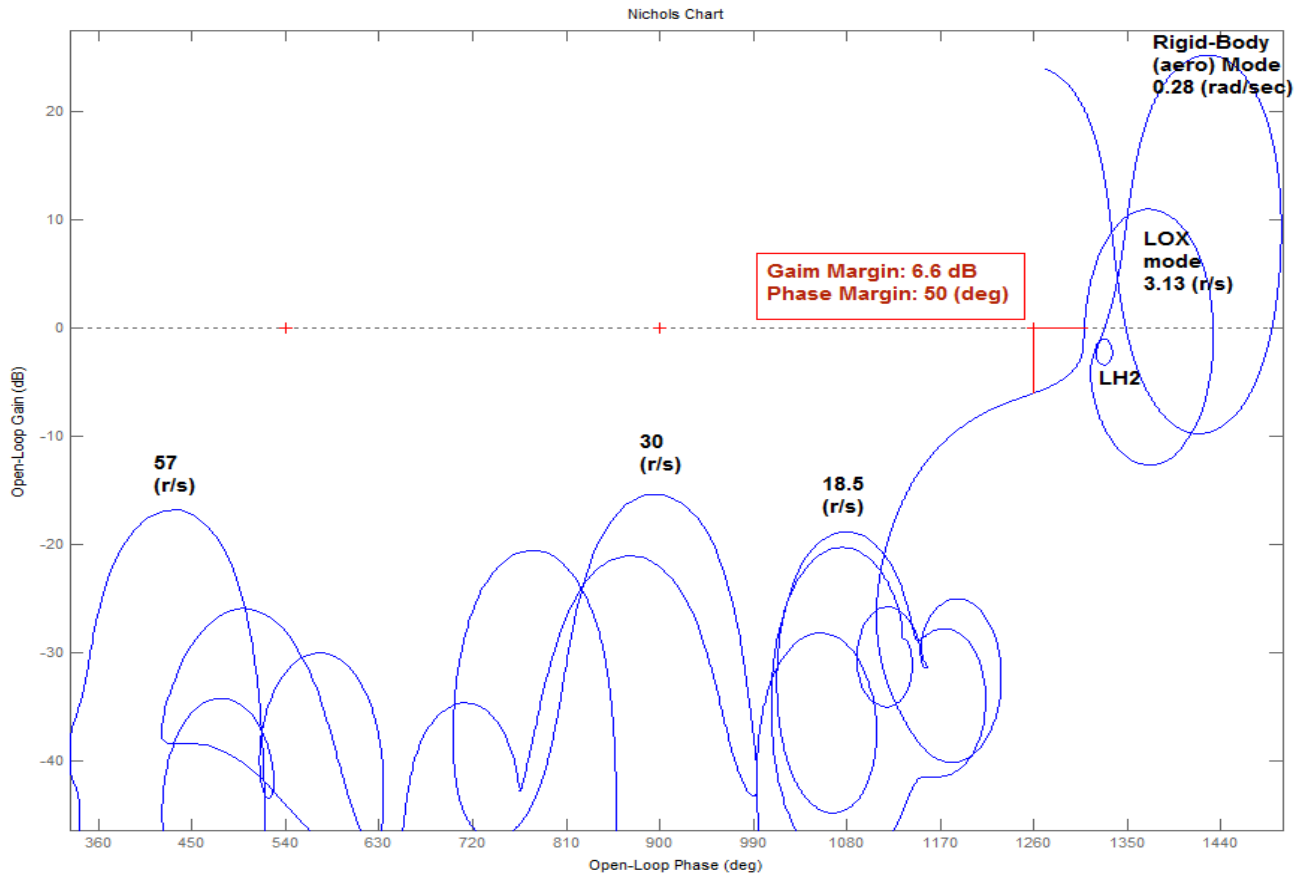
Figure (1.7.2) Open-Loop Analysis Model "*Pitch_Open_Flex2.Mdl*" using the pre-combined plant model



Pitch Axis Bode Plot



Pitch Axis Stability Analysis



The third closed-loop simulation model is “*Pitch-Flex-Sim3.Mdl*”, shown in figure (1.8.3), and it was combined together and discretized in Flixan. The discrete system sample-rate is 40 (msec) and its title is “*Closed Loop (Plant Model + Controller)*”. It is loaded into Matlab from file “*closed_loop.m*”. The simulation results from all three models are very similar.

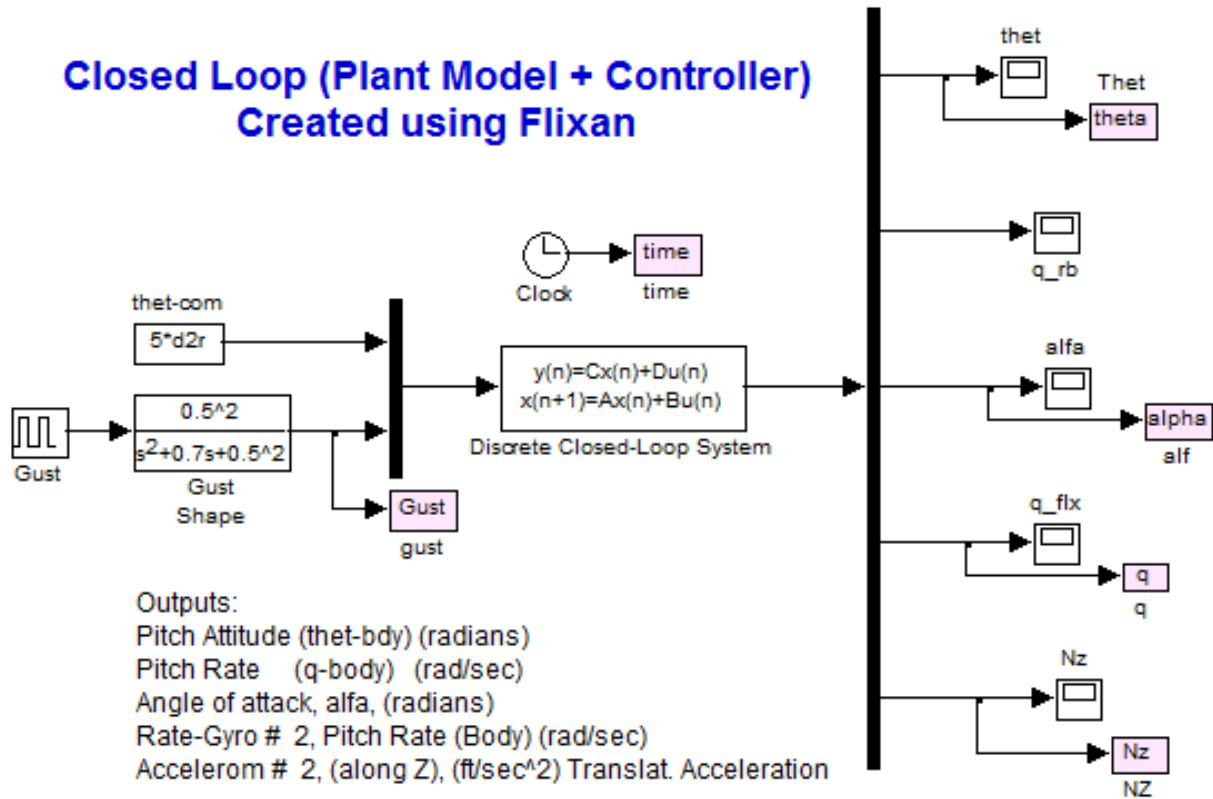
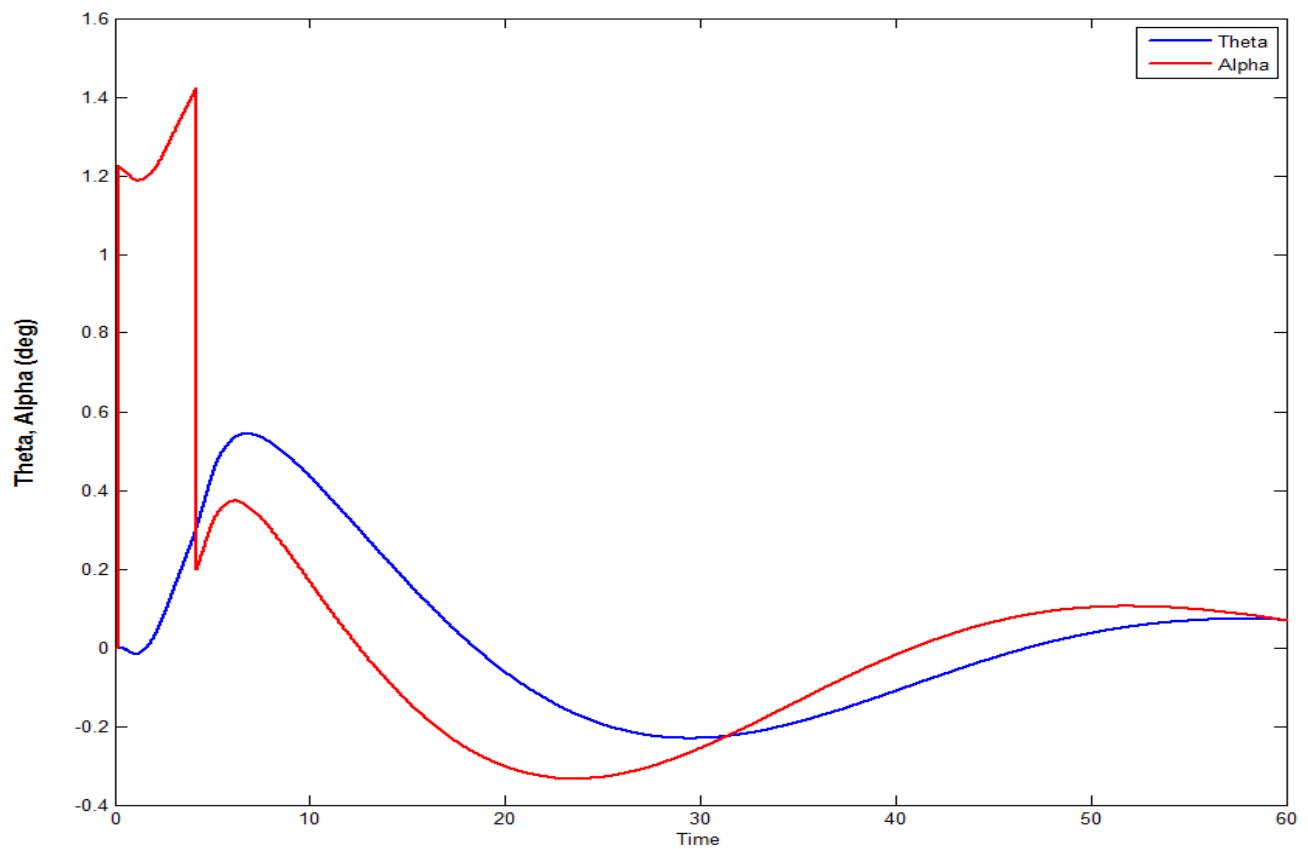
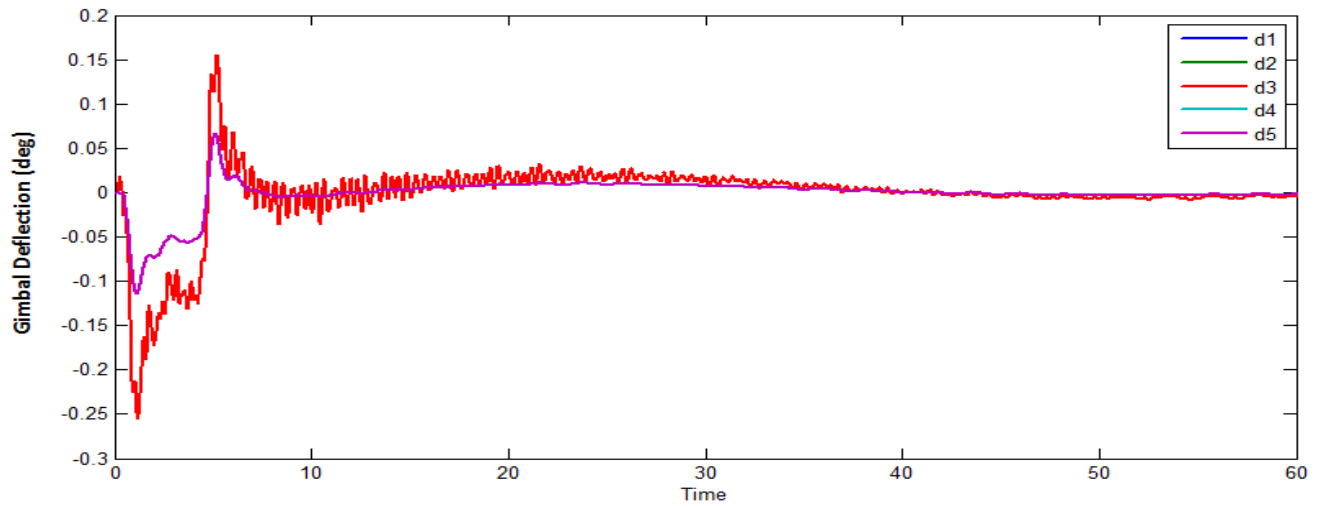
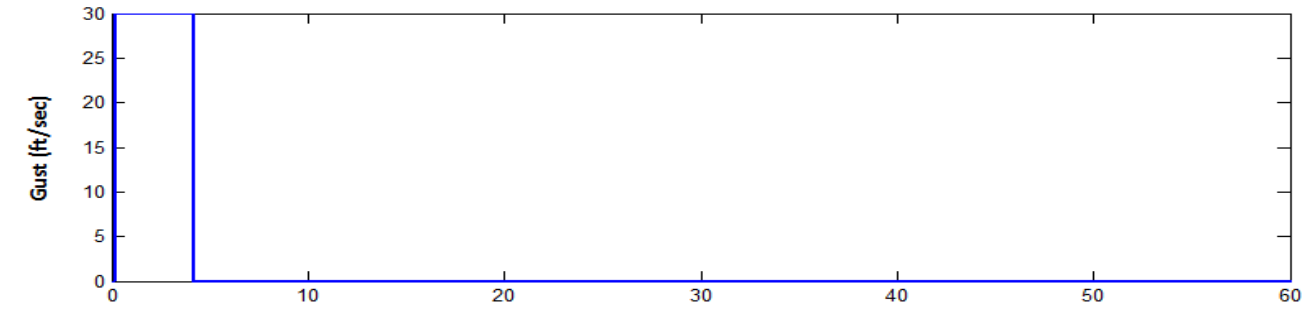


Figure 1.8.3 Shuttle Ascent Closed-Loop Simulation Model “Pitch_Flex_Sim3.Mdl”

The simulation models have two inputs, one representing an attitude (θ_{cmd}) coming from guidance and the second input represents the wind gust velocity. The direction of the wind gust is defined in the vehicle input data. When the simulations are complete a script file “pl.m” is used to plot the results.

Figures (1.8.4), below, show the vehicle response to a sharp wind pulse of 30 (ft/sec). It was obtained using the simulation model “*Pitch_Flex_Sim.Mdl*”. Initially the angle of attack jumps due to the wind incidence and the TVC engines gimbal to counteract the aero disturbance. This excites structure flexibility which is visible at the gyro, the accelerometer, and the gimbals. Slosh oscillations are also visible at the gimbal deflections. The SSME deflections are larger since they have bigger deflection capability than the SRB. The gimbal accelerations contribute to the TWD forces and the load-torques that feed back into the actuator.

Shuttle Ascent Stage-1 Response to 30 (ft/sec) Wind Gust Pulse



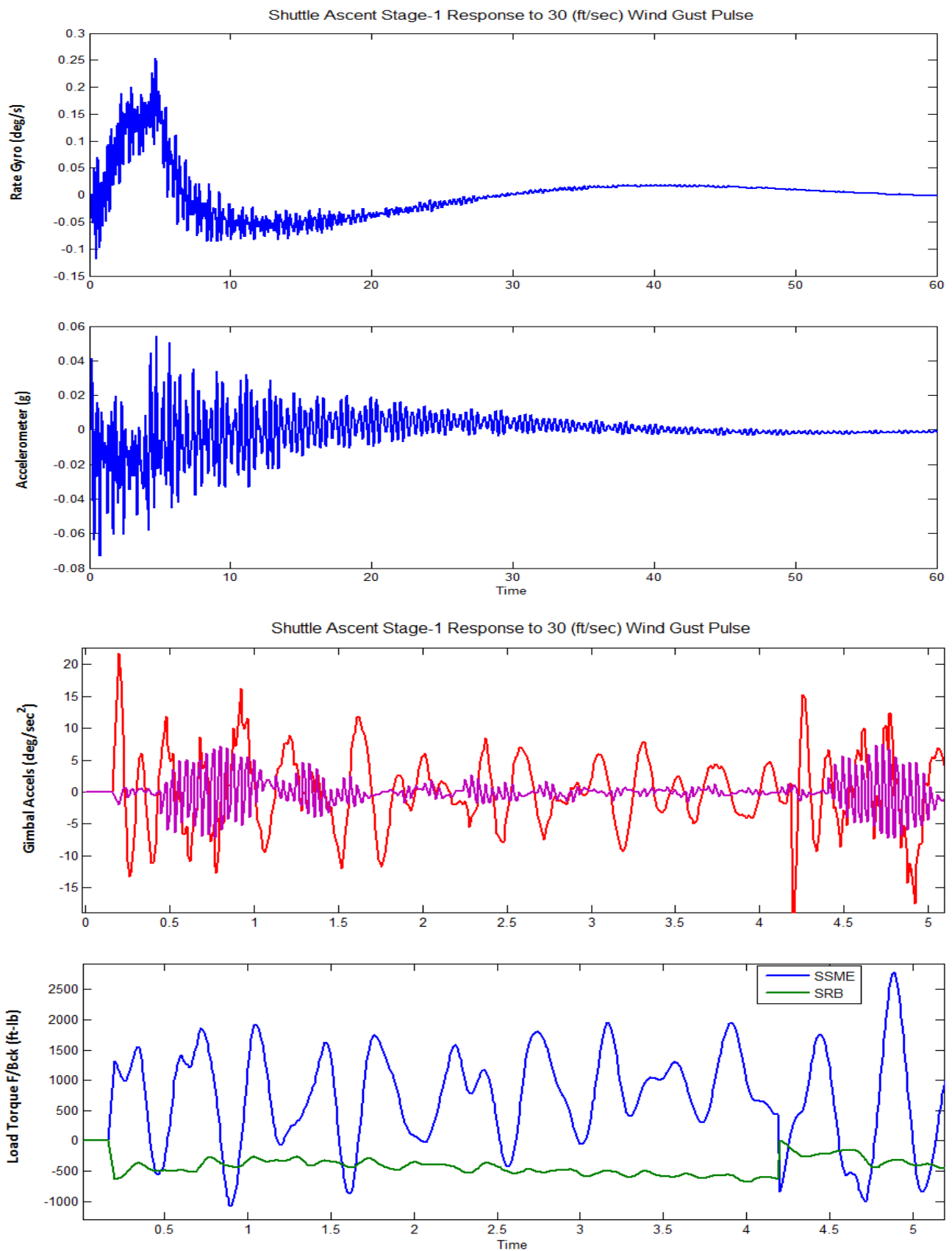
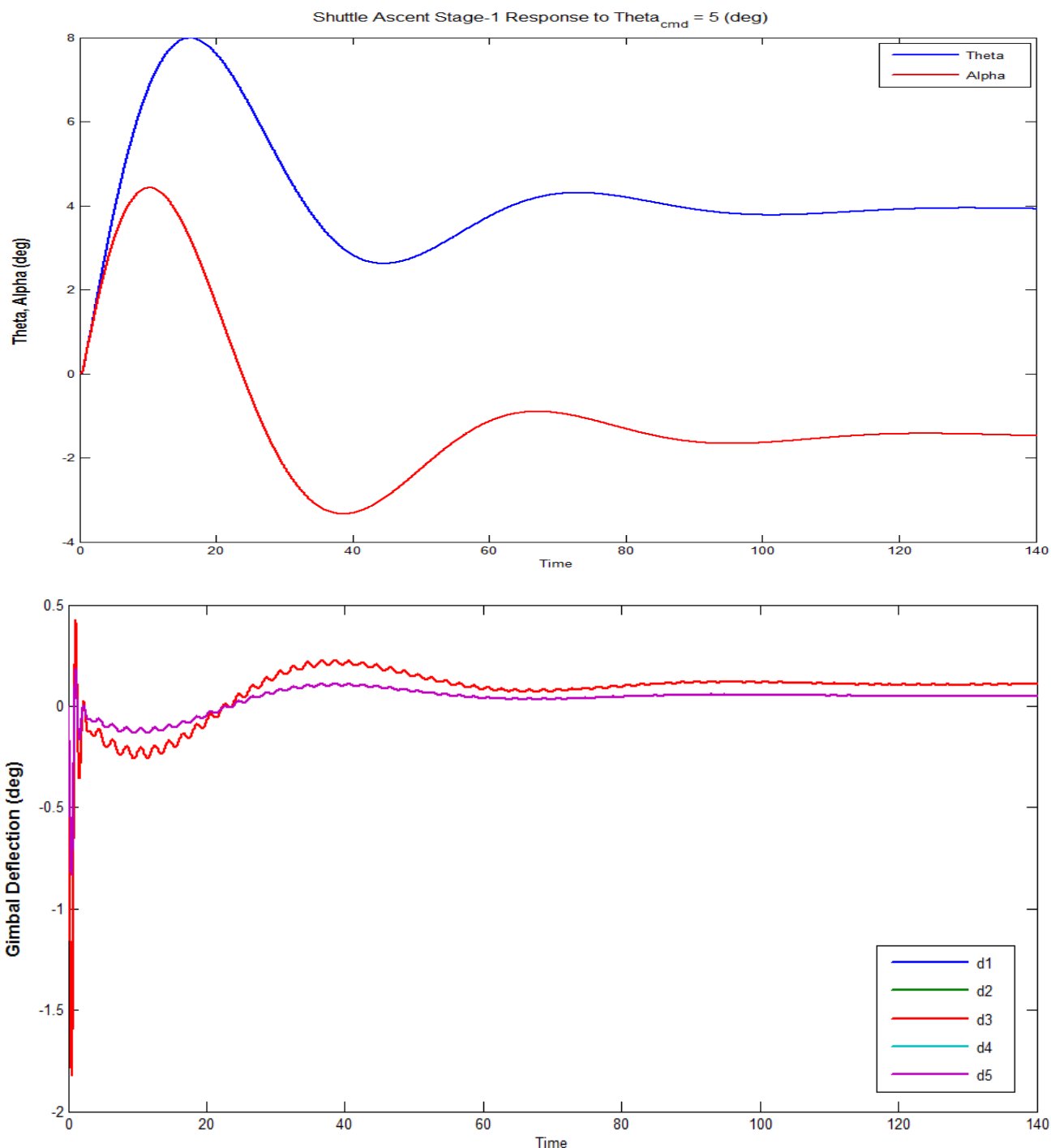


Figure 1.8.4 Response to a Wind Pulse of 30 (ft/sec) amplitude

The simulation results in figure (1.8.5) show the Shuttle response to a 5 (deg) attitude change command. The angle of attack reaches peaks to a value of 4.4° and then it decays to -1.5° as a result of the load-relief action which is intended to reduce the normal load. For the same reason the pitch attitude (θ) never reaches its commanded value because the load-relief compromises the command performance at high dynamic pressures. Both the SSME and the SRB engines gimbal responding to the pitch command by deflecting in the negative direction causing a pitch-up. The SSME deflections are bigger and they also excite the slosh resonances which are visible in the gimbal deflections and at the sensors. Flexibility is also visible initially in the gimbal accelerations.



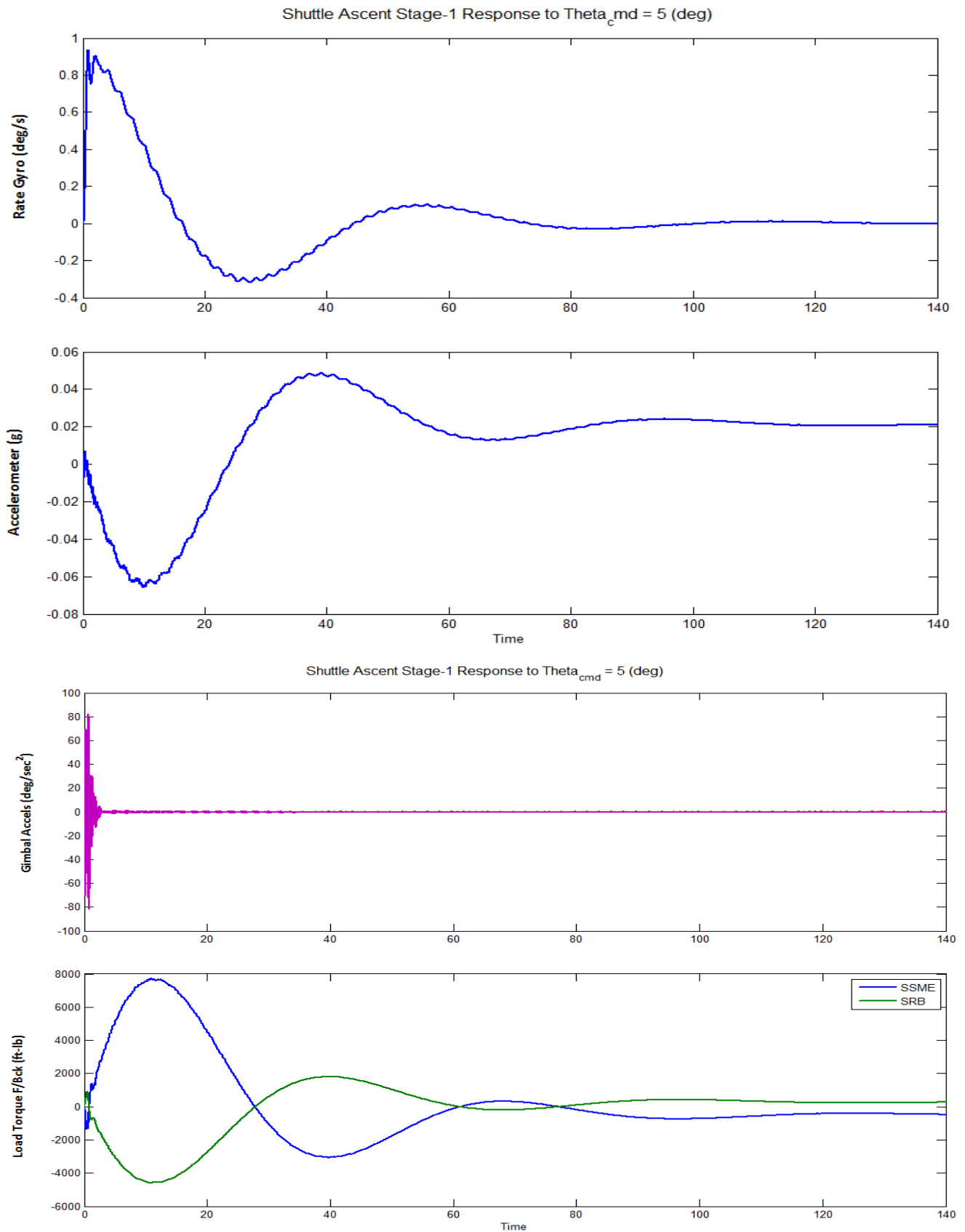


Figure 1.8.5 Response to a 5 (deg) Pitch Attitude Command at Max-Q

2.0 Pitch and Lateral Axes Analysis Using a Coupled Model

We will now repeat a similar analysis by using a vehicle model that has the pitch and lateral dynamics fully coupled together and combined with discrete flight control systems, the actuators, the sensors, and the TVC matrix. We will use Flixan to generate state-space models for the Shuttle vehicle, both rigid and flexible, combine the flexible vehicle with the actuators, sensors, TVC, and flight control system, and create open-loop and closed-loop models for frequency response analysis and simulations. The control analysis is performed using the Matlab program. For tutorial purposes we shall demonstrate three types of modeling options using Flixan and Matlab/ Simulink. In the first case we create the individual subsystem models using Flixan and they are combined together and analyzed in Matlab/ Simulink. In the second option the vehicle, actuators, TVC, and sensor subsystems are combined together as a system and it is discretized using Flixan. Then we use Simulink to combine them with the discrete pitch and lateral flight control systems and analyzed them using Matlab. In option three all subsystems are combined together using Flixan, loaded into Matlab and the analysis is performed using Matlab/ Simulink. Notice that the Flixan interconnection utility is more efficient in combining subsystems together because Simulink has difficulty combining systems that involves algebraic loops. In this example we have algebraic loops because of the load-torque mechanical feedback.

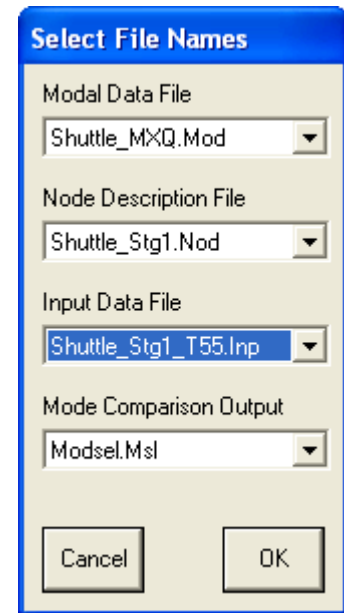
The coupled axes analysis is performed in directory: *"C:\Flixan\Examples\Shuttle Ascent\Coupled Vehicle"*. The Shuttle vehicle input data and the selected modal data are in file *"Shuttle-Stg1-T55.Inp"*. If you look inside this file there are two sets of vehicle data. One set for creating a simple rigid-body model with title: *"Shuttle Ascent, Max_Q, T=55 sec (Rigid Body)"*, and a second set for building a high order vehicle model with slosh and structural bending having the title: *"Shuttle Ascent, Max_Q, T=55 sec, Flex Vehicle with Slosh and TWD"*. The vehicle modeling program will generate the Shuttle state-space systems from the vehicle data, which are identical with those used in the pitch axis except that the flex model is using a different sets of modal data. It uses a set of 29 modes which include both symmetric and anti-symmetric modes, and have already been pre-selected, scaled, and saved in file *"Shuttle-Stg1-T55.Inp"*. The title of the modal data set is *"Flex Modes for Shuttle Ascent, Max_Q, T=55 sec"*. Notice that this title must also appear at the bottom of the flex vehicle data-set. It is the last line below the line "Number of Bending Modes: 29". This file also includes two sets of actuator data. One set for modeling the Shuttle main engine dynamics and another set for the Solid Rocket Booster engine. The Flixan generated state-space systems are saved in file *"Shuttle_Stg1-T55.Qdr"*. They are also converted to Matlab format by the "Export to Matlab" utility. The Matlab analysis is performed in the same folder. In this example we will not run each Flixan subprogram separately and interactively as in the pitch axis analysis. We have created a batch set that processes all the data-sets in file *"Shuttle-Stg1-T55.Inp"* together in batch mode, faster and without user interaction. The batch consists of a set of processing statements that appear on the top of the input data file. It creates the vehicle models, the actuator and sensor models, and the flight control systems. It combines them together, discretizes them, and transforms them to Matlab for further analysis. The batch set has a title: *"Batch for preparing the Shuttle Ascent, First Stage Max-Q, Coupled Axes Models"* and it is followed by some comment lines that describe the overall analysis performed in this project file *"Shuttle-Stg1-T55.Inp"*. In section (2.2) we will discuss the batch execution and describe the function of each individual set of data in the input file, but before we get to that let's talk about the selection of the modal data.

2.1 Mode Selection

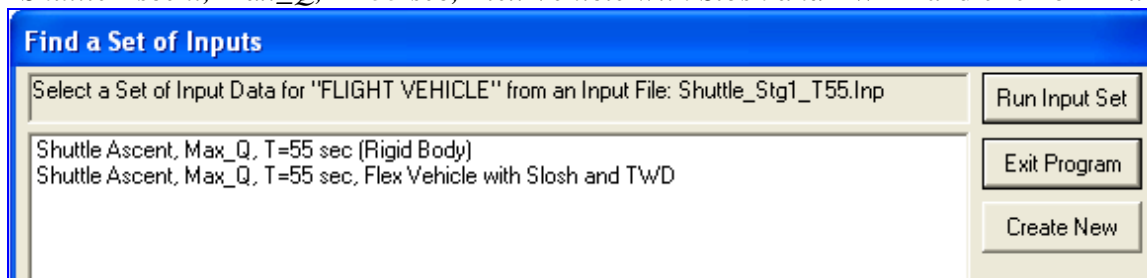
The mode selection in this case is very similar to the pitch mode selection, perhaps a little more laborious because we may have to do it more than once using different excitation and sensor points and directions. This is to make sure that we excite and sense in all directions in order to capture both, symmetric modes which dominate in the pitch direction and anti-symmetric modes which are strong in roll and yaw. For demonstration purposes, however, we are going to run the mode-selection process only once. Since the vehicle does not have perfect symmetry a lot of modes couple into all three directions.

We start the Flixan program and go to directory "... \Examples\ Shuttle Ascent\ Coupled Vehicle". From the Flixan main menu select "Analysis Tools", "Flight Vehicle Modeling Options", and then "Flex Mode Selection". In the filenames selection menu we select the finite elements file "Shuttle-MXQ.Mod", the nodes map file "Shuttle_Stg1.Nod", the input data file "Shuttle-Stg1-T55.Inp", and the default mode-selection output file.

Click "ok" to continue. In the menu that selects a set of flight vehicle data choose the second title "Shuttle Ascent, Max_Q, T=55 sec, Flex Vehicle with Slosh and TWD" and click on "Run Input Set".



