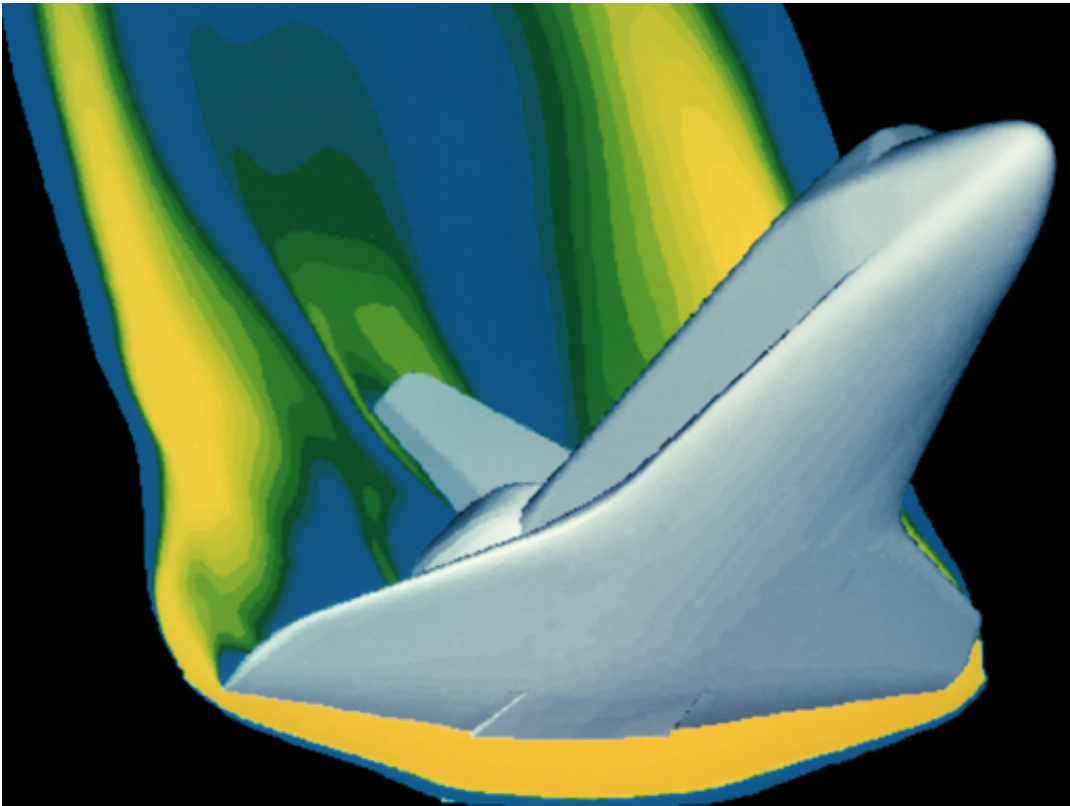


Re-Entry Glider Vehicle



In this example we will use the Flixan/ Trim program to analyze the performance of a re-entry, Shuttle type of unpowered vehicle in different phases, from the point where it begins to enter the atmosphere at 360,000 (ft) of altitude, all the way to landing. Descent begins after the vehicle fires its orbital maneuvering engines to slow-down, performs a large pitch attitude maneuver and positions itself at an angle of attack of approximately 41° , and gravity begins to take effect reducing its flight-path angle to $\gamma = -1^\circ$. Initially the dynamic pressure is very low and the vehicle uses mainly reaction control jets in combination with aero-surfaces for trimming and control. As the dynamic pressure increases the surfaces become more effective in controlling the vehicle and the RCS usage is reduced.

The vehicle uses six aero-surfaces for trimming and control: 2 flaps, 2 rudders, a body-flap, and a speed-brake, see Figure (4.1). The arrows show the hinge vector directions for positive rotations about the hinges. The speed-brake is only used near landing for speed control. The body-flap is only used for trimming and not flight control. Initially it is positioned at -20° which causes the vehicle to enter the atmosphere with a stable trim of approximately $\alpha = 41^\circ$. The RCS jets configuration consisting of 6 continuous (analog) jets is preliminary and intended mainly for sizing the thrusters and not for detail simulations. A flight control system consisting of RCS and aero-surfaces helps maintain a shallow flight-path angle $\gamma = 1^\circ$ and $\alpha = 41^\circ$, which prevent the vehicle from overheating. Although alpha is constant during the early part of re-entry, the bank angle is not always zero. As soon as the dynamic pressure increases to 5 (psf) the vehicle rolls about its velocity vector, and banks approximately 60° which

prevents it from bouncing back off into space. Further down it performs several bank reversal maneuvers while the angle of attack slowly decreases. The bank reversals at high Mach numbers are used for managing its excess energy. When the speed drops below Mach 1 the flight control mode switches to normal acceleration, N_z -control, for controlling altitude, and the flight path angle comes down steeper at -20° to maintain high speed for the approach and landing maneuver. During this period the vehicle also uses its speed-brake for velocity control.

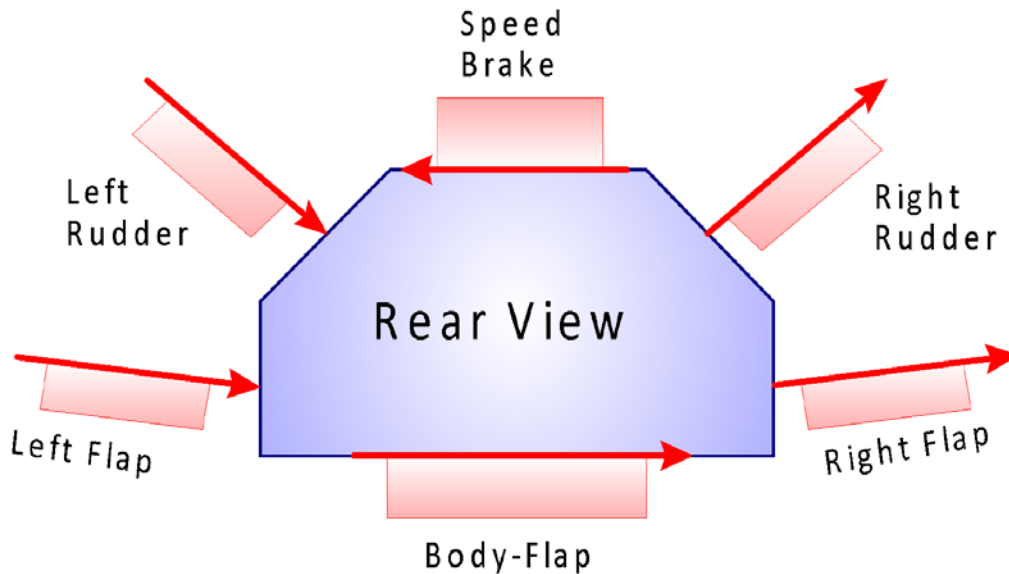


Figure 4.1 Six Aero-Surfaces and the Directions of the Hinge Vectors

The analysis that follows is separated in three sections.

1. An early phase where the dynamic pressure is low, the angle of attack is 41° , and the flight path angle is -1° . The pitch control system is initially controlling alpha at 41° and later it switches to γ -control. In the lateral direction it controls roll about the velocity vector V_0 and performs roll maneuvers.
2. A mid-phase analysis during which the vehicle begins by controlling the angle of attack, initially at 41° and then reducing it to lower values. Further down the flight-path angle is controlled at a steady shallow value of -1° . Although the dynamic pressure is sufficient for aero-surfaces control the RCS is also partially active in order to augment controllability. During periods of reversed or uncertain LCDP the RCS controls the roll and yaw axes and the control surfaces control the longitudinal axes.
3. The approach and landing phase during which the RCS jets are turned off and the speed-brake and body-flap become active in longitudinal control. The vehicle altitude and speed are controlled independently. The altitude is controlled by a combination of pitching using the V-tails and N_z -control using the flaps, and the speed using a combination of speed-brake and body-flap from their partially deployed positions. In lateral the heading direction is controlled by banking about the velocity vector V_0 .

This is a great example for demonstrating a vehicle that uses a combination of aero-surfaces and RCS jets for trimming and control. We will analyze each of these phases separately by trimming the effectors, analyzing static performance along the trajectory, using contour plots and vector diagrams for analyzing performance and maneuverability, generating dynamic models, designing flight control laws, and analyzing dynamic stability at selected flight conditions.

1.0 Early Re-Entry Phase

In this early phase of the trajectory the dynamic pressure is very low and the vehicle uses mainly the reaction control jets in combination with the aero-surfaces for flight control. As the dynamic pressure increases the surfaces become more effective and the RCS is gradually phased out. During this phase the vehicle uses only 5 of its aero-surfaces. The 2 flaps, 2 rudders, and the body-flap. The speed-brake is reserved for near landing. The aero-surfaces and mainly the body-flap are trimmed to provide static stability and a steady angle of attack at approximately 41° . The integrated RCS and aero-surfaces flight control system helps maintain a shallow flight-path angle of approximately -1.2° to prevent the vehicle from burning due to friction. Although alpha is constant the bank angle is changing. As soon as the dynamic pressure increases to 5 (psf) the vehicle rolls about its velocity vector and banks approximately 70° to the right to prevent it from bouncing off back into space. It continues performing several bank reversal maneuvers while it is slowly decreases its angle of attack. The bank reversals are also used to manage its excess energy since the speed-brake is not used in hypersonic speeds.

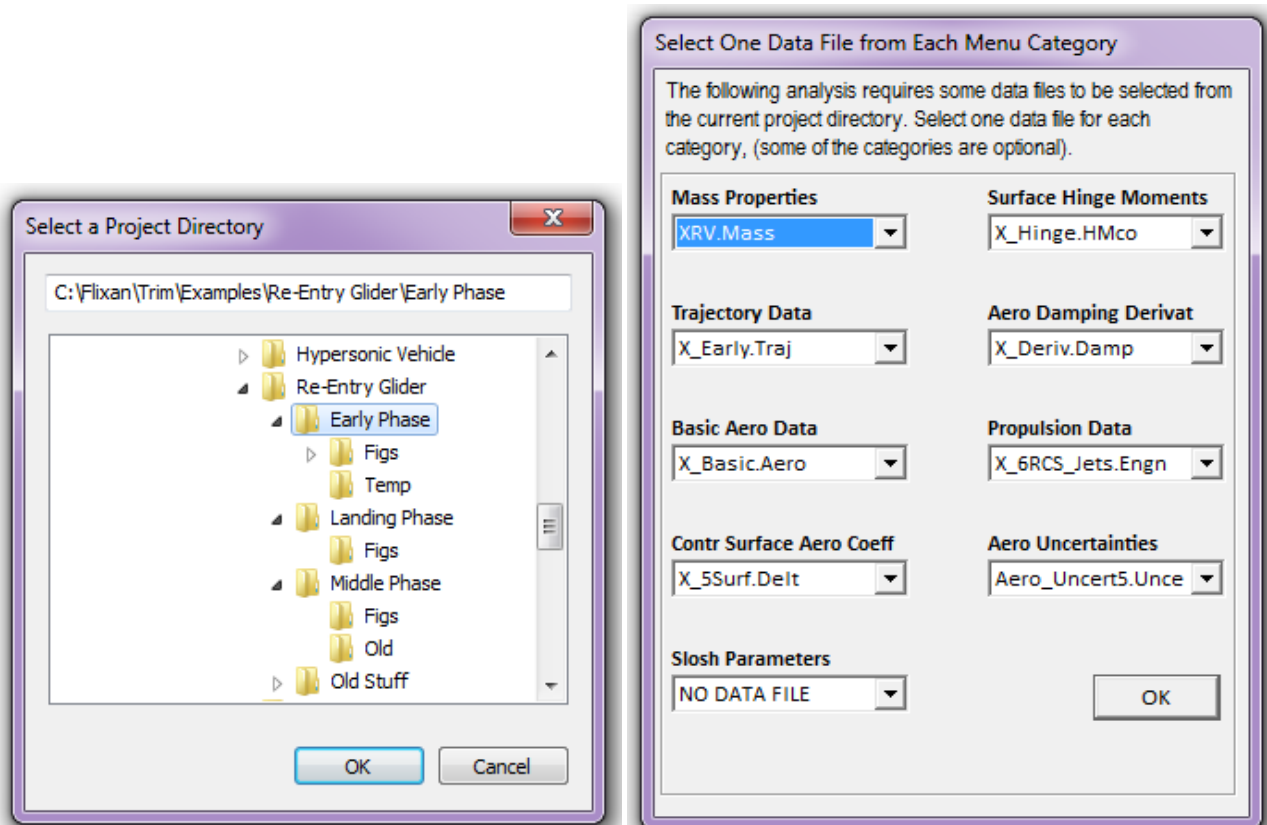
In this early re-entry phase we are not interested to control or trim along the normal and axial accelerations. In the pitch direction we want to accurately control the angle of attack and the flight path angle because this regulates heating. In the lateral direction we should be able to perform roll maneuvers about the velocity vector V_0 because this minimizes sideslip and lateral loading. The control system, therefore, consists of roll, pitch, and yaw control by means of a combination of RCS and aero-surfaces that helps maintain a predefined alpha and flight path angle trajectory and to perform roll maneuvers about the velocity vector. The simplified RCS system used in this analysis is only for sizing purposes and it does not represent a typical RCS consisting of multiple thrusters in various directions. Although both aero-surfaces and RCS operate in parallel during this phase, the RCS jets dominate during the first 350 sec and the surfaces gradually take over when the dynamic pressure increases.

The files for this early re-entry phase are in directory "C:\Flixan\ Trim\ Examples\Re-Entry Glider\Early Phase". The trajectory file "X_Early.Traj" contains only the early part of the descent trajectory. The definitions of the RCS jets are in file "X_6RCS_Jets.Engn", which consist of 6 throttling jets that provide moments in all 3 axes. Each thruster is defined with a throttling parameter of (1) which represents a pair of back-to-back firing jets with zero nominal thrust, that can generate either positive or negative continuous thrust. In contrast with a throttling engine that has a non-zero nominal thrust T_e , a throttling parameter which is less than one, and can vary its thrust about T_e . Trimming is used to determine the thrust requirement for each jet. The exact modeling of the RCS locations, thrusting directions, and bang-bang control laws is typically implemented later in the simulation models which are created by the Flixan vehicle modeling program (FVMP).

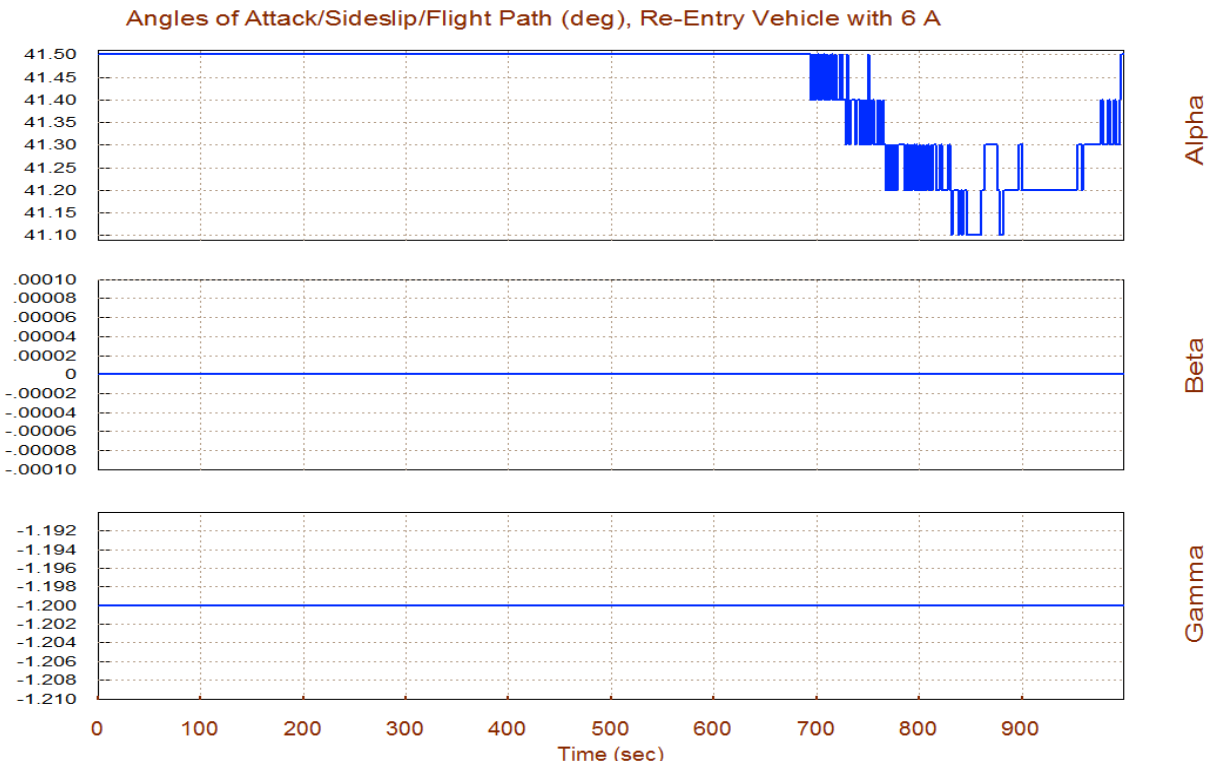
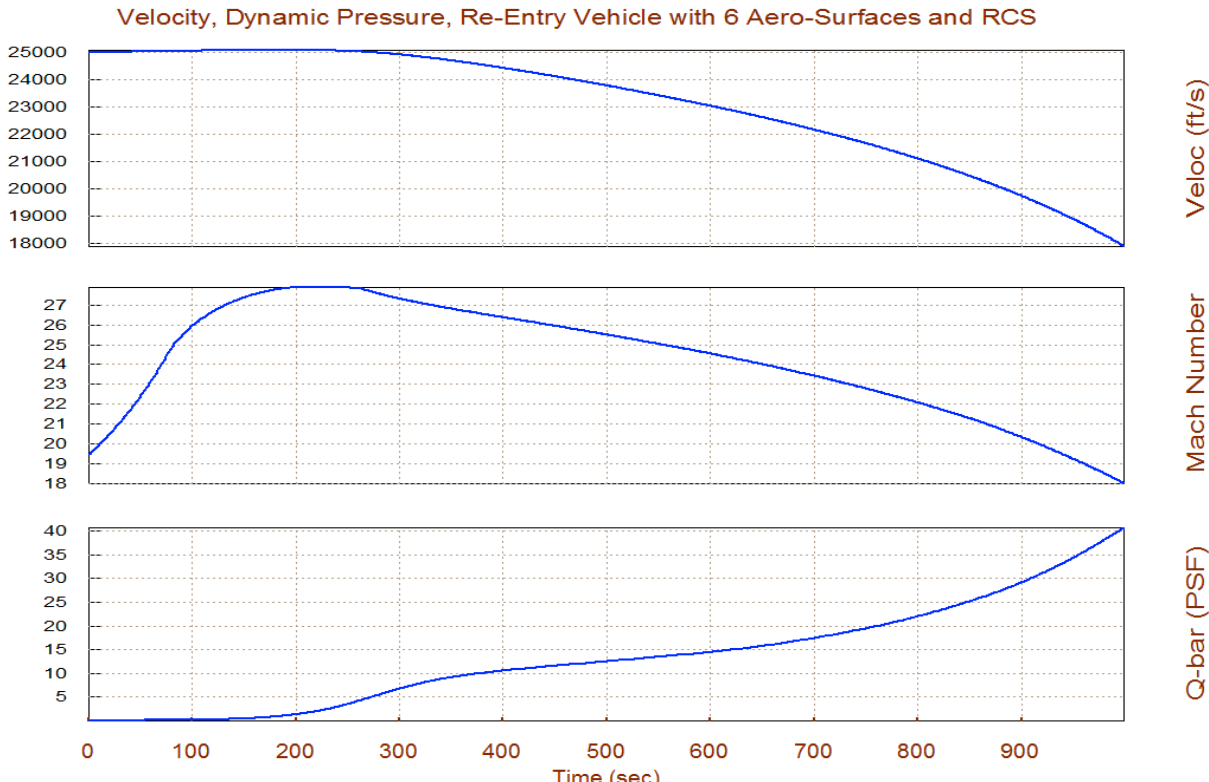
The coefficients for the six aero-surfaces are in file "X_5Surf.Delt". The Body-Flap is biased at -20° in the aero-data file. This body-flap angle trims the vehicle at an $\alpha=41^\circ$ which is optimal for heat protection. A zero Body-Flap command corresponds to -20°. Only the first 5 surfaces are used in this file. The speed-brake is not used before the approach and landing phase. The same argument applies for the hinge-moment coefficients file "X_Hinge.HMco". The base aero coefficients are in file "X_Basic.Aero", the damping derivatives are in "X_Deriv.Damp", and the mass properties are in file "XRV.Mass".