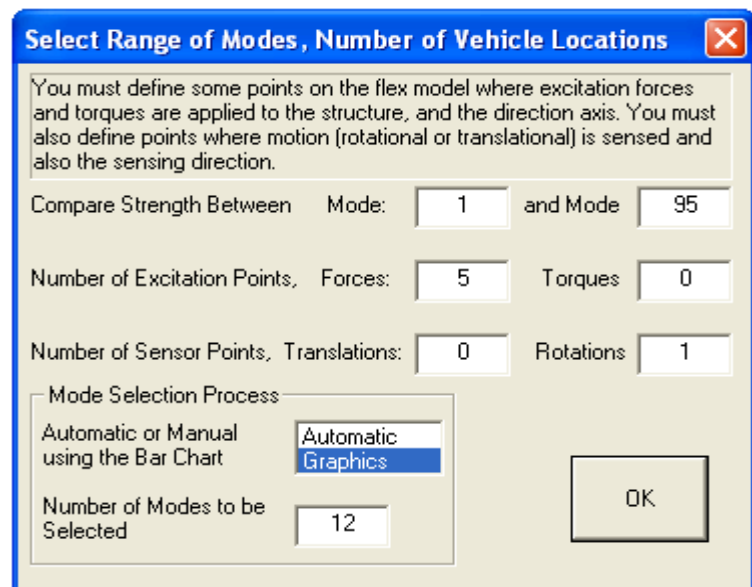
The "Select File Names" dialog box has a blue title bar. It contains four file selection fields, each with a dropdown arrow: "Modal Data File" (Shuttle_MXQ.Mod), "Node Description File" (Shuttle_Stg1.Nod), "Input Data File" (Shuttle_Stg1_T55.Inp), and "Mode Comparison Output" (Modsel.Msl). At the bottom are "Cancel" and "OK" buttons.



The "Find a Set of Inputs" dialog box has a blue title bar. It contains a text area with the instruction "Select a Set of Input Data for 'FLIGHT VEHICLE' from an Input File: Shuttle_Stg1_T55.Inp". Below this are two list items: "Shuttle Ascent, Max_Q, T=55 sec (Rigid Body)" and "Shuttle Ascent, Max_Q, T=55 sec, Flex Vehicle with Slosh and TWD". To the right are three buttons: "Run Input Set", "Exit Program", and "Create New".

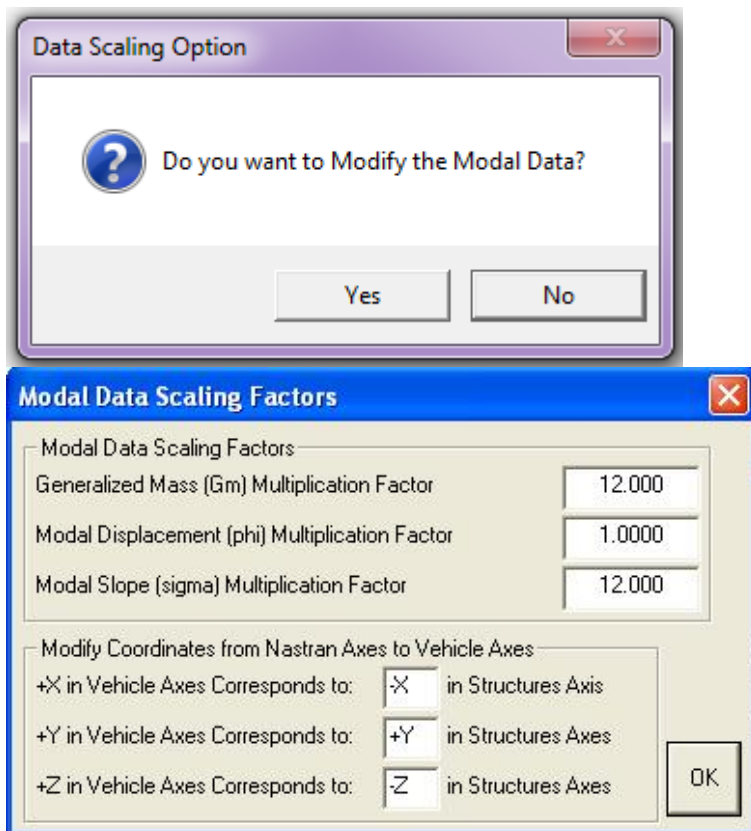
In this example we will attempt to excite the vehicle structure in the roll direction in order to select modes which are strong in roll. In the following menu choose 5 force excitation points, zero torques, zero translational sensors, and one rotational measurement point. We also select the "Graphic" mode selection option and click "ok". Ignore the request for the number of modes to be selected because this applies only to auto-selection.

The program will ask you if you would like to rescale the modal data, and you should reply "Yes" because the modal data units and directions are different than our vehicle units and directions. We allow the default modal data scaling and axes transformation option shown in the dialog below. This will rescale the modal data from Nastran to flight control units and directions.



The "Select Range of Modes, Number of Vehicle Locations" dialog box has a blue title bar with a close button. It contains a text area with instructions: "You must define some points on the flex model where excitation forces and torques are applied to the structure, and the direction axis. You must also define points where motion (rotational or translational) is sensed and also the sensing direction." Below this are several input fields: "Compare Strength Between Mode: 1 and Mode 95", "Number of Excitation Points, Forces: 5 Torques 0", "Number of Sensor Points, Translations: 0 Rotations 1". There is a "Mode Selection Process" section with two options: "Automatic or Manual using the Bar Chart" and "Automatic Graphics" (which is selected). At the bottom is a "Number of Modes to be Selected" field with the value 12. An "OK" button is at the bottom right.

The following menu is used for unit conversions and axis transformation. This is because the units and directions used in GN&C models are usually different from those used by typical FEM such as Nastran. In a typical GN&C analysis model the x-axis is forward (in the direction of the velocity vector), and the z-axis is down towards the floor. The Nastran models, almost always, they point the x axis aft toward the back of the vehicle and the z-axis up towards the ceiling of the airplane. The y-axis is the same in both models. The modal mass from Nastran needs also to be scaled up by a factor of 12 because Nastran uses (snails) while GN&C uses (slugs). The modal rotations (slopes) also need to be scaled up by a factor of 12 because in Nastran they are (rad/inch) and they need to be converted to (rad/ft). The modal displacements do not require scaling because their units change from (inches/inch) to (feet/foot). The conversion dialog below is used for scaling the modal data. It has the default conversion parameters described but the scaling values, signs, and axes can be modified as needed to make the modal data compatible with the vehicle input data.



The next step is to identify the nodes for the 5 excitation points and a node for one gyro sensor. Remember, these locations are only for mode selection purposes and they do not have to be the same as the actual locations of the gimbals and the flight control sensors that will be defined later. Since in this case we are interested in selecting modes which dominate in the roll direction we must chose nodes that correspond to the 5 engine gimbal force excitations and select the force directions to excite the vehicle structure in roll. The gyro measuring direction should also be in roll. The mode comparison will be performed between the 5 excitation points and the roll sensor point. The nodes map, which is in file "Shuttle_Stg1.Nod" is shown in a dialog/menu and it helps the user selecting the proper nodes and in identifying the excitation and sensor locations in the modal data file. It also helps define the directions of the excitation forces and sensing directions, only for mode selection purposes. In this case the force excitations are differential in pitch in order to excite roll.

The force excitation point #1 is chosen to be the top SSME which is engine #1, at node #3, generating a force in the +Y direction to excite roll and yaw. The force excitation point #2 is the left SSME engine #2, at node #4, with a force along -Z. The force excitation point #3 is the right SSME which is engine #3, at node #5, with a force along +Z. The force excitation point #4 is the left SRB engine #4, at node #6, with a force along -Z. The force excitation point #5 is the right SRB engine #5, at node #7, along +Z. The combined differential forces in the $\pm Z$ direction of the two SSME engines #2 and #3 excite the structure in the positive roll direction. The same thing applies for the differential forces applied in the two SRB engines #4 and #5.

Table of Vehicle Structure FEM Nodes

In mode selection, in order to calculate the relative mode strength of a number of modes in a specified direction you must define some node points in the Nastran model where the excitation forces or torques will be applied and also the forcing directions.

Similarly, you must also define the sensor points (translations or rotations) and the sensing directions.

Select a Location (Node) for Force Excitation : 1

LOX SLOSH Mass	1	238	142.0	0.0
LH2 SLOSH Mass	2	239	86.0	0.0
Shuttle Main Engine # 1	3	2088	19.0	0.0
Shuttle Main Engine # 2 (left)	4	2254	17.0	-4.5
Shuttle Main Engine # 3 (right)	5	2091	17.0	4.5
Solid Rocket Booster # 4 (left)	6	1367	0.0	-21.0
Solid Rocket Booster # 5 (right)	7	367	0.0	21.0
IMU/ Accelerometer (right)	8	2322	108.3	1.0
IMU/ Accelerometer (left)	9	2323	108.3	-1.0
Aft Payload Gyro (a)	10	2179	-166.72	0.0
Aft Payload Gyro (b)	11	2183	-166.72	0.0
Booster Gyro (right)	12	372	-166.72	0.0
Booster Gyro (left)	13	1372	-166.72	0.0
Forward Payload Gyro	14	1502	0.0	0.0

Axis

Along-X
Along-Y
Along-Z

Direction

+ (positive)
- (negative)

The location of the single rotational sensor #1 (defined for the mode-selection process) is chosen to be in the right booster, node #12, measuring in the positive roll direction. The program uses the excitation and sensor points to locate the mode shapes and slopes from the modal data file and from the mode shapes it calculates the modal strength for each mode between the force excitations and the roll sensor.

Table of Vehicle Structure FEM Nodes

In mode selection, in order to calculate the relative mode strength of a number of modes in a specified direction you must define some node points in the Nastran model where the excitation forces or torques will be applied and also the forcing directions.

Similarly, you must also define the sensor points (translations or rotations) and the sensing directions.

Select a Location (Node) for Rotational Sensor: 1

LOX SLOSH Mass	1	238	142.0	0.0
LH2 SLOSH Mass	2	239	86.0	0.0
Shuttle Main Engine # 1	3	2088	19.0	0.0
Shuttle Main Engine # 2 (left)	4	2254	17.0	-4.5
Shuttle Main Engine # 3 (right)	5	2091	17.0	4.5
Solid Rocket Booster # 4 (left)	6	1367	0.0	-21.0
Solid Rocket Booster # 5 (right)	7	367	0.0	21.0
IMU/ Accelerometer (right)	8	2322	108.3	1.0
IMU/ Accelerometer (left)	9	2323	108.3	-1.0
Aft Payload Gyro (a)	10	2179	-166.72	0.0
Aft Payload Gyro (b)	11	2183	-166.72	0.0
Booster Gyro (right)	12	372	-166.72	0.0
Booster Gyro (left)	13	1372	-166.72	0.0
Forward Payload Gyro	14	1502	0.0	0.0

Axis

Roll
Pitch
Yaw

Direction

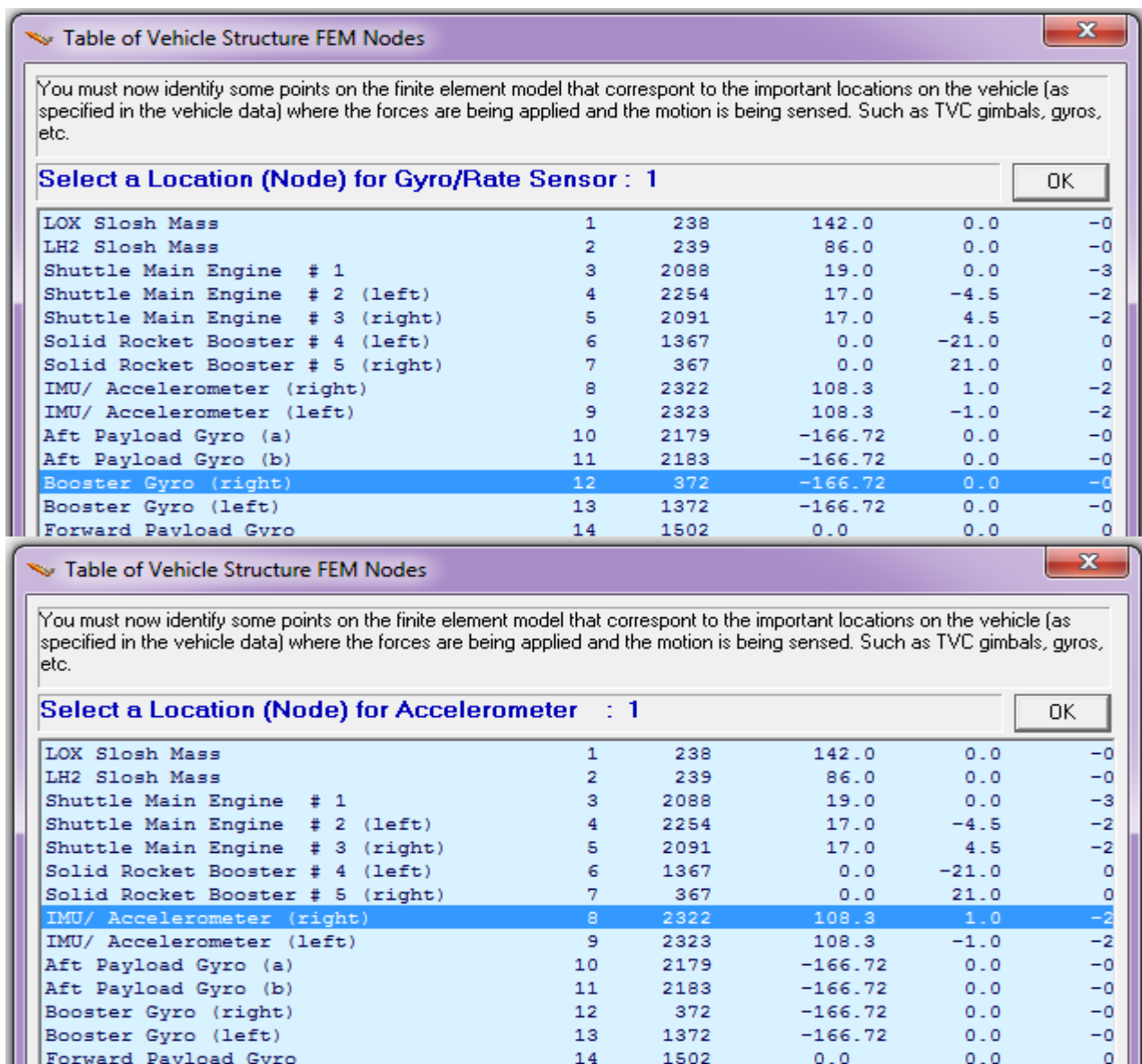
+ (positive)
- (negative)

The mode selection process, however, is not finished yet because the program needs additional information from the user in order to calculate the modal strength and selecting the modes. The next step is to match important vehicle locations (such as engine gimbals, sensors, slosh mass locations, which are specified in the vehicle input data) with their corresponding structure locations. The important vehicle locations are determined by the mode selection program from the vehicle input data. These locations must be matched with the corresponding nodes in the modal data. The mapping between structure and vehicle locations in the input data is performed by the user using menus similar to the previous menus but this time it is for a different purpose. The program expects the user to identify nodes for the 5 engines, the 3 gyros (roll, pitch, and yaw), the 2 accelerometers (Ny and Nz), the 2 slosh masses (LOX and LH2), and one additional node for an optional disturbance point, not used in this example. Notice, that each sensor in the flight vehicle input data measures only one direction.

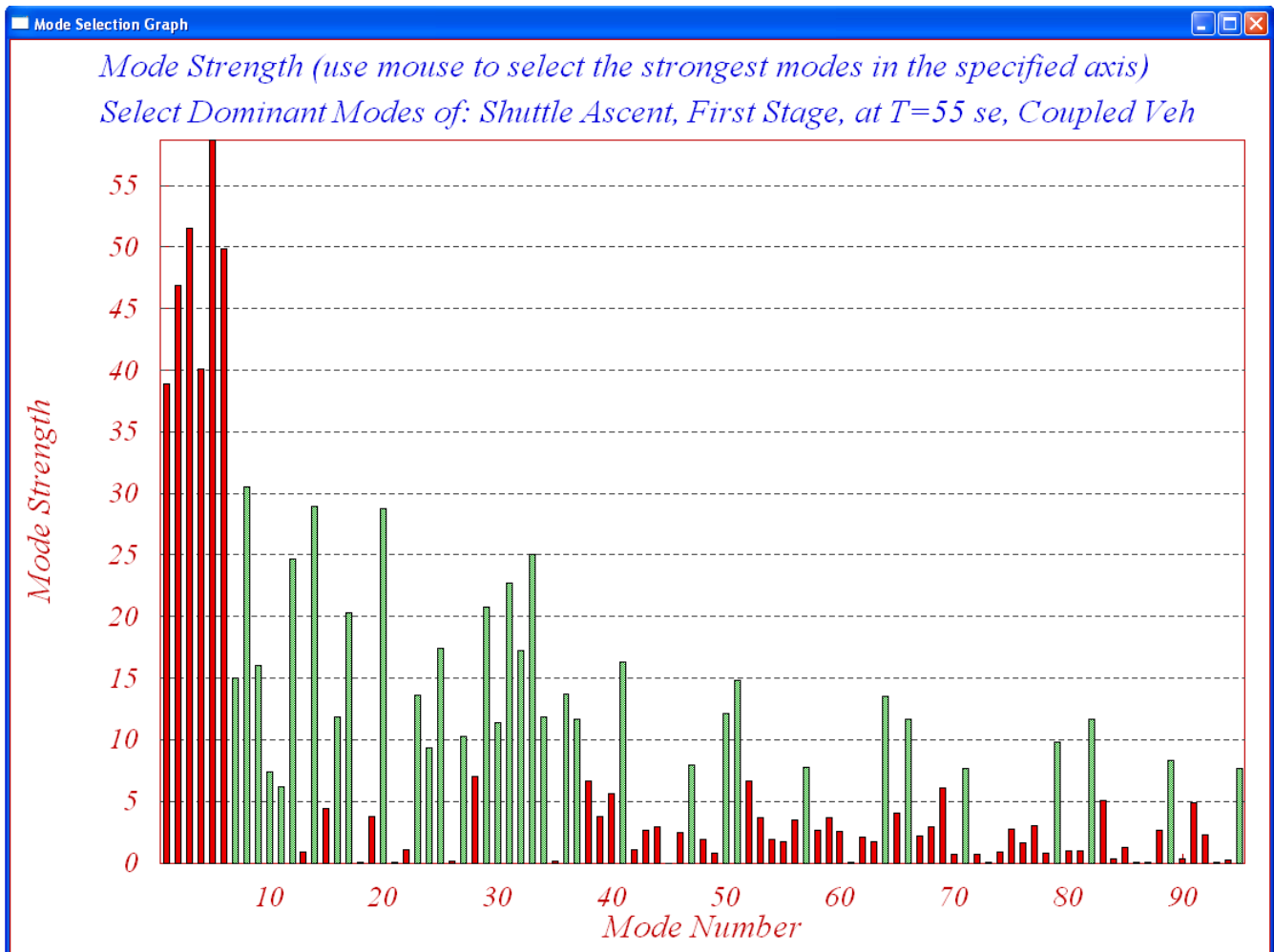
Notice, that each sensor in the flight vehicle input data measures only one direction. If you want a measurement in 3 axes you must define 3 separate sensors. For the three (roll, pitch, yaw) gyros we must select node #12 three times, and for the two (Ny and Nz) accelerometers we select node #8 twice. We also choose nodes #1 and #2 for the LOX and the LH2 slosh masses respectively, and one disturbance point that we are not using in this example.

Table of Vehicle Structure FEM Nodes					
You must now identify some points on the finite element model that correspond 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 Thruster Engine : 1					OK
LOX Slosh Mass	1	238	142.0	0.0	-0
LH2 Slosh Mass	2	239	86.0	0.0	-0
Shuttle Main Engine # 1	3	2088	19.0	0.0	-3
Shuttle Main Engine # 2 (left)	4	2254	17.0	-4.5	-2
Shuttle Main Engine # 3 (right)	5	2091	17.0	4.5	-2
Solid Rocket Booster # 4 (left)	6	1367	0.0	-21.0	0
Solid Rocket Booster # 5 (right)	7	367	0.0	21.0	0
IMU/ Accelerometer (right)	8	2322	108.3	1.0	-2
IMU/ Accelerometer (left)	9	2323	108.3	-1.0	-2
Aft Payload Gyro (a)	10	2179	-166.72	0.0	-0
Aft Payload Gyro (b)	11	2183	-166.72	0.0	-0
Booster Gyro (right)	12	372	-166.72	0.0	-0
Booster Gyro (left)	13	1372	-166.72	0.0	-0
Forward Payload Gyro	14	1502	0.0	0.0	0

The user must also enter a short label that will be included in the end of the selected modes title. To identify, for example, the type of modes.



At this point a bar chart comes up on a screen dialog from where the user can select the dominant flex modes. It shows the modal strengths by means of vertical red bars, and the height of each bar is logarithmically proportional to the relative mode strength. The mode strengths were calculated between the 5 engine forces and the roll sensor. The results would have been different if different forces and measuring directions were chosen. The strong modes are tall and the weak modes are short. The modal strength is not a physical number but it is measured relative to the weakest mode. The user manually selects some of the strongest modes by pointing the mouse cursor at the bar and clicking the mouse. The modes change color from red to green when they are selected. Notice, that the first six modes, although strong, they were not selected because they are rigid-body modes. The rigid-body dynamics are already included in the vehicle model. The mode selection was repeated in all three roll, pitch and yaw directions in order to capture the dominant modes in all 3 rotational axes. In yaw axis selection the 5 excitation forces are pointed in the +Y direction and the gyro sensor is placed in the same structural location but measuring in the positive yaw direction.



The bar chart above is showing the relative mode strength for each mode and the selected modes are shown in green. In this case we select 29 flex modes (from all 3 directions) and press the "Enter" key to complete the mode selection. The mode selection program will create a smaller subset of the original modal data set and it will save it in the input data file "Shuttle-Stg1-T55.Inp", under a separate title: "Flex Modes for Shuttle Ascent, Max_Q, T=55 sec". The selected modal data-set will contain modal frequencies and mode shapes only for the selected modes and only at the locations defined in the flight vehicle model, such as, the engine gimbals, the sensors, the slosh mass locations, and the disturbance point.

Before closing, the mode selection program the user may also type-in some notes regarding the conditions and criteria applied in the mode selection process for book keeping purposes. The notes describe, for example, information regarding what kind of modes were selected and the conditions of mode selection, the excitation and measurement points, directions, etc. This information will be included as comments below the title in the selected modes set in file "Shuttle-Stg1_T55.Inp". The title of the selected modes set must also be included at the bottom of the flexible vehicle input data set (below the number of flex modes). This is how the flight vehicle modeling program will associate the flex modes with the vehicle input data.

2.2 Processing the Input Data in Batch Mode

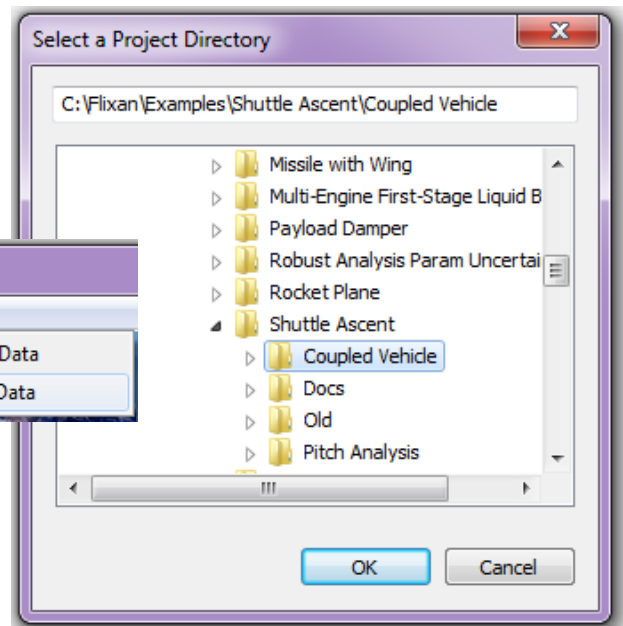
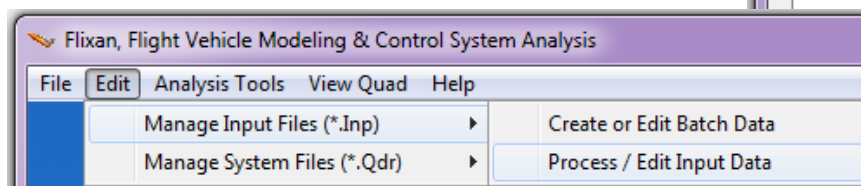
The systems which are already saved in file “*Shuttle_Stg1_T55.Qdr*” are Flixan generated systems that have been created after processing the input data file “*Shuttle_Stg1_T55.Inp*”. The only matrix in this systems file that is not a Flixan output but it has been manually placed there is the TVC matrix on the top of the file. This matrix must be preserved in the systems file after reprocessing it. We will now process the input data in batch mode because it is much faster. Batch processing requires a batch data-set that is usually located at the top of the input data file. Let us take a look inside the input file: “*Shuttle_Stg1_T55.Inp*”.

1. The first set of data in this file is a batch for processing the remaining data-sets in batch mode. Its title is “*Batch for preparing the Shuttle Ascent, First Stage Max-Q, Coupled Axes Models*”. Below the title there are comment lines describing the models created by this file, followed by the batch instruction lines. Each batch instruction line corresponds to a data-set in the file that will be processed by Flixan. Notice that the first instruction line “*Retain Matrix: Shuttle Stage-1 TVC Matrix at Max-Q*” is for preserving the TVC matrix after re-processing the systems file.
2. The next two data-sets below the batch generate two vehicle models in the same max-Q flight condition. The first one is a rigid-body model and its title is “*Shuttle Ascent, Max_Q, T=55 sec (Rigid Body)*”. The second one is a high order model that includes flexibility, slosh, and tail-wag-dog dynamics. Its title is “*Shuttle Ascent, Max_Q, T=55 sec, Flex Vehicle with Slosh and TWD*”. This system is also discretized at 40 (msec) by an s to z transform set. Its title is “*Shuttle Ascent, Max_Q, T=55 sec, Flex Vehicle with Slosh and TWD, Z-transform*”. These systems are also saved in files “*Vehicle_rb.m*”, “*Vehicle_flex_s.m*”, and “*Vehicle_flex_z.m*”, which are loaded into Matlab for further analysis.
3. The next data-set is a collection of 29 selected modes both symmetric and anti-symmetric which are combined with the second vehicle model and introduce flexibility in the model. The selection of this set of modes by the mode-selection process was described in section (2.1). The modal data title is “*Flex Modes for Shuttle Ascent, Max_Q, T=55 sec*” and it is also included in the vehicle data.
4. The next two data-sets are actuator data used to generate actuator models for the Shuttle main engines and for the rocket booster nozzles. Their titles are: “*Shuttle Main Engine Actuator*” and “*Solid Rocket Booster Actuator*” respectively. The actuator model outputs include deflection, rate, and acceleration. The inputs include deflection command and load-torque feedback. These two systems are also saved in files “*Actuator_ssme.m*” and “*Actuator_srb.m*” for Matlab analysis.
5. The next set of data combines 5 actuators together in parallel, 3 SSMEs and 2 SRBs. Its title is “*System of Five Actuators*”. This system is also discretized at 40 (msec) and its title is “*System of Five Actuators, Z-Transform*”. Two of these systems will be used, one for pitch and one for yaw TVC deflections. The continuous and discrete actuator combination systems are also saved in files “*Actuators_5s.m*” and “*Actuators_5z.m*” respectively.
6. The next data-set consists of 8 transfer-functions used to represent the sensor dynamics (IMU, gyros, and accelerometers). Its title is “*IMU, Gyro, Accelerometer Sensors*”. This system is also

discretized at 40 (msec) and its title is *"IMU, Gyro, Accelerometer Sensors, Z-transform"*. This system is also saved in file *"Sensors_z.m"*.

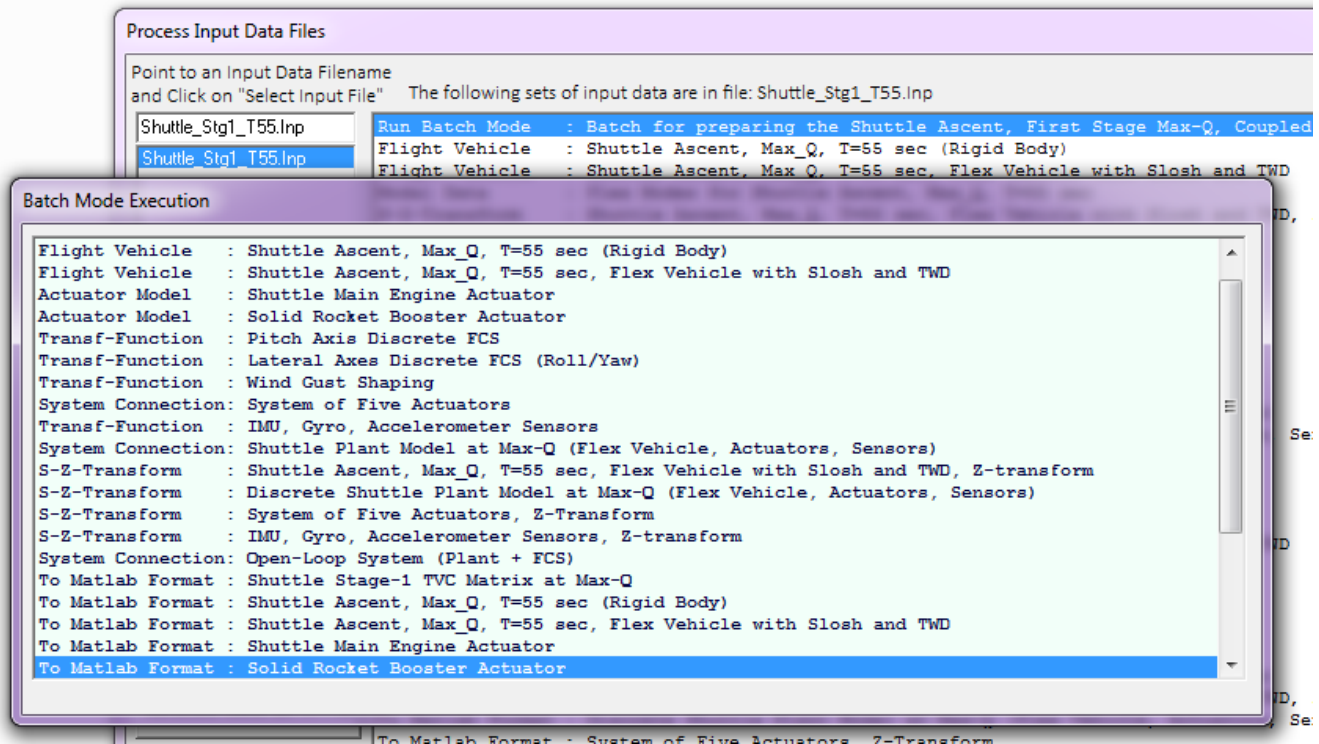
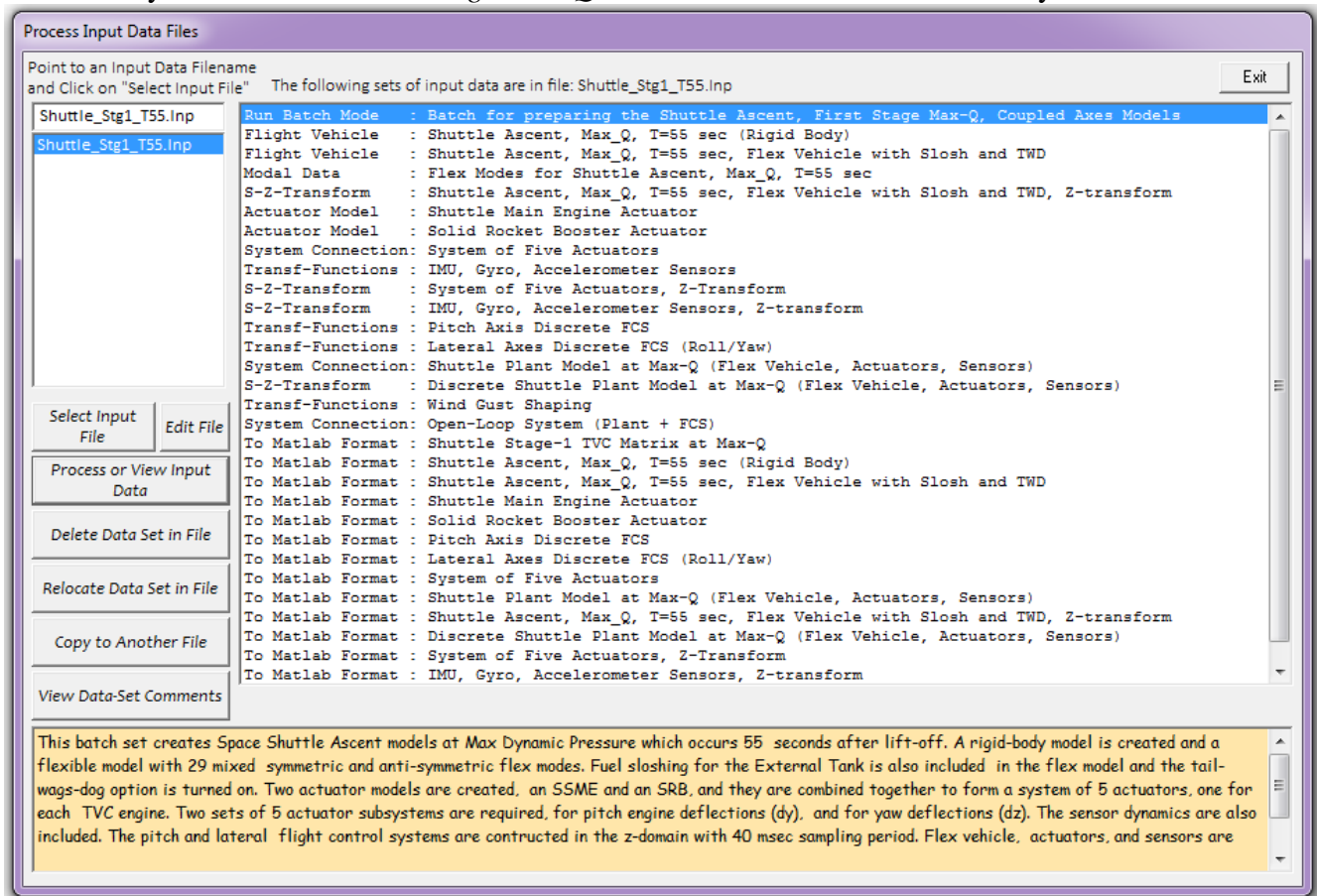
7. The next two sets are transfer-function systems that define the pitch and lateral discrete flight control system for the Space Shuttle at max-Q. The sampling rate is 40 (msec). Their titles are *"Pitch Axis Discrete FCS"* and *"Lateral Axes Discrete FCS (Roll/Yaw)"*. Flixan converts these transfer-function interconnection data-sets to state-space systems. These system are also saved in files *"Pitch_FCS.m"* and *"Lateral_FCS.m"* respectively for Matlab analysis.
8. The next data-set is a systems interconnection that combines the flexible pitch vehicle model with the actuators, and the sensor dynamics in a single continuous subsystem. The interconnection includes tail-wag-dog and load-torque feedback dynamics as already described. Its title is *"Shuttle Plant Model at Max-Q (Flex Vehicle, Actuators, Sensors)"*. This system is discretized at 40 (msec) using the s to z conversion utility. The discrete system's title is *"Discrete Shuttle Plant Model at Max-Q (Flex Vehicle, Actuators, Sensors)"*. These two systems are also saved in files *"Vehi_Plant_s.m"* and *"Vehi_Plant_z.m"* for Matlab analysis.
9. The next set is a transfer function used for shaping a gust pulse. Its title is *"Wind Gust Shaping"*.
10. The next data-set is a systems interconnection that combines four discrete systems together: the discrete plant model created in step-8, the discrete pitch and lateral flight control systems created in step-7, and the wind-gust shaping filer created in step-9. Its title is *"Open-Loop System (Plant + FCS)"*. This system is also saved in file *"open_loop.m"*.
11. The remaining data-sets are used to convert the systems from file *"Shuttle_Stg1_T55.Qdr"* to Matlab format and they will be loaded in Matlab to perform system analysis.