As you already noticed, in this early phase, the vehicle is using multiple effectors and some of them are contributing in the same directions. Even though the aero-surfaces and the RCS are both active during trimming they should be prioritized by the analyst. The jets should be used during the period where the surfaces are ineffective and they should be turned off from trimming when the surfaces become effective. This is a great example for demonstrating how to prioritize the effectors during trimming. The Trim program if left unconstrained it typically allows all effectors to participate in trimming according to their capability in certain directions. There are situations, however, where we would like to de-emphasize some effectors and to allow other effectors to take over, such as during this early re-entry situation, where we would like to de-emphasize the jets for fuel saving purposes. This prioritization is accomplished by adjusting the deflection limits prior to trimming.

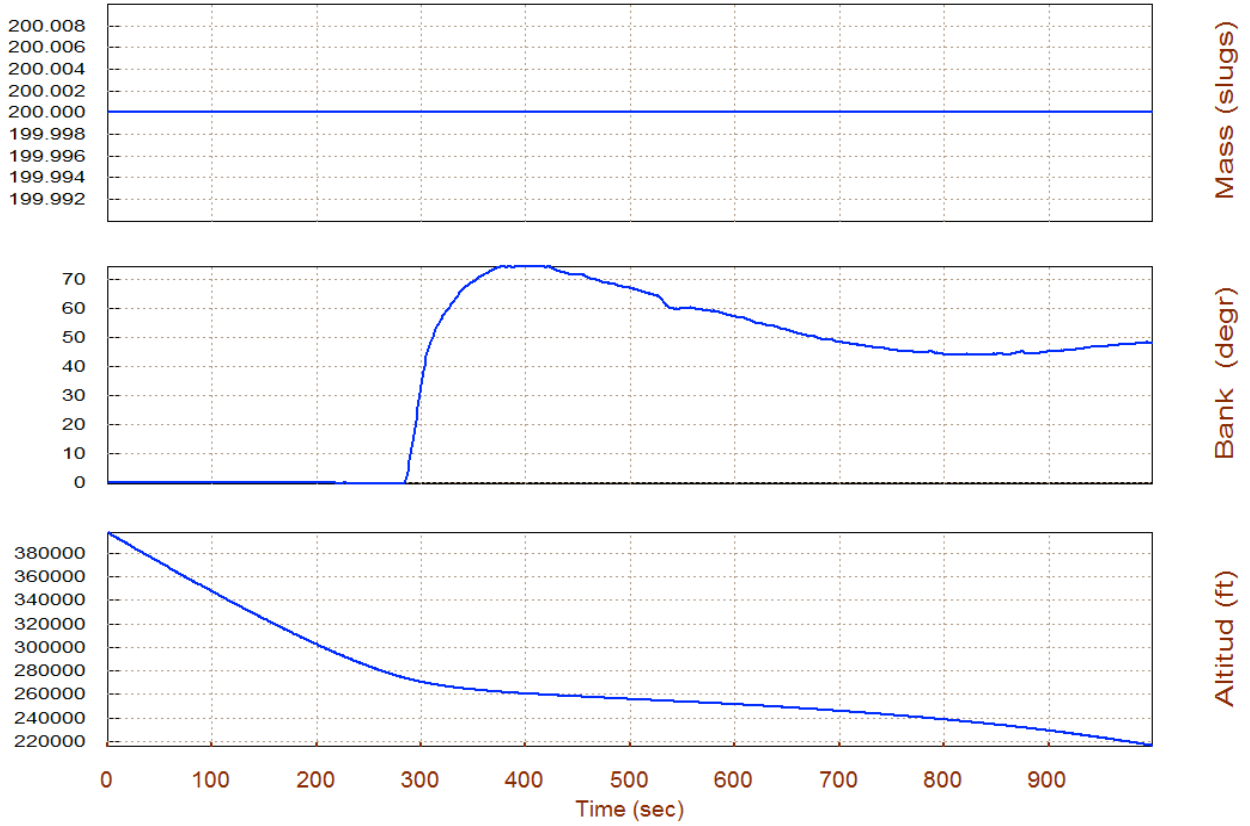
The idea is better explained with an example. Let us begin Flixan, choose the project folder that contains the data for the early re-entry phase, and select the files that were already described, as shown. Then from the Trim main menu select option (2) to take a look at the trajectory.



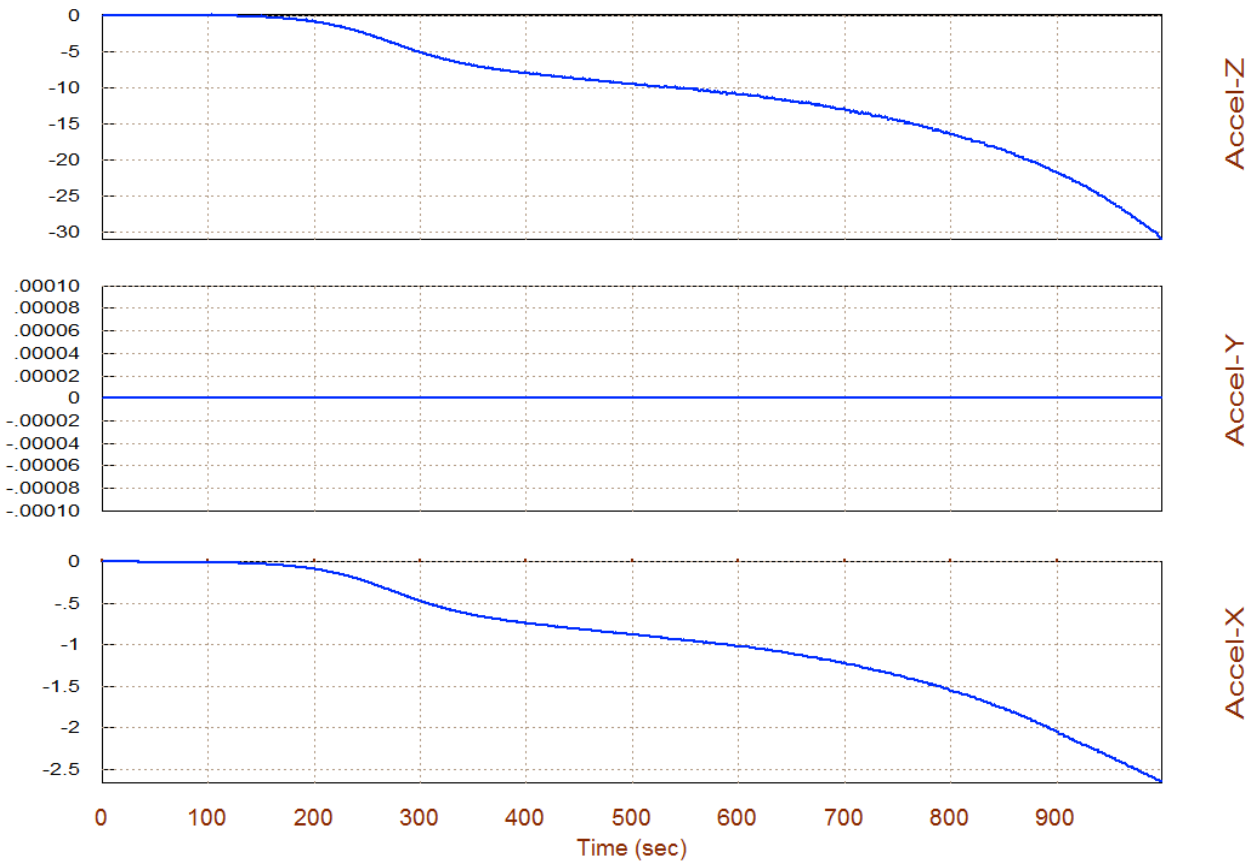
The angle of attack during this phase is constant at 41°. The re-entry velocity begins at 25,000 (ft/sec) and it begins to come down as the dynamic pressure builds up. During this phase Q-bar starts at zero and increases to 40 (lb/ft²). The altitude starts at 400,000 (ft) and it gradually decreases, as shown. At t=280 sec the vehicle begins its first bank maneuver.



Vehicle Altitude, Mass, Bank Angle, Re-Entry Vehicle with 6 Aero-Surfa

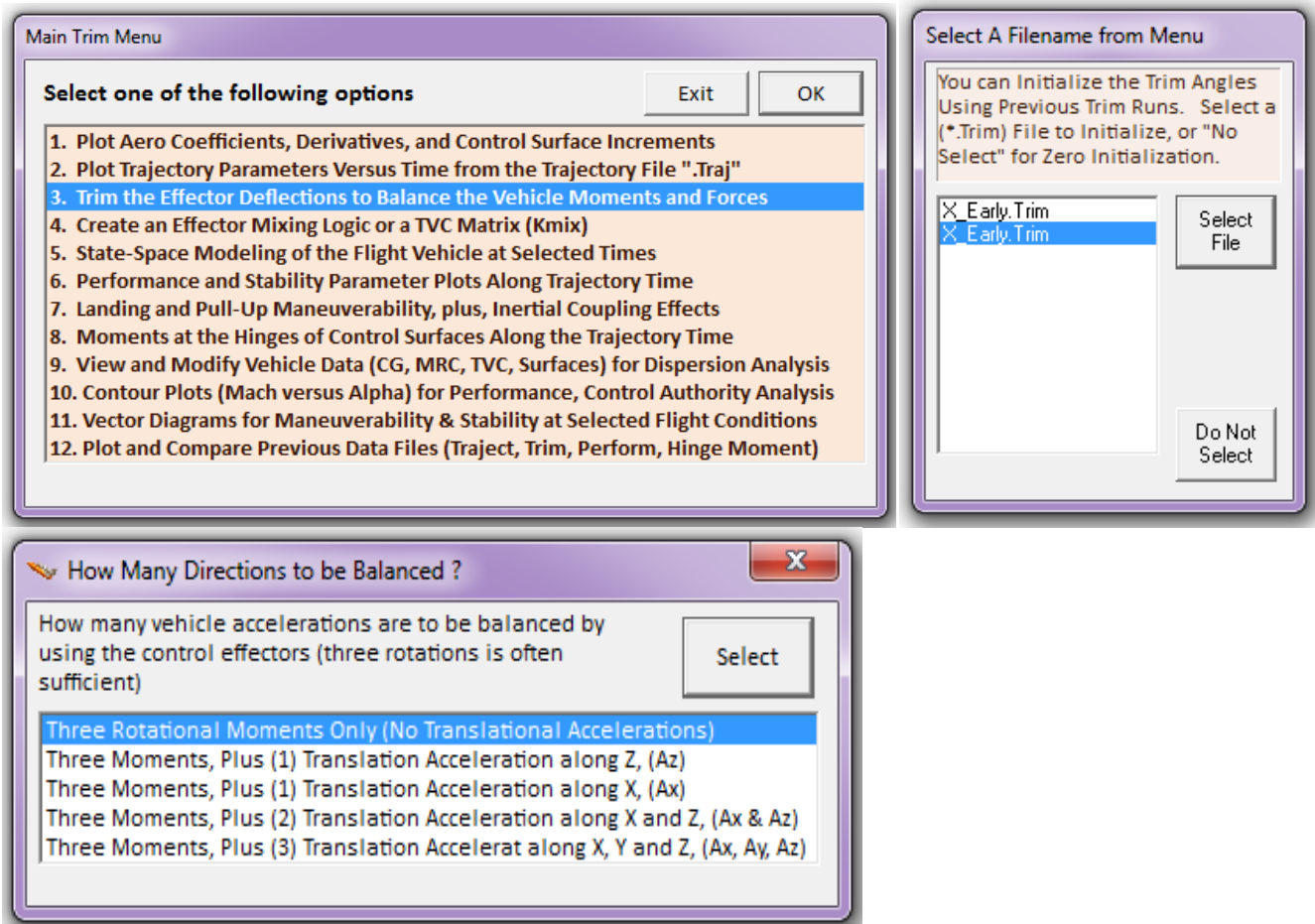


Sensed Acceleration in (ft/sec^2), Re-Entry Vehicle with 6 Aero-Surfa



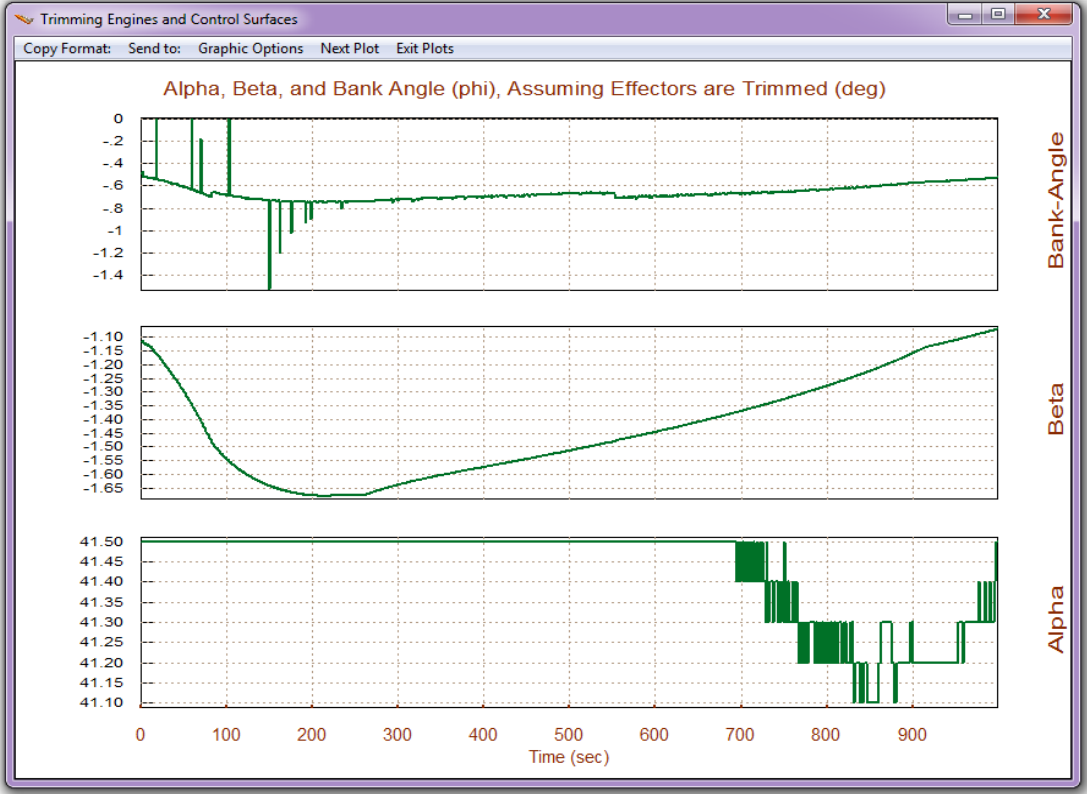
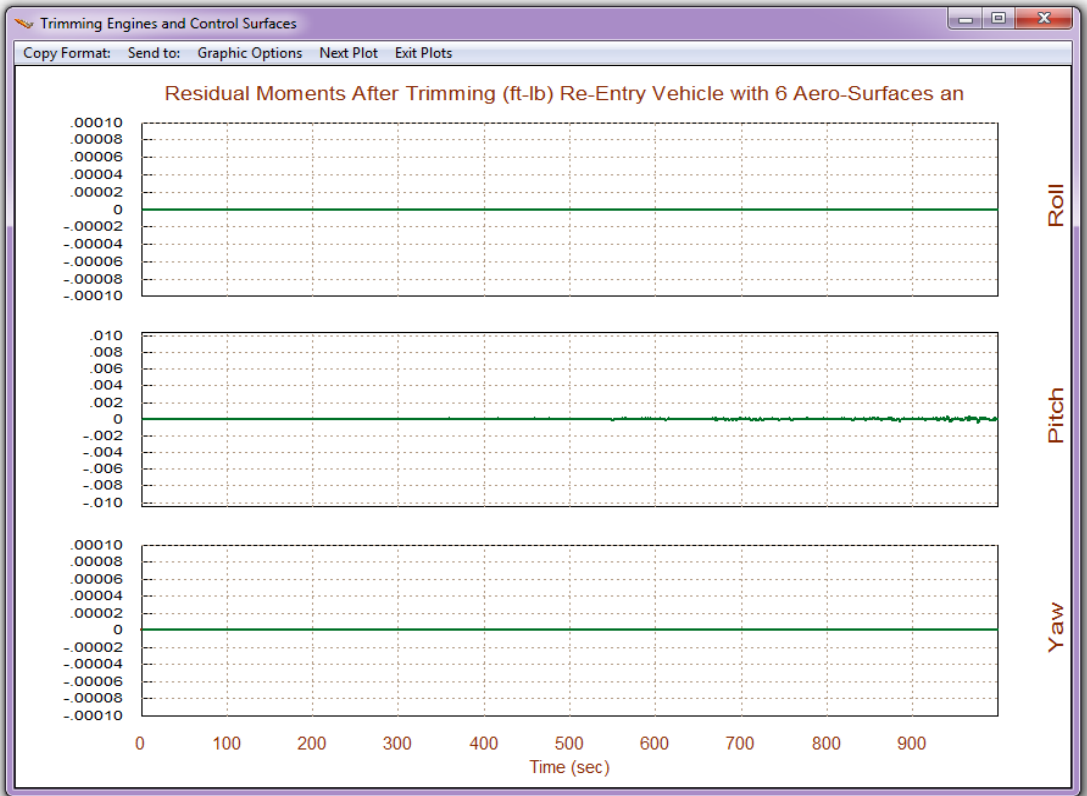
1.1 Trimming

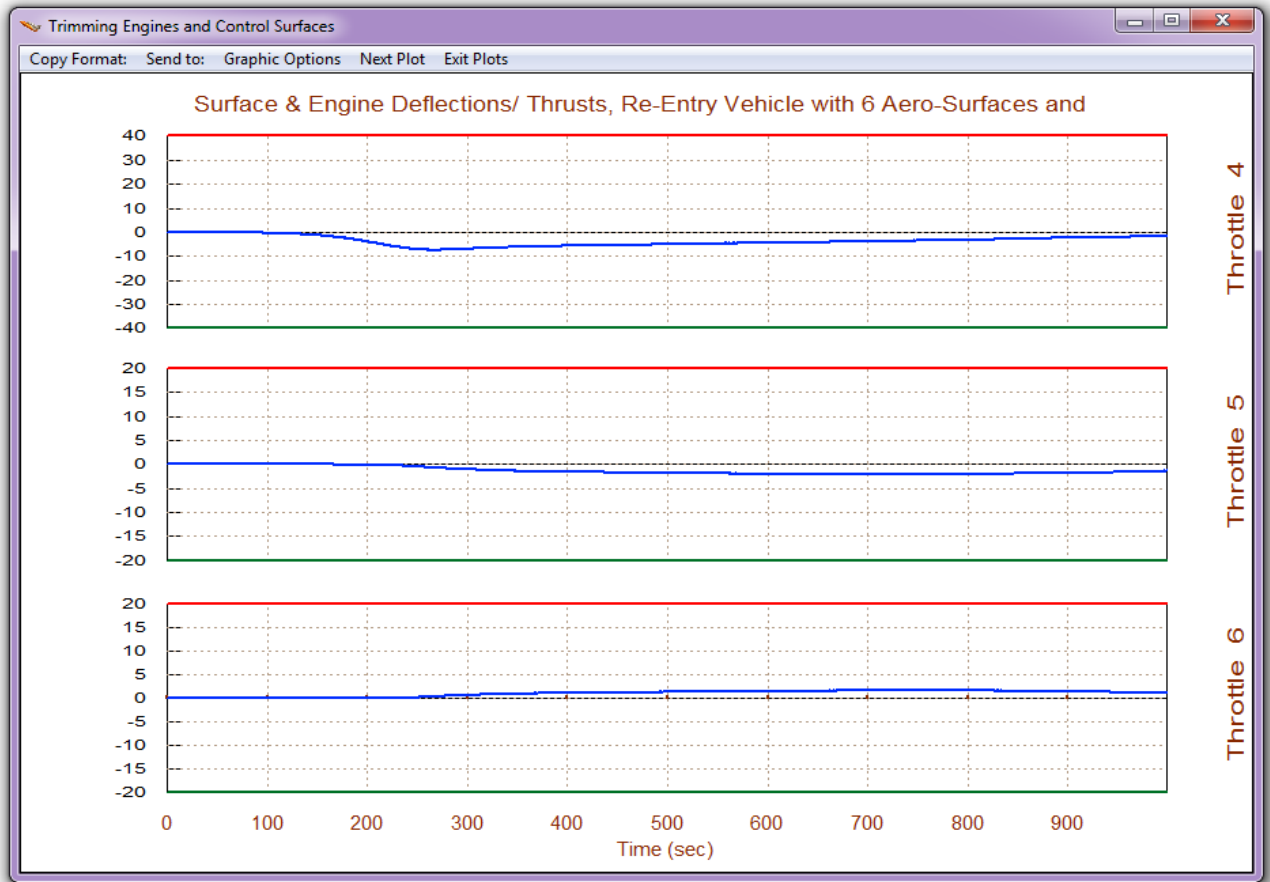
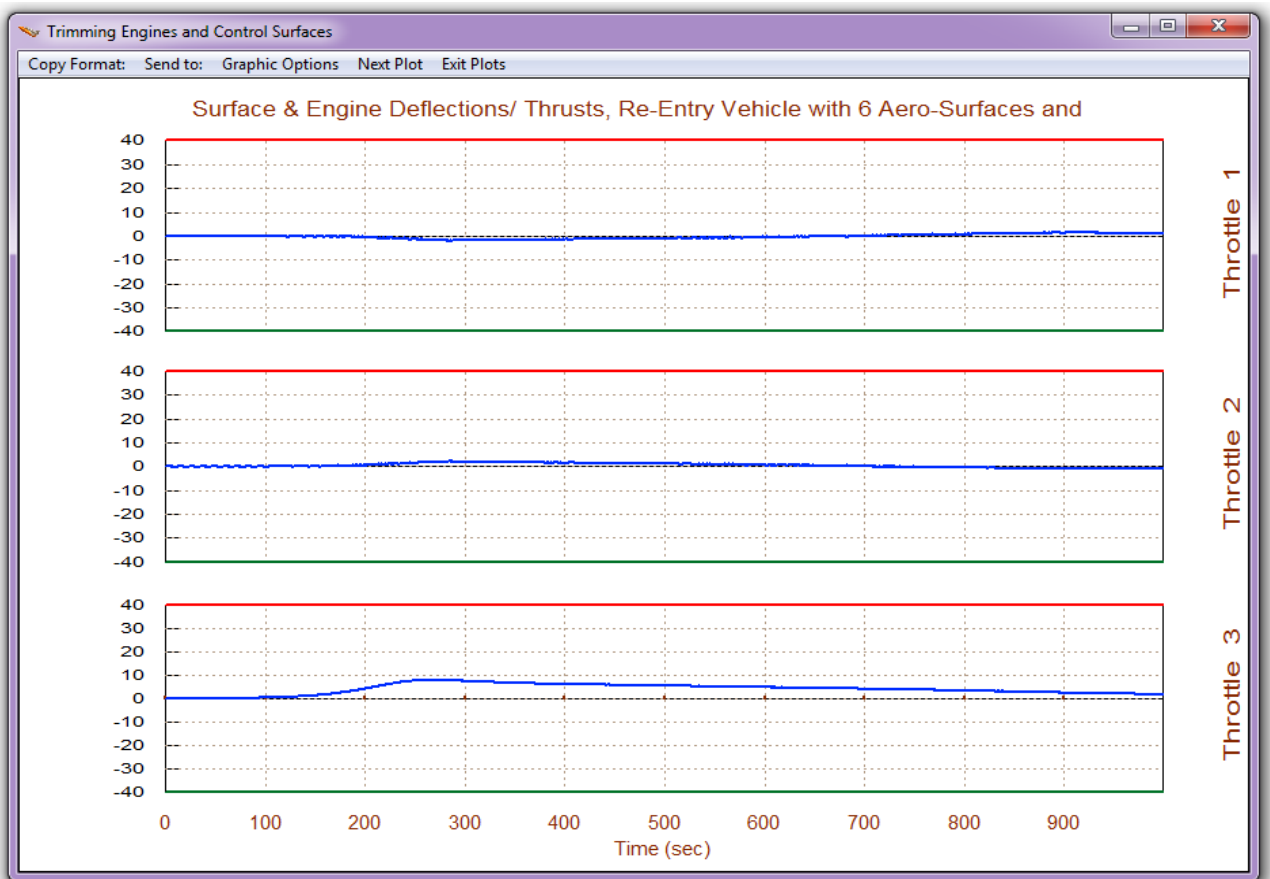
Trimming is an open-loop process that calculates the positions of the effectors in order to balance the moments on the vehicle along a trajectory. It is also used for sizing the control effectors. When the vehicle has multiple types of effectors controlling the same direction some of them will be more active along that direction than others. This compromise in trimming must be determined by the analyst who decides which effectors will dominate after trading-off between benefits and disadvantages for optimizing vehicle performance. During flight, the pre-calculated effector trim positions are usually commanded open-loop (scheduled) as a function of the flight condition or time. The flight control deflection commands are superimposed on the top of the pre-scheduled commands. This vehicle is using both aero-surfaces and reaction jets to trim. We will first use the trim program to trim the effectors without any assistance from the user. Return to the Trim main menu and choose option (3) for trimming. Do not select a trim initialization file and select to trim only along the three rotational moments, roll, pitch, and yaw. The algorithm calculates a combination of jet thrusts plus aero-surface deflections to trim based on their control authority in each direction.

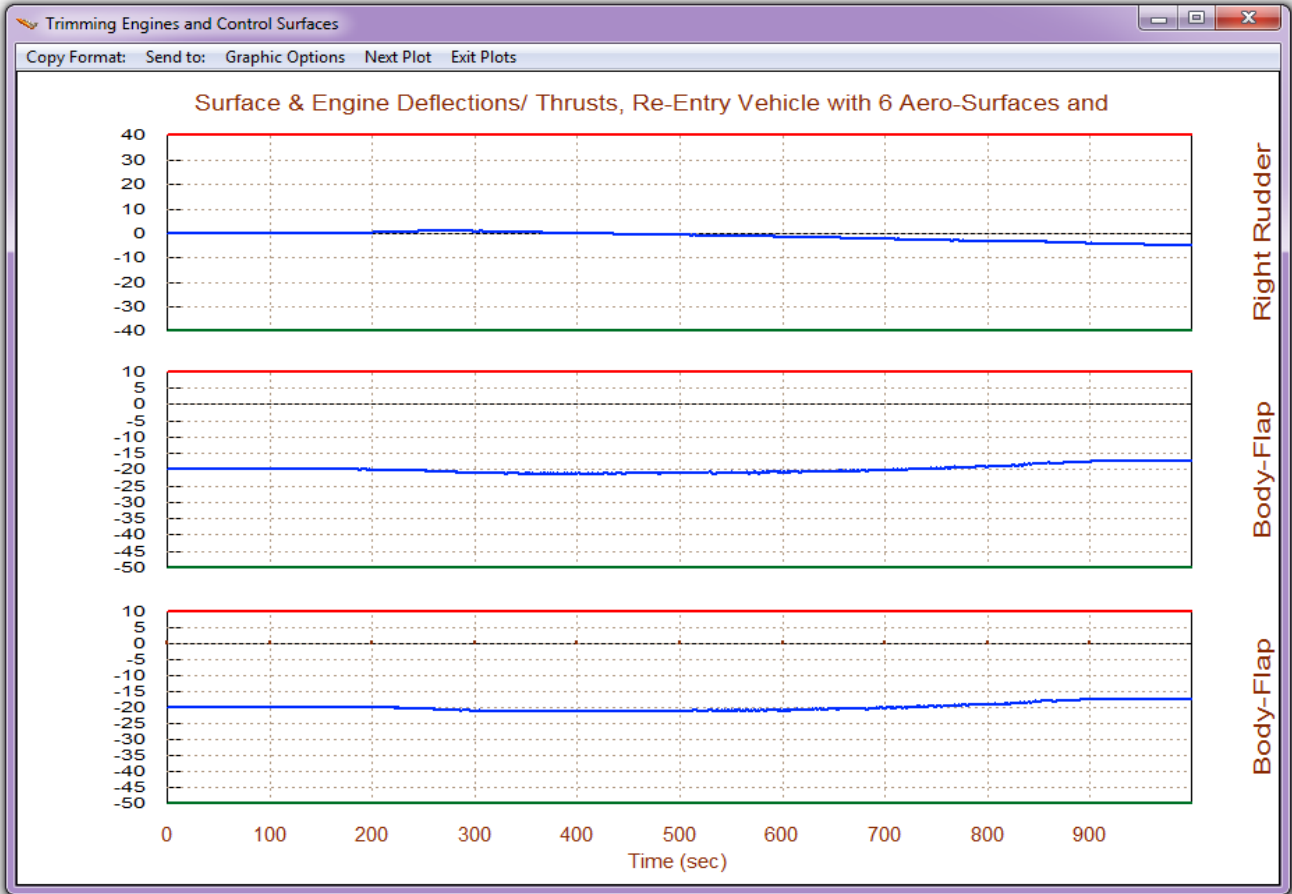
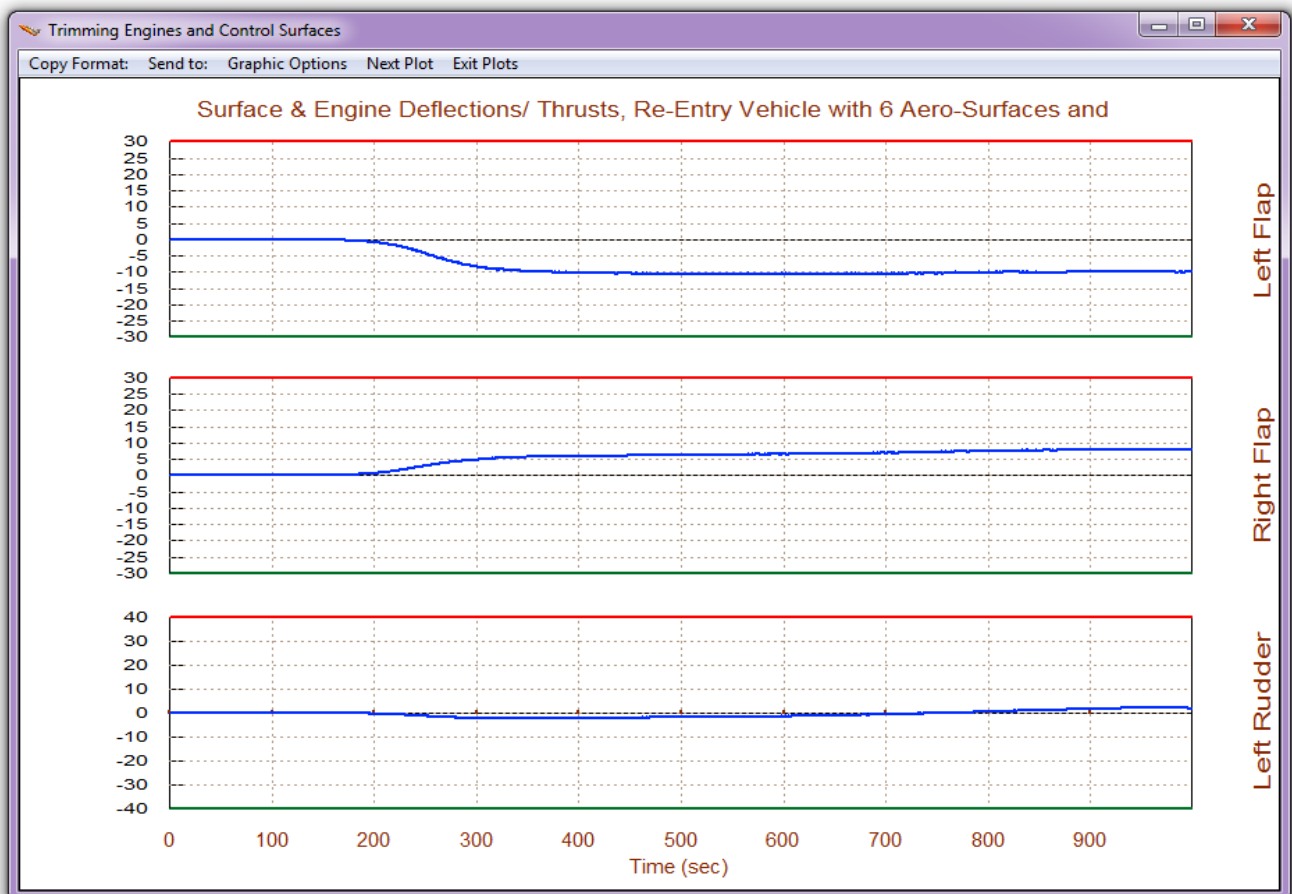


In the mass properties data we have included a small (0.1 ft) YCG offset. This introduces some activity in the lateral directions and a small sideslip angle beta. The residual moments after trimming are zero which means that the trimming was successful. The figures that follow show the 6 RCS jet throttle

positions and the 5 aero surface deflections which are required to balance the vehicle moments along the pitch, yaw, and roll axes in this part of the trajectory.



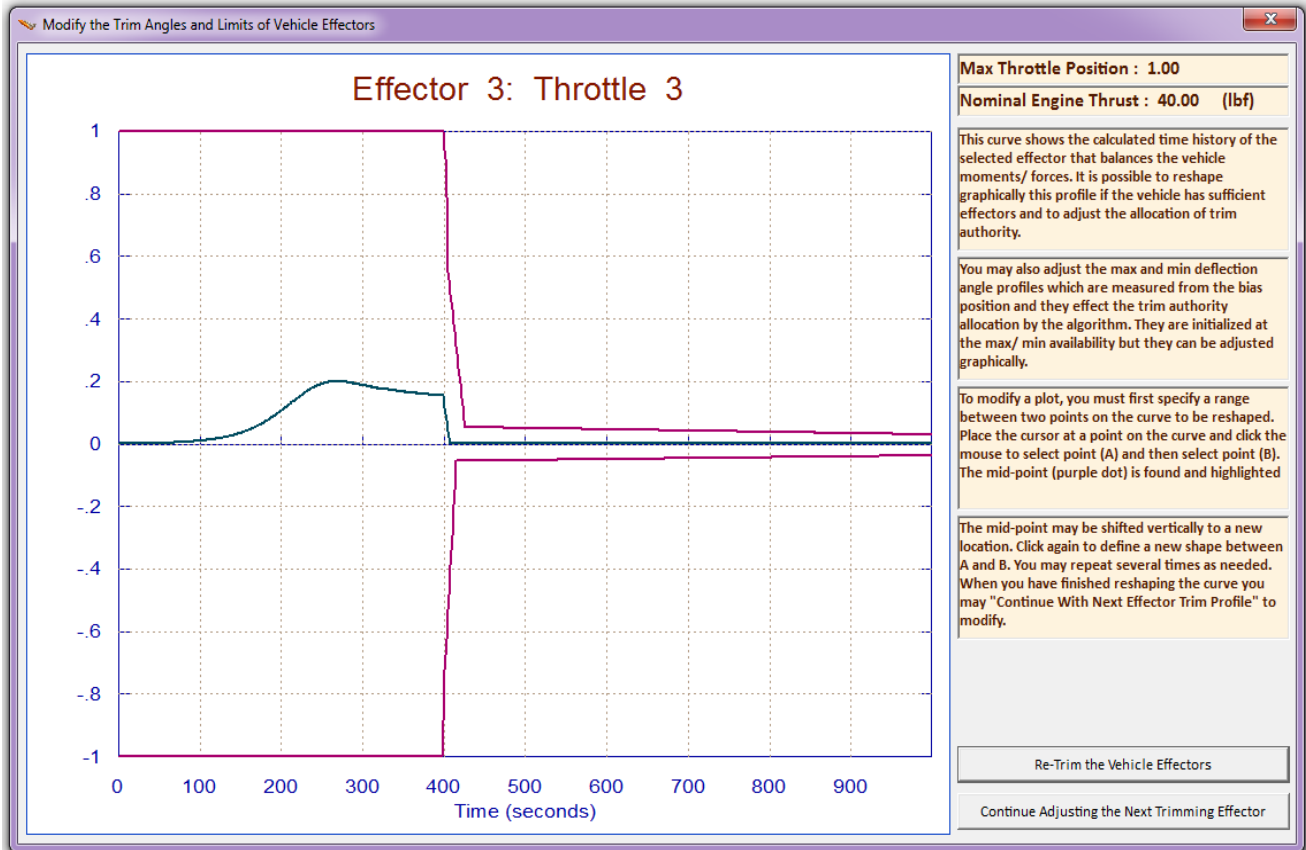
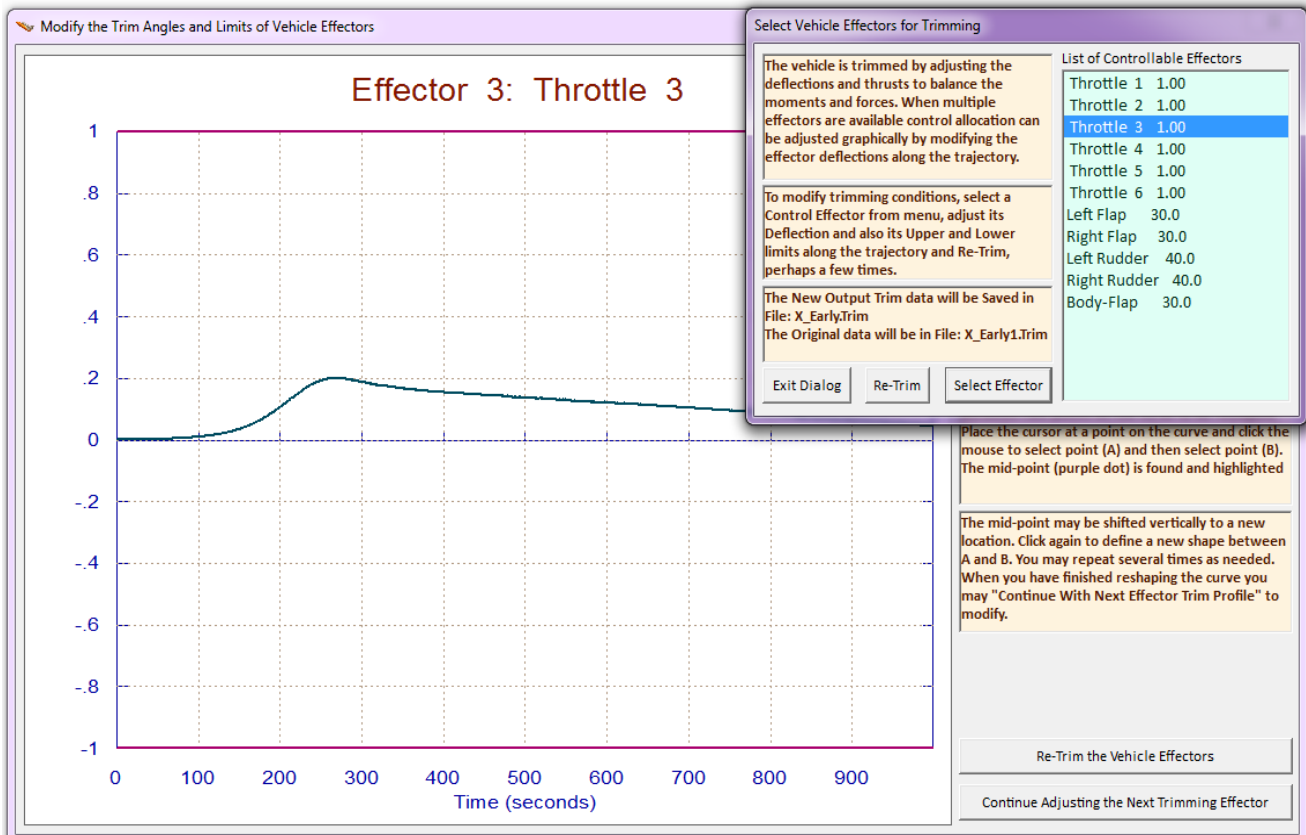