To run the batch mode utility in Flixan you must first select the project directory *"...Examples\ Shuttle Ascent\ Coupled Vehicle"* and go to the Flixan main menu and click on *"Edit"*. Then go to *"Manage Input Files"*, and then *"Process/ Edit Input Data"*.

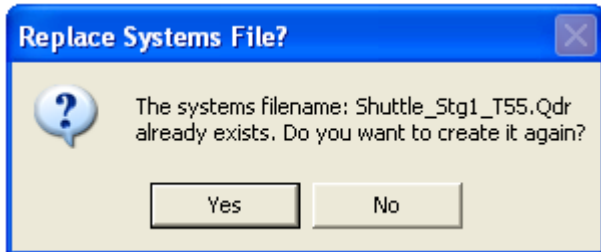


This will open the utility dialog for processing input data, as shown below. The menu in the upper left hand side of the dialog displays all the input data files (having an extension .inp) existing in the project directory. In this case there is only one input data file *"Shuttle_Stg1_T55.Inp"* and we select it by clicking on *"Select Input File"*. The menu on the right side shows the data-sets which are included in file *"Shuttle_Stg1_T55.Inp"*. It shows the utility program that will be used for processing each set followed by the title of the data set in one line. Each set may be processed individually, but in this case we select the batch set on the top to process them all together

and click on “*Process or View Input Data*” to process the batch. Flixan will process the input file and create the systems in file “*Shuttle_Stg1_T55.Qdr*”. It will also create the Matlab system files.



The batch utility will save all the systems generated by the various Flixan programs in the systems file “*Shuttle_Stg1_T55.Qdr*”. Since this file already exists and it may contain info that needs to be saved, the batch processing program will ask the user if he wants to replace the old systems file with a new “*Shuttle_Stg1_T55.Qdr*” file. In this case we answer “Yes” because the TVC matrix is preserved with a “Retain Matrix” statement in the batch set.



The above display shows the batch instructions while Flixan is processing the data. Each statement line calls a separate Flixan utility program and passes it the title of the corresponding input data. The instruction line is highlighted while it is being processed. The batch executes each instruction line separately starting from the top of the list. The utility program processes the data, creates a system and saves it in the systems file. It is also calling the “Export to Matlab” utility which converts the subsystems to Matlab format. Let us now take a closer look at each instruction line in the batch.

1. **Retain Matrix: Shuttle Stage-1 TVC Matrix at Max-Q:** The first instruction is for preserving the TVC matrix in the systems file “*Shuttle_Stg1_T55.Qdr*” when you re-process the input data.
2. **Flight Vehicle: Shuttle Ascent, Max_Q, T=55 sec (Rigid Body):** This instruction calls the flight vehicle modeling program to create a rigid body model for the Shuttle vehicle at max dynamic pressure.
3. **Flight Vehicle: Shuttle Ascent, Max_Q, T=55 sec, Flex Vehicle with Slosh and TWD:** This instruction also calls the flight vehicle modeling program to create a high order Shuttle model at max dynamic pressure that includes TWD, flex, and slosh. It uses the modal data set “**Flex Modes for Shuttle Ascent, Max_Q, T=55 sec**”, which was created in Section 2.1.
4. **Actuator Model: Shuttle Main Engine Actuator:** This instruction calls the actuator modeling program to create a hydraulic type-B model for the SSME, using the SSME parameters.
5. **Actuator Model: Solid Rocket Booster Actuator:** This instruction calls the actuator modeling program to create a hydraulic type-B model for the SRB, using the SRB parameters.
6. **Transf-Function: Pitch Axis Discrete FCS:** This instruction calls the transfer function modeling program to create a state-difference system (sampled at 40 msec) for the discrete pitch flight control system at Max-Q.
7. **Transf-Function: Lateral Axes Discrete FCS (Roll/Yaw):** This instruction calls the transfer function modeling program to create a state-difference system (sampled at 40 msec) for the discrete lateral flight control system at Max-Q.

8. **Transf-Function: Wind Gust Shaping:** This is a discrete second order transfer function used for wind gust modeling. It shapes a square pulse (generated by Simulink) to a smoother and more realistic gust excitation input.
9. **System Connection: System of Five Actuators:** This instruction uses the systems interconnection program to combine five actuators in parallel, three SSME and two SRB state-space systems obtained in steps 4 and 5.
10. **Transf-Function: IMU, Gyro, Accelerometer Sensors.** This instruction uses the transfer function interconnection program to generate a combined state-space model for the IMU, rate gyro, and accelerometer sensor dynamics, which are defined in terms of transfer functions.
11. **System Connection: Shuttle Plant Model at Max-Q (Flex Vehicle, Actuators, Sensors):** This instruction uses the systems interconnection program to create a continuous plant model consisting of the flex vehicle, the sensors, and two sets of 5 actuator subsystems, obtained in steps 3, 10, and 9. One set of 5-actuators is used to drive the pitch gimbals, and the other set drives the yaw gimbals for the five vehicle engines.
12. **S-Z-Transform: Shuttle Ascent, Max_Q, T=55 sec, Flex Vehicle with Slosh and TWD, Z-transform:** This instruction discretizes the flexible vehicle model created in step-3, using the z-transform and a 40 msec sampling rate.
13. **S-Z-Transform: Discrete Shuttle Plant Model at Max-Q (Flex Vehicle, Actuators, Sensors):** In this step we discretize the plant model created in step-11, using the z-transform and a 40 msec sampling rate
14. **S-Z-Transform: System of Five Actuators, Z-Transform:** In this step we discretize the system of five parallel actuators created in step-9, using the z-transform and a 40 msec sampling rate.
15. **S-Z-Transform: IMU, Gyro, Accelerometer Sensors, Z-transform:** This instruction discretizes the flight control sensors subsystem which was created in step-10, using the z-transform and a 40 msec sampling rate.
16. **System Connection: Open-Loop System (Plant + FCS):** This instruction uses the systems interconnection program to combine four discrete subsystems and a matrix: (a) the discrete plant model obtained in step-13, (b) the pitch flight control system obtained in step-6, (c) the lateral flight control system obtained in step-7, (d) the wind-gust shaping function obtained in step-8, and (e) the thrust vector control matrix TVC that was already in the systems file and was retained by step-1. It combines all these subsystems and creates an open-loop system. This system will be loaded to Matlab for frequency domain analysis and simulations. The feedback loops will be closed in the Simulink models.
17. **To Matlab Format: Shuttle Stage-1 TVC Matrix at Max-Q:** This instruction converts the TVC matrix to Matlab -ascii format in file "*TVC.Mat*".

18. **To Matlab Format: Shuttle Ascent, Max_Q, T=55 sec (Rigid Body):** This instruction converts the rigid-body vehicle model to Matlab format in file “*Vehicle_rb.m*”.
19. **To Matlab Format: Shuttle Ascent, Max_Q, T=55 sec, Flex Vehicle with Slosh and TWD:** Converts the flexible vehicle model to Matlab format in file “*Vehicle_flex_s.m*”.
20. **To Matlab Format: Shuttle Main Engine Actuator:** Converts the SSME actuator model to Matlab format in file “*Actuator_ssme.m*”.
21. **To Matlab Format: Solid Rocket Booster Actuator:** Converts the SRB actuator model to Matlab format in file “*Actuator_srb.m*”.
22. **To Matlab Format: Pitch Axis Discrete FCS:** Converts the discrete pitch flight control system to Matlab format in file “*Pitch_fcs.m*”.
23. **To Matlab Format: Lateral Axes Discrete FCS (Roll/Yaw):** Converts the discrete lateral flight control system to Matlab format in file “*Lateral_fcs.m*”.
24. **To Matlab Format: System of Five Actuators:** Converts the combined system of five actuators to Matlab format in file “*Actuators_5s.m*”.
25. **To Matlab Format: Shuttle Plant Model at Max-Q (Flex Vehicle, Actuators, Sensors):** Converts the combined plant model to Matlab format in file “*Vehi_Plant_s.m*”.
26. **To Matlab Format: Shuttle Ascent, Max_Q, T=55 sec, Flex Vehicle with Slosh and TWD, Z-transform:** Converts the discrete flex vehicle model to Matlab format in file “*Vehicle_flex_z.m*”.
27. **To Matlab Format: Discrete Shuttle Plant Model at Max-Q (Flex Vehicle, Actuators, Sensors):** Converts the discrete plant model to Matlab format in file “*Vehi_Plant_z.m*”.
28. **To Matlab Format: System of Five Actuators, Z-Transform:** Converts the discrete system of five actuators to Matlab format in file “*Actuators_5z.m*”.
29. **To Matlab Format: IMU, Gyro, Accelerometer Sensors, Z-transform:** Converts the discrete sensors subsystem to Matlab format in file “*Sensors_z.m*”.
30. **To Matlab Format: Open-Loop System (Plant + FCS):** Converts the discrete open-loop system to Matlab format in file “*Open-Loop.m*”.

2.3 Lateral Axes Digital Flight Control System

The lateral flight control system is defined as a combination of discrete transfer functions sampled at 40 msec. The transfer function interconnections title is: “*Lateral Axes Discrete FCS (Roll/Yaw)*” and the data are in file “*Shuttle_Stg1_T55.Inp*”. The flight control system inputs are: yaw attitude error (Ψ_e) in (radians), roll attitude error (Φ_e) in (radians), yaw rate (r), roll rate (p), in (rad/sec), and lateral acceleration (N_y) in (ft/sec^2). The outputs are roll and yaw flight control demands (DP_TVC and DR_TVC) to the thrust vector control matrix. The transfer functions interconnection program converts the data to a discrete state-space system. In this case it is executed by the batch. To run the transfer functions program manually, go to “*Analysis Tools*” then to “*Create State-Space Systems*” and then to “*Combine Transfer Functions*”. In the filename selection menu the user selects the input data and systems filenames used in this project. In the transfer functions interconnection title selection select “*Lateral Axes Discrete FCS (Roll/Yaw)*”. Run the selected set and the transfer function interconnections dialog appears showing the interconnection info. Click on “Run” to execute it. The program transforms the lateral FCS transfer function interconnection data into a state-space system and saves it in file “*Shuttle_Stg1_T55.Qdr*”, under the same title: “*Lateral Axes Discrete FCS (Roll/Yaw)*”. The discrete FCS is also exported to Matlab as a state-space system m-file “*lateral_fcs.m*” in directory “*\Shuttle Ascent\Coupled Vehicle*”. It will be combined with the vehicle and actuators to perform the lateral stability analysis and simulations.

2.4 Stability Analysis

This example is mainly for tutorial purposes and the stability analysis is performed using three different approaches of combining the various subsystems together. Three open-loop Simulink models were, therefore, created and used for stability analysis. They are dynamically equivalent producing very similar results but they were synthesized differently. Pitch and lateral are not separated but they are dynamically coupled. All models consist of three loops (roll, pitch, and yaw) and for stability analysis only one loop must remain open for frequency response analysis while the other two loops are closed. The Matlab file “run.m” loads the state-space subsystems for the vehicle, actuators, pitch and lateral flight control systems, and the TVC matrix to the Matlab workspace. They were created by the batch in section 2.1 and converted to Matlab format as m-functions. The file “run.m” uses these open-loop models to calculate the Nichols and Bode plots for stability analysis.

```

r2d= 180/pi; d2r=1/r2d; Ts=0.04;
[Afls,Bfls,Cfls,Dfls]= vehicle_flex_s;
[Aflz,Bflz,Cflz,Dflz]= vehicle_flex_z;
[Alfc,Blfc,Clfc,Dlfc]= lateral_fcs;
[Apfc,Bpfc,Cpfc,Dpfc]= pitch_fcs;
[Azpl,Bzpl,Czpl,Dzpl]= vehi_plant_z;
[Acts,Bcts,Ccts,Dcts]= actuators_5s;
[Actz,Bctz,Cctz,Dctz]= actuators_5z;
[Asz, Bsz, Csz, Dsz] = sensors_z;
[Aol, Bol, Col, Dol] = open_loop;
load TVC.Mat -ascii

% Radian to degree converts
% Shuttle Ascent, Max_Q, T=55 sec, Flex Vehicle with Slosh and TWD
% Discrete Shuttle Plant Model at Max-Q (Flex Vehicle, Actuators, Sensors)
% Lateral Flight Control System
% Pitch Flight Control System
% Load Discrete Plant (Vehi,Actuat,Sensors)
% System of Five Actuators
% System of Five Actuators, Z-Transform
% IMU, Gyro, Accelerometer Sensors, Z-transform
% Open-Loop System (Plant + FCS)
% Shuttle Stage-1 TVC Matrix at Max-Q

[As,Bs,Cs,Ds]= dlinmod('Sensitivity',0.04);
[Ao,Bo,Co,Do]= dlinmod('Open_Flex1',0.04);
%[Ao,Bo,Co,Do]= dlinmod('Open_Flex2',0.04);

% Create Open-Loop SS System
% Create Closed-Loop SS System
% Define Frequ Range
% Plot Nichol's Chart
% Plot Bode
% Plot Nyquist

syso= SS(Ao,Bo,Co,Do,Ts);
syss= SS(As,Bs,Cs,Ds,Ts);
w=logspace(-2.5, 2, 24000);
figure(1); Nichols(syso,w)
figure(2); Bode(syso,w)
figure(3); Sigma(syss,w)

```

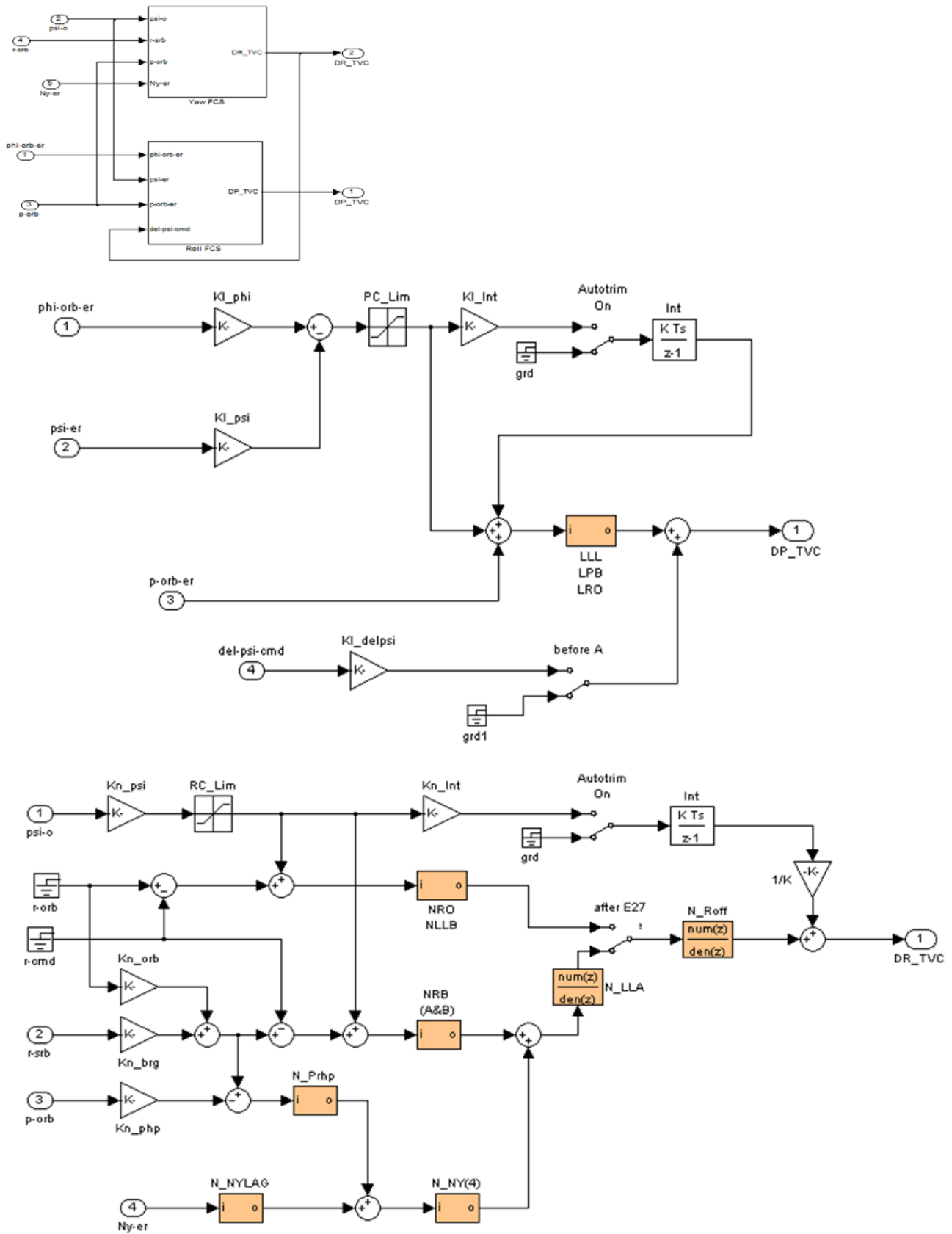



Figure (2.4.0) Shuttle Ascent Lateral Flight Control System

Option-1 All Subsystems Combined in Simulink

Figure (2.4.1) below shows the first open-loop analysis model where the subsystems that were created in Flixan are combined together using the Simulink model “*Open_Flex1.mdl*”. The frequency response analysis is performed using the file (run.m) in Matlab which calls the Simulink model.

Shuttle Stage-1 at Max-Q, Pitch and Lateral Coupled, Open-Loop Model-1

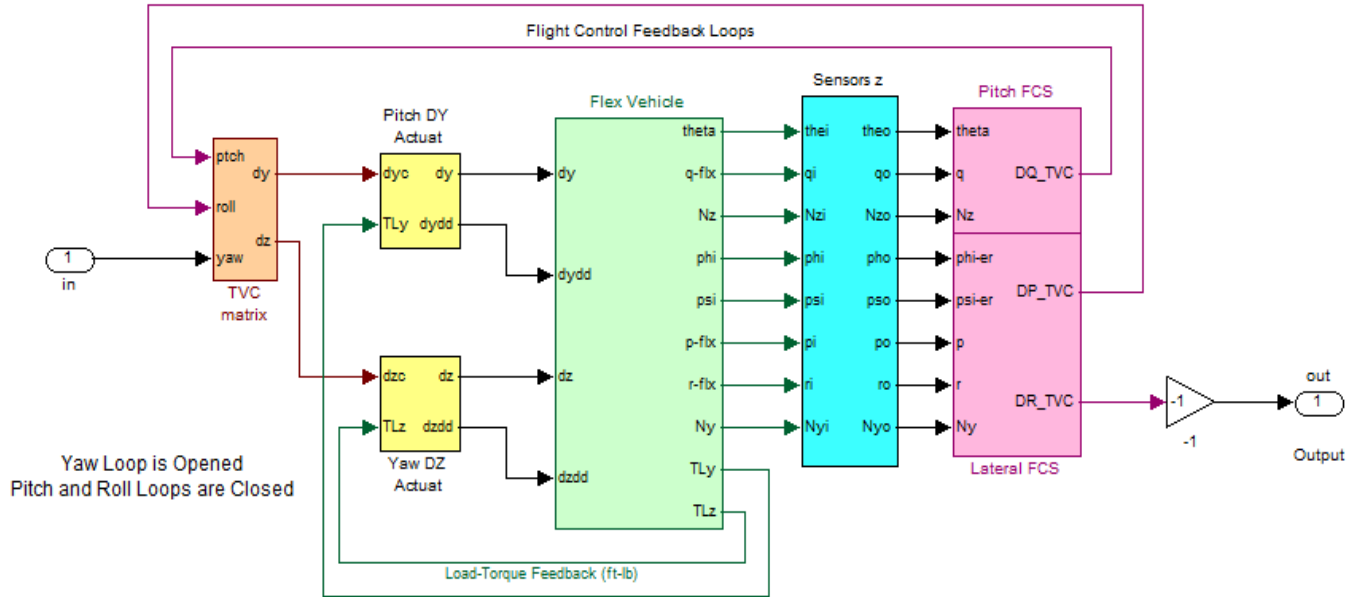
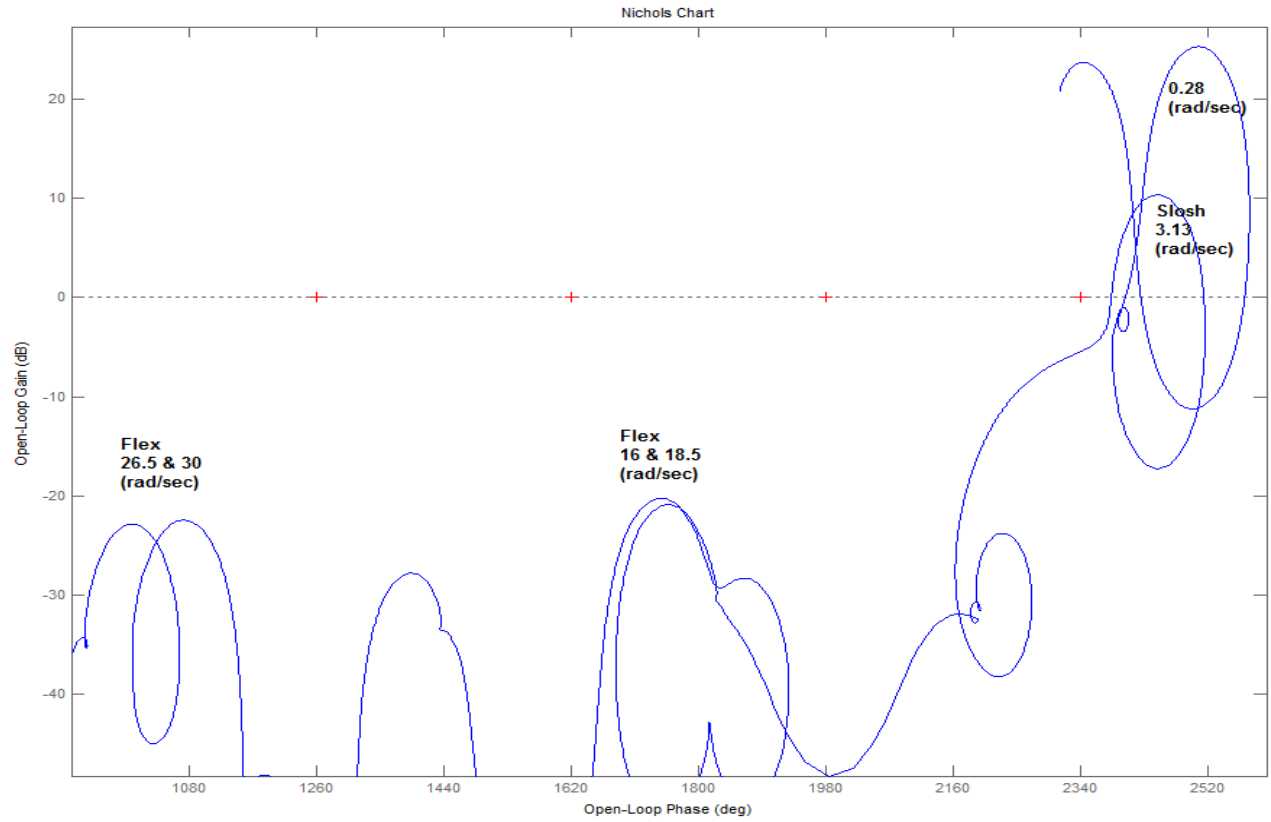


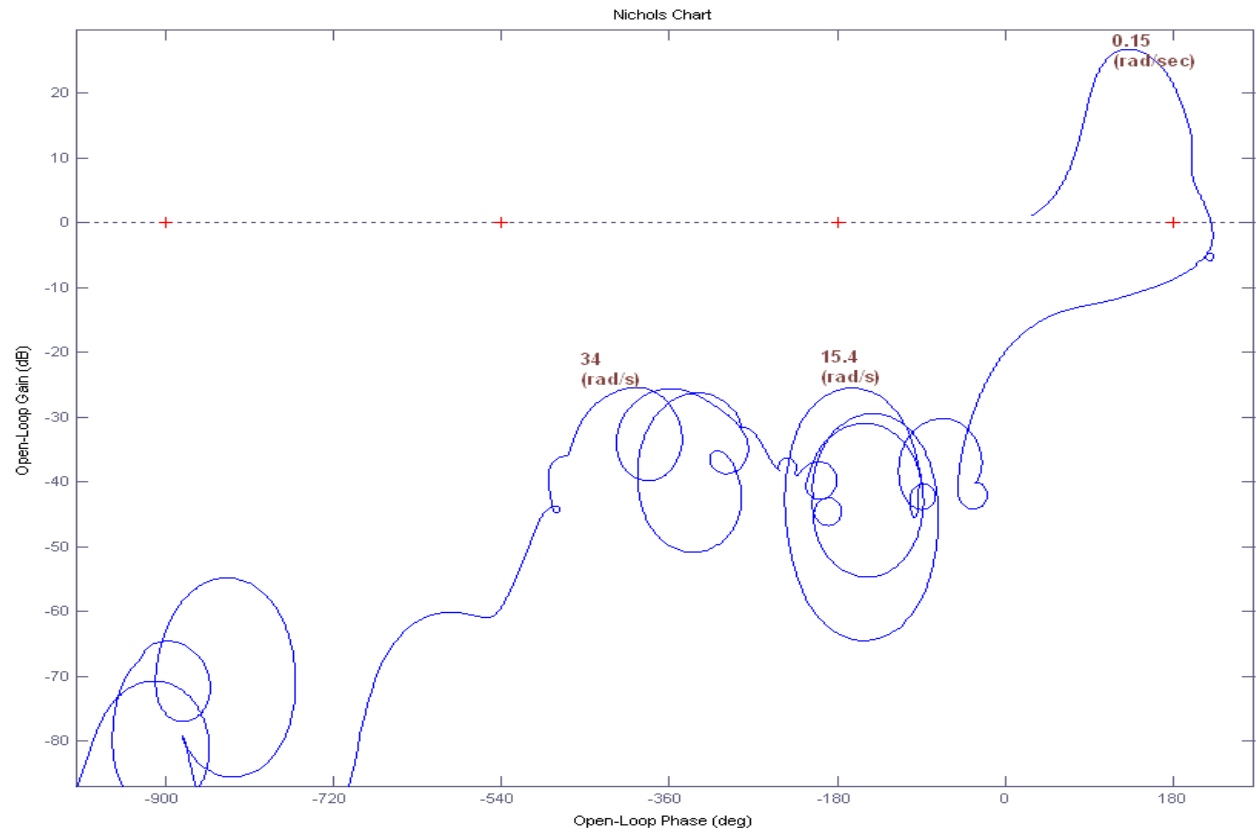
Figure 2.4.1 Simulink Model “*Open_Flex1.mdl*” for Open-Loop Analysis

The Matlab file creates the three Nichols plots, shown in Figure (2.4.2). The Simulink model in Figure (2.4.1) must be modified by opening and closing the appropriate loops before running the file run.m. For stability analysis we must open one loop at a time and close all the other loops. For yaw analysis, for example, we open the yaw loop and close the roll and pitch loops, as shown above. For roll analysis, on the other hand, we close the yaw and pitch loops and calculate the frequency response across the opened roll loop. We must include a (-1) gain in the opened loop in order to place the critical point correctly on the Nichols or the Nyquist plots (assuming positive feedback). The vehicle model is the continuous system “*Shuttle Ascent, Max_Q, T=55 sec, Flex Vehicle with Slosh and TWD*” from file “*vehicle_flex_s.m*”. The pitch and yaw actuator subsystems are “*System of Five Actuators*” loaded from file “*actuators_5s.m*”. The sensors subsystem is “*IMU, Gyro, Accelerometer Sensors, Z-transform*” loaded from file “*sensors_z.m*”. The TVC matrix is (10x3) loaded from file “*TVC.mat*” that converts the roll, pitch, and yaw flight control demands to pitch and yaw actuator deflection commands. The pitch and lateral FCS subsystems are loaded from files “*pitch_fcs.m*” and “*lateral_fcs.m*” respectively.

Pitch Axis Stability Analysis



Roll Axis Stability Analysis



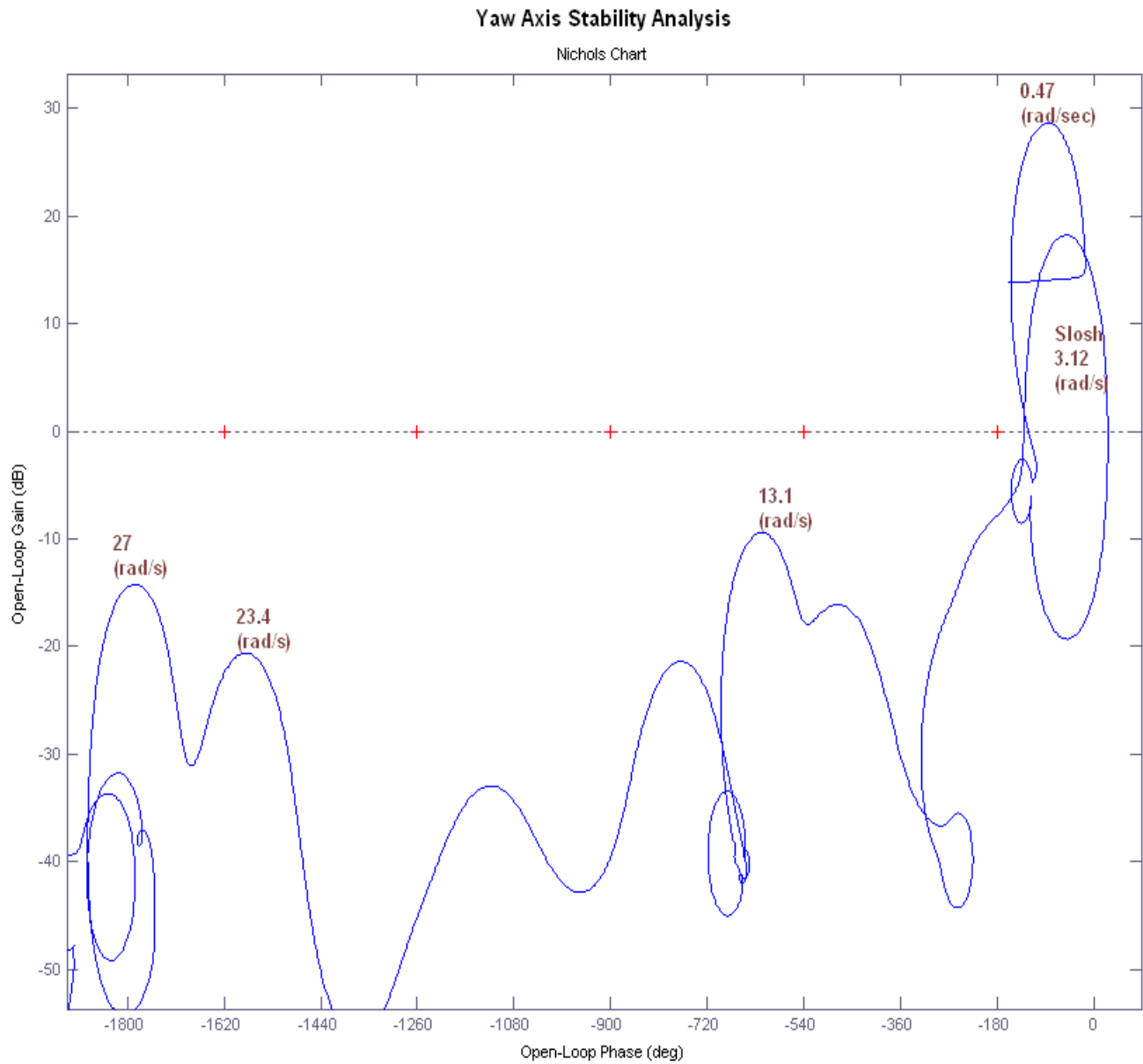


Figure (2.4.2) Nichols plots showing the stability margins in Roll, Pitch, and Yaw directions

Option-2 Plant Model Combined Using Flixan

The second open-loop configuration model uses the subsystems that were partially combined in Flixan and created the discrete plant “*Discrete Shuttle Plant Model at Max-Q (Flex Vehicle, Actuators, Sensors)*”. This model is loaded from file “*vehicle_flex_z.m*” and it is now running inside the green block in the Simulink model “*Open_Flex2.mdl*”, shown in Figure (2.4.3) below with the roll loop opened. The file (run.m) is used for the frequency response analysis.

Shuttle Stage-1 at Max-Q, Pitch and Lateral together, Open-Loop Model-2

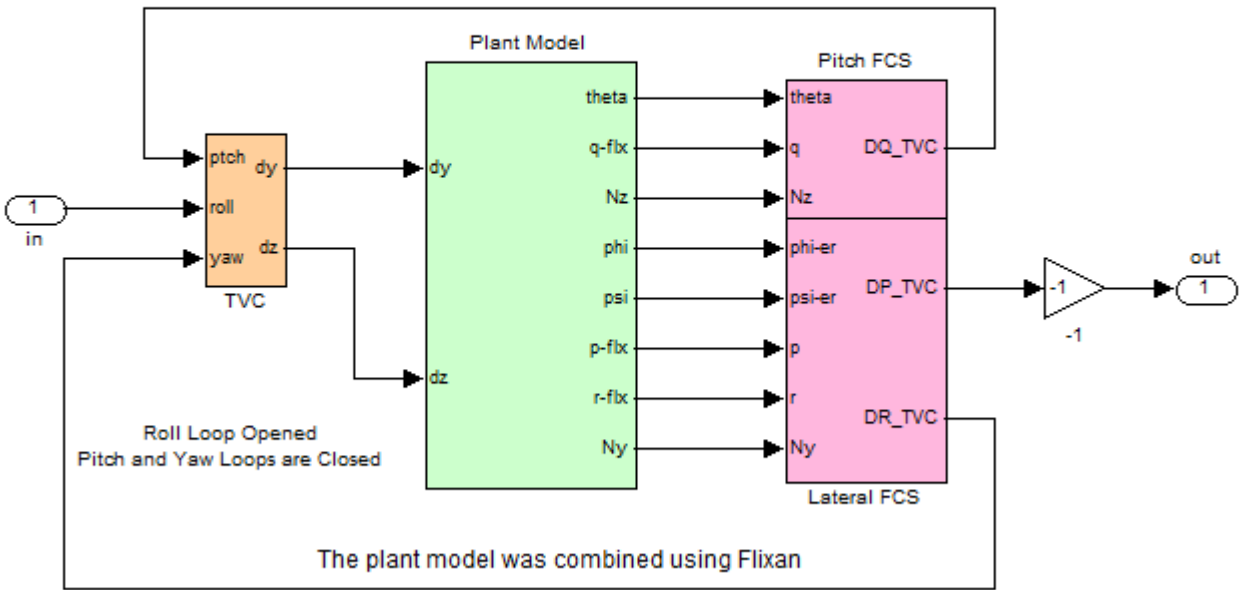


Figure 2.4.3 Simulink Model “*Open_Flex2.mdl*” for Open-Loop Analysis Using Option-2, (the plant model is combined using Flixan)

The Nichols plots in this case are very similar to the option-1 plots and they are not shown. There is a 4° difference, however, in the phase-margin. Option-1 has 4° less phase margin, possibly because Simulink has difficulty handling the 10 algebraic loops in the load-torque mechanical feedback.

Option-3 All Subsystems Combined in Flixan

In this configuration all the discrete subsystems were combined together in Flixan creating the discrete system “*Open-Loop System (Plant + FCS)*”. This model is loaded from file “*open-loop.m*” and it is running inside the green block in the Simulink model “*Open_Flex3.mdl*”, shown in Figure (2.4.4) below. In the case shown below, the roll loop opened (pitch and yaw are closed). The frequency response analysis is also performed using file (run.m) which must be modified to call the Simulink model “*Open_Flex3.mdl*”.

Shuttle Stage-1 at Max-Q, Pitch and Lateral together, Open-Loop Model-3

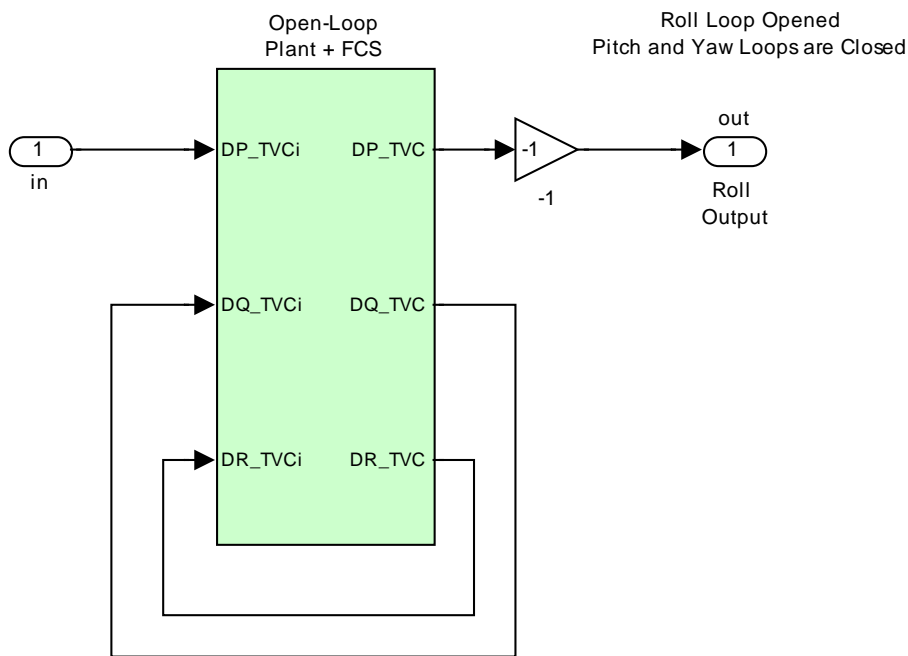


Figure 2.4.4 Simulink Model “*Open_Flex3.mdl*” for Open-Loop analysis using option-3

The Nichols plots in this case are identical to the option-2 plots. However, instead of Nichols in this case we are showing the Nyquist diagrams for the roll and pitch axes, see figures (2.4.5) and (2.4.6) respectively.

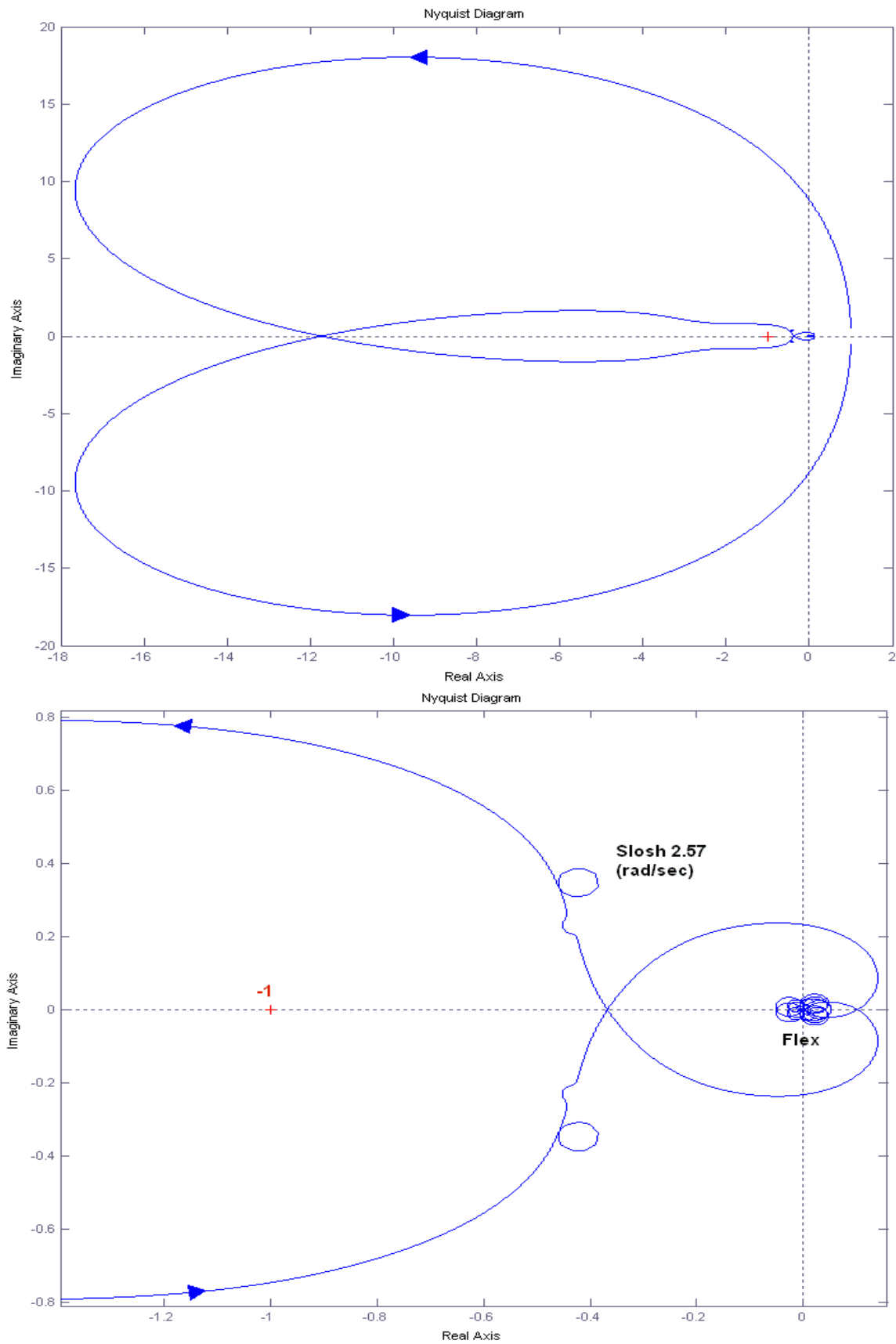


Figure 2.4.5 Nyquist diagrams showing stability in the roll axis. The lower figure expands the area near the origin

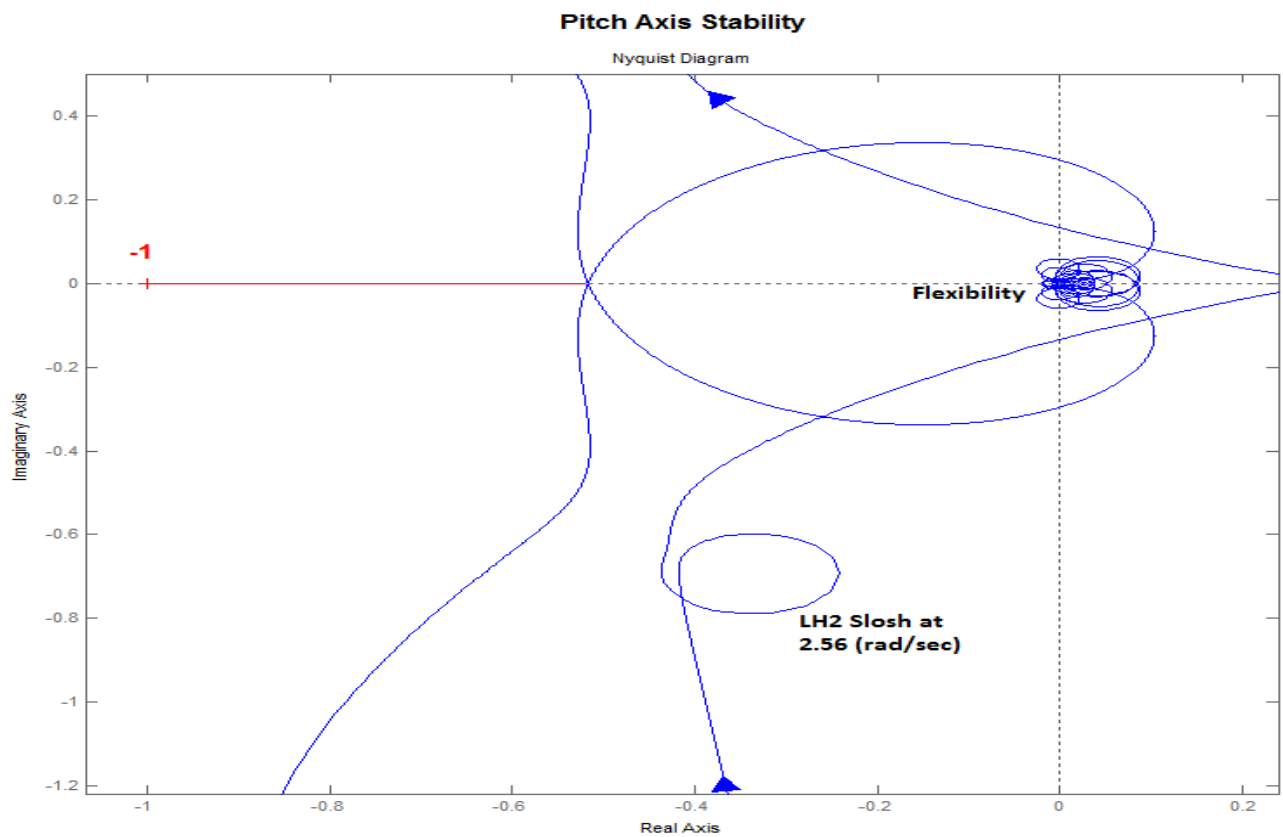
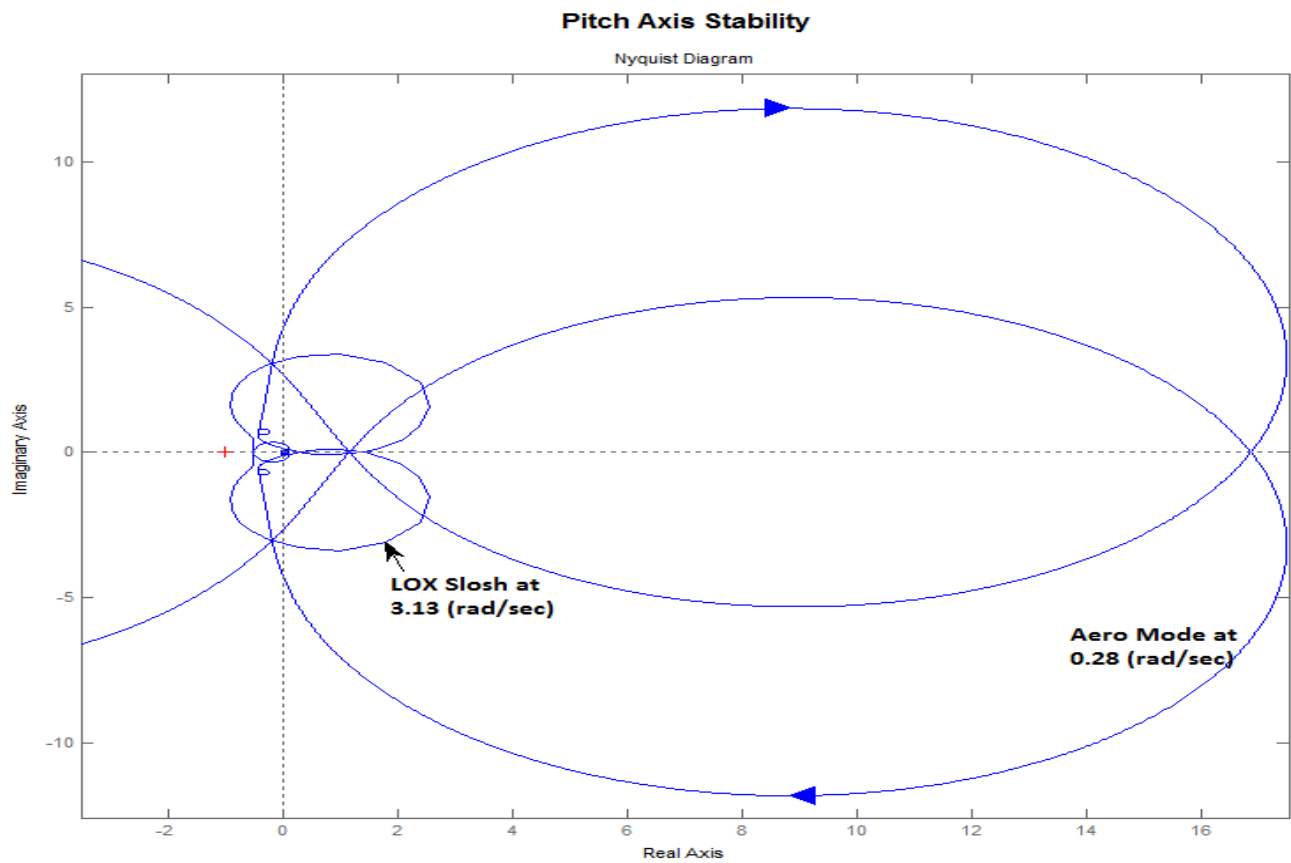


Figure 2.4.6 Nyquist diagrams showing stability in the pitch axis. The lower figure expands the area near the origin

2.5 Sensitivity Analysis to Wind Gusts

Figure (2.5.1) below is a closed-loop Simulink model in file “*Sensitivity.Mdl*”, used for analyzing the system's sensitivity to wind-gust disturbances. It is used to calculate the Singular Value frequency response between the wind-gust input and the vehicle output at the rate gyros. The SV sensitivity response is a measure of magnitude from all 3 gyros (roll, pitch, yaw) combined in response to the gust excitations across the relevant frequency range. The gust direction is defined in the vehicle data, set at (45° azimuth and 90° elevation) to excite both pitch and lateral dynamics simultaneously.

Shuttle Stage-1 at Max-Q, Pitch and Lateral Coupled, Closed-Loop Sensitivity Analysis Model

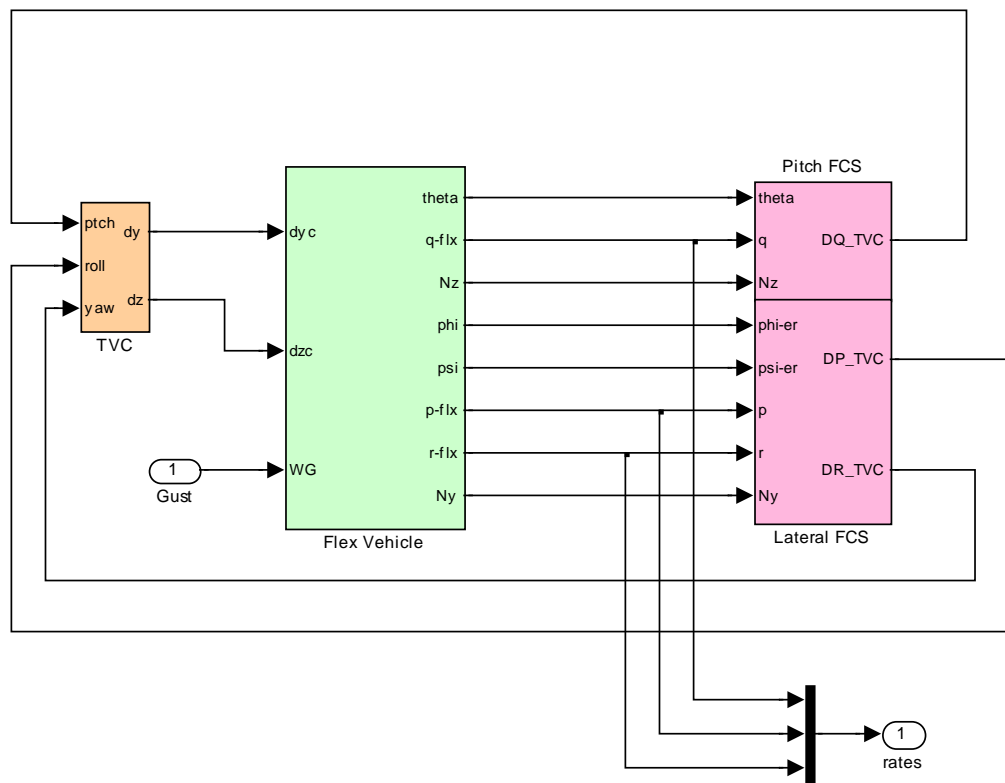


Figure 2.5.1 Wind-Gust Sensitivity Analysis Model “*Sensitivity.Mdl*”

The Matlab file “run.m” uses the closed-loop sensitivity model to calculate the sigma plot between gust and the 3 gyros, as shown in Figure (2.5.2) below. It indicates that the rate gyros are sensitive to the flex structure modes. It also shows a significant amount of sensitivity to aerodynamic disturbances at around 0.8 (rad/sec). The sensitivity is mainly in the lateral direction and it is an indicator that the Shuttle during ascent is sensitive to lateral wind disturbances in the frequency range between 0.1 to 0.14 Hz, at high dynamic pressures. This is an important finding because it shows that the vehicle is vulnerable to wind excitations in this frequency range as it crosses various layers of atmosphere having different wind speeds. The big vertical stabilizer amplifies this sensitivity to lateral winds which excite roll oscillations that have been observed in actual flights.

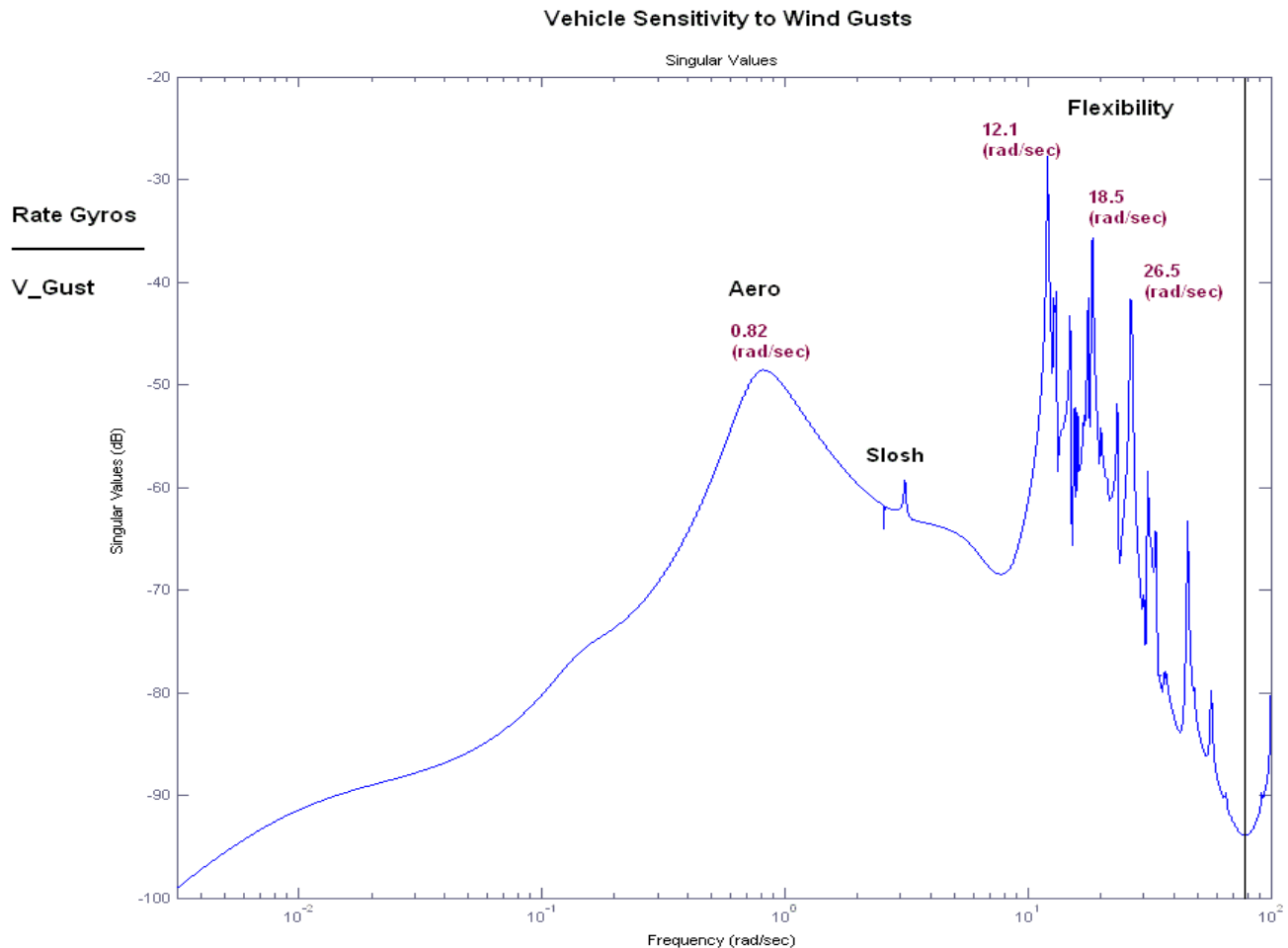


Figure 2.5.2 The Closed-Loop system is sensitive to Aero Disturbances at frequency 0.8 (rad/sec)

2.6 Coupled Vehicle Simulations

Similar to the stability analysis models, three Simulink models were created for simulation purposes in directory "Shuttle Ascent\Coupled Vehicle". They are dynamically equivalent, producing the same results, but they were synthesized differently. The first Simulink model is “*Sim-Flex1.mdl*”, shown in Figure (2.6.1), and it uses separate subsystems generated by Flixan and combined together in Simulink. The second implementation is “*Sim_Flex2.mdl*” consisting of a plant model (vehicle plus actuators) combined in Flixan, and the third model “*Sim_Flex3.mdl*” which is entirely combined and discretized using the Flixan program. A Matlab file “Pl.m” is used for plotting the simulation results.

Option-1 All Subsystems Combined in Simulink

The first closed-loop implementation is in Simulink file “*Sim_Flex1.mdl*”, shown in Figure (2.6.1) below. The subsystems in this model are the same as in Figure (2.4.1). They were created using Flixan and combined in Simulink as shown. The vehicle model is the continuous system “*Shuttle Ascent, Max_Q, T=55 sec, Flex Vehicle with Slosh and TWD*” from file “*vehicle_flex_s.m*”. The pitch and yaw actuator subsystems are “*System of Five Actuators*” loaded from file “*actuators_5s.m*”. The sensors subsystem is “*IMU, Gyro, Accelerometer Sensors, Z-transform*” loaded from file “*sensors_z.m*”. The pitch and lateral FCS subsystems are loaded from files “*pitch_fcs.m*” and “*lateral_fcs.m*” respectively, and the TVC matrix is loaded from file “*TVC.mat*”.

Shuttle Stage-1 at Max-Q, Pitch and Lateral Coupled, Closed-Loop Simulation Model-1

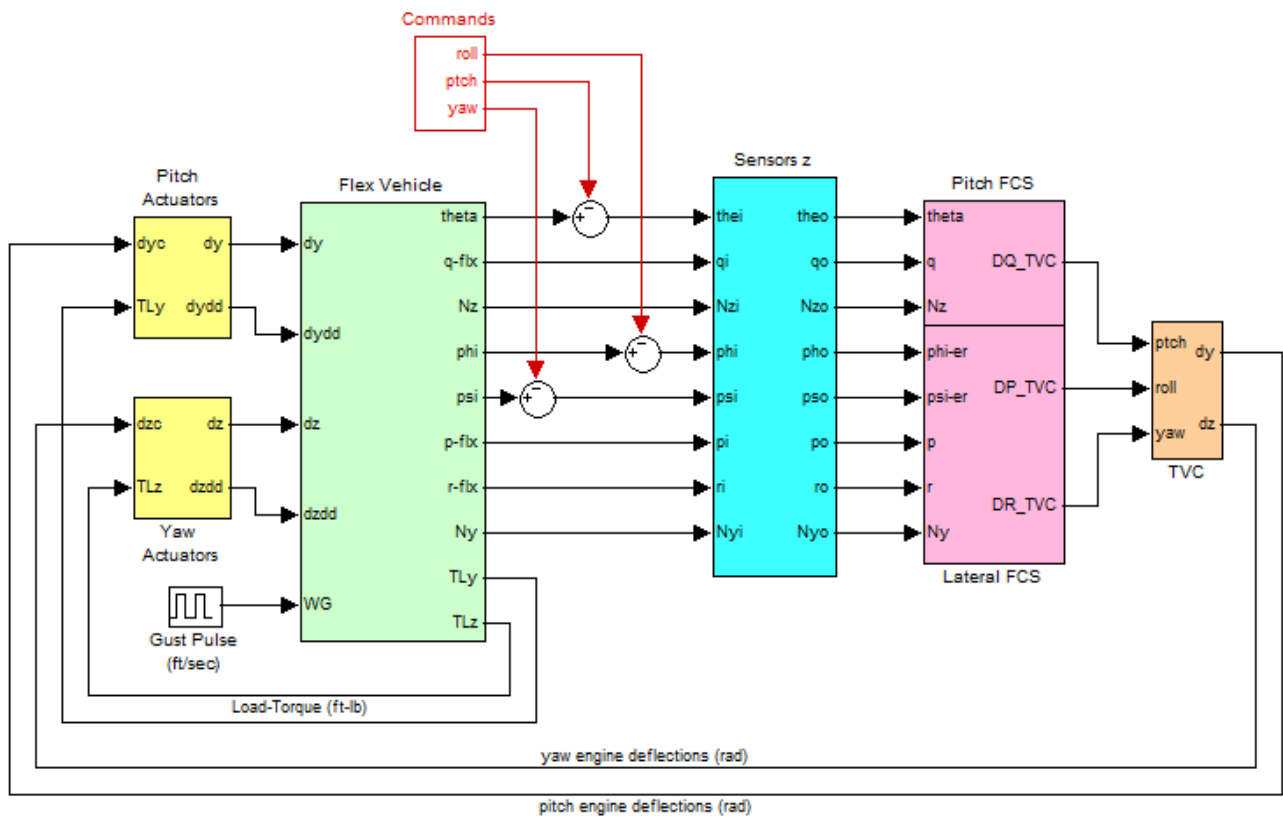


Figure 2.6.1 Closed-Loop Simulink Model “*Sim_Flex1.Mdl*” used for Simulations

Option-2 Plant Model Created in Flixan

In the second simulation model the flexible vehicle and the actuators are combined together using Flixan to create a discrete plant model which is included inside the green block in Figure (2.6.2). The discrete plant title is “*Discrete Shuttle Plant Model at Max-Q (Flex Vehicle, Actuators, Sensors)*”. The plant model is combined with the FCS, and the TVC by the Simulink model “*Sim_Flex2.mdl*” shown in Figure (2.6.2) below.

Shuttle Stage-1 at Max-Q, Pitch and Lateral Coupled, Closed-Loop Simulation Model-2

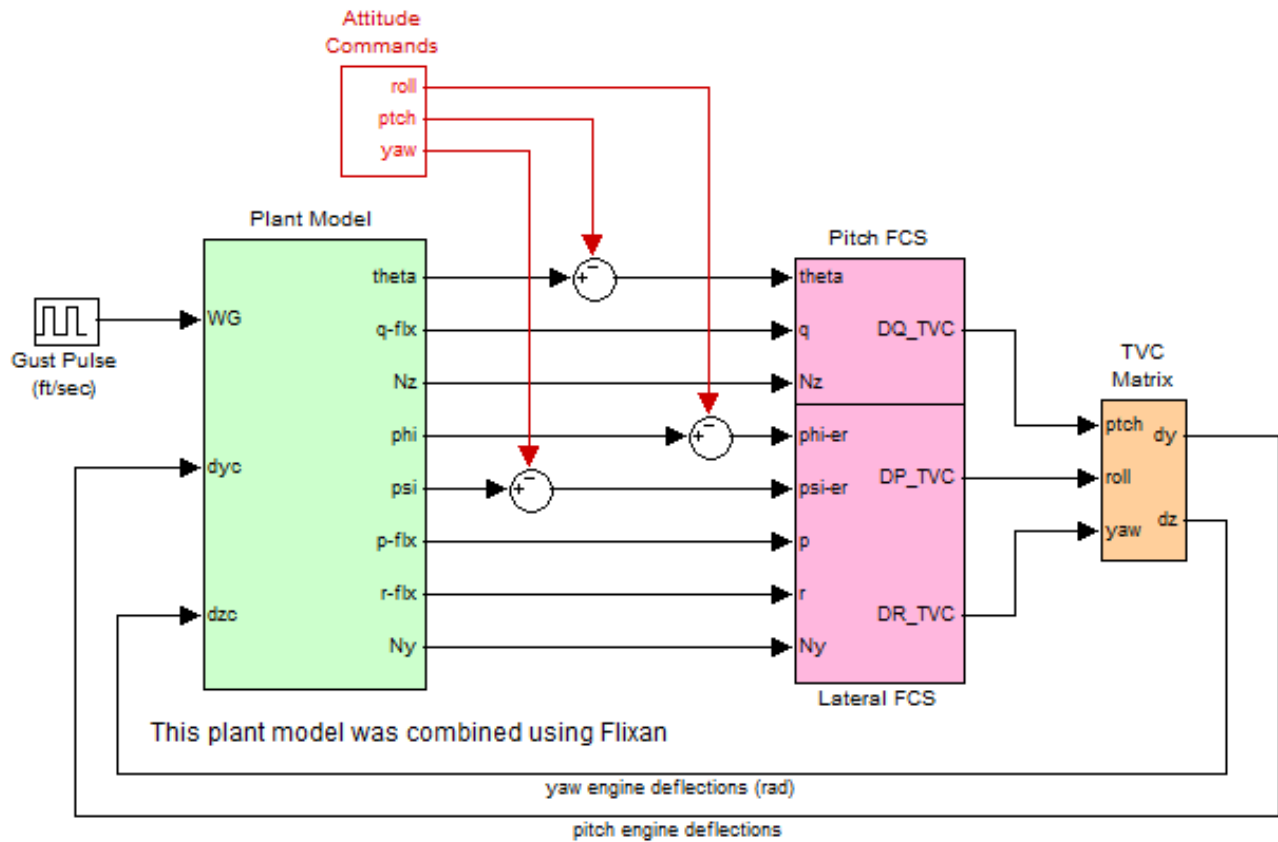
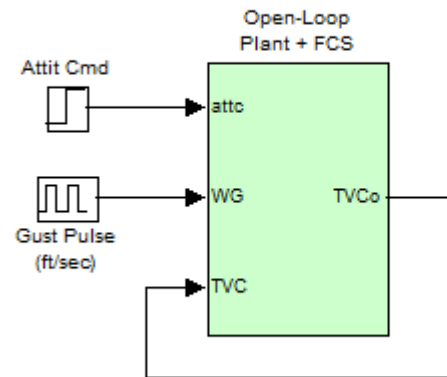


Figure 2.6.2 Closed-Loop Simulink Model “*Sim_Flex2.Mdl*” used for time domain simulations

Option-3 All Subsystems Combined in Flixan

In this configuration all the subsystems were combined together in Flixan creating the discrete system “Open-Loop System (Plant + FCS)”. This system is loaded from file “open-loop.m” and it is running inside the green block, in Simulink model “Sim_Flex3.mdl”, shown in Figure (2.6.3) below. The inputs to the system are: TVC demands, attitude commands, and wind-gust velocity. The flight control loop is closed via the TVC feedback.