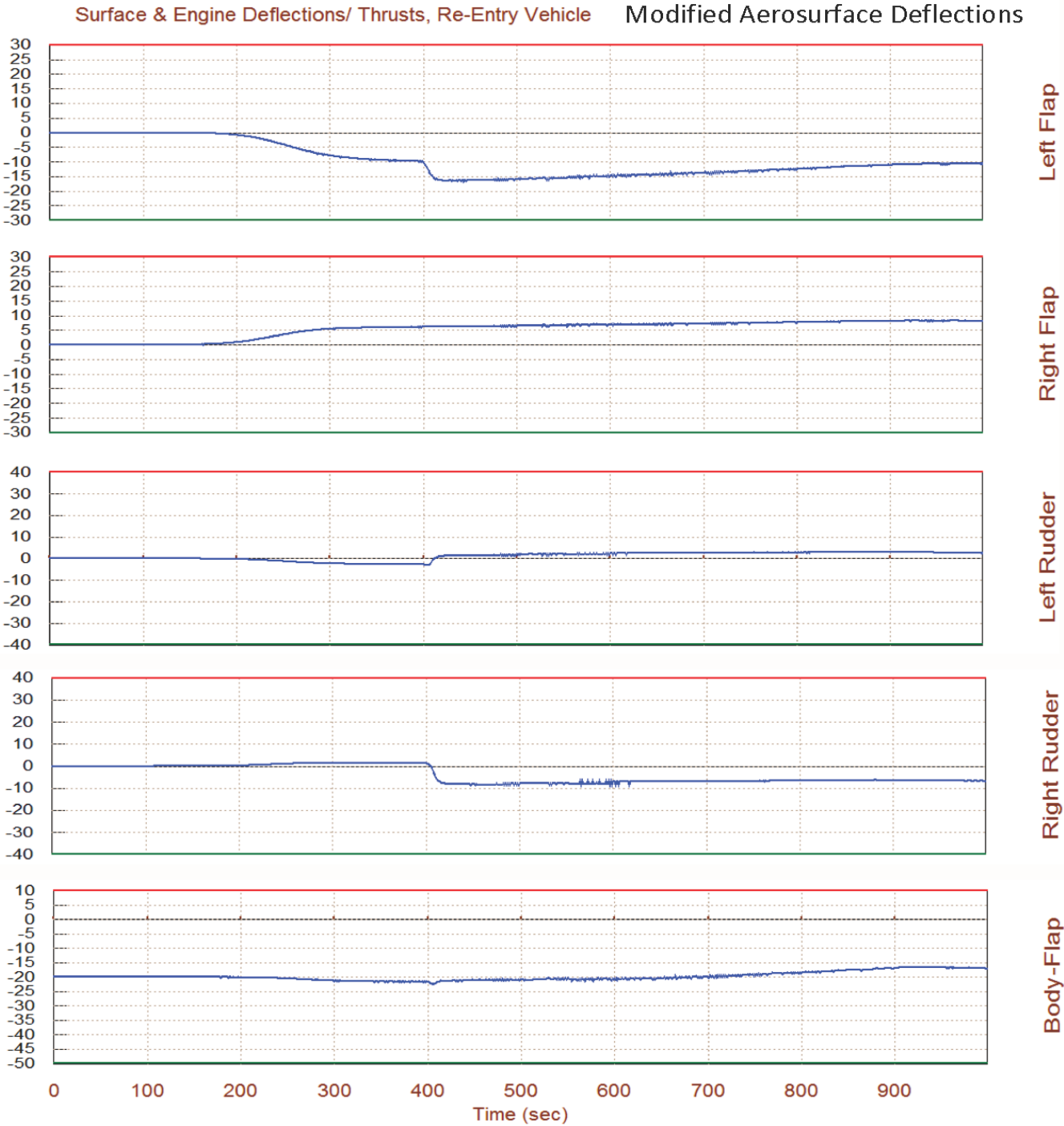
The combination of the first two thrusters "Throttle #1" and "Throttle #2" firing in the $\pm z$ direction provide the pitch torque required to counteract the small aerodynamic moment on the vehicle generated as it enters the atmosphere at $\alpha=41^\circ$. It is small because the vehicle is almost balanced at this angle of attack. The thrusters combination of "Throttle #3 and #4" provide the negative torque needed to balance the positive rolling moment on the vehicle due to the $+Y_{CG}$ offset. The two flaps also rotate in the opposite directions to provide negative torque to balance the rolling moment on the vehicle due to the $+Y_{CG}$ offset. The rudder deflections are also not symmetrical. Notice that the throttle control begins earlier than surface control begins. The thruster combination "Throttle #5 and #6" provide a small negative yawing moment on the vehicle to balance the yawing moment produced due to the unsymmetrical flap deflections. Their activity begins at the same time as the surfaces, rather than the RCS activity.

As already stated, the effectors activity obtained from our first trimming attempt is using too much RCS. It is not fuel optimal and we would like to change it. The trimming algorithm allows all effectors to participate as long as they can influence some of the control directions. The previous results show that all effectors (both RCS and aerosurfaces) are sharing the effort in balancing the moments. However, for fuel saving purposes we would like the aerosurfaces to become more active and to reduce the thruster usage at times greater than 400 seconds where the dynamic pressure increases above 5 (psf). The effector activity trade-off can be accomplished by reducing, prior to trimming, the upper and lower throttling limits of the RCS jets at times greater than 400 sec. By constraining the jet throttle limits it forces the aero-surface deflections to open-up to bigger amplitudes during trimming. This adjustment helps us define better trimming positions for the aerosurfaces that can be scheduled open-loop during flight. The modified aerosurface schedule should reduce the RCS activity and ultimately fuel consumption.

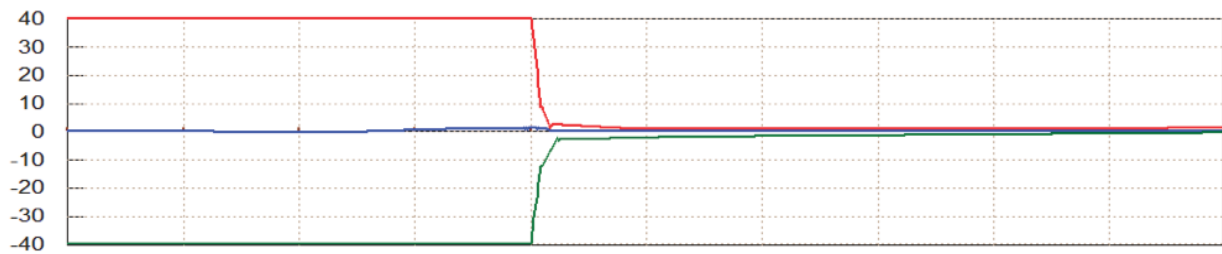
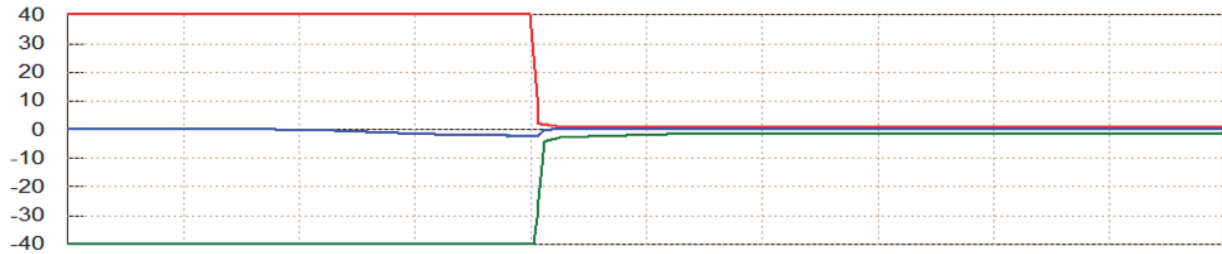
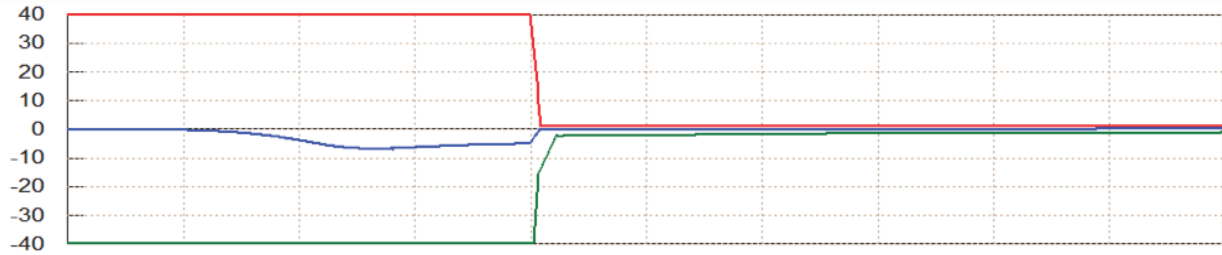
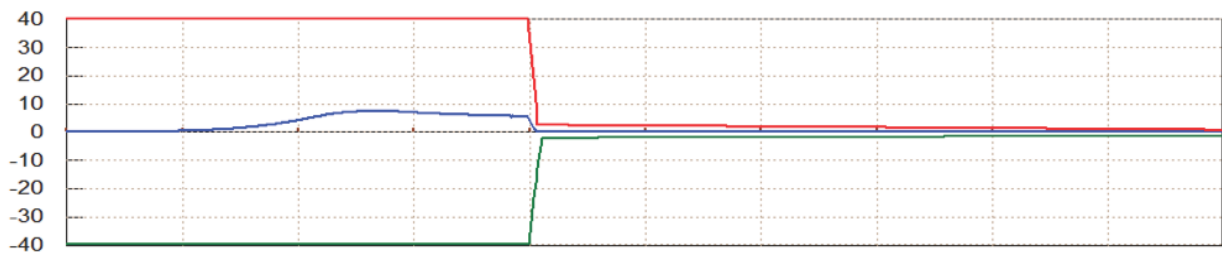
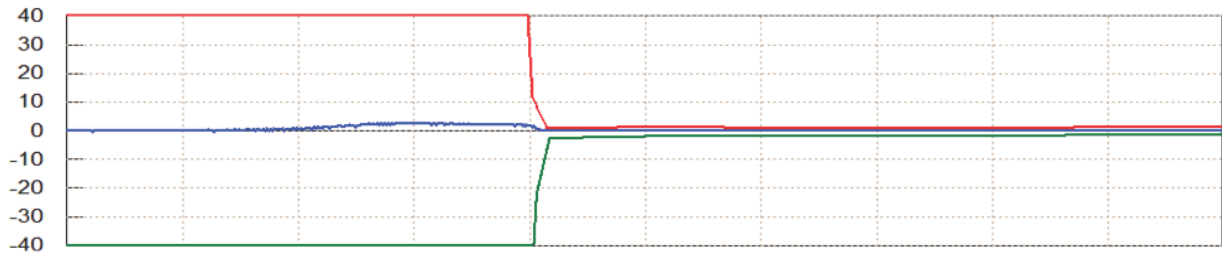
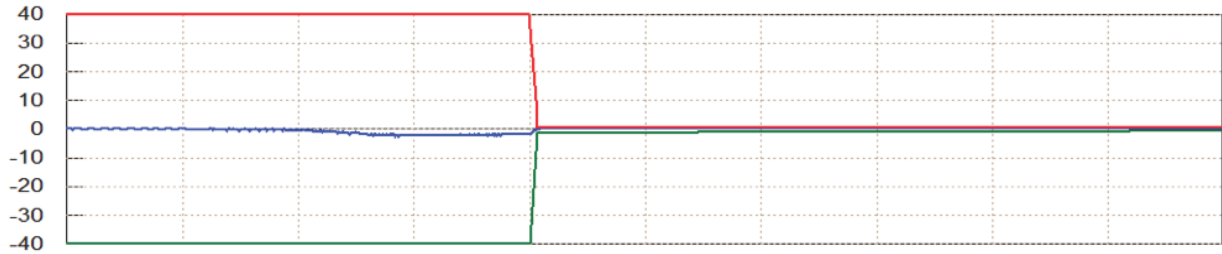
To modify the throttle activity at times greater than 400 sec, after trimming, go to the horizontal menu bar at the top of one of the effector trim history plots, click on "*Graphic Options*", and from the pop-up menu choose "*Modify Trajectory Plot*". The menu/dialog in the next page shows the names of the 11 effectors controlling the vehicle. We want to modify the top 6, which are the throttling jets, one at a time, by reducing their throttling activity at times greater than 400 sec. Click on one of the effectors, "Throttle 3" shown below, and click on "*Select Effector*". The plot under the menu shows the throttle history of the third thruster (green line) as it was calculated from the previous Trim. The two horizontal magenta lines define its upper and lower throttle limits initially defined by the max throttling capability of the jet in the thruster data file "*X_6RCS_Jets.Engn*". In order to reduce throttle usage we must modify this plot, not only its trim history but also its upper and lower limits. We must reduce it as close to zero as possible at times greater than 400. We do this graphically using the mouse by clicking on the curves and modifying one small segment at a time. The modified trim curve and limits are shown in the second plot below. It represents the desired throttle position and its reduced upper and lower limits which will constraint RCS activity in the next trim. Do not click on the "Re-Trim" button yet, but continue modifying the rest of the throttling jets (from #1 to #6) the same way as #3, by clicking on "Select an Effector".



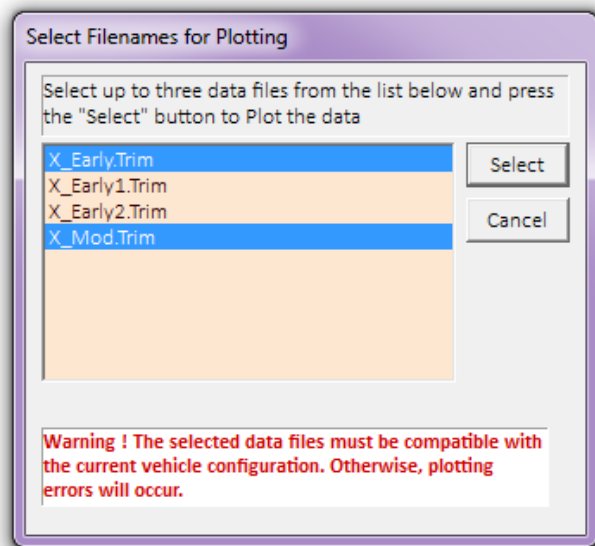
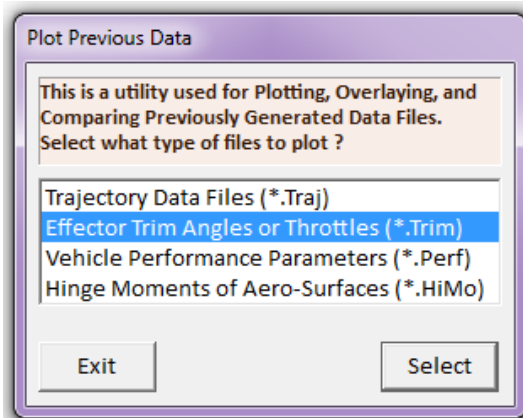
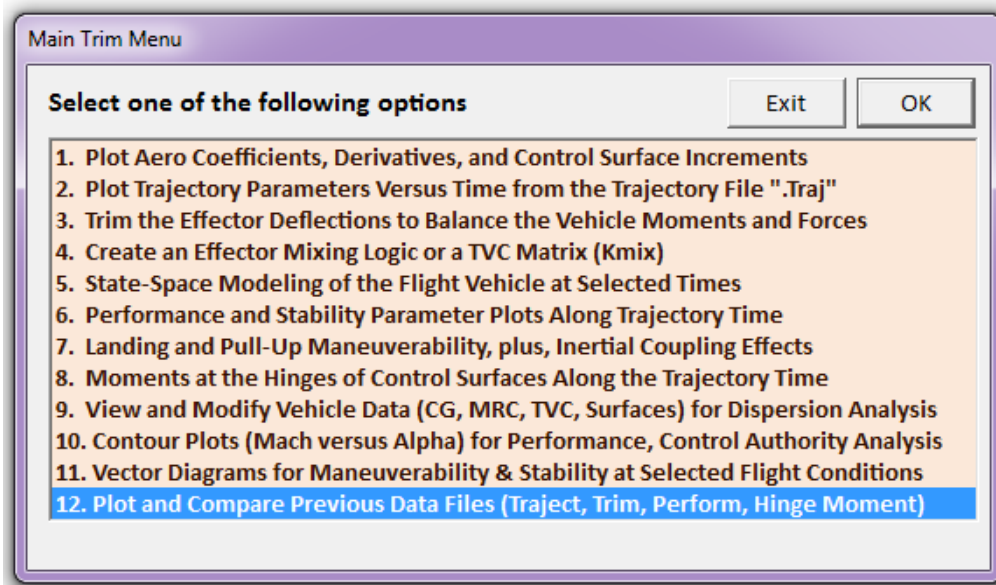
When you finish modifying the trim characteristics and limits of one effector, click on "Continue Adjusting the Next Trimming Effector" to select the next one from the effectors menu. When all 6 thruster modifications are complete, click on "Re-Trim" and the Trim program will re-trim the effectors by taking into consideration the user modifications that limit the thruster usage after 400 sec. The program will use the aerosurface effectors which are capable to contribute more and provide the necessary balancing moments under the new throttling limitations, and it will converge to a new solution. Otherwise, if it cannot find other effectors it will violate the position limits. The figures below show the new aerosurface deflections and the user modified RCS trim activity in file "X_Mod.Trim".



Surface & Engine Deflections/ Thrusts, Re-Entry Vehicle RCS Activity and Modified Limits

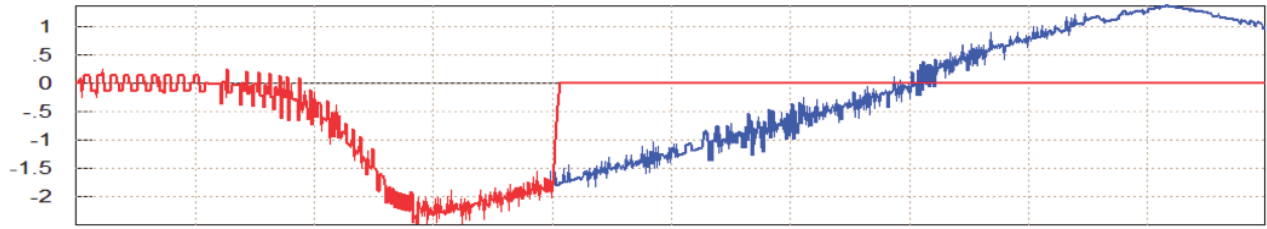


Now let us compare the original trim against the user modified trim by plotting the two trimming results together and see how the throttling constraints affected the aerosurface deflections. We expect to see a reduction in the thruster activity and as a result an increase in the aero-surface deflections to make up for the difference. We must first rename the modified trim file under a different name "X_mod.Trim". The original trim file is also saved under "X_Early1.Trim". From the Trim main menu select option-12 and from the next menu select to plot trim files (.Trim). A menu comes up showing all the trim files which are present in the work folder. Select the two shown below.