Shuttle Stage-1 at Max-Q, Pitch and Lateral Coupled, Closed-Loop Simulation Model-3



This system was combined using Flixan

Open-Loop System (Plant + FCS)

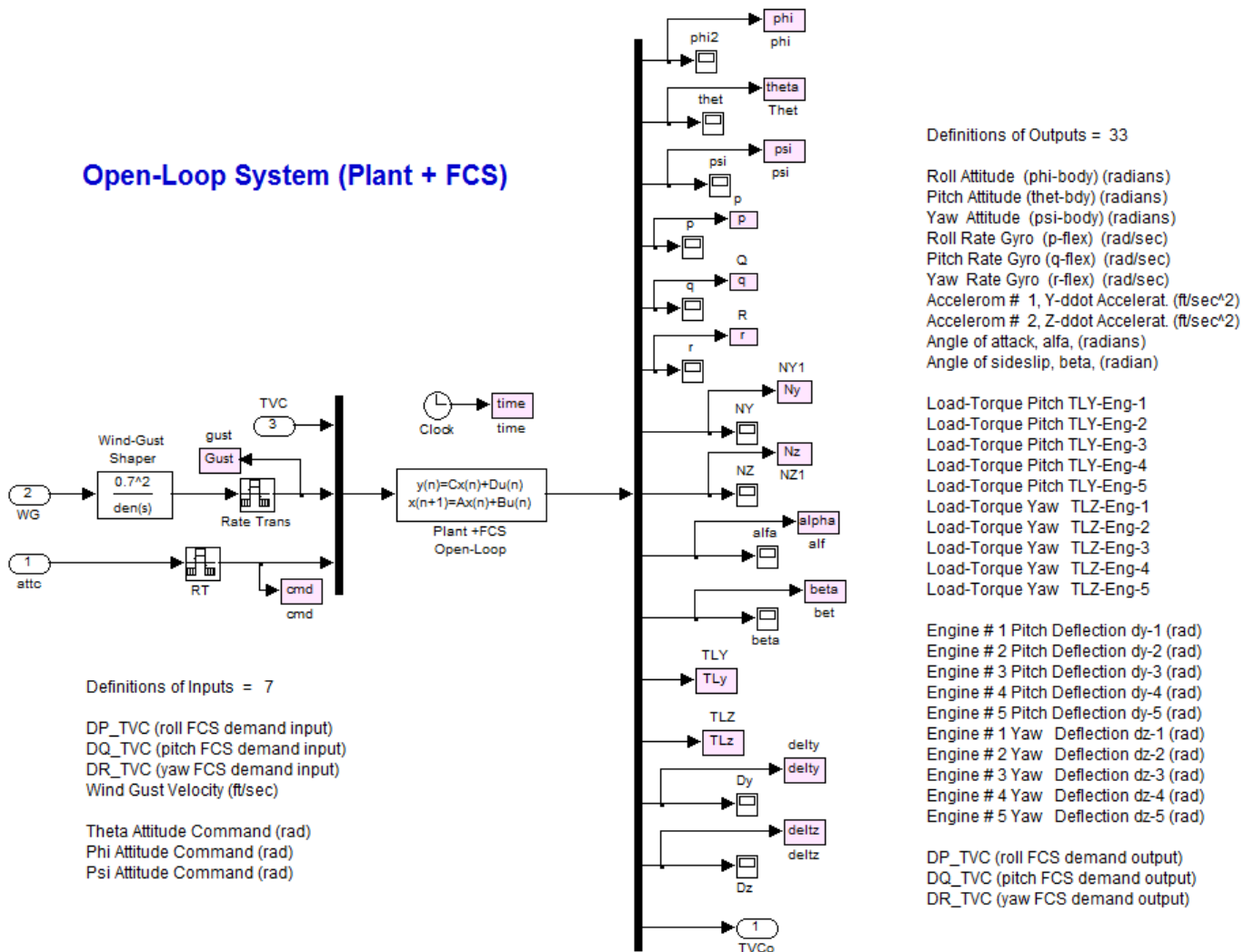
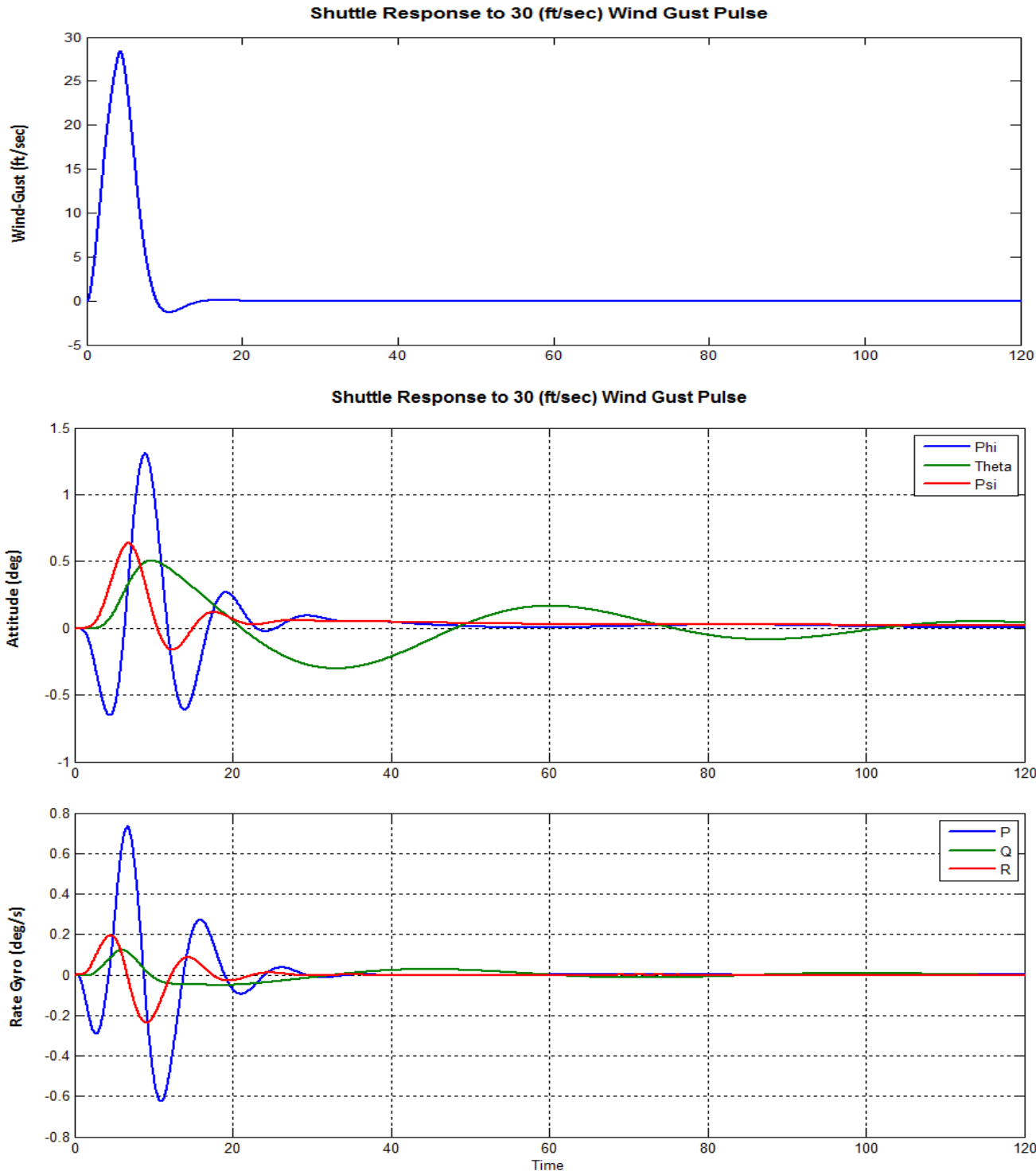
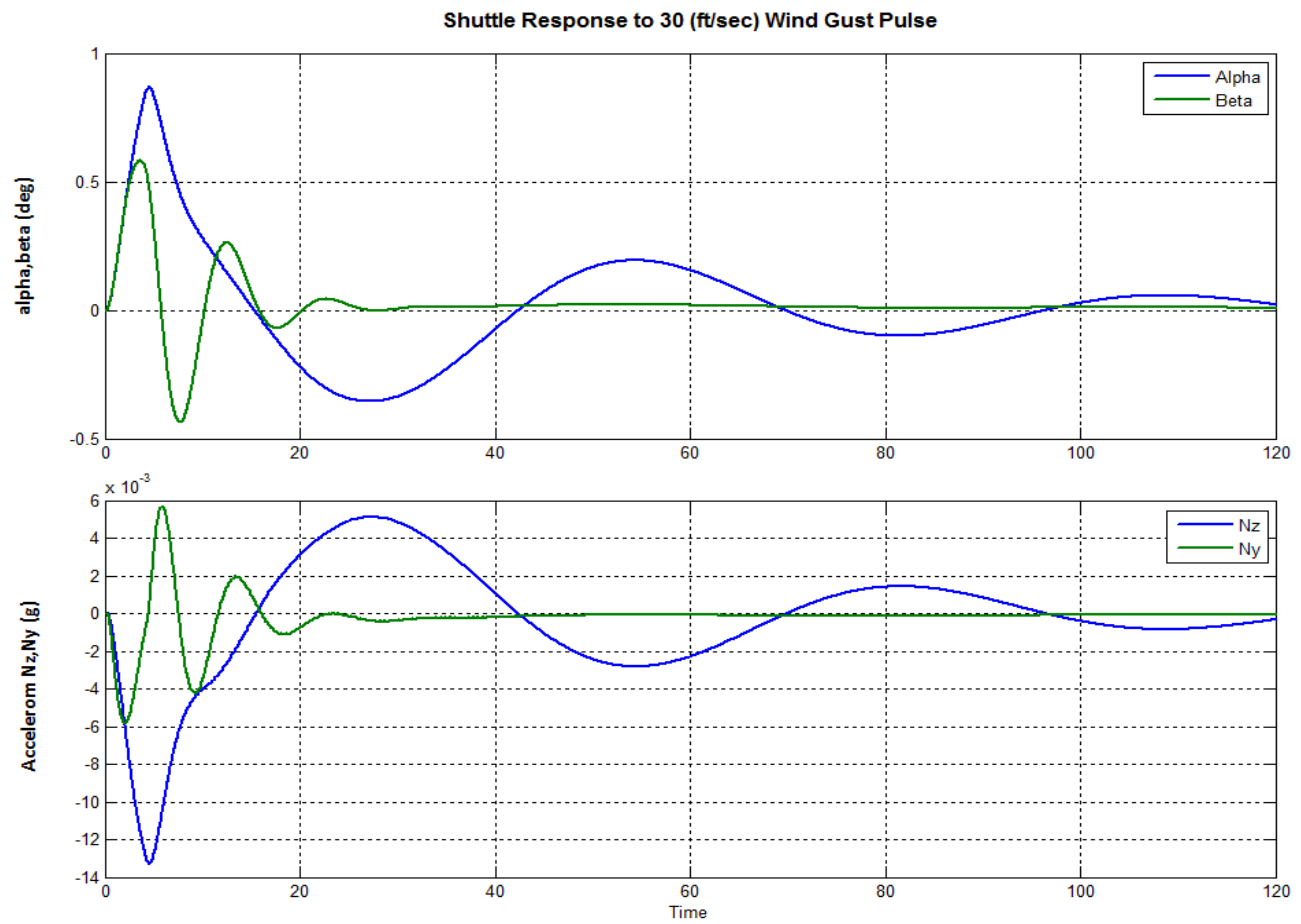
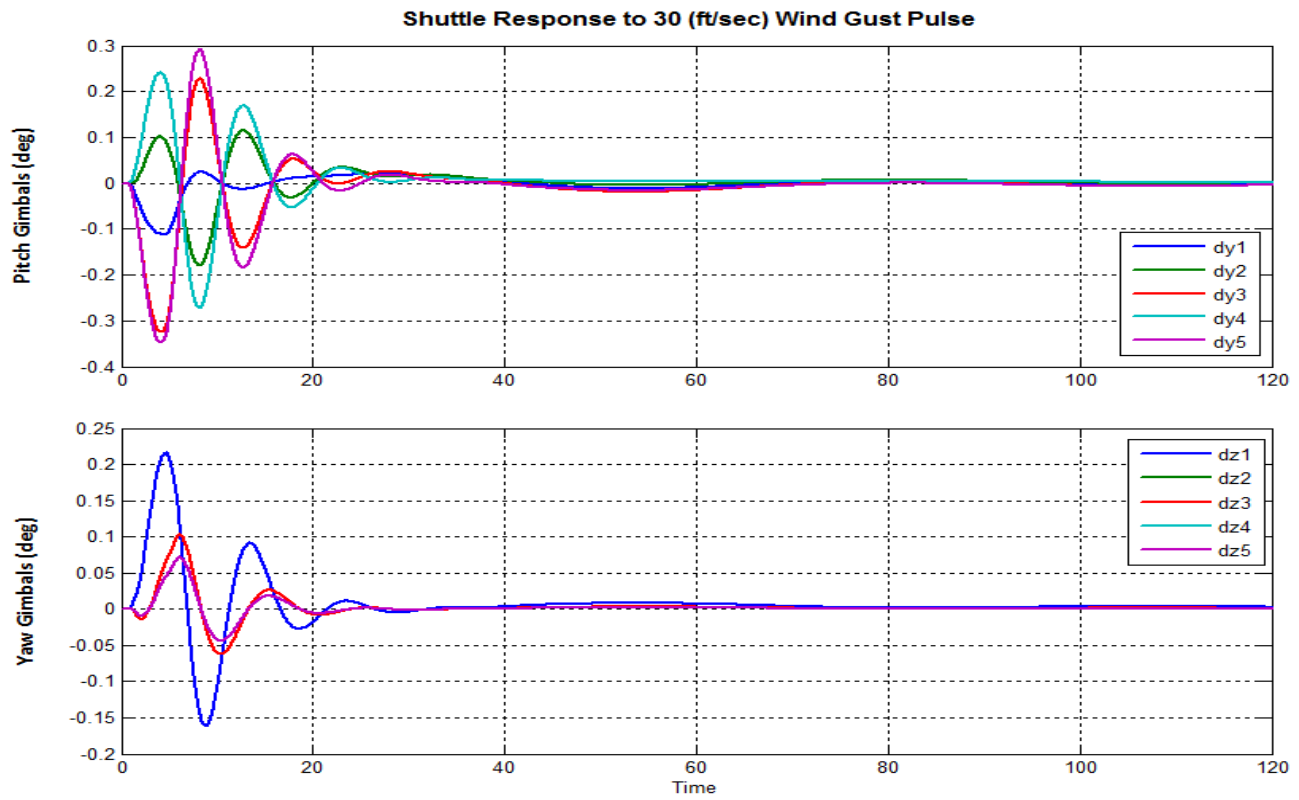


Figure 2.6.3 Closed-Loop Simulation Model “Sim_Flex3.Mdl”

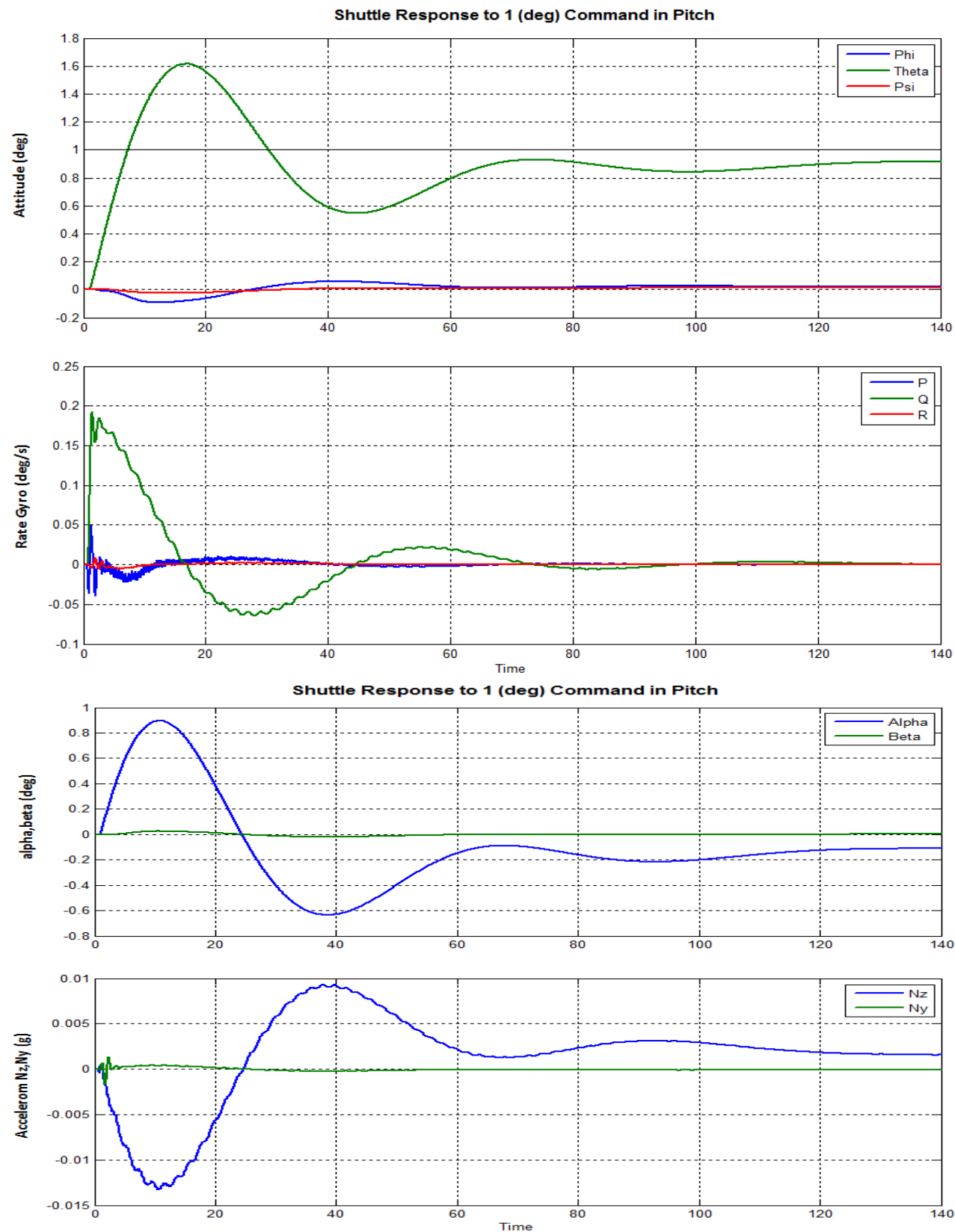
Closed-Loop Simulation Results

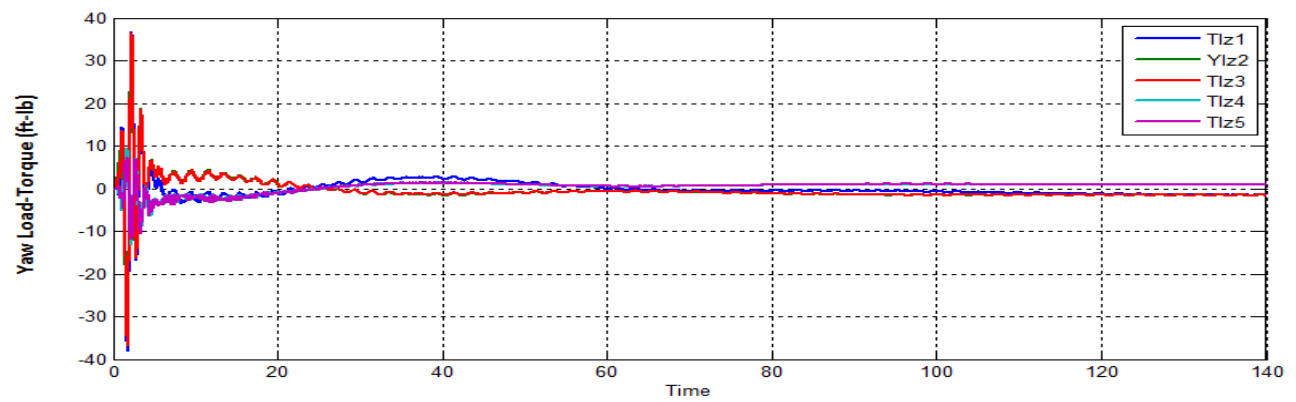
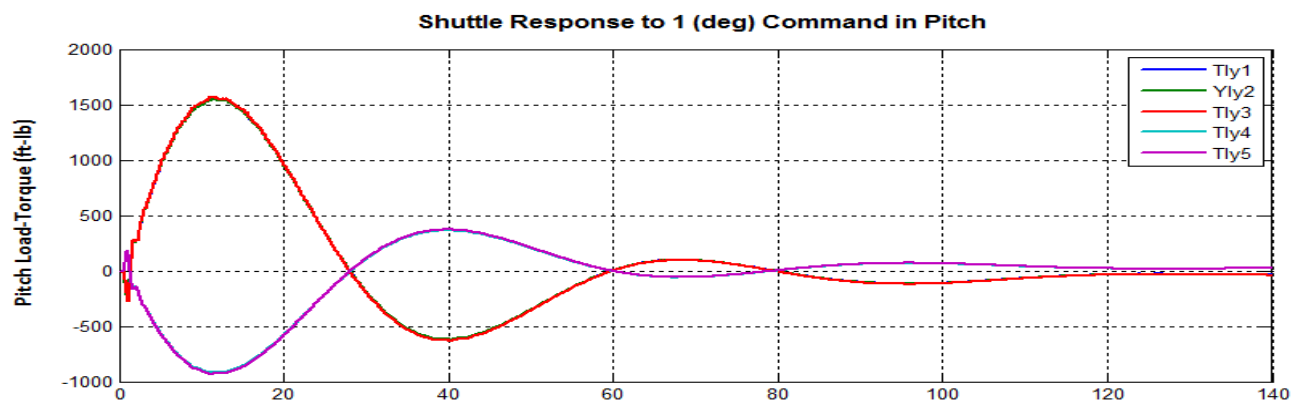
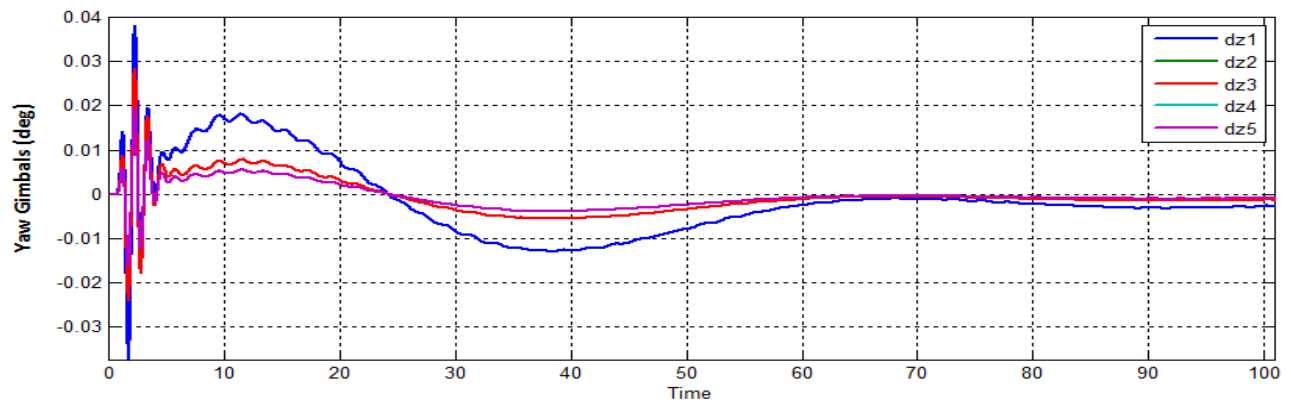
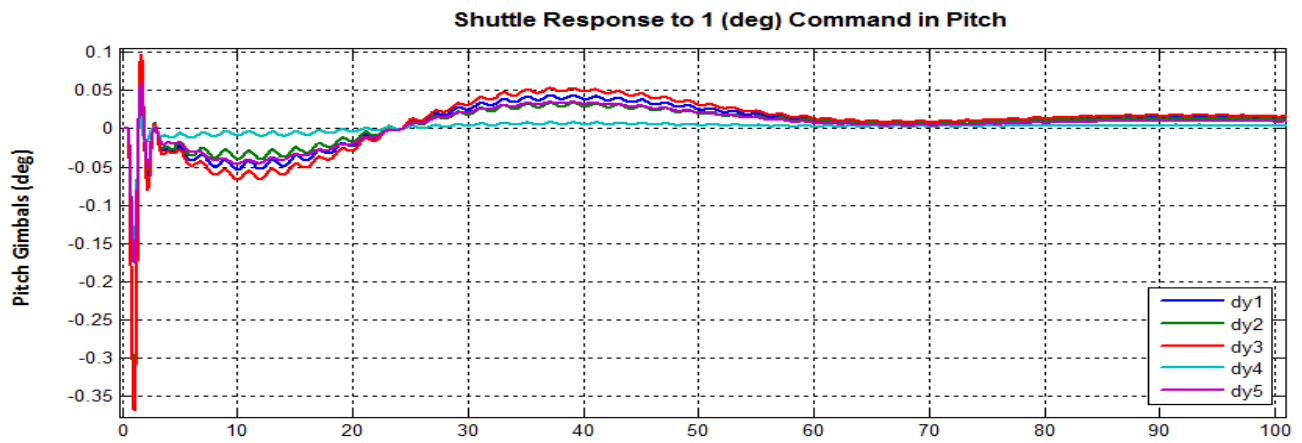
Three sets of simulation results were obtained from separate runs using the simulation models. In the first case, a wind-gust pulse is applied perpendicular to the vehicle x axis, at 45° between the +Y and the +Z axes. The gust causes simultaneously alpha and beta transient angles which the flight control system attempts to correct.



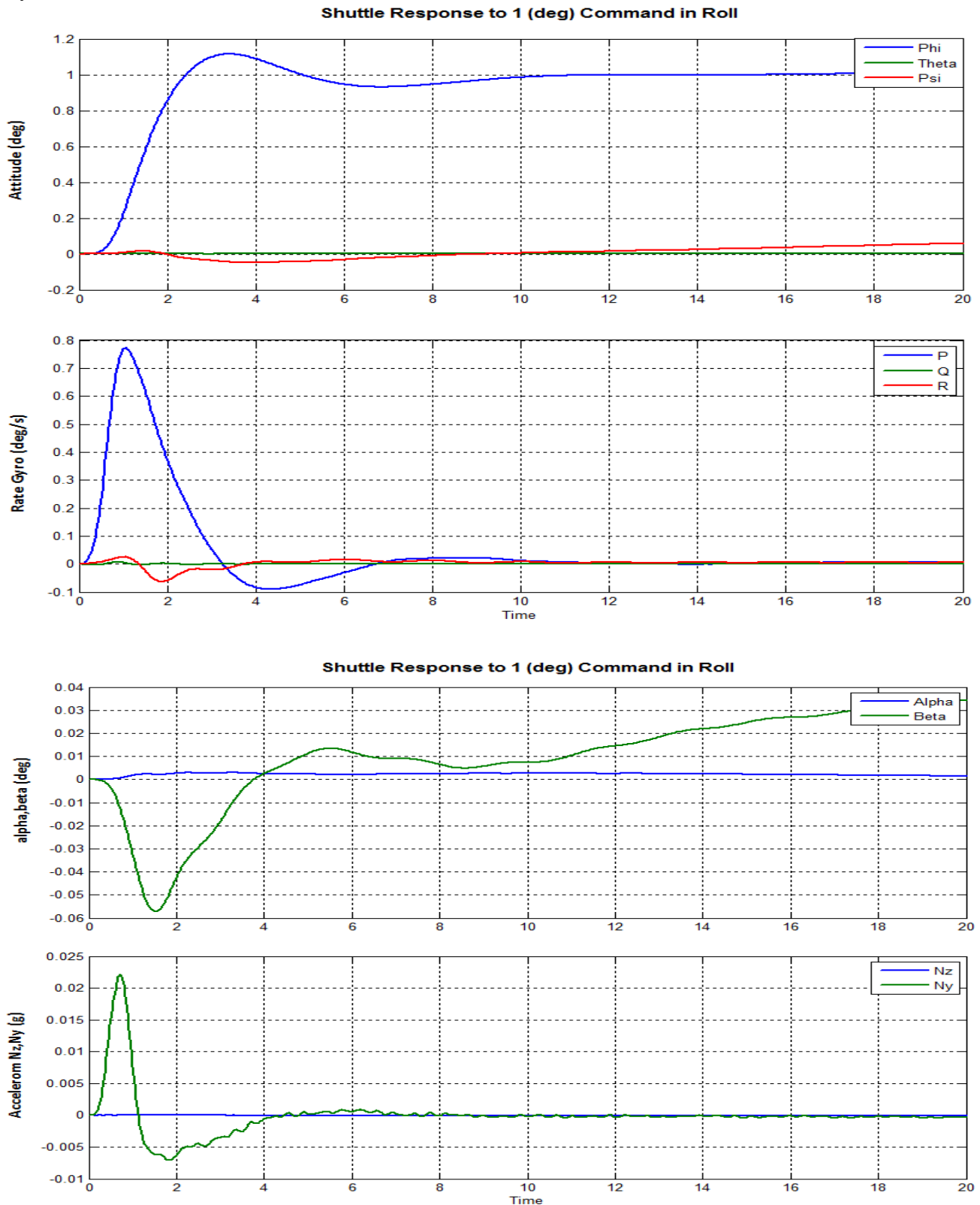


In the second case, a 1 (deg) attitude command is applied in the pitch direction. The system response is slow due to the load-relief that prevents developing large values of normal acceleration (Nz).

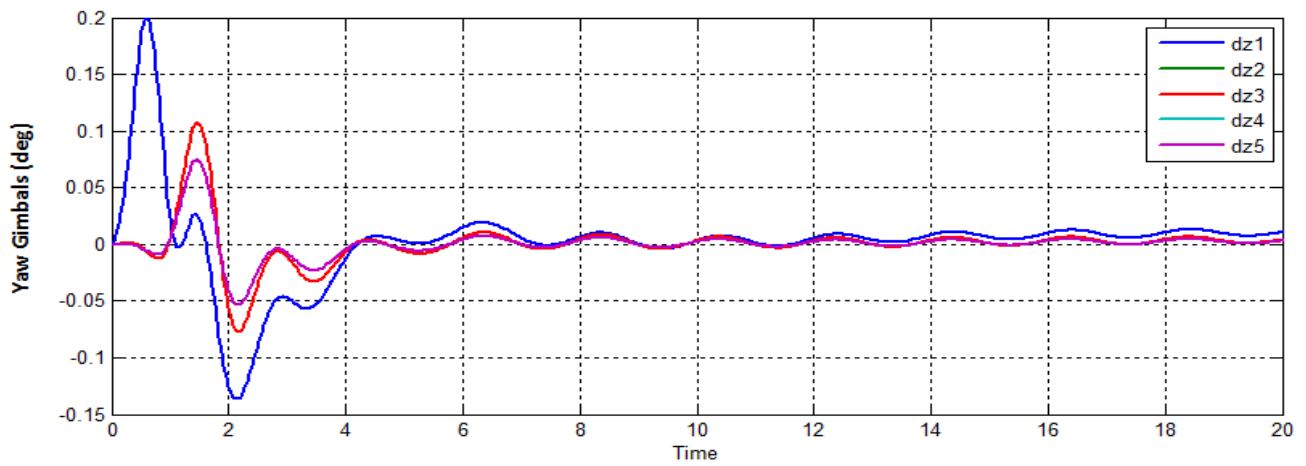
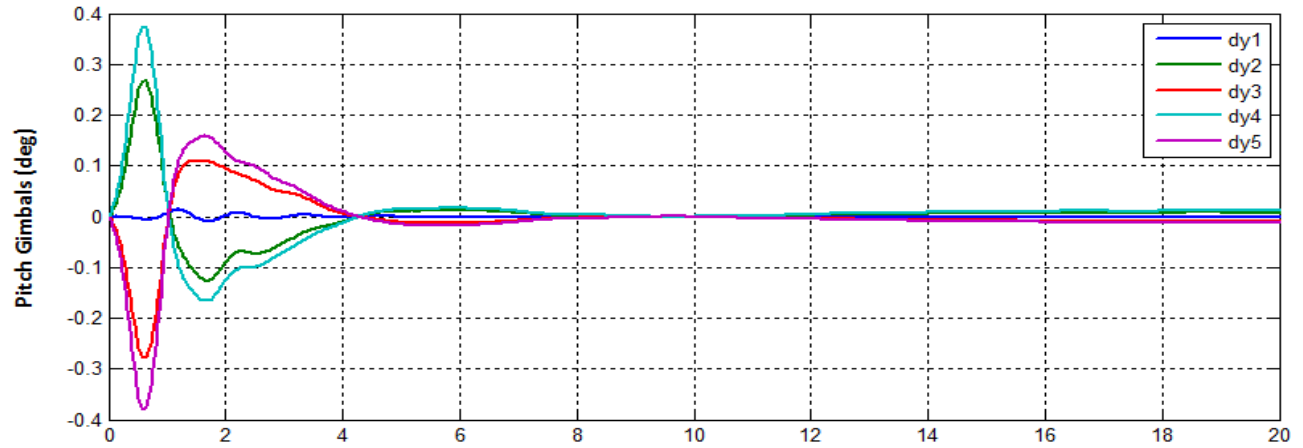




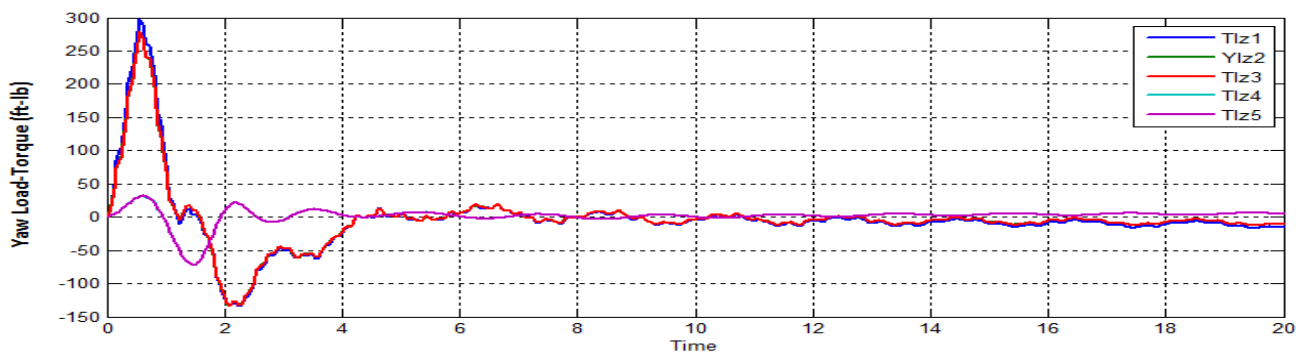
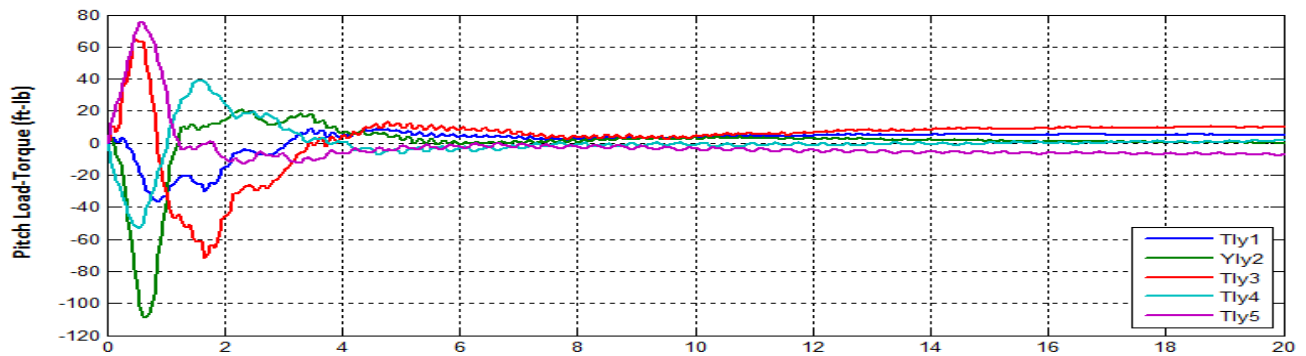
In the third simulation the vehicle is commanded to rotate 1° in roll. The left and right SSMEs and the left and right SRBs deflect differentially in pitch to generate the rolling torque on the vehicle. The roll attitude (ϕ) responds to the command after 2.5 sec. The maneuver causes transients in (β) and in the (N_y) acceleration.



Shuttle Response to 1 (deg) Command in Roll



Shuttle Response to 1 (deg) Command in Roll



3.0 Shuttle Ascent Redesign Using H-Infinity Control

The Space Shuttle flight control system was designed in the mid 70's using classical methods, before the robust control design methods were invented. It was designed based entirely on stability using phase and gain margins as control criteria without taking into consideration directly the system sensitivity to wind-gusts. The sensitivity analysis results show that the lateral system at high dynamic pressures is very vulnerable to wind-gust disturbances with a peak resonance occurring at frequencies around 1 (rad/sec), see Figure (3.1). This sensitivity is further aggravated by the fact that the disturbance itself is cyclic and it occurs at approximately the same frequency, on the average. The reason why the disturbance is cyclic is because the vehicle is ascending at a steep angle and it encounters various atmospheric layers that have different horizontal speeds. The air-speed variations occur with an average frequency of approximately 1 (rad/sec), almost the same frequency as the sensitivity resonance. This sensitivity is mostly due to the vertical stabilizer and causes undesirable roll oscillations.

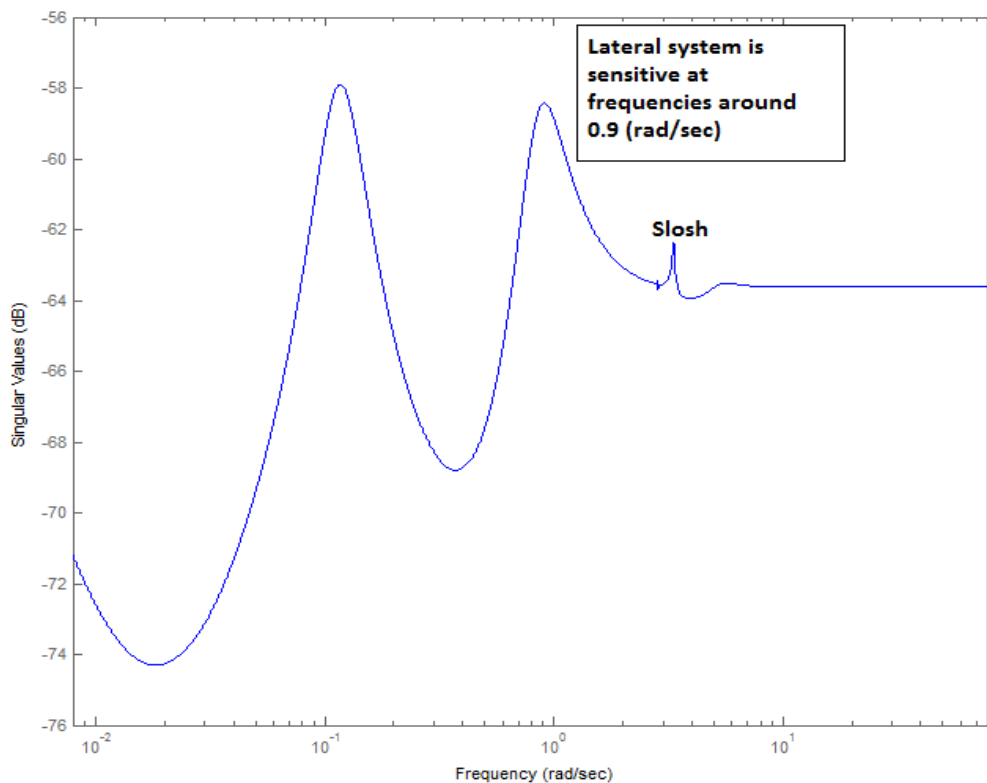


Figure (3.1) The Sensitivity Function from Gust Velocity to Alpha/ Beta response has an undesirable resonance

This classical analysis and the sensitivity function calculation for the original Shuttle control design at Max-Q is in folder "C:\Flixan\ Examples\Shuttle Ascent\Hinfinity Design\Original Shuttle FCS". The file "run.m" loads the already discretized vehicle and flight control systems and calculates the sensitivity function using the closed-loop model "Sensitivity.mdl", in Figure (3.2). The green vehicle block consists of the system "Discrete Shuttle Plant Model at Max-Q (Flex Vehicle, Actuators, Sensors)" from file "vehi_plant_z.m" that already includes the actuators, sensors, and TWD. The FCS subsystems are loaded from files "pitch_fcs.m" and "lateral_fcs.m". In addition to the sensitivity model, a closed-loop simulation model "Simz.mdl", and an open-loop analysis model "Open_Loop.mdl" are also included in this folder.

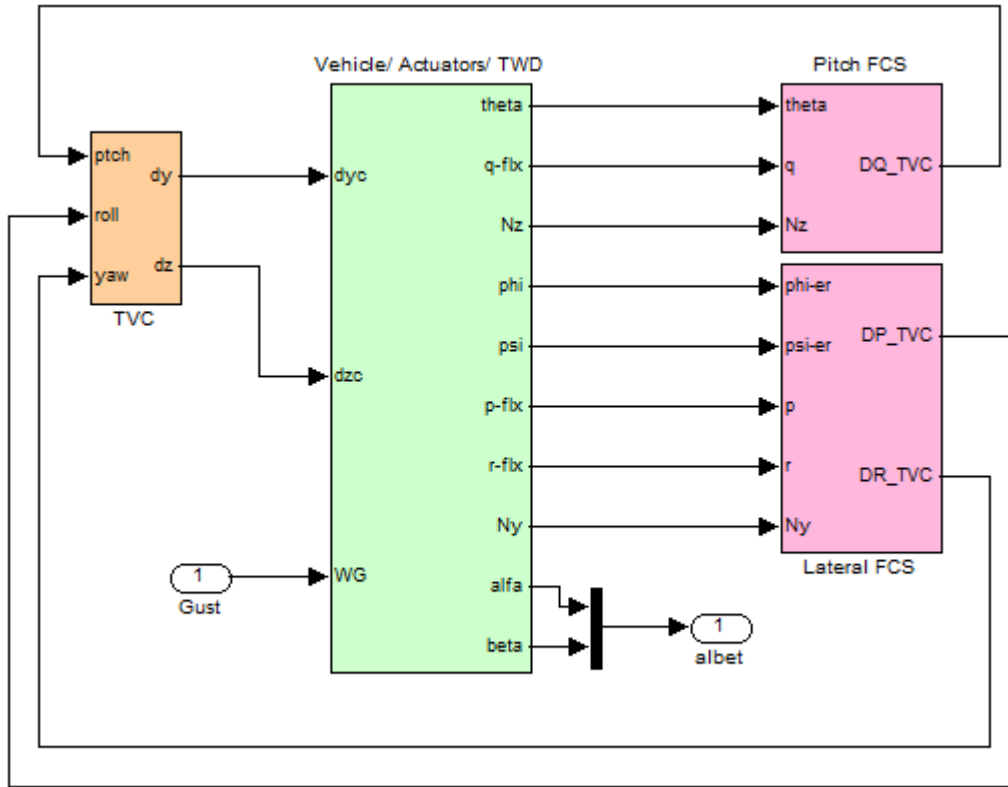


Figure (3.2) Simulink System "Sensitivity.Mdl" which calculates the Sensitivity Transfer-Function between the Gust and the Angles of Attack and Sideslip

The question arises, how would we re-design the Shuttle ascent control system if the robust control design methods were available? At high dynamic pressures the control emphasis is in minimizing the normal loading on the vehicle due to winds and the command following performance is compromised. The H-infinity method is very suitable in defining this performance versus sensitivity trade-off, because in addition to stability it also takes into consideration the transfer-function between the disturbance input and the vehicle response criteria. In this case we shall attempt to minimize the transfer function between the gust input and the angles of attack and sideslip (α & β) which is equivalent to the classical load-relief action applied in launch vehicles.

3.1 Pitch Axis H-infinity Design

At Max-Q the vehicle response to attitude commands is not a major issue and its response to pitch and yaw commands is not expected to be very efficient due to an increased load-relief, which is feedback from the accelerometers. The command response performance is sacrificed in order to gain sensitivity reduction against winds. The load-relief system causes the vehicle to turn towards the wind, as soon as the control bandwidth permits, in order to minimize the normal and lateral wind loading rather than maintaining its commanded direction. This slows-down the command performance and the original Shuttle design exhibits the same characteristic at high dynamic pressures.

The H-infinity method is based on a synthesis model (SM) of the vehicle plant, typically consisting only of the rigid-body dynamics. The SM has two sets of input vectors and two sets of output vectors, see Figure (3.3). The inputs are disturbances (w) and controls (u). The outputs are the criteria to be

optimized (z) and measurements (y) which are processed by the control system to generate the controls (u). The criteria to be minimized (z) are not necessarily measurable variables but they can be defined by equations. The H-infinity methodology synthesizes a controller $K(s)$ that closes the control loop between the measurements and the controls. This controller minimizes the infinity norm of the transfer function between the disturbance and the criteria. In this case, however, we know that the disturbance is likely to occur at around 1 (rad/sec). It is possible, therefore, to introduce the disturbance as a 2nd order resonance inside the SM, as shown in Figure (3.4). This will entice the H-infinity algorithm to provide additional control at that frequency in order to further attenuate the disturbance, as we shall see.

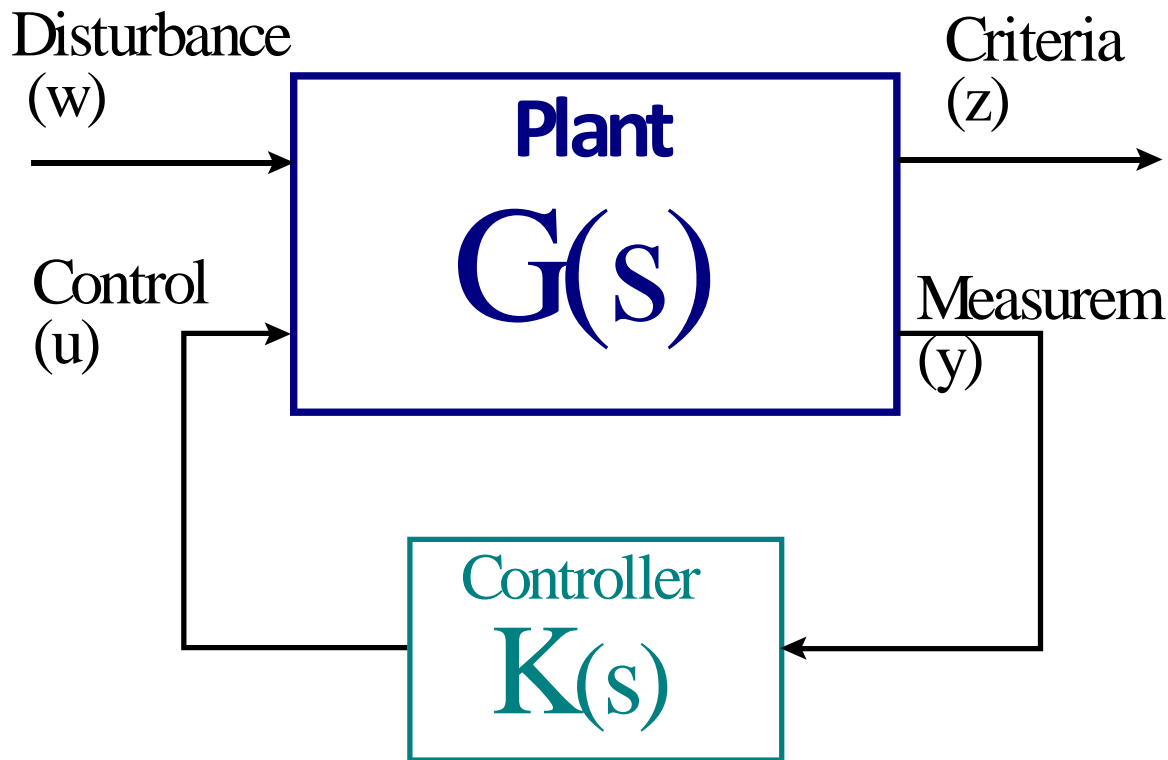
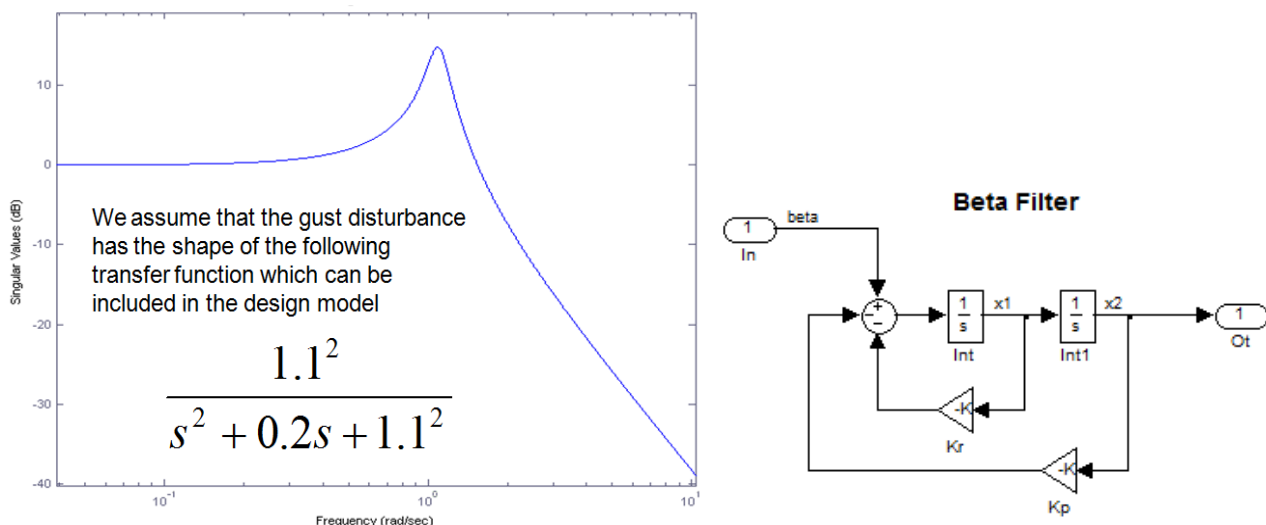


Figure (3.3) Synthesis Model $G(s)$ used in H-infinity Control Design. $K(s)$ minimizes the Infinity-Norm of the Transfer-Function between (w) and (z)

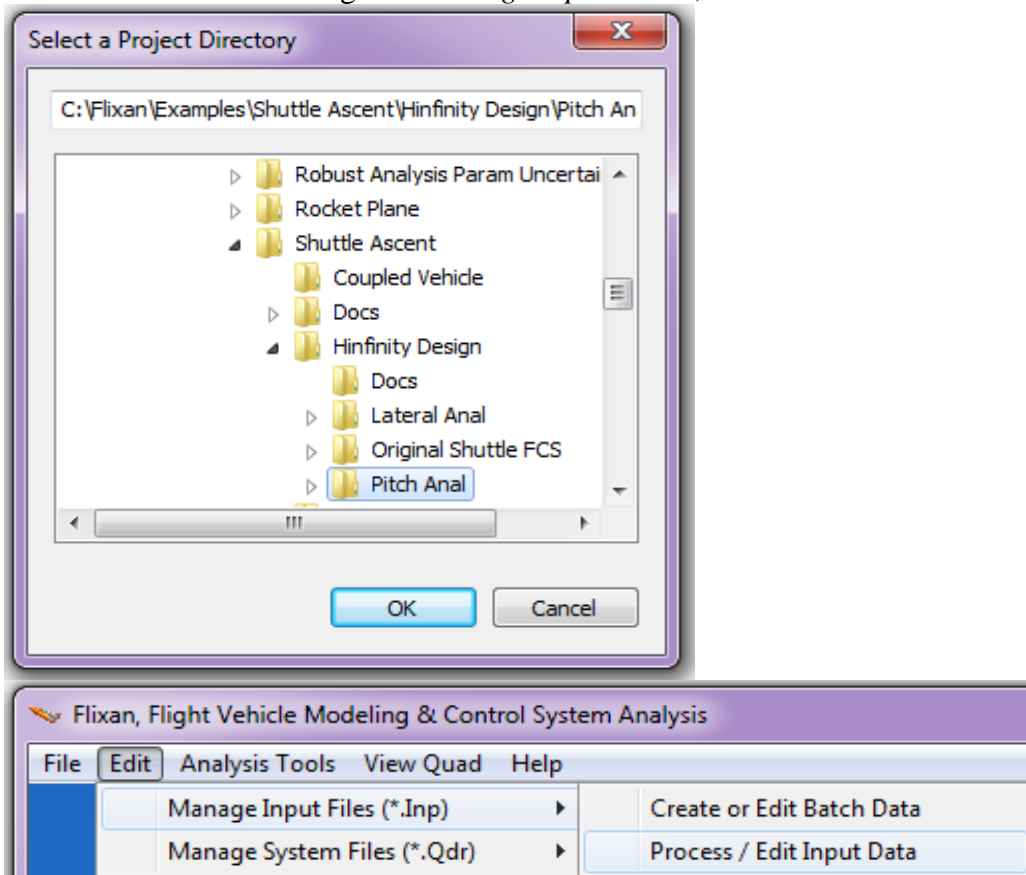


Processing the Input Data in Batch Mode

Let us first create the systems and matrices that will be used in the pitch H-infinity design and analysis. The files are in folder "C:\Flixan\Examples\Shuttle Ascent\Hinfinitiy Design\ Pitch Anal". The systems are generated by Flixan in file "*Pitch_MaxQ.Qdr*" by processing the input data file "*Pitch_MaxQ.Inp*". The batch set in file "*Pitch_MaxQ.Inp*" is used for processing the data-sets in batch mode. Its title is "*Batch for preparing the Pitch Shuttle Ascent Models at First Stage Max-Q, T=61 sec*". It creates the following systems.

- A pitch design system "*Shuttle Ascent, Max_Q, Pitch Hinf Design Model*" in file "*pitch_des.m*". This system includes the TVC matrix and it is used to create the H-infinity SM. Its inputs are pitch FCS demand and wind disturbance in (ft/sec).
- A second pitch system "*Shuttle Ascent, Max_Q, Pitch Analysis with Slosh & TVC*" in file "*pitch_anal.m*". This system includes slosh and the TVC matrix. It is used for preliminary stability and sensitivity analysis using Simulink files "Anal3.Mdl" and "Sensit3.Mdl".
- A plant system "*Shuttle Plant Model at Max-Q (Flex Vehicle, Actuators, Sensors)*" in file "*plant.m*". This system includes the actuator and sensor dynamics and it is combined together using Flixan. It is used for the final (complete) analysis in Simulink systems "Anal4.Mdl", "Sensit4.Mdl", and "Sim4.Mdl" which perform stability and sensitivity analysis, and time simulations.

To process the input file in batch mode using Flixan you must first select the project directory "C:\Flixan\Examples\Shuttle Ascent\Hinfinitiy Design\Pitch Anal", then go to the Flixan main menu and click on "Edit". Then go to "Manage Input Files", and then "Process/ Edit Input Data".



This will open the utility dialog for processing input data, as shown below. The menu in the upper left hand side of the dialog displays the input data files (having an extension .inp) existing in the project directory. In this case there is only one input data file "*Pitch_MaxQ.Inp*" and we select it by clicking on "*Select Input File*". The menu on the right side shows the data-sets which are included in file "*Pitch_MaxQ.Inp*". It shows the utility program that will be used for processing each set followed by the title of the data set in one line. Select the batch set on the top to process the data in batch mode and click on "*Process or View Input Data*". Flixan will process the input file and create the systems in file "*Pitch_MaxQ.Qdr*". It will also create the Matlab system files. Answer "Yes" in the next dialog to overwrite the previous systems data. However, some of the data (TVC matrix, actuators, sensors) will be preserved in file "*Pitch_MaxQ.Qdr*" after processing, because "Retain" statements are included in the batch.

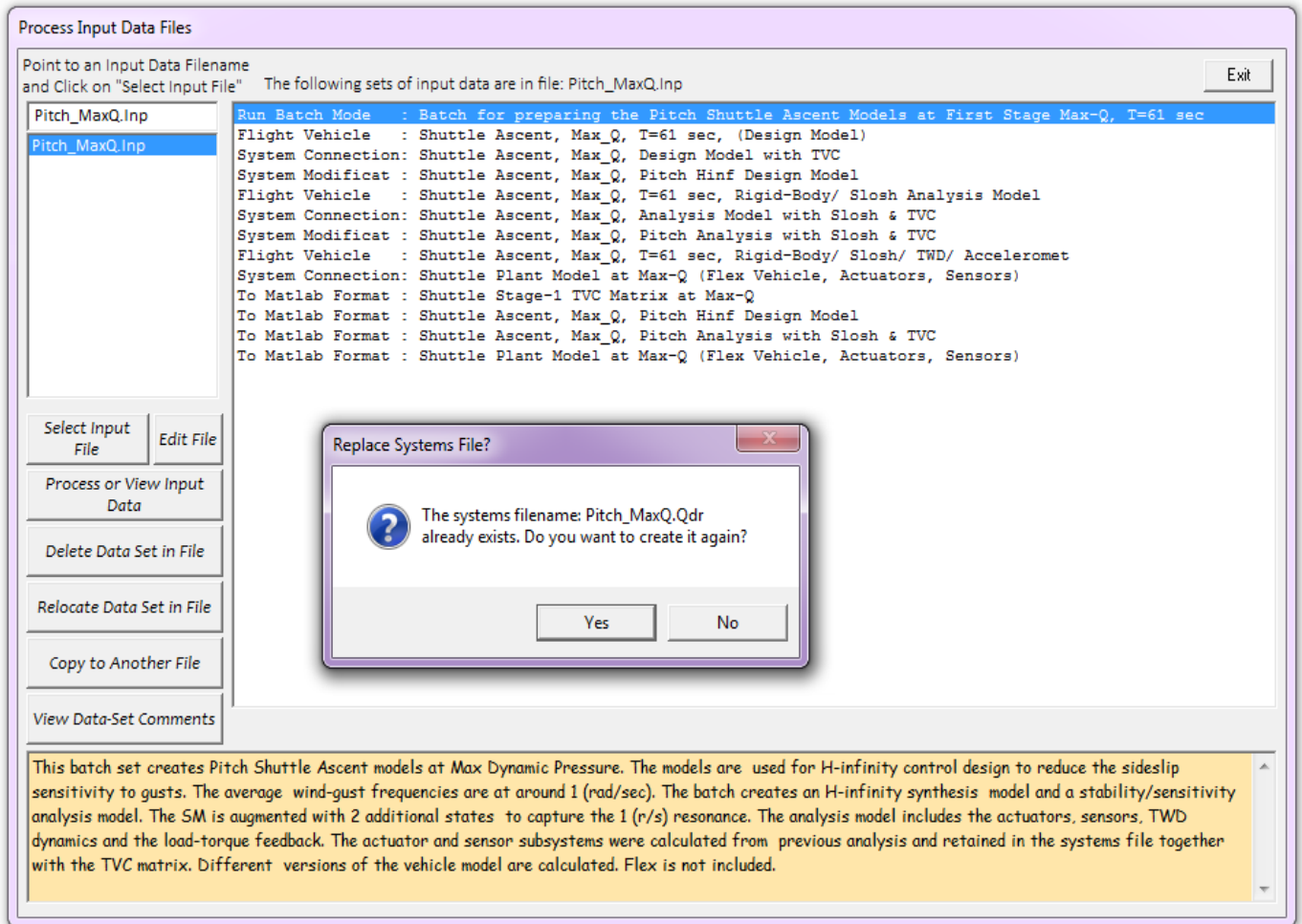


Figure (3.4) shows the H-infinity SM for the pitch axis. It uses the Flixan generated vehicle system "*Shuttle Ascent, Max_Q, Pitch Hinf Design Model*" from file "*pitch_des.m*". The TVC is already included in this system and the control input is a scalar pitch demand (dQ). The disturbance input (w) is the wind-gust velocity in (ft/sec), also a scalar. The wind-gust direction relative to the vehicle body is defined in the vehicle data to excite both pitch and lateral axes.

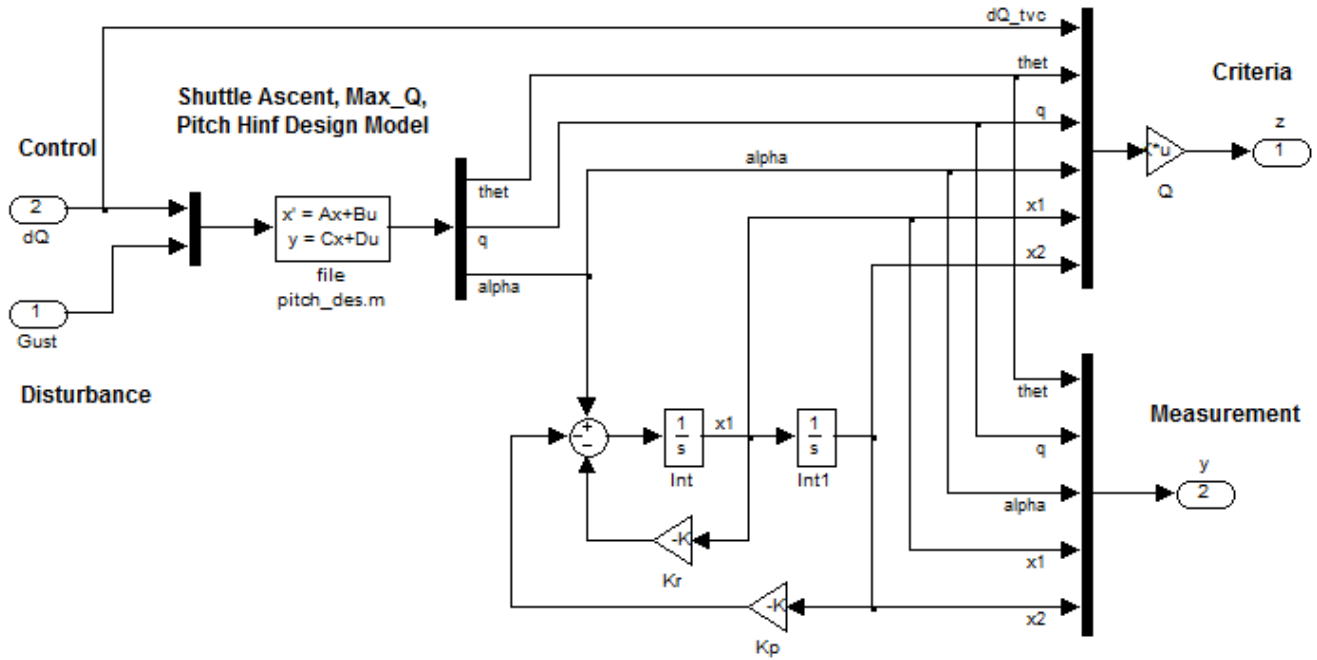


Figure (3.4) Pitch Synthesis Model captured in Simulink file "Design.Mdl"

Notice that the 1 (rad/sec) resonance is included in the SM and it is excited by the angle of attack (α) which is the key variable to minimize. It introduces two additional filter states $x1$ and $x2$ which become part of the measurement and also the criteria output vectors. The criteria consist of mainly α related states because the angle of attack is directly related to the normal load and this is what we desire to relieve at high Q . The criteria variables also include the pitch attitude and rate, and also the control (dQ). The criteria penalties are attached in the diagonal matrix Q . Notice that the pitch attitude (θ) is not penalized much because, as we said, the command following is compromised at high pressures. The weight on the control (dQ) prevents it from becoming too big under closed-loop control. Increasing the dQ weight in matrix Q decreases the control bandwidth. On the other hand, increasing the penalties that correspond to (α , $x1$, and $x2$) it improves sensitivity but it increases bandwidth. The measurements vector consists of the five states, 3 vehicle and 2 filter. Notice that only the α -state is not measurable and it must be estimated, mainly from Nz and the gimbal deflections (δy).

The Matlab file "run.m" loads the systems and the TVC matrix and performs the design and control analysis. It uses the H-infinity method to design a (1x5) state-feedback gain $Kp3$ from the 5-states vector (θ , q , α , $x1$, $x2$) that appear in the measurements, although (α) is not directly measureable. The H-infinity derived state-feedback matrix $Kp3$ minimizes sensitivity between the gust disturbance and the criteria defined. Having designed the state-feedback controller the next step is to analyze the (α) sensitivity to the gust disturbance. This is performed in the frequency domain by calculating the singular-value response between the gust input and the angle of attack using the closed-loop Simulink system "Sensit4.mdl" in Figure (3.5). Notice that the actual angle of attack (α) is used for output in the sensitivity calculation. In the state-feedback, however, (α) is estimated using an α -estimator block, shown in detail in Figure (3.6). Also the input to the disturbance filter (which calculates states $x1$ and $x2$) is α -estimate rather than real α .

```

k2d=180/pi; d2r=pi/180;
[Ad, Bd, Cd, Dd]= pitch_des;           % Pitch design plant
[An, Bn, Cn, Dn]= pitch_anal;          % Simple analysis plant
[Ap, Bp, Cp, Dp]= plant;                % Plant w actuators, sensors, TWD
load TVC.mat -ascii                     % TVC Matrix

%... Beta Estimator parameters
Mass=93215; Sref= 2690; Qbar=745.4; Cza=-0.0574;
Thr=[470000, 470000, 470000, 0.245e7, 0.245e7]';

%... Hinfinty Design ...
%      [DQttvc, thet, q,   alfa, x1,   x2]
Q=diag([0.06, 0.005, 0.2, 0.03, 0.03, 0.03]);
om=1.0; zt=0.14; Kp=om^2; Kr=2*zt*om;
[Ad, Bd, Cd, Dd]= linmod('Design'); sys= SS(Ad,Bd,Cd,Dd);
sysd=MKTITO(sys,5,1);
[K,CL,GAM,INFO] = hinfsyn(sysd);
Kp3=INFO.KFI(:,1:5)
%Kp3 = [0.3042  3.4539  0.5105  0.0711 -0.2670];

[Ao, Bo, Co, Do]= linmod('Anal4');
[As, Bs, Cs, Ds]= linmod('Sensit4');
w=logspace(-3, 2, 10000);              % Define Frequ Range
syso= SS(Ao,Bo,Co,Do);                  % Create SS System
syss= SS(As,Bs,Cs,Ds);                  % Create SS System
figure(1); Nichols(syso,w)              % Plot Nichol's Chart
figure(2); Bode(syso,w)                  % Plot Bode
figure(3); Sigma(syss,w)                 % Plot Sensitivity

```

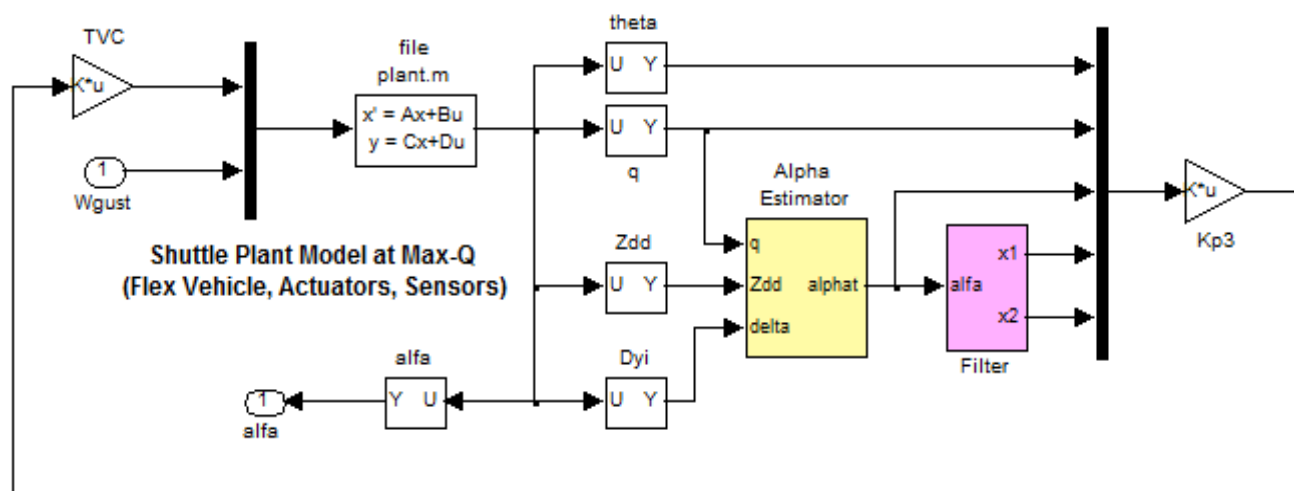


Figure (3.5) Simulink System "Sensit4.mdl" used for Sensitivity Analysis

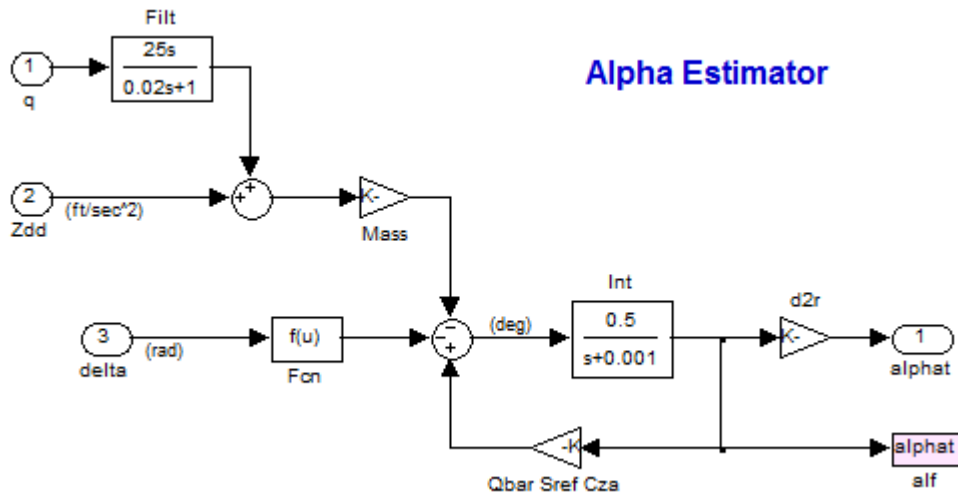


Figure (3.6) Estimator of the Angle of Attack is using measurements from the Normal-accelerometer, Gimbal Deflections, and Pitch Rate. It solves the following equation for (α) . The pitch rate derivative compensates the accelerometer measurement because it is not located at the vehicle CG.

$$M \ddot{z} = \bar{Q} S_{ref} C_{Z\alpha} \alpha + \sum T_i \delta_{yi}$$

Notice that the big plant model "Shuttle Plant Model at Max-Q (Flex Vehicle, Actuators, Sensors)" from file "plant.m" is used in the sensitivity analysis model "Sensit4.mdl". This system does not include the TVC matrix and it is added in the Simulink diagram (3.5). Figure (3.8) is a SV frequency response plot that shows the alpha-sensitivity of the closed-loop system to wind-gust disturbances. A similar Simulink model "Anal4.Mdl" is used for the pitch axis stability analysis, see Figure (3.7). The Bode and Nichols plots in Figure (3.9) show the pitch axis phase and gain margins.