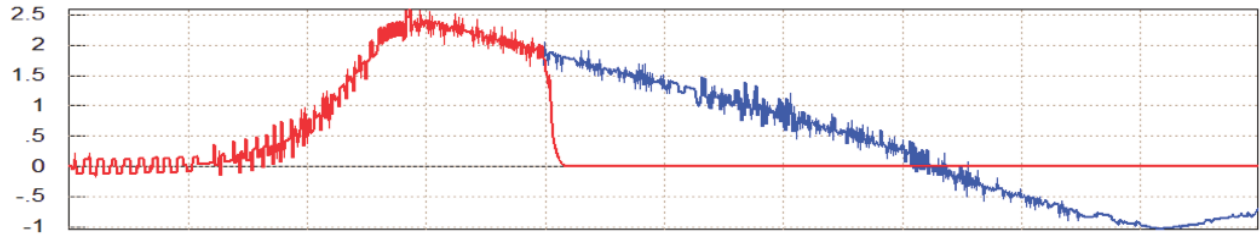


The original trim results are the blue curves and the modified are shown in red. The 6 thrusters are now reduced to zero at $t > 400$ sec because of the modifications. Consequently, the surfaces were affected, mainly the left flap, and the two rudders. They must now deflect further to provide the negative moment necessary to balance the Y_{CG} offset. Notice that the body-flap deflection is biased at 20° in the aero data file.

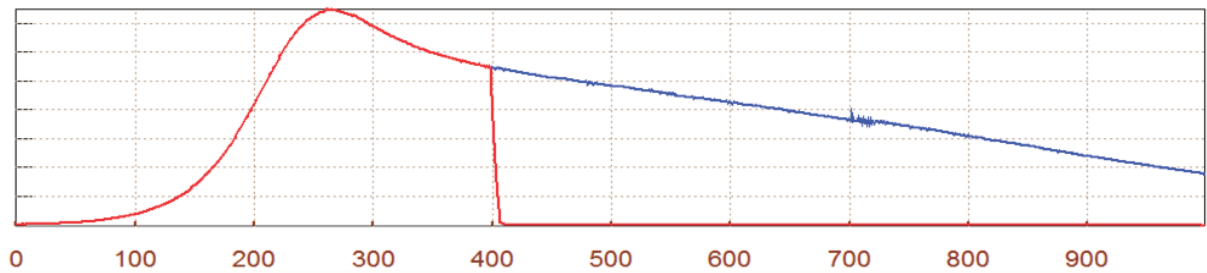
Surface & Engine Deflections/ Thrusts, Re-Entry Vehicle with 6 Aero-Surfaces an



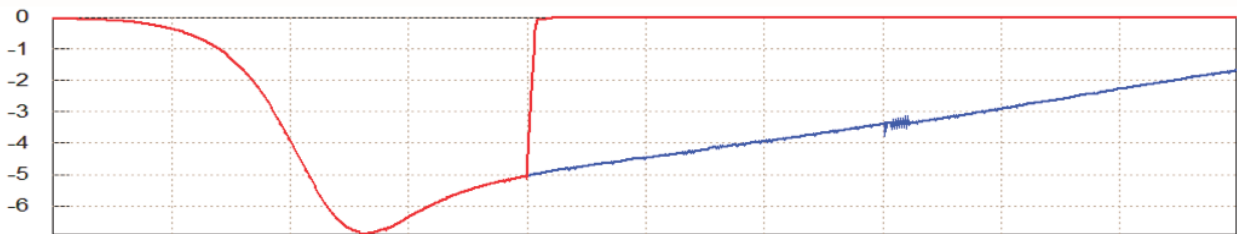
Throttle 1



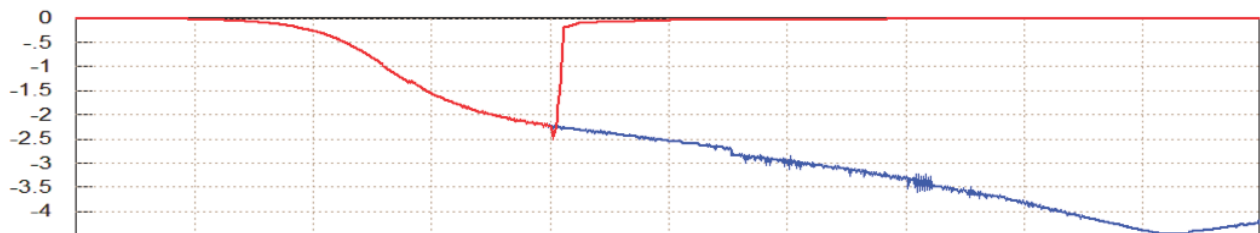
Throttle 2



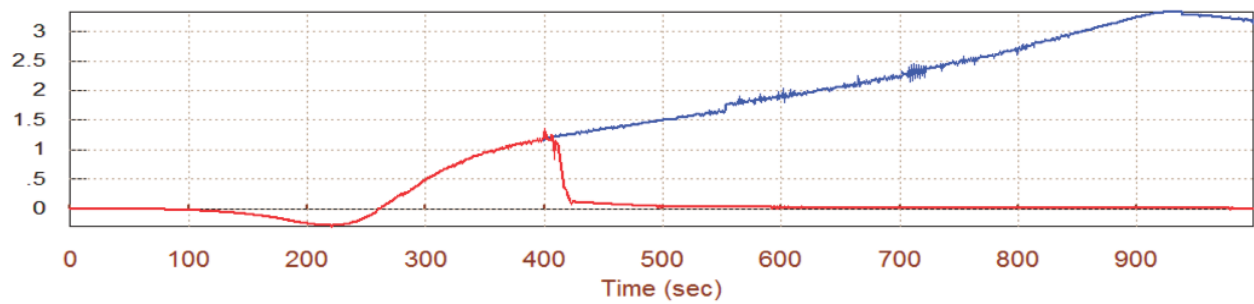
Throttle 3



Throttle 4

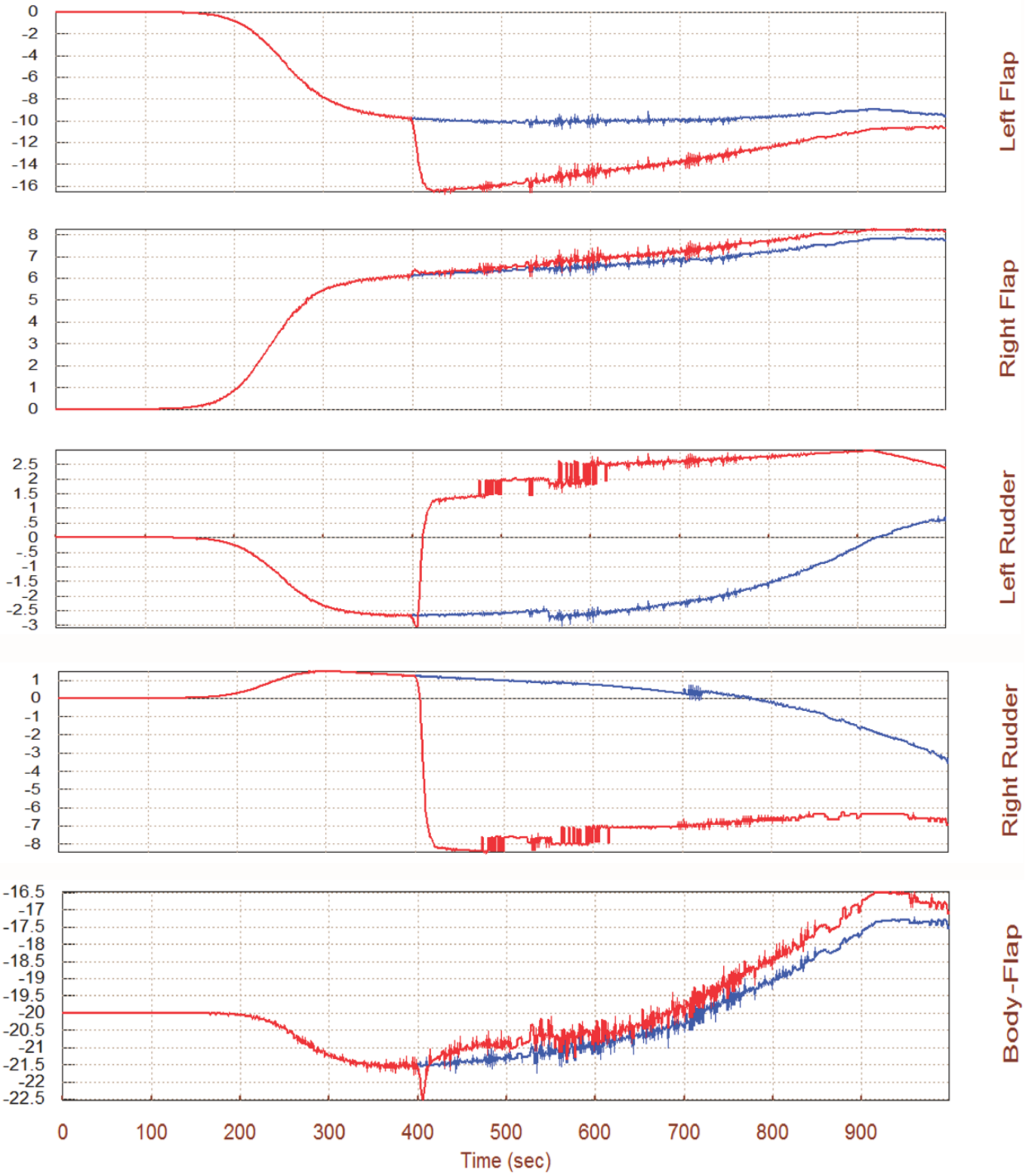


Throttle 5



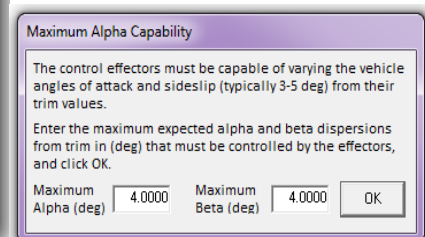
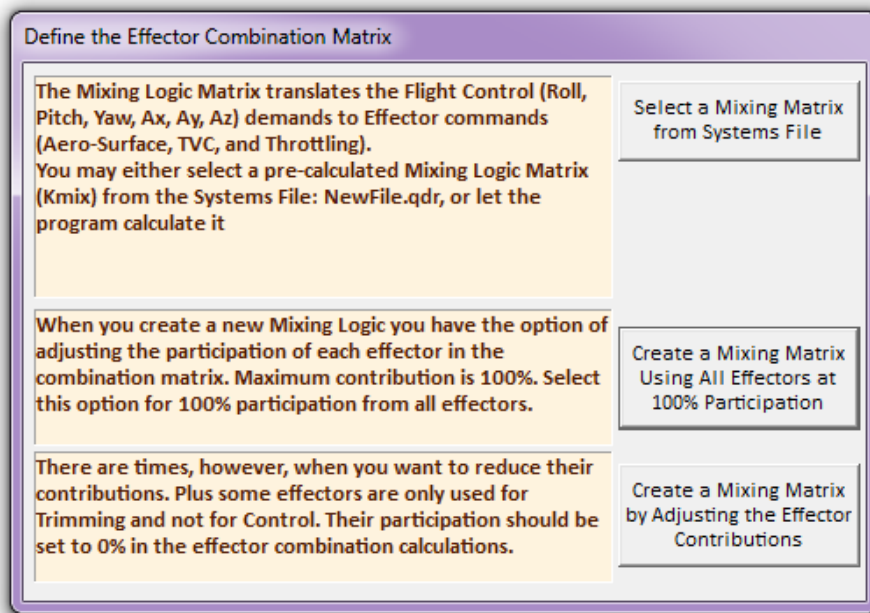
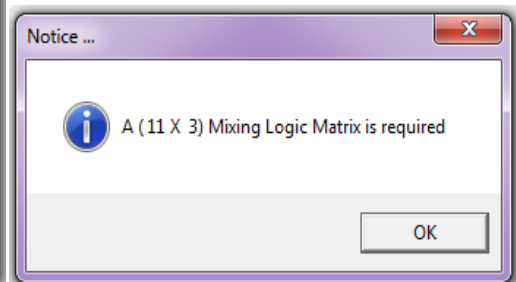
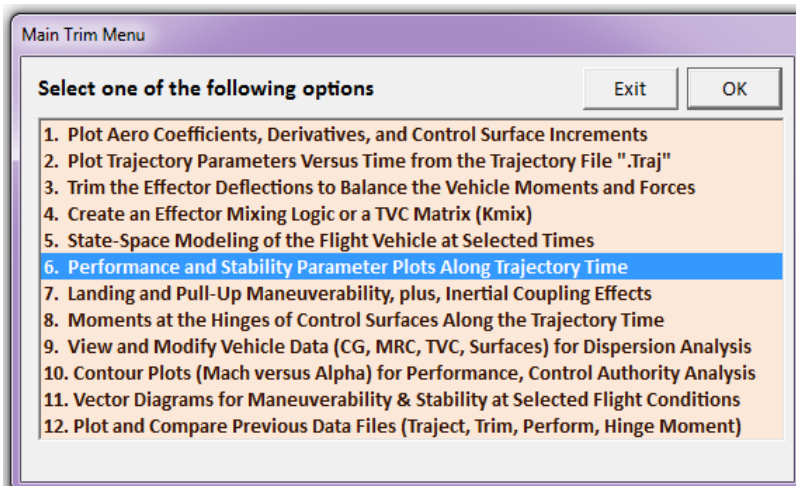
Throttle 6

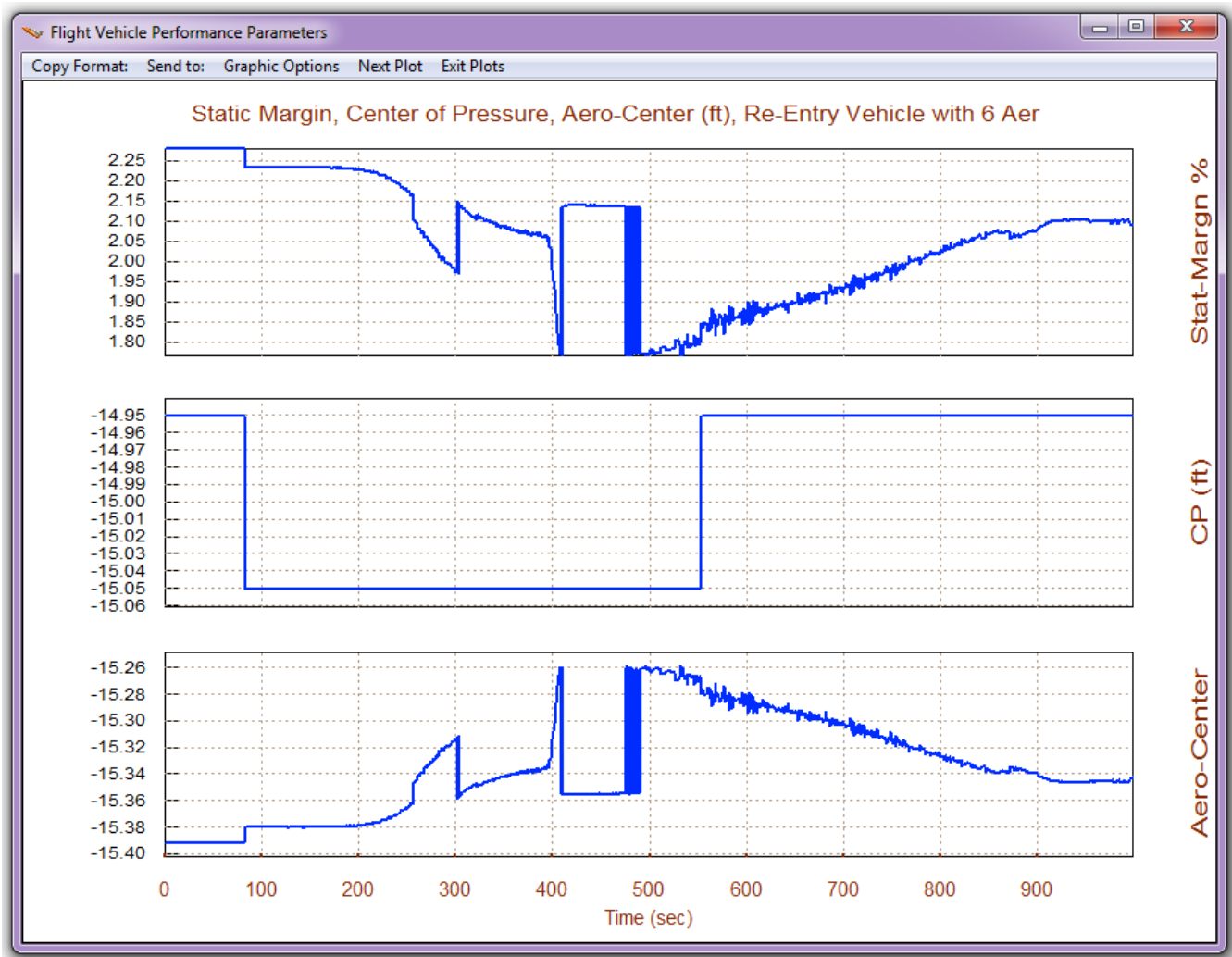
Surface & Engine Deflections/ Thrusts, Re-Entry Vehicle with 6 Aero-Surfaces an



1.2 Performance Analysis along the Trajectory

We now return to the main menu, re-trim using the modified trim file "X_mod.Trim", and from the main menu select option (6) to plot the static performance and stability parameters along the trajectory. These parameters are described in Section 3. Before analyzing the vehicle performance, however, the program needs to know how the 11 effectors combine together to control the 3 moments. The mixing logic matrix defines the effectors allocation along roll, pitch, and yaw axes, and the control effectiveness strongly depends on this matrix. We choose the second option that allows the Trim program to calculate the mixing-logic matrix by a full participation from all effectors. This is done at every point along the trajectory. Note that, even though we have restricted the RCS jets from trimming at times greater than 400 sec, we are not restricting them from participating in the mixing matrix and hence in the control system, since Kmix is part of the FCS. We must also define the maximum wind disturbance in terms of α_{\max} and β_{\max} angles, which are both set to 4° .



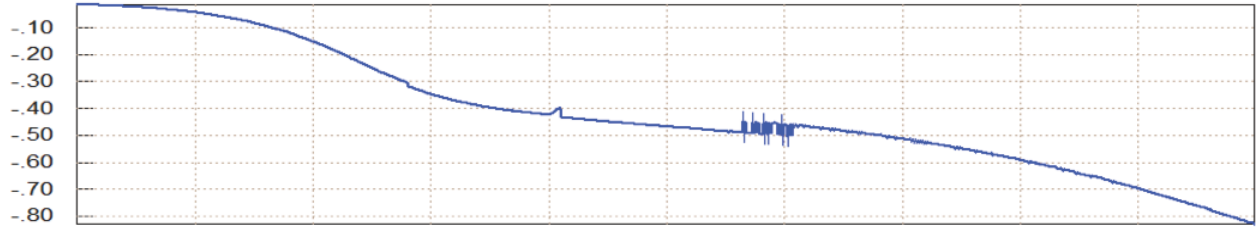


Both pitch and lateral axes are statically stable. The short-period and Dutch-roll resonances begin at zero when the dynamic pressure is zero and increase to 0.8 and 1.3 (rad/sec) respectively. The control effort is sufficiently small, less than 0.5 in all three axes to reserve some authority for other functions. It increases after 400 sec, meaning less control authority and less margin, because the RCS contribution is intentionally reduced and the aerosurfaces are mainly responsible for trimming.