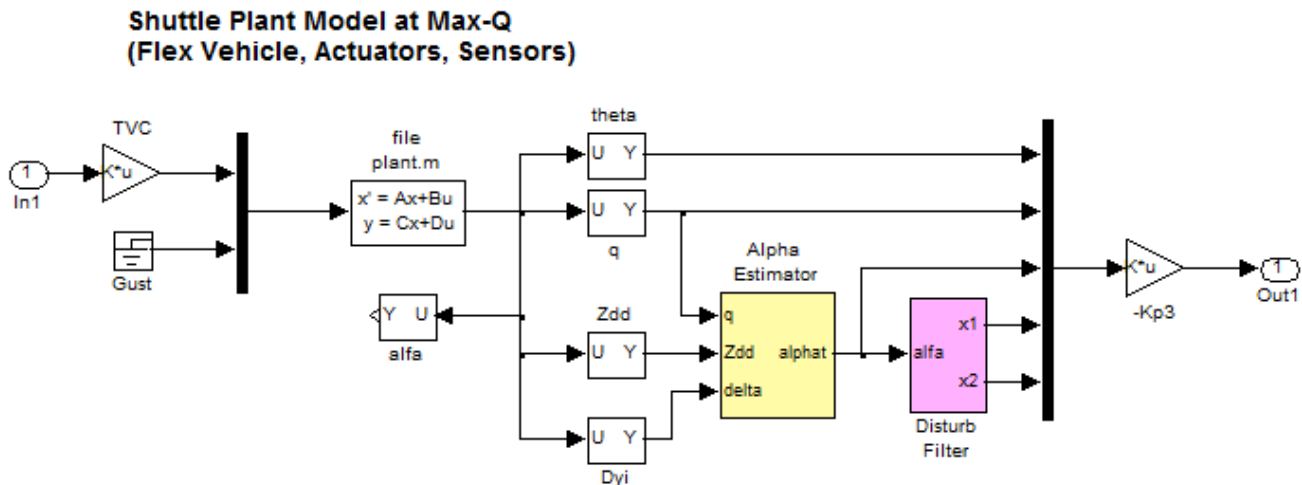


Figure (3.7) Simulink System "Anal4.mdl" used for Pitch Stability Analysis

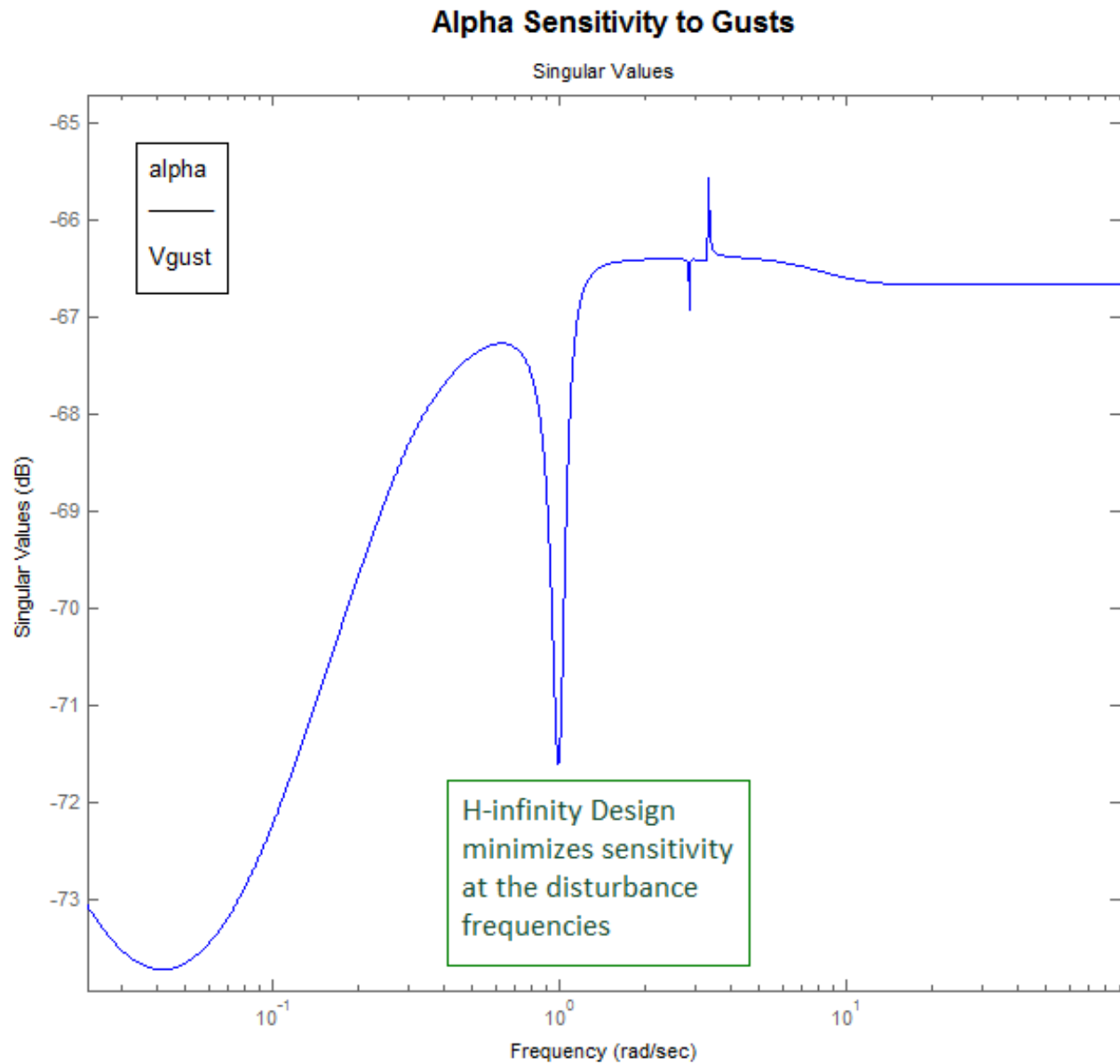


Figure (3.8) Sensitivity function between the gust velocity disturbance and the angle of attack. It shows how the disturbance filter provides additional attenuation at the expected disturbance frequency which is around 1 (rad/sec).

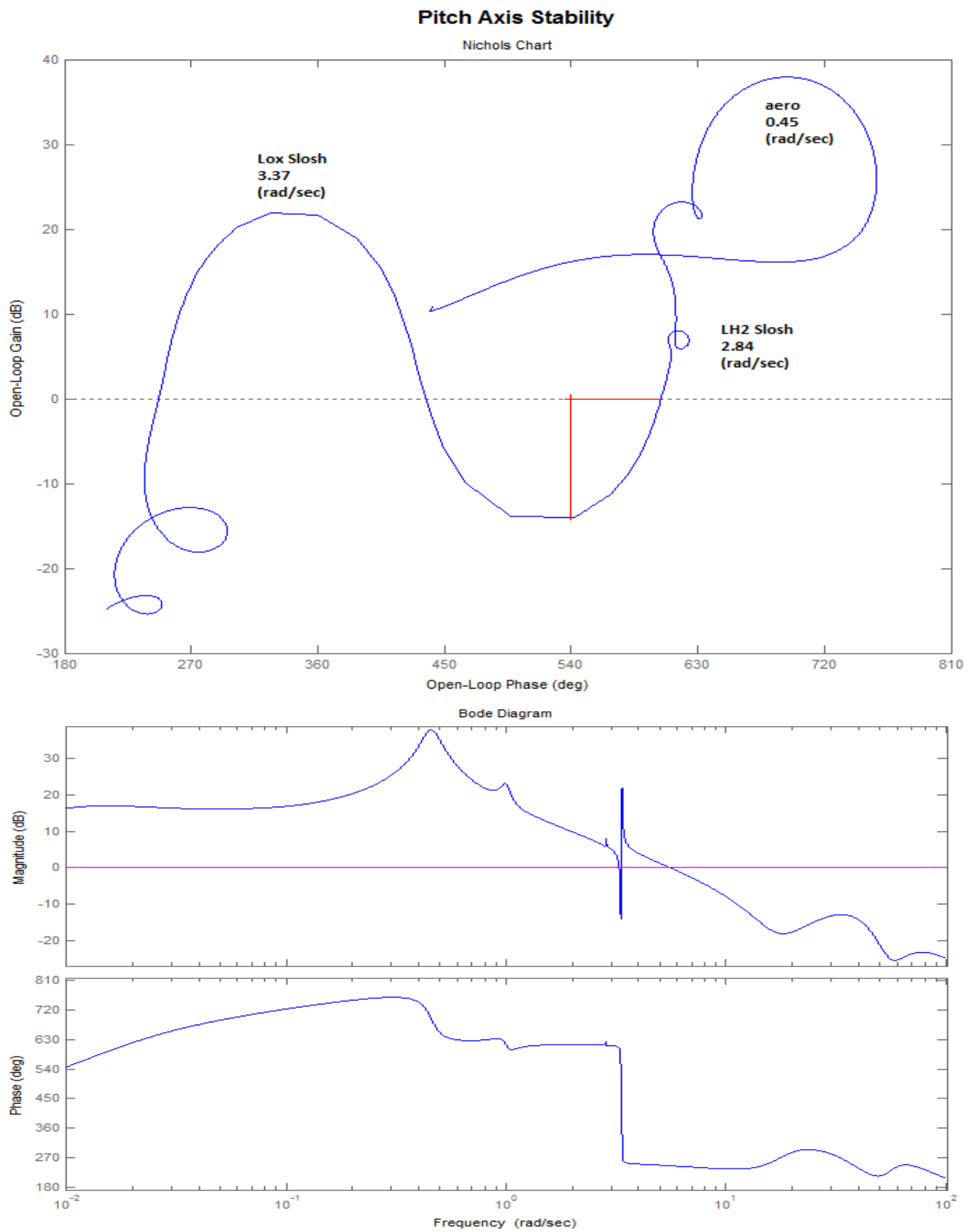


Figure (3.9) Open-Loop Nichols and Bode plots for the pitch axis system showing the phase and gain margins

3.2 Lateral Axes H-infinity Design

A very similar approach is used in the lateral flight control system design where the original Shuttle design demonstrated poor sideslip sensitivity to gust disturbances. The control system architecture is shown in Figure (3.10). The flight control system, in addition to attitude step commands, it receives also a load-relief feedback signal from the sideslip angle (β) which is estimated from the lateral accelerometer (N_y).

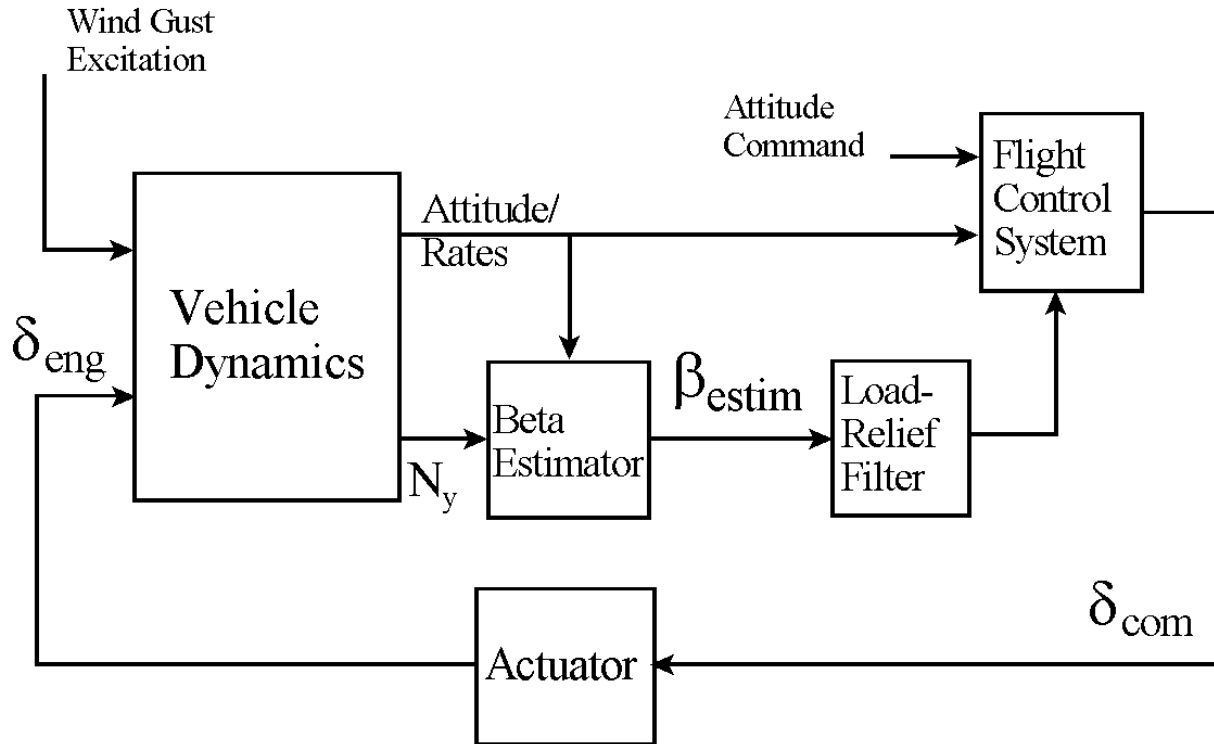


Figure (3.10) Lateral Control System Architecture has a load-relief feedback via a beta-estimator.

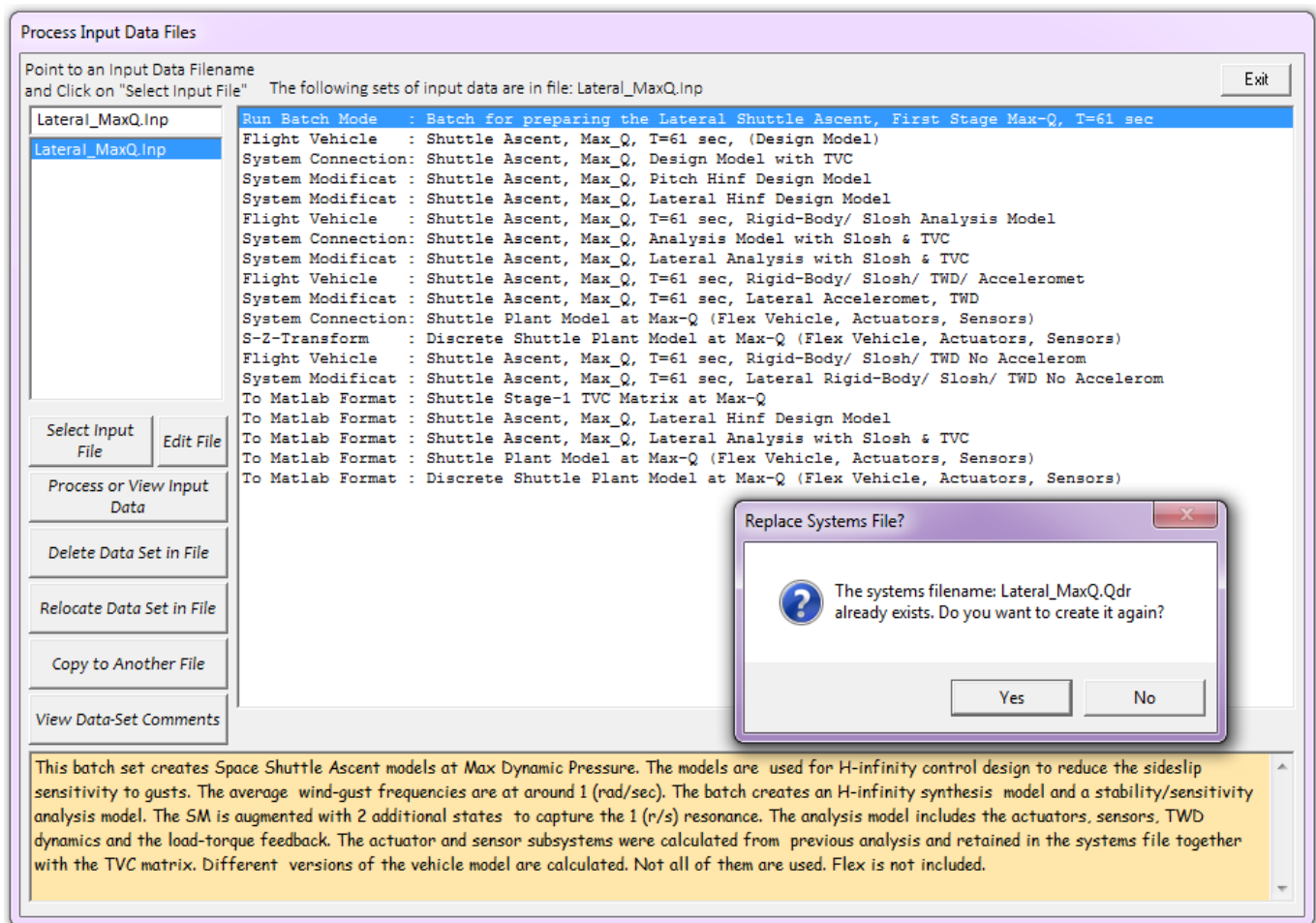
Processing the Input Data in Batch Mode

The analysis is similar to the pitch axis. The analysis files are in folder "C:\Flixan\Examples\Shuttle Ascent\Hinfinity Design\ Lateral Anal". The input file that creates the systems is "*Lateral_MaxQ.Inp*". This file is processed by Flixan and the systems generated are saved in "*Lateral_MaxQ.Qdr*". There is a batch set on the top of file "*Lateral_MaxQ.Inp*" that processes the data-sets in batch mode. Its title is "*Batch for preparing the Lateral Shuttle Ascent Models at First Stage Max-Q, T=61 sec*". It creates the following systems.

- A lateral design system "*Shuttle Ascent, Max_Q, Lateral Hinf Design Model*", saved in file "*later_des.m*". This system includes the TVC matrix and it is used to create the H-infinity synthesis model "*design.mdl*". Its inputs are roll and yaw FCS demands, and wind disturbance in (ft/sec).
- A second lateral system "*Shuttle Ascent, Max_Q, Lateral Analysis with Slosh & TVC*", saved in file "*later_anal.m*". This system includes slosh and also the TVC matrix. It is used for preliminary stability and sensitivity analysis using the Simulink files "*Anal2.Mdl*" and "*Sensitiv2.Mdl*".

- A plant system "*Shuttle Plant Model at Max-Q (Flex Vehicle, Actuators, Sensors)*" in file "*plant.m*". This system includes slosh and the actuator/ sensor dynamics. It is combined together using Flixan, and used for the final (complete) analysis in the Simulink systems "*Anal4.Mdl*", "*Anal5.Mdl*" "*Sensitiv4.Mdl*", and "*Sim4.Mdl*" which perform stability and sensitivity analysis, and time simulations.

To process the input file in batch mode using Flixan you must first select the project directory "*C:\Flixan\Examples\Shuttle Ascent\Hinfinit Design\Lateral Anal*", then go to the Flixan main menu and click on "*Edit*". Then go to "*Manage Input Files*", and then "*Process/ Edit Input Data*". This will open the utility dialog for processing input data, as shown below. The menu in the upper left hand side of the dialog displays the input data files (having an extension .inp) existing in the project directory. In this case there is only one input data file "*Lateral_MaxQ.Inp*" and we select it by clicking on "*Select Input File*". The menu on the right side shows the data-sets which are included in file "*Lateral_MaxQ.Inp*". It shows the utility program that will be used for processing each set followed by the title of the data set in one line. Select the batch set on the top to process the data in batch mode and click on "*Process or View Input Data*". Flixan will process the input file and create the systems in file "*Lateral_MaxQ.Qdr*". It will also create the Matlab system files. Answer "Yes" in the next dialog to overwrite the previous systems data. However, some of the data, such as: TVC matrix, actuators, and sensors, will be preserved in the systems file "*Lateral_MaxQ.Qdr*" after processing, because "Retain" statements are included in the batch.



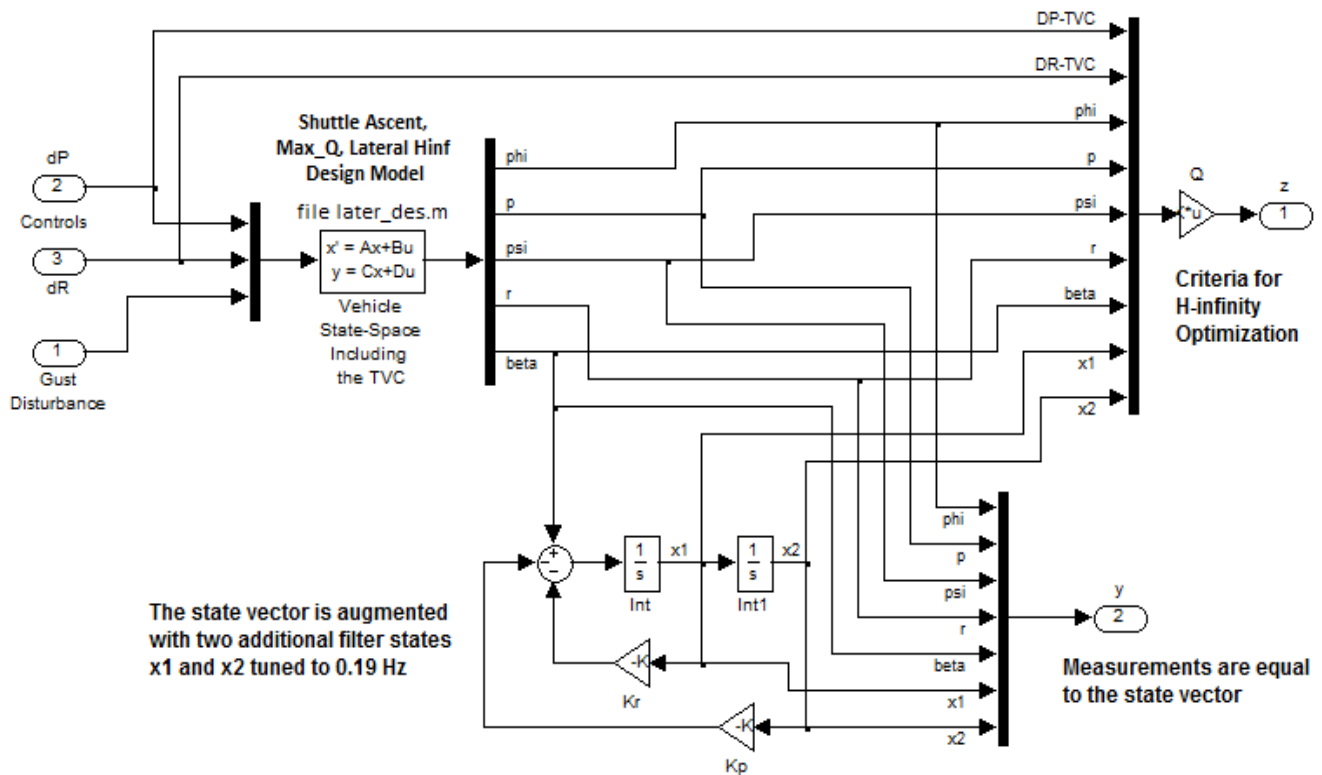


Figure (3.11) Lateral H-infinity Synthesis Model included in Simulink file "Design.Mdl"

Figure (3.11) shows the H-infinity synthesis model for the lateral axes. It uses the Flixan generated vehicle system "Shuttle Ascent, Max_Q, Lateral Hinf Design Model" from file "later_des.m". The TVC matrix is already included in this system and the control inputs are roll and yaw demands (dP , dR). The disturbance input (w) is the wind-gust velocity in (ft/sec). The wind-gust direction relative to the vehicle body is defined in the vehicle data to excite both pitch and lateral axes. The 1 (rad/sec) disturbance resonance is included in the SM and it is excited by the angle of sideslip (β) which is the key variable to minimize by the H-infinity design. It introduces two additional resonance states $x1$ and $x2$ which become part of the measurement and also the criteria output vectors. The criteria consist of mainly beta related states because the angle of sideslip is directly related to the lateral load and this is what we desire to relieve at high Q. The criteria variables also include the roll and yaw attitudes and rates, and also the controls (dP , dR). The criteria penalties are attached in the diagonal matrix Q. Notice that the attitudes (ϕ , ψ) are not penalized much because command following is compromised at high pressures. The control penalties prevent them from becoming too big under closed-loop control. Increasing the Q elements that correspond to the controls (dP , dR) decreases the control bandwidth. On the other hand, increasing the penalties that correspond to (β , $x1$, and $x2$) it improves sensitivity but it increases the control bandwidth. The measurements vector consists of the 7 states, 5 vehicle and 2 filter states. Notice that only the β -state is not directly measurable and it must be estimated, mainly from N_y and the gimbal deflections (δz).

The Matlab file "run.m" loads the systems and the TVC matrix and performs the design and control analysis. It uses the H-infinity method to design a (2×7) state-feedback gain K_{I3} from the 7-states vector (ϕ , p , ψ , r , β , $x1$, $x2$) that appear in the measurements, although (β) is not directly measurable. The H-infinity derived state-feedback matrix K_{I3} minimizes sensitivity between the gust disturbance

and the criteria defined. Having designed the state-feedback controller the next step is to analyze the (β) sensitivity to the gust disturbance. This is performed in the frequency domain by calculating the singular-value frequency response between the gust input and the angle of sideslip using the closed-loop Simulink system "Sensitiv4.mdl" shown in Figure (3.12). Notice that the actual angle of sideslip (β) is used for output in the sensitivity calculation. In the state-feedback, however, (β) is estimated using an β -estimator block, shown in detail in Figure (3.14). Also the input to the disturbance filter (which calculates states x_1 and x_2) is β -estimate rather than real β .

```

r2d=180/pi; d2r=pi/180;
om=1.2; zt=0.14; Kp=om^2; Kr=2*zt*om; %frq; % Disturb Filter Characteristics
[Ad, Bd, Cd, Dd]= later_des; % Shuttle Ascent, Max_Q, Lateral Hinf Design Model
[An, Bn, Cn, Dn]= later_anal; % Shuttle Ascent, Max_Q, Lateral Analysis with Slosh & TVC
[Ap, Bp, Cp, Dp]= plant; % Shuttle Plant Model at Max-Q (Flex Vehicle, Actuators, Sensors)
load TVC.mat -ascii % Shuttle Stage-1 TVC Matrix at Max-Q
load orig.mat % from Classical Design

%... Alpha/Beta Estimator parameters
Mass=93215; Sref= 2690; Qbar=745.4; Cyb=-0.0353; Cza=-0.0574;
Thr=[470000, 470000, 470000, 0.245e7, 0.245e7]';

%... Hinf Design ...
% [DPtvc,DRtvc, phi, p, psi, r, beta, x1, x2]
Q=diag([0.09, 0.12, 0.001, 0.1, 0.001, 0.1, 0.24, 0.13, 0.07]);
[Ad, Bd, Cd, Dd]= linmod('design');
sys = SS(Ad,Bd,Cd,Dd);
sysd=MKTITO(sys,7,2);
[K,CL,GAM,INFO] = hinfsyn(sysd,7,2);
K13=INFO.KFI(:,1:7);
Kp3 = [0.3042 3.4539 0.5105 0.0711 -0.2670];

% [Ao, Bo, Co, Do]= linmod('Anal2');
% [As, Bs, Cs, Ds]= linmod('Sensitiv2');
[Ao, Bo, Co, Do]= linmod('Anal5');
[As, Bs, Cs, Ds]= linmod('Sensitiv4');
%w=logspace(-3, 2.5, 10000); % Define Freq Range
syso= SS(Ao,Bo,Co,Do); % Create SS System
syss2= SS(As,Bs,Cs,Ds); % Create SS System
figure(1); Nichols(syso,w) % Plot Nichol's Chart
figure(2); Bode(syso,w) % Plot Bode
sig2=Sigma(syss2,w); % SV Bode
figure(3); loglog(w,sig1,'r',w,sig2,'b') % Plot SV Bode

```

**Shuttle Plant Model at Max-Q
(Flex Vehicle, Actuators, Sensors)**

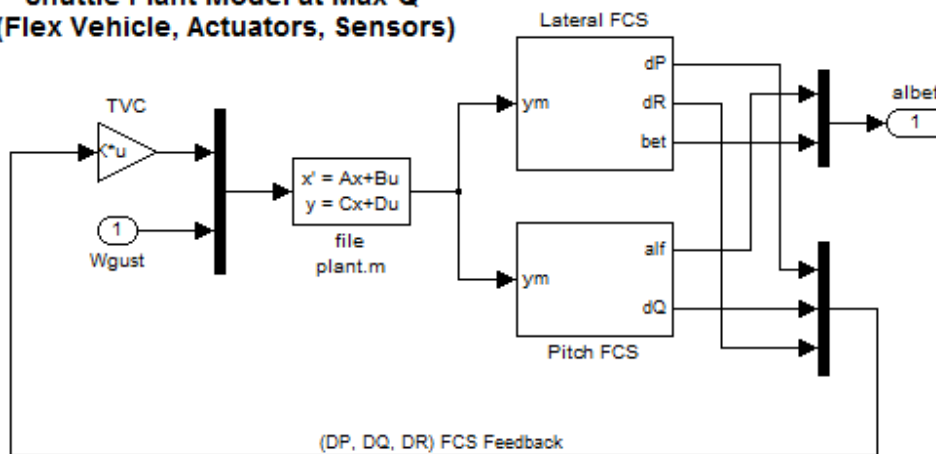


Figure (3.12a) Simulink System "Sensitiv4.mdl" used for Sensitivity Analysis

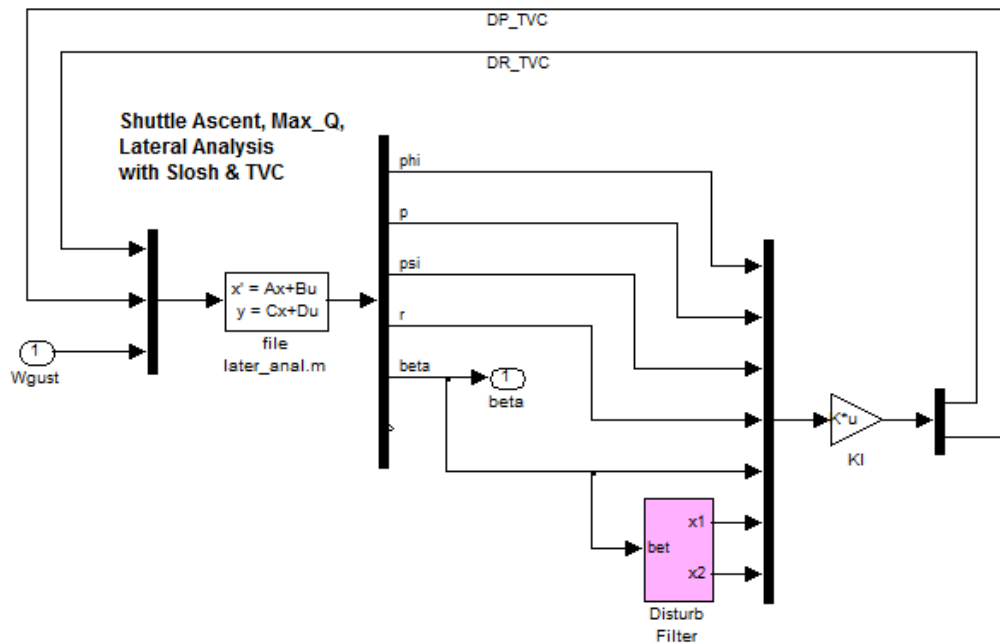


Figure (3.13) Simulink System "Sensitiv2.mdl" used for Preliminary Sensitivity Analysis. It has a direct measurement of Beta (not estimate)