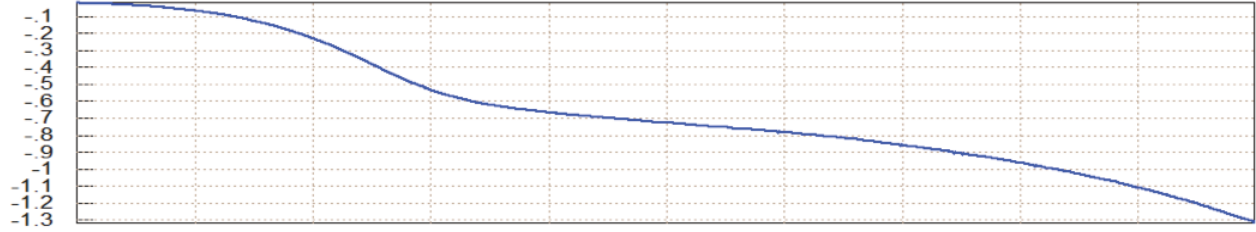
The $C_n\beta$ -dynamic is positive meaning that the vehicle is directionally stable. The LCDP ratio is negative and small. It means that roll control is reversed and weak, and that we may have to rely on the RCS for directional control during this period. Notice that although we reduced the RCS activity for trimming after 400 sec, we still need the RCS to assist the aerosurfaces for flight control.

The last plot shows that the combined effectors system provides enough acceleration for flight control. It should typically be greater than 1.5 (deg/sec^2). Notice how the max acceleration capability drops at $t=400$ sec when the jets activity is reduced. It gradually improves as the dynamic pressure increases.

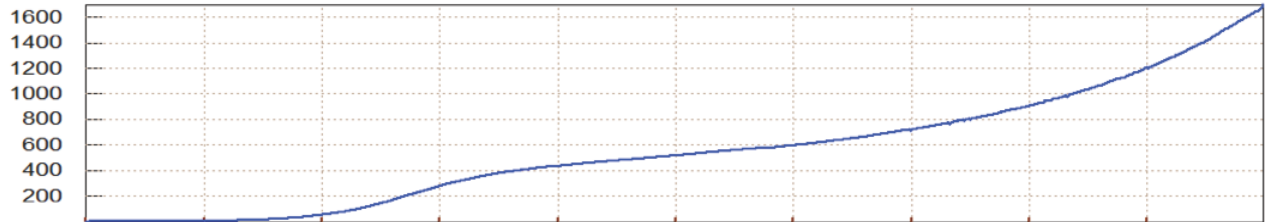
Short-Period (w/ Time-to-Double-Ampl-Inverse (/sec), Q_alpha_beta (deg-lb/ft^2)



Ptch T2-inv

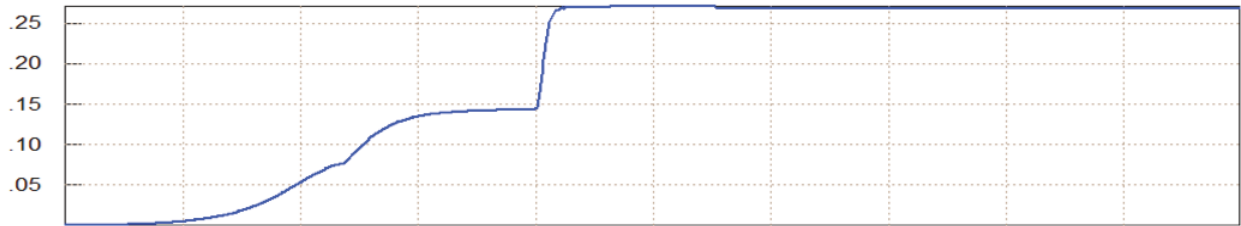


Yaw T2-inv

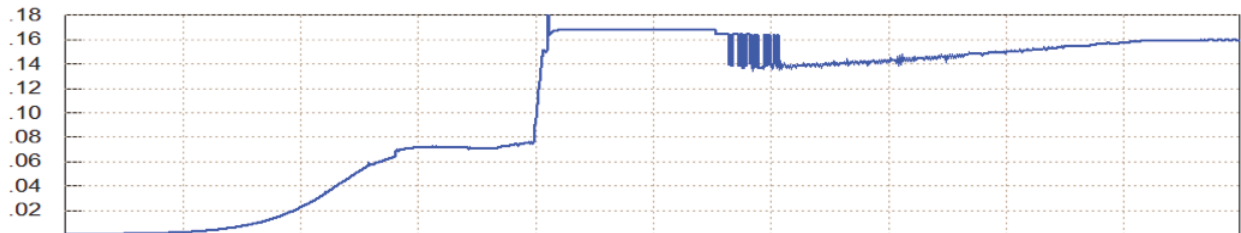


Q_alpha_beta

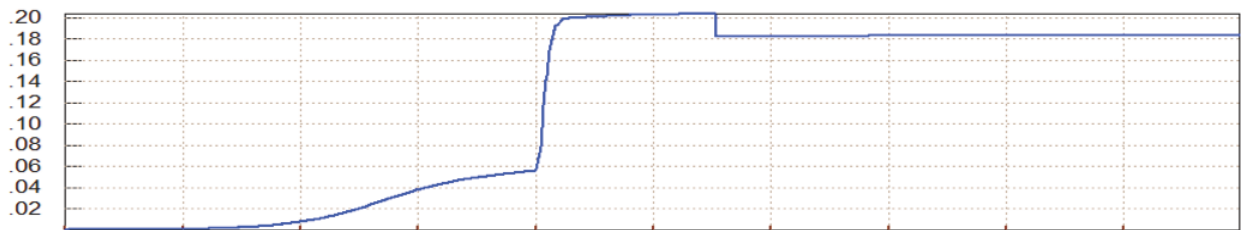
Rotation Control Authority (dQ/dQmax)<1 for 4 (deg) of Alpha & Beta Variation



Roll Effort



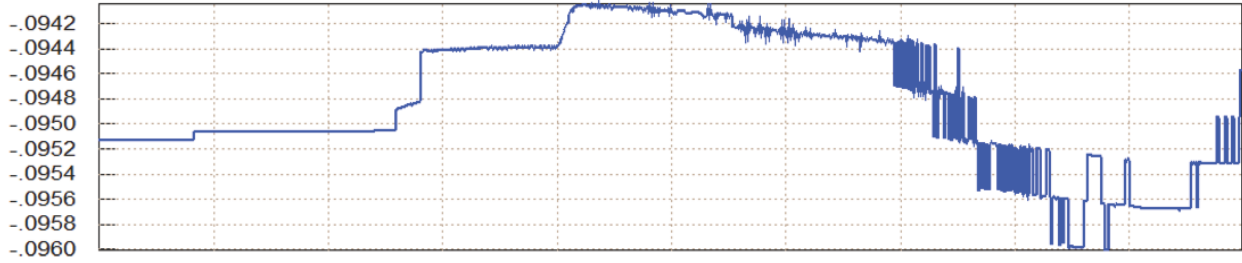
Pitch Effort



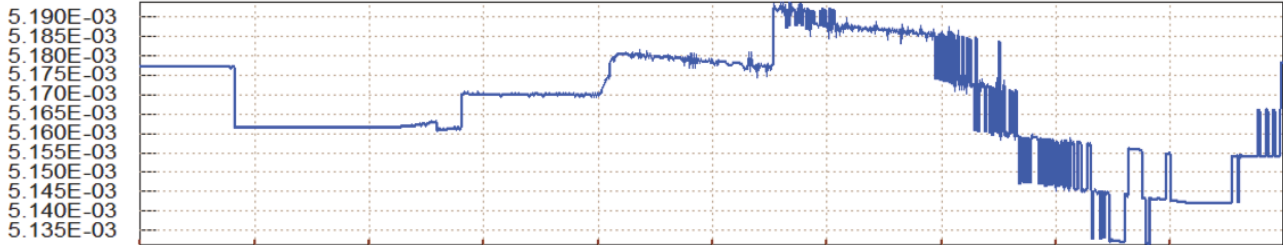
Yaw Effort

0 100 200 300 400 500 600 700 800 900
Time (sec)

LCDP Ratio, Cnbeta_dynamic, Maximum Accelerations

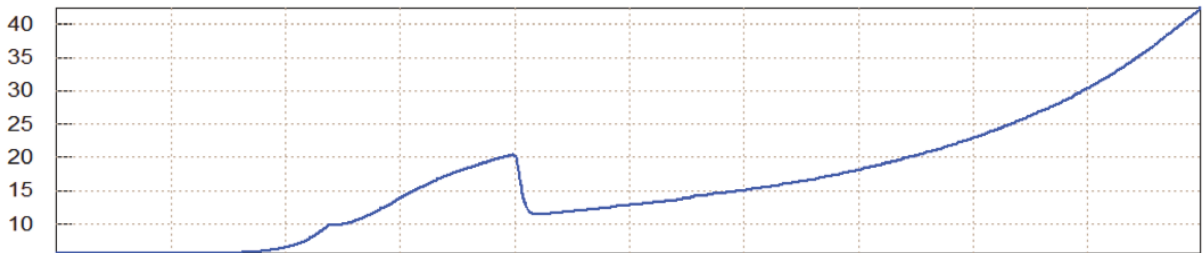


LCDP

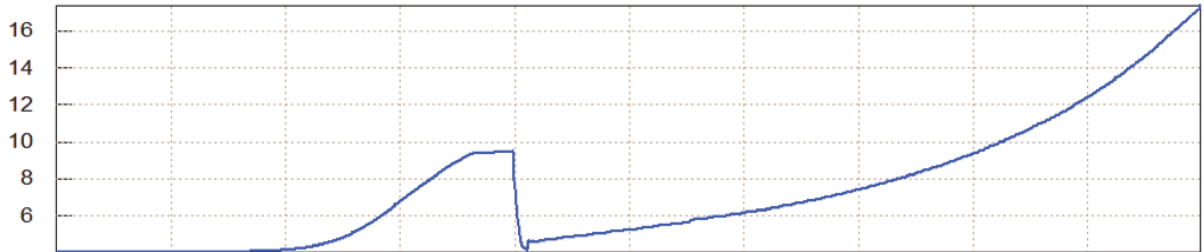


Cnbeta-dyn

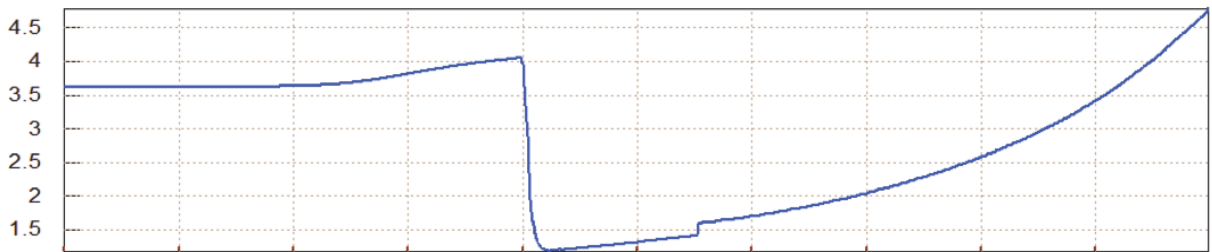
Max Angular Accelerat (deg/sec²), at Max Control Demand Re-Entry Vehicle with 6



P dot (Max)



Q dot (Max)



R dot (Max)

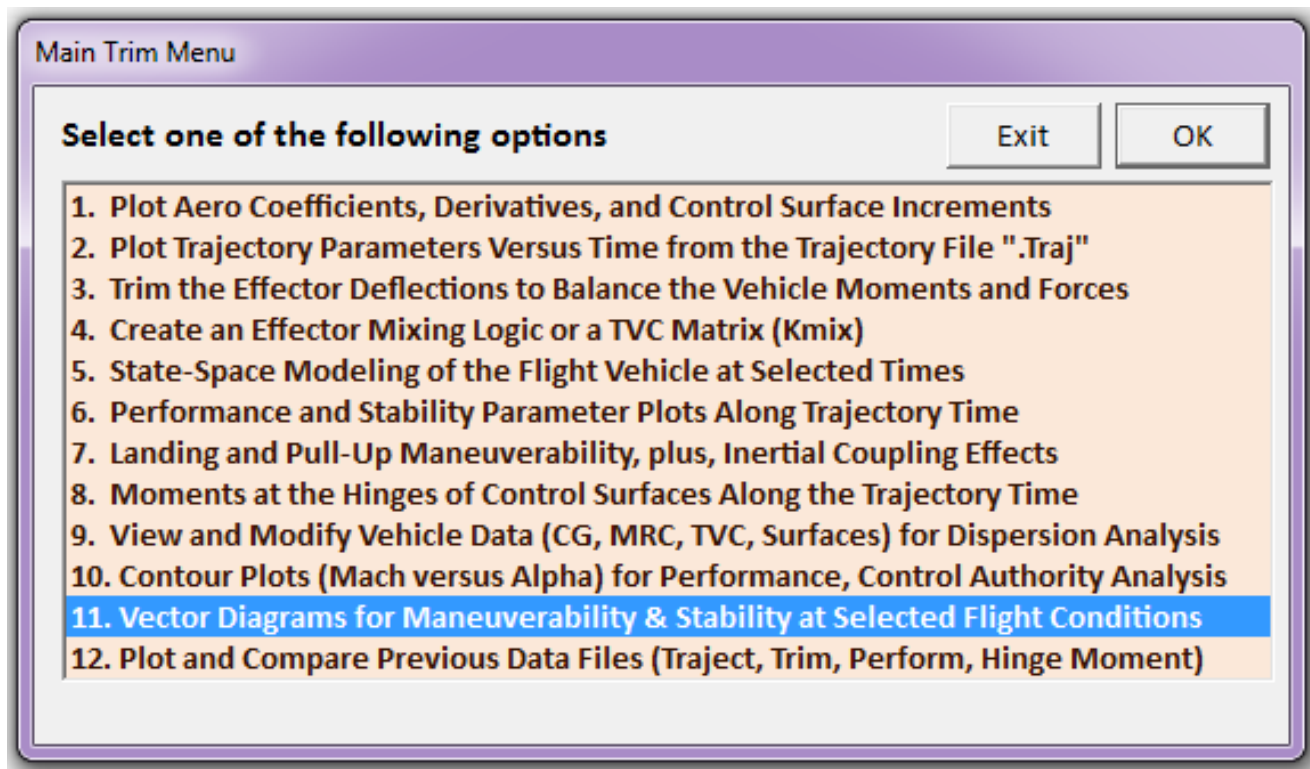
0 100 200 300 400 500 600 700 800 900
Time (sec)

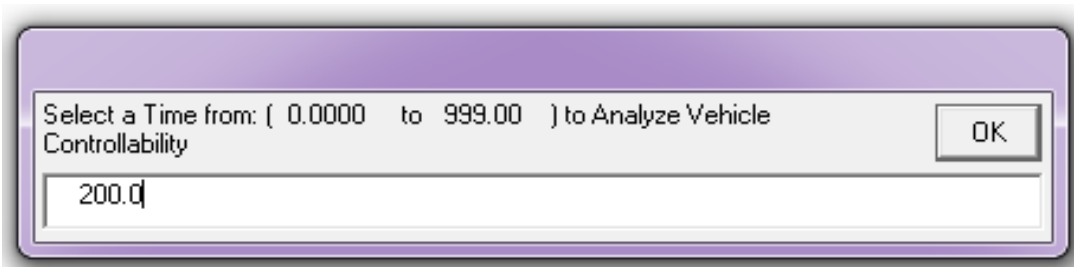
1.3 Vector Diagrams Analysis

Vector diagrams are used for analyzing the vehicle static controllability at specific flight conditions against aerodynamic dispersions. We use vectors to compare the moments, force, and accelerations on the vehicle produced by the control effectors against those generated by α_{max} and β_{max} dispersions due to winds, and evaluate if the effector system has sufficient control authority to counteract them. Vector diagrams also allow us to check the acceleration directions of the controls against the disturbance effects, analyze controllability and the orthogonality of the effectors. Since our vector plots are limited to 2 directions we typically need several plots to analyze the control authority in multiple directions. In this flight phase we will analyze the vehicle controllability at two flight conditions: at $t=200$ sec which is a flight condition where the aero-surfaces are weak and the jets dominate, and at $t=700$ sec where the surfaces are more active and the jets are used more like a back-up system. The Body-Flap is not used for flight control during this phase. It is only used for trimming, as already discussed, and it will not be included in the effector mixing logic matrix calculations.

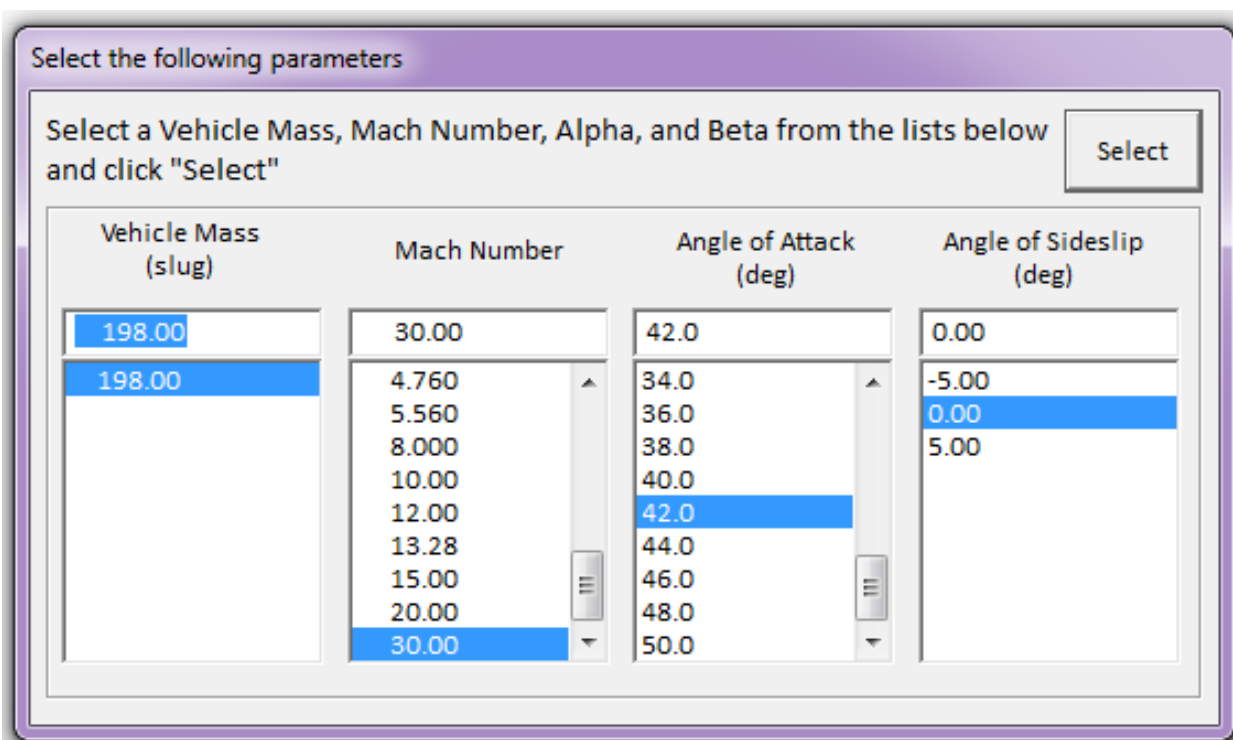
Low Dynamic Pressure Analysis Using RCS and Aerosurfaces

So let us return to the Trim main menu, select option-11 for vector diagram analysis, and then enter a time= 200 sec to analyze. We must also define the wind disturbance in terms of maximum dispersion angles (α_{max} and β_{max}) from trim (α_0 and β_0). They are both set to 4° .





Use the following menus to select the default options for vehicle mass, Mach number, Alpha, and Beta that correspond to $t=200$ sec. The next dialog is for defining the mixing logic matrix that is needed for the calculation of the control vectors. The user has the option to either select a pre-calculated matrix or to let the program calculate it from the vehicle and effector data. In this case we choose the third option which calculates the mixing-logic matrix with adjustable effector participation. This is because we do not want to include the Body-Flap in the flight control system, and therefore, we prevent it from participating in the mixing-logic matrix. It was included in the trim process, however, and its position will be commanded open-loop.



When you click at the bottom button of the effector combination matrix selection dialog a menu opens-up on its right side. It shows the titles of the 11 effectors: (6 RCS jets and 5 aerosurfaces). Their control participation is initially set to 100%. Since we are not going to use the Body-Flap, we must reduce its participation to 0%, as shown, and click on the button in the upper right hand corner. This will allow the 6 RCS thrusters, the two Elevons (flaps), and the two Rudders to participate fully in the calculation of the mixing-logic matrix in this early reentry flight condition. The Body-Flap will not participate in the mixing-logic matrix calculation.

Define the Effector Combination Matrix

The Mixing Logic Matrix translates the Flight Control (Roll, Pitch, Yaw, Ax, Ay, Az) demands to Effector commands (Aero-Surface, TVC, and Throttling). You may either select a pre-calculated Mixing Logic Matrix (Kmix) from the Systems File: NewFile.qdr, or let the program calculate it

When you create a new Mixing Logic you have the option of adjusting the participation of each effector in the combination matrix. Maximum contribution is 100%. Select this option for 100% participation from all effectors.

There are times, however, when you want to reduce their contributions. Plus some effectors are only used for Trimming and not for Control. Their participation should be set to 0% in the effector combination calculations.

Select a Mixing Matrix from Systems File

Create a Mixing Matrix Using All Effectors at 100% Participation

Create a Mixing Matrix by Adjusting the Effector Contributions

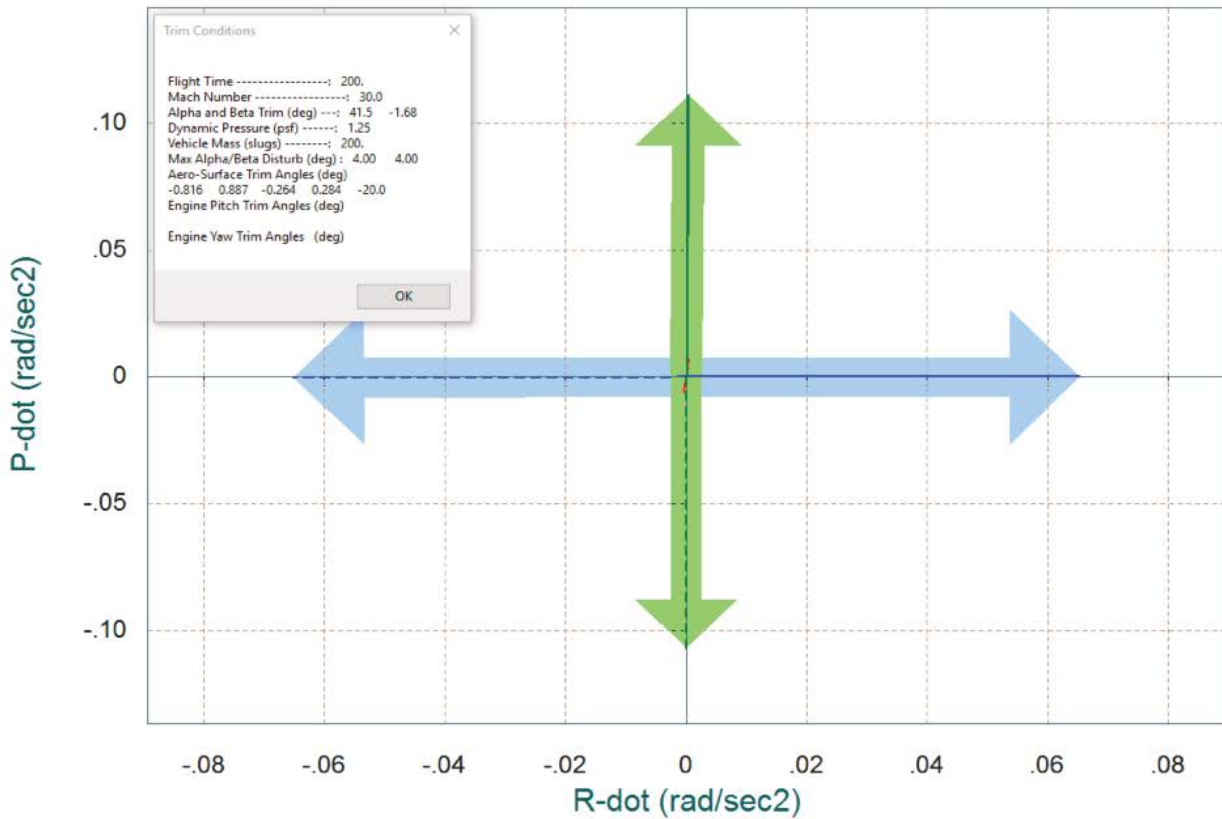
	Effector	Participation %
1	Throttle 1	100
2	Throttle 2	100
3	Throttle 3	100
4	Throttle 4	100
5	Throttle 5	100
6	Throttle 6	100
7	Left Flap	100
8	Right Flap	100
9	Left Rudder	100
10	Right Rudder	100
11	Body-Flap	0
12		
13		
14		

Adjust the Effectors Participation and Click Here

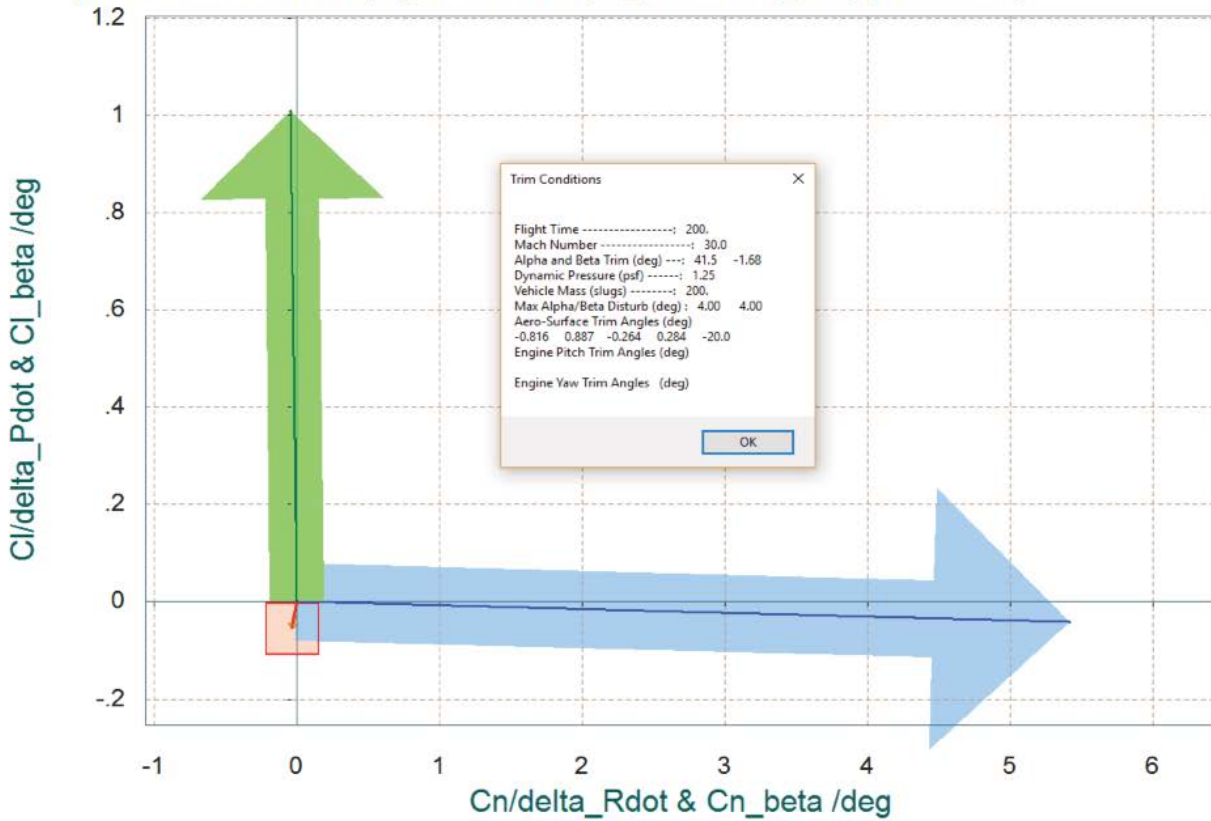
The following vector diagram compares the maximum roll and yaw accelerations due to the maximization of the roll and yaw demands, green and blue vectors respectively, against the accelerations generated by the α_{max} and β_{max} aero dispersions. The disturbance accelerations in this flight condition are small because the dynamic pressure is small. The cross-coupling between the roll and yaw accelerations is almost zero.

The second diagram below shows the roll and yaw moment partials. The blue vector is the moment partials $\{C_n \delta R_{FCS}, C_l \delta R_{FCS}\}$ per yaw control demand and the green vector is the moment partials $\{C_n \delta P_{FCS}, C_l \delta P_{FCS}\}$ per roll demand. They are practically orthogonal to each other and pointing in their corresponding directions. The small red vector is the scaled $(C_l \beta$ and $C_n \beta)$ partials. The red square centered at the tip of the vector is due to the uncertainties in $C_l \beta$ and $C_n \beta$.

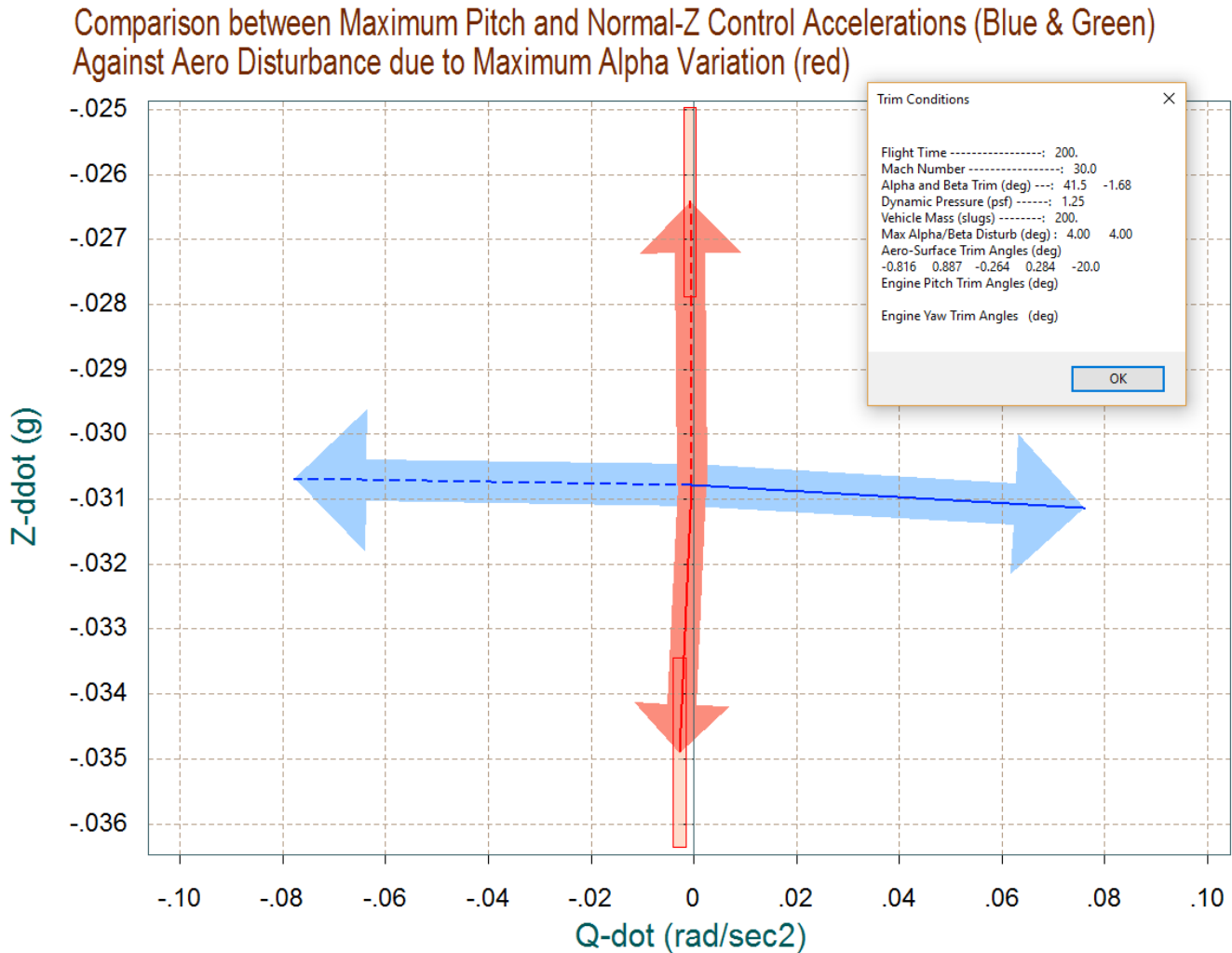
Comparison between Maximum Roll & Yaw Control Accelerations (Green & Blue)
Against Disturbance Accelerations due to Maximum Alpha/ Beta Dispesions (Red)



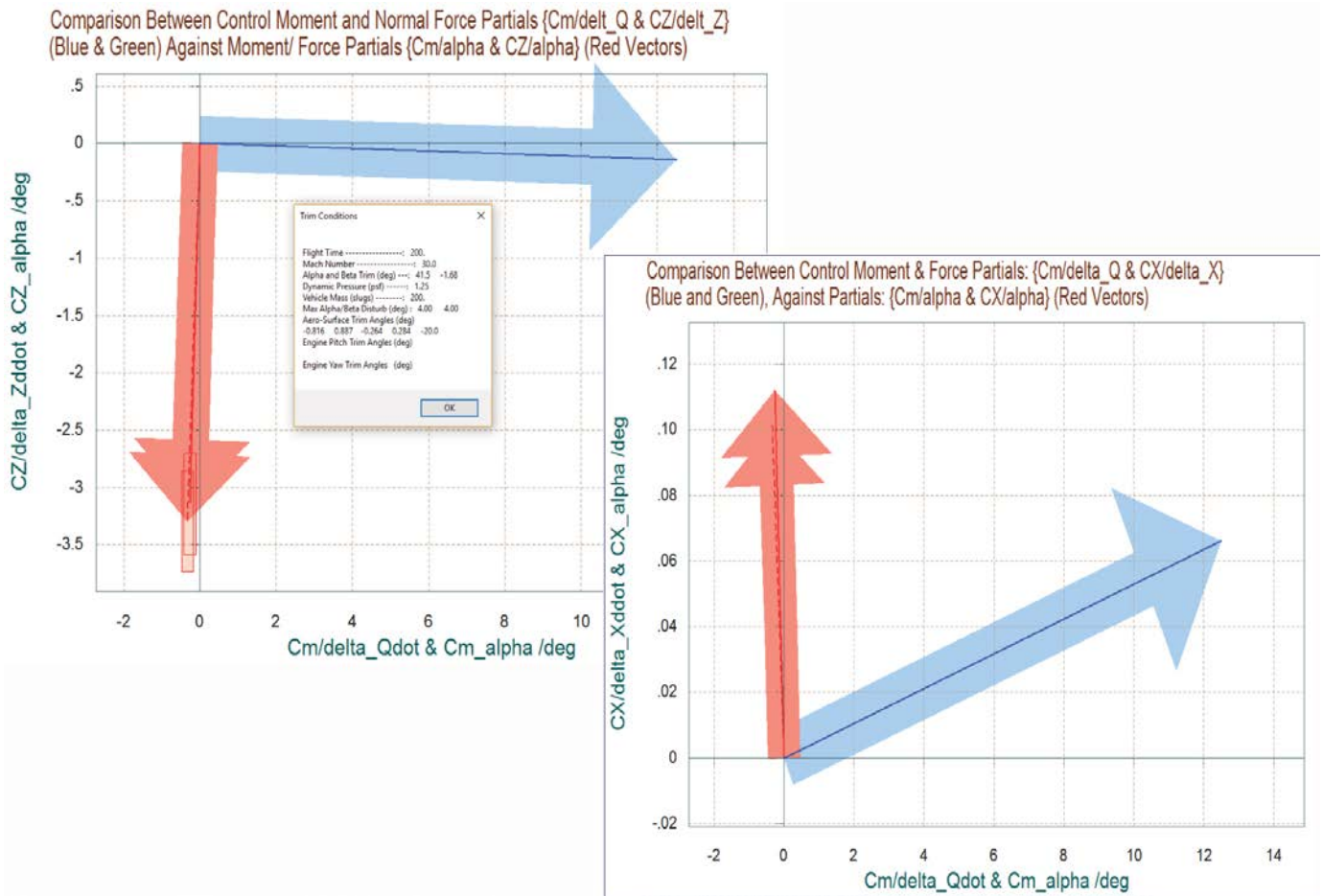
Comparison Between Yaw & Roll Control Moment Partial {Cn/delta_R and Cl/delta_P}
(Blue and Green Vectors) Against Partial: {Cn_beta and Cl_beta} (Red Vectors)



The following vector diagram shows the pitch acceleration in (rad/sec^2) and the normal z-acceleration in (g). At trim the z-acceleration is only -0.031 g because the vehicle is practically still in orbit. The pitch acceleration is zero because the vehicle is trimmed. The blue vectors show the accelerations achieved when the pitch control is maximized in positive and in negative directions. They are pointing in the proper directions, affecting mainly the pitch acceleration and not Z. The red vectors show the effects (in the same two directions) of varying alpha and beta $\pm 4^\circ$ about $\alpha_0=42^\circ$. It obviously affects mainly the z acceleration but not pitch. The pitch control is much stronger in the pitch direction in comparison with the dispersion red vectors.

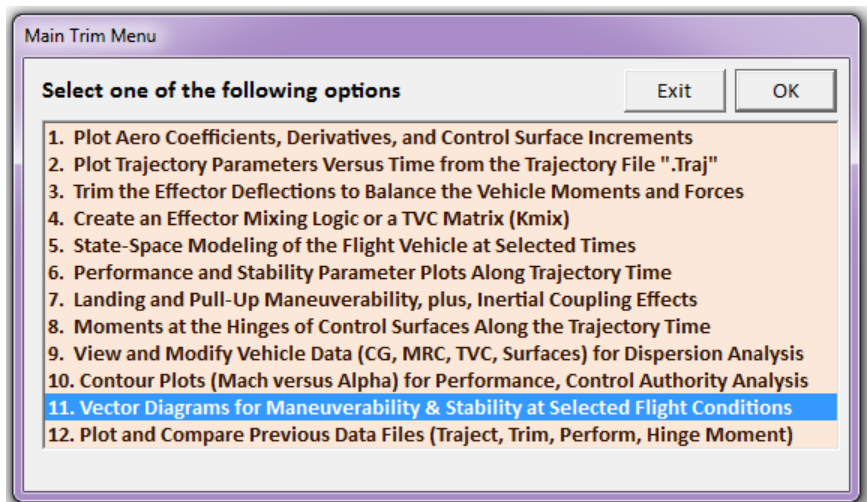


The blue vector in the partial vector diagrams below shows the partials of the pitch moment, Z and X forces per pitch demand. The control vector affects mostly the pitch acceleration. The red vectors are the scaled partials: $(Cm\alpha, Cz\alpha, Cx\alpha)$. Obviously the pitch control dominates the dispersion effects in the pitch direction. We don't care about the X and Z dispersion effects because we do not control those directions in this phase.