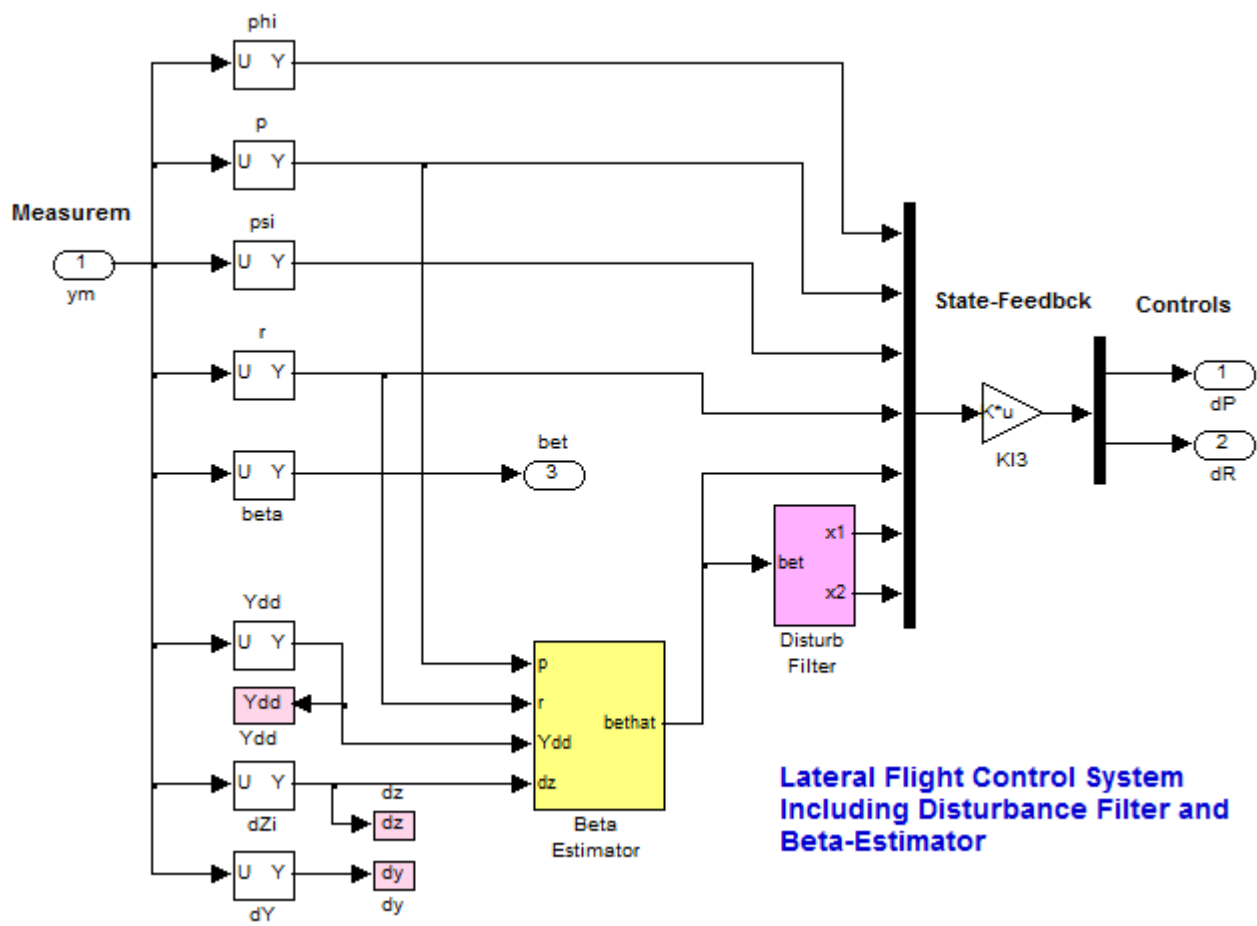


Figure (3.12b) Lateral Flight Control System Used in "Sensitiv4.mdl"

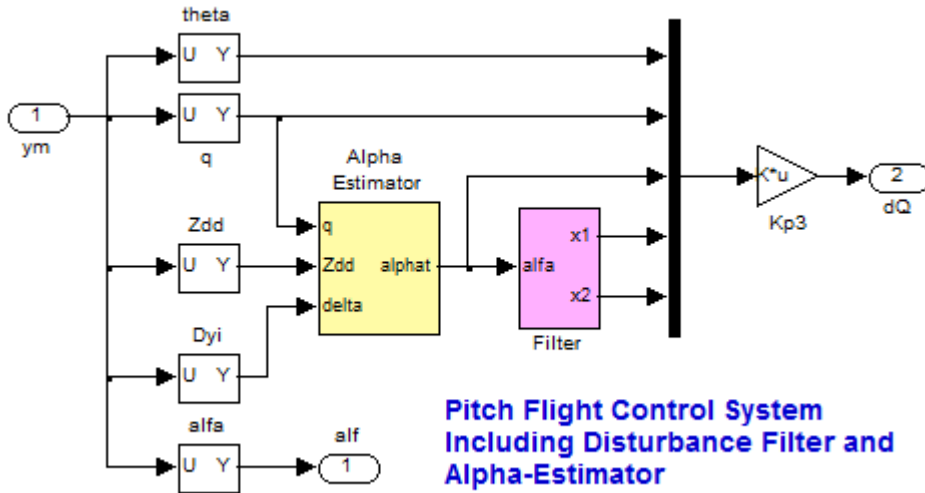


Figure (3.12c) Pitch Flight Control System Used in "Sensitiv4.mdl"

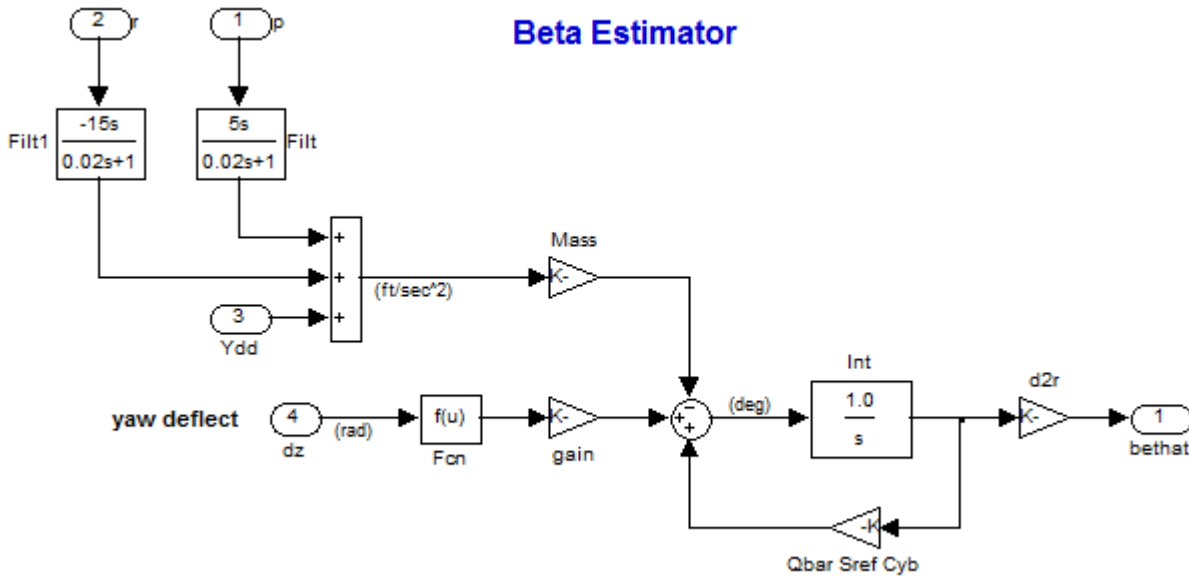


Figure (3.14) Estimator of the Angle of Sideslip is using measurements from the Lateral-Accelerometer, Gimbal Deflections, and Body Rates. It solves the following equation for (β). The rate derivatives compensate the accelerometer measurement because it is not located at the vehicle CG.

$$M \ddot{y} = \bar{Q} S_{ref} C_{y\beta} \beta + \sum T_i \delta_{zi}$$

Notice that the big plant model "Shuttle Plant Model at Max-Q (Flex Vehicle, Actuators, Sensors)" from file "plant.m" is used in the sensitivity analysis model "Sensitiv4.mdl". This system does not include the TVC matrix and it is added in the Simulink diagram (3.12a). This system for completeness it includes also the pitch state-feedback loop via matrix Kp3 that was calculated in Section (3.1). A similar Simulink model "Anal5.Mdl" is used for stability analysis, see Figure (3.15). The loop opening and closure in this case is configured for yaw stability analysis. The Bode and Nichols plots in Figure (3.16) show the yaw axis phase and gain margins.

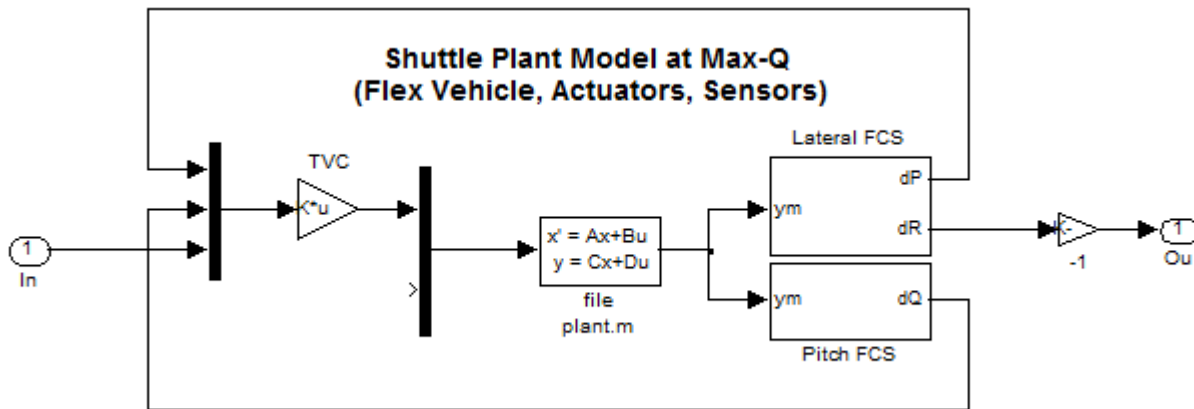
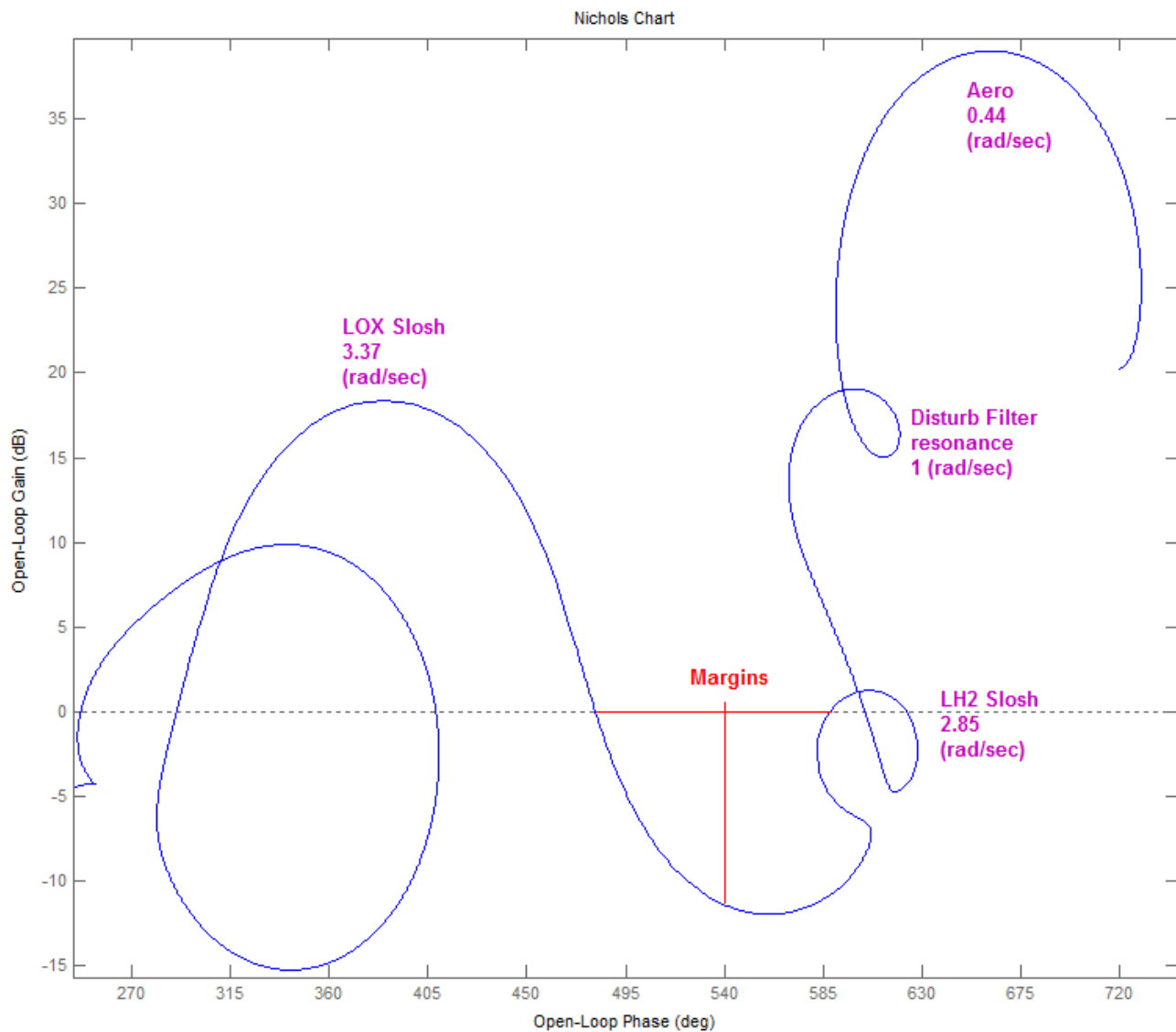


Figure (3.15) Simulink System "Anal5.mdl" used for Yaw Stability Analysis

Yaw Axis Stability (H-infinity design)



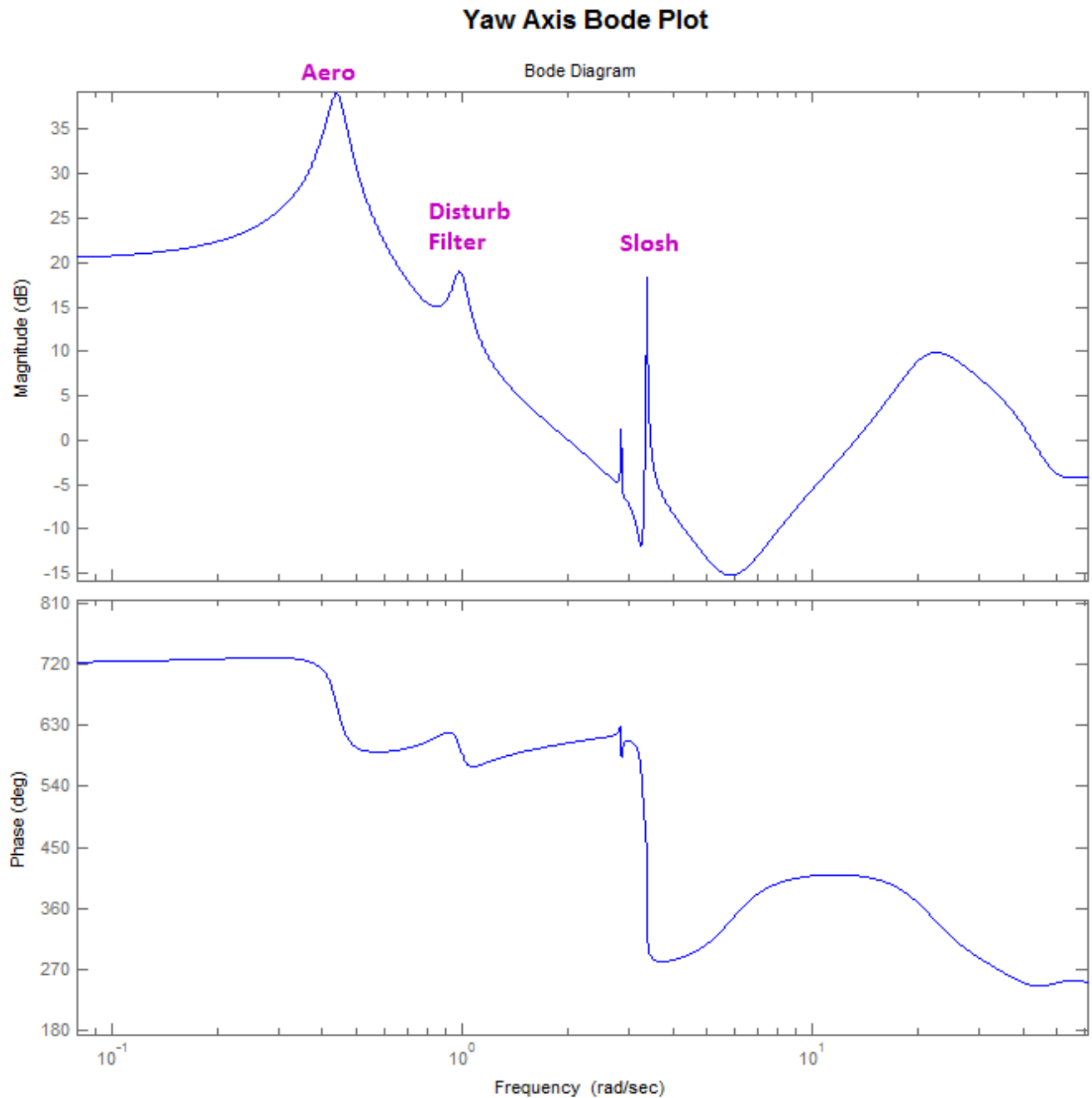


Figure (3.16) Nichols and Bode Open-Loop frequency response plots for the Yaw axis obtained using the Simulink System "Anal5.mdl". It shows an additional resonance at 1 (rad/sec) introduced by the disturbance filter. The high frequency resonance is typically attenuated with low-pass filters which are not included in this analysis.

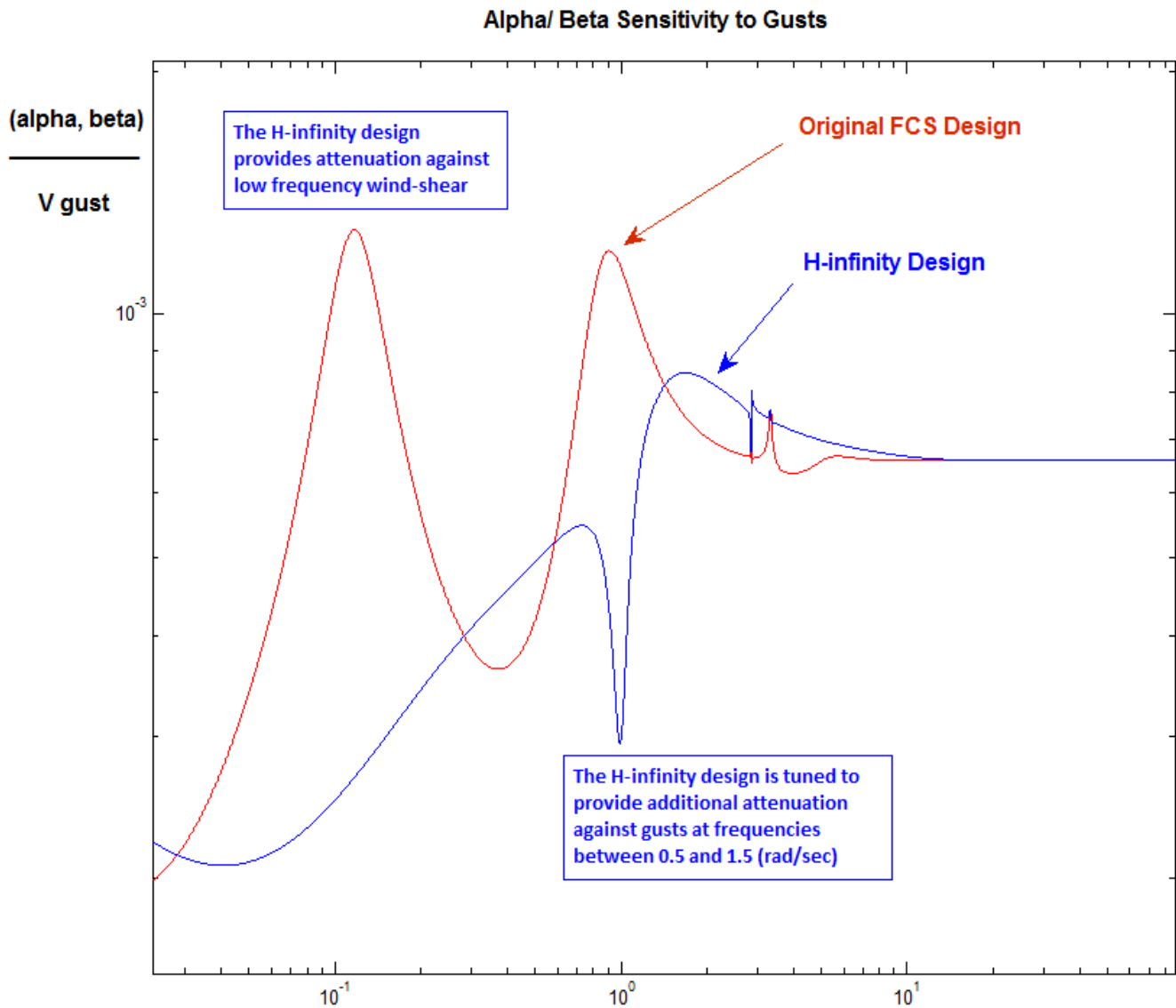
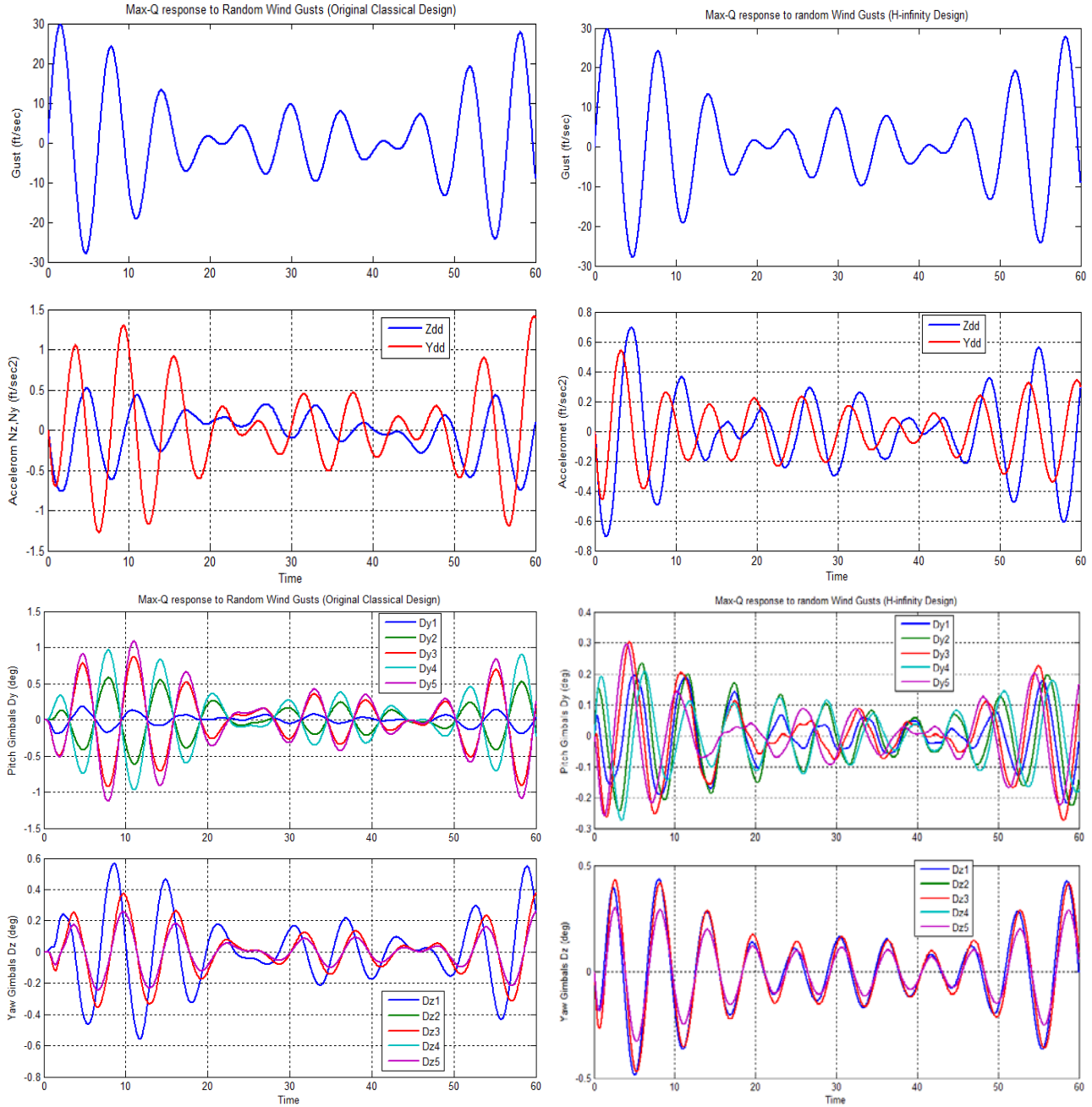
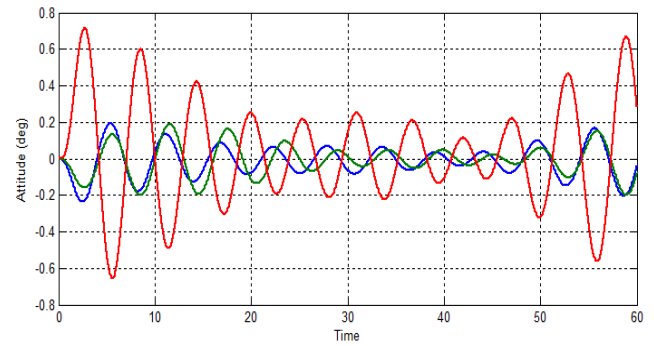
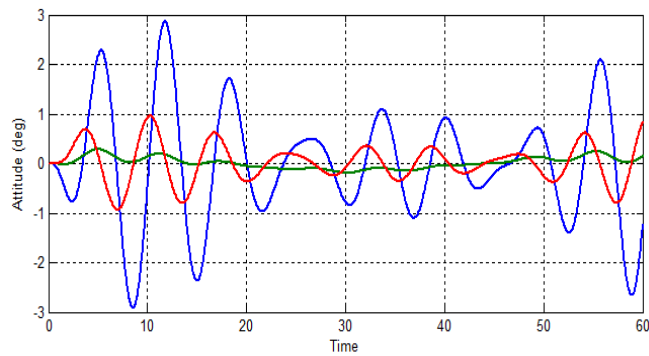
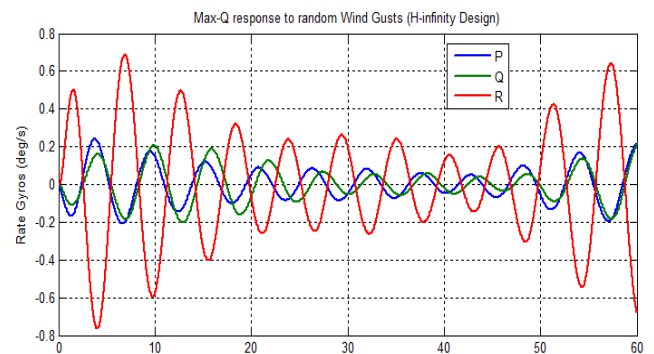
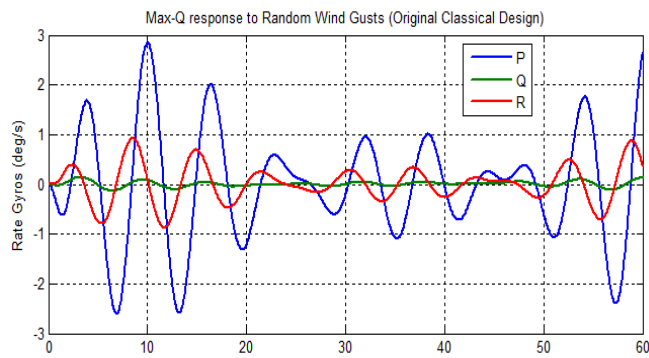
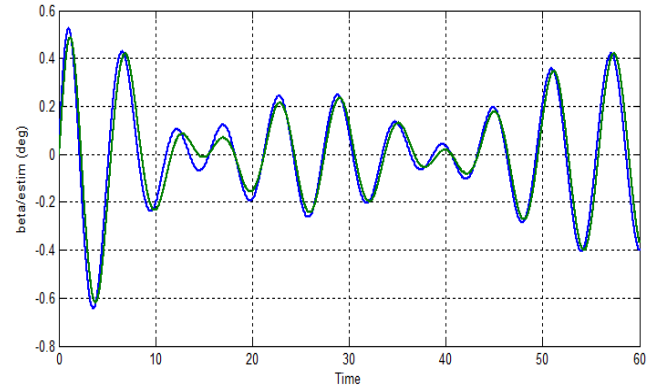
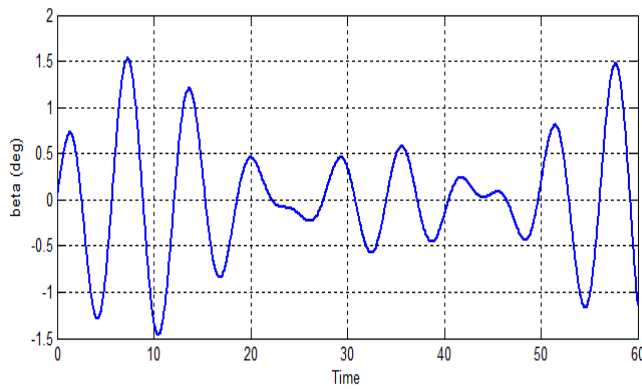
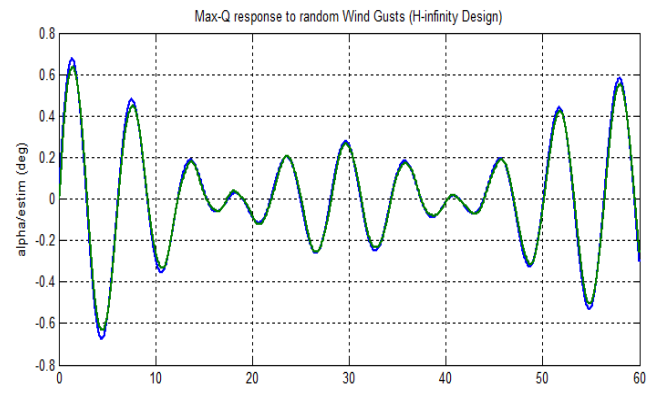
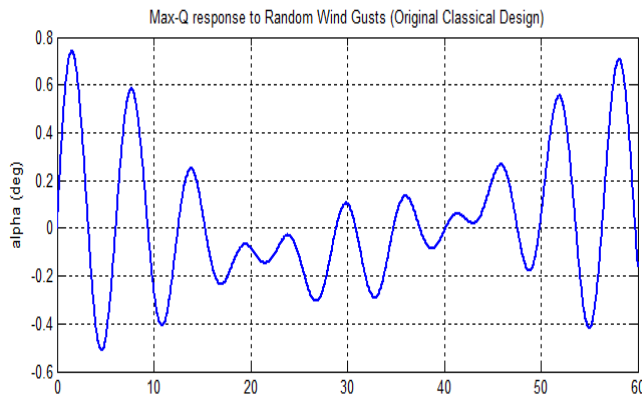


Figure (3.17) Sensitivity analysis plot showing the singular values for the transfer-function between the Gust input and (α, β) together. The frequency is in (rad/sec). It is comparing the sensitivity to gust disturbances between the original Shuttle FCS design and the H-infinity design. The blue curve is obtained using Simulink model "Sensitiv4.mdl" in Figure (3.12). The red curve was obtained from the original classical FCS design in section 3.0, Figure (3.1), as already described. The H-infinity design demonstrates superiority in the sensitivity both: at low frequencies against wind-shear, and also at 1 (rad/sec) which is the anticipated frequency of wind-gust disturbances.

3.3 Sensitivity Comparison Using Simulation

The following plots show a sensitivity comparison between the original and the H-infinity designs. The systems are excited with superimposed sinusoidal disturbances at around 1 (rad/sec). The response from the original FCS is obtained from the Simulink model "*Simz.mdl*" in folder "*C:\Flixan\Examples\Shuttle Ascent\Hinfinity Design\Original Shuttle FCS*", and the response from the H-infinity design is obtained from the Simulink model "*Sim4.mdl*" in folder "*C:\Flixan\Examples\Shuttle Ascent\Hinfinity Design\Lateral Anal*". The simulation results show that the H-infinity design significantly improves the system's sensitivity to cyclic gusts mainly in the lateral direction.





The results show that in addition to improving the lateral loading, the roll and yaw rates are also significantly reduced by the H-infinity control design. The improvement, however, in the pitch direction is not as significant because the original design was not as sensitive as the lateral to begin.