Higher Dynamic Pressure Analysis Using Only Aerosurfaces

Return to the Trim main menu and select again option (11) to repeat the vector diagrams analysis in a different flight condition, at time 700.0 sec, which is in the region where the aerosurfaces are stronger and the RCS is used as a back-up system. In this case we expect the maximum wind-shear disturbance due to α_{\max} and β_{\max} dispersion angles to be 2° . In the mixing-logic definition dialog we select again the third option to let the program calculate the mixing-logic matrix with adjustable effector participation. This time we are disabling the RCS jets from participating in the mixing-logic calculation and allowing only the four aerosurfaces to control the vehicle. We are also disabling the Body-Flap because it is used only for trimming and not for flight control.



Select a Time from: (0.0000 to 999.00) to Analyze Vehicle Controllability

OK

700.0

Select the following parameters

Select a Vehicle Mass, Mach Number, Alpha, and Beta from the lists below and click "Select"

Select

Vehicle Mass (slug)	Mach Number	Angle of Attack (deg)	Angle of Sideslip (deg)
198.00	20.00	42.0	0.00
198.00	4.760	34.0	-5.00
	5.560	36.0	0.00
	8.000	38.0	5.00
	10.00	40.0	
	12.00	42.0	
	13.28	44.0	
	15.00	46.0	
	20.00	48.0	
	30.00	50.0	

Define the Effector Combination Matrix

The Mixing Logic Matrix translates the Flight Control (Roll, Pitch, Yaw, Ax, Ay, Az) demands to Effector commands (Aero-Surface, TVC, and Throttling). You may either select a pre-calculated Mixing Logic Matrix (Kmix) from the Systems File: NewFile.qdr, or let the program calculate it

Select a Mixing Matrix from Systems File

When you create a new Mixing Logic you have the option of adjusting the participation of each effector in the combination matrix. Maximum contribution is 100%. Select this option for 100% participation from all effectors.

Create a Mixing Matrix Using All Effectors at 100% Participation

There are times, however, when you want to reduce their contributions. Plus some effectors are only used for Trimming and not for Control. Their participation should be set to 0% in the effector combination calculations.

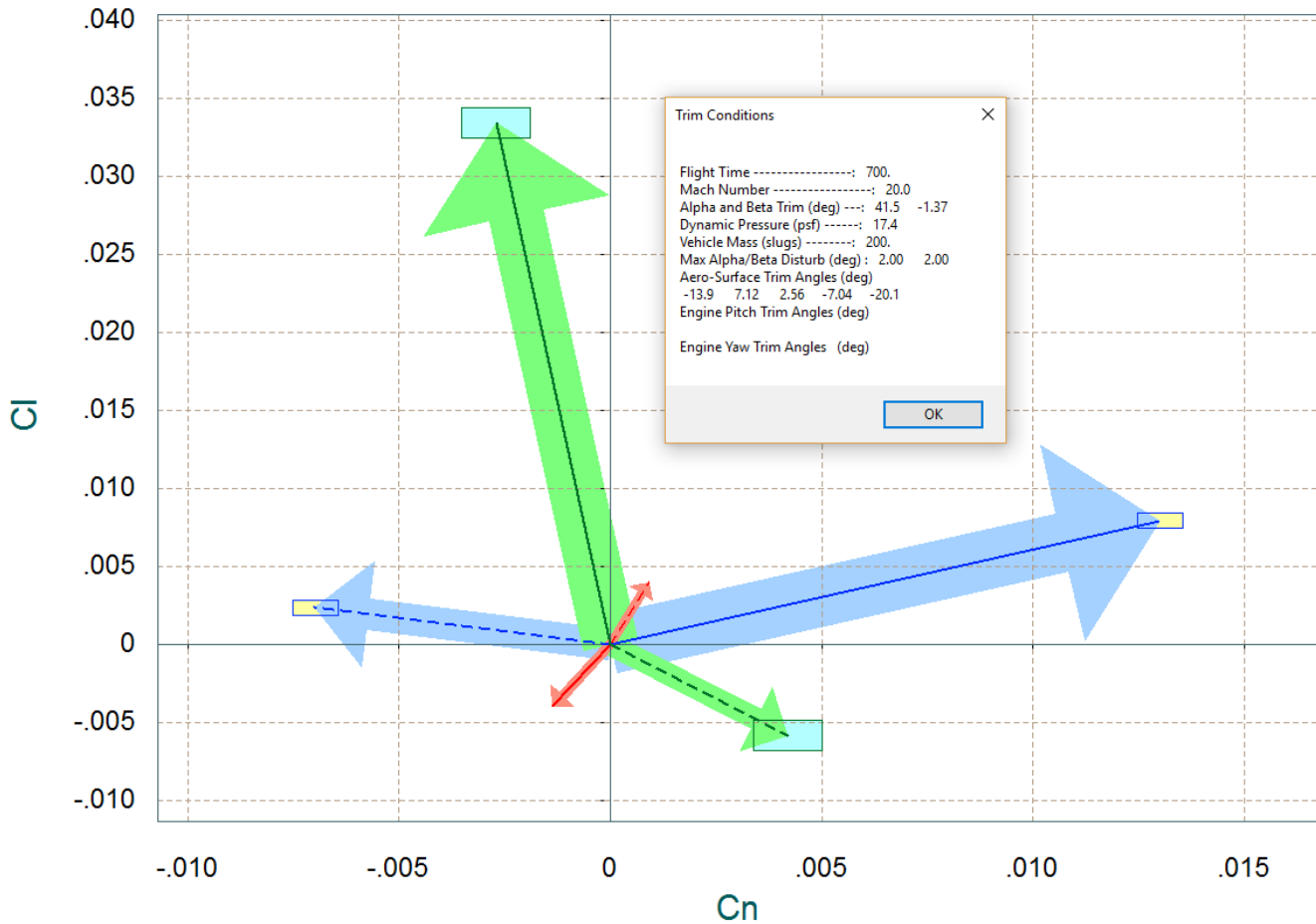
Create a Mixing Matrix by Adjusting the Effector Contributions

	Effector	Participation %
1	Throttle 1	0
2	Throttle 2	0
3	Throttle 3	0
4	Throttle 4	0
5	Throttle 5	0
6	Throttle 6	0
7	Left Flap	100
8	Right Flap	100
9	Left Rudder	100
10	Right Rudder	100
11	Body-Flap	0
12		
13		
14		

Adjust the Effectors Participation and Click Here

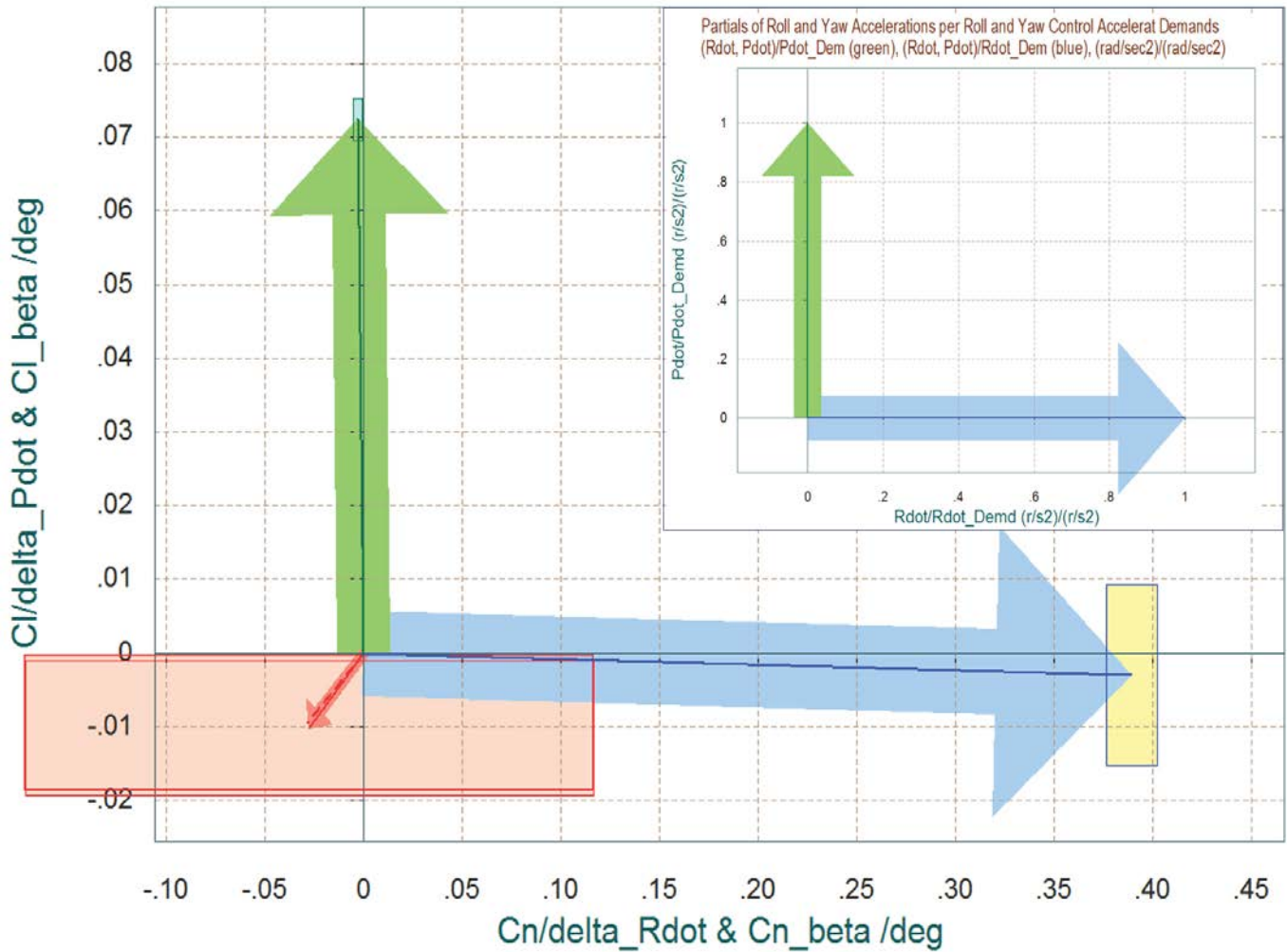
This time the results are not as symmetrical as they were at low dynamic pressures when mainly the jets were used for control and trimming the moments. The plot below shows the maximum roll and yaw moments produced when the roll and yaw demands are maximized. The $+Y_{CG}$ offset and $\beta_0 = -1.37^\circ$ cause asymmetric deflections of the flaps and rudders. Notice that the negative β_0 makes it easier for the vehicle to rotate in the positive roll and yaw directions than it is to rotate in the negative directions. Despite the asymmetry, the control moments are stronger than the disturbance moments. The aerodynamic uncertainties are represented by the rectangles centered at the tips of the vectors.

Comparison between Maximum Roll & Yaw Control Moments (Green & Blue) versus Moments due to Maximum Alpha/ Beta Dispesions (Red), Non-Dimensional



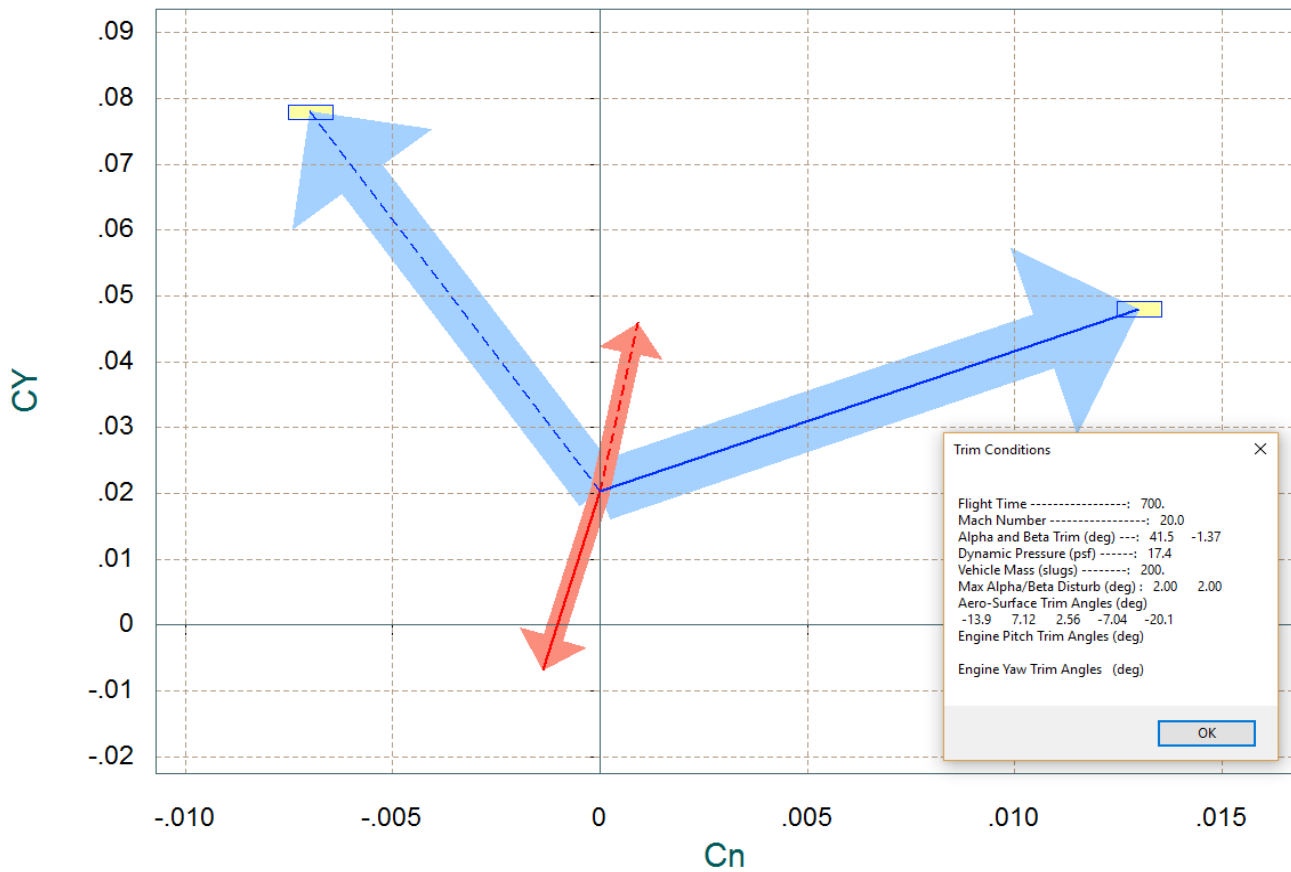
The next figure shows the roll and yaw partials per roll and yaw control demands (green and blue vectors) against the scaled disturbance partials $C_{l\beta}$ and $C_{n\beta}$ (red vectors). The control vectors are orthogonal and pointing in the proper directions with very small cross-coupling. The disturbance partials due to $C_{l\beta}$ and $C_{n\beta}$ are much smaller than the controls. The yellow and cyan rectangles at the tips of the control vectors represent the uncertainties in the aerosurface coefficients. The uncertainties in $C_{l\beta}$ and $C_{n\beta}$ are also shown by the red rectangle centered at the tip of the disturbance vector. The smaller figure shows the roll and yaw acceleration partials which are unit vectors and pointing exactly in the commanded directions.

Comparison Between Yaw & Roll Control Moment Partial {Cn/delta_R and Cl/delta_P} (Blue and Green Vectors) Against Partial: {Cn_beta and Cl_beta} (Red Vectors)



The next vector diagram shows the maximum yaw moment and side-force produced when the yaw demand is maximized in positive and negative directions. The side-force C_{y0} at trim is slightly positive mainly because β_0 is negative. The vehicle trims at $\beta_0 = -1.37^\circ$ due to the $+Y_{CG}$ offset. The angle of attack is $\alpha_0 = 41.5^\circ$. The solid blue vector towards the right shows the variation in C_n and C_y when the yaw control is maximum positive and the dashed blue vector shows the C_n and C_y variations when the yaw control is maximized in the negative direction. The red vectors show the yaw moment and y-force due to $\pm\beta_{max}$ variations. An increase in beta (solid red vector) causes a negative side-force. The chart shows that the control moments are stronger than the disturbance moments in the yaw direction.

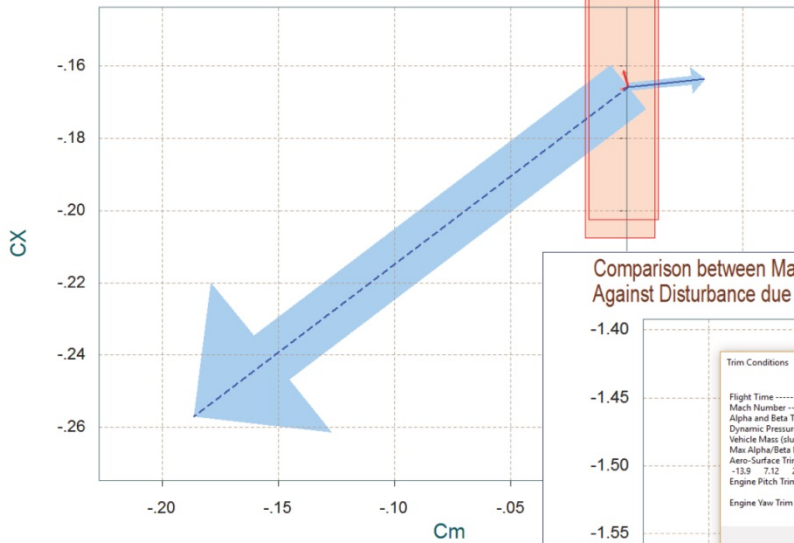
Comparison Between Maximum Yaw Control Moment C_n and Side-Force C_Y (Green & Blue) Versus Disturbance due to Maximum Beta Variation (red), Non-Dimensional



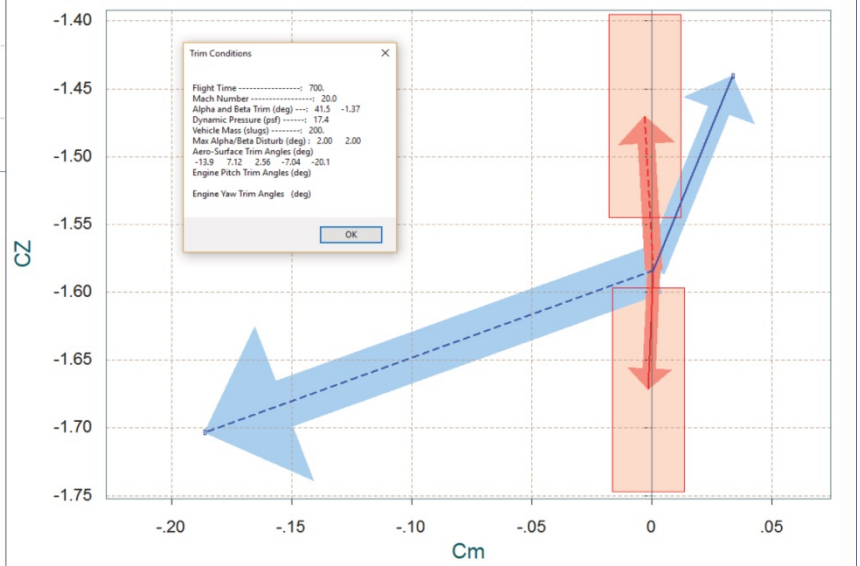
The next pair of vector diagrams show the pitch moment C_m and the axial and normal forces: C_x and C_z produced by maximizing the pitch control δQ_{FCS} . The accelerations are negative because the vehicle descending without thrust and it is trimmed at: $C_{x0} = -0.165$ and $C_{z0} = -1.58$. The blue vectors show the effects on C_m , C_x and C_z when the pitch control demand is maximized, in the positive (solid blue line), and in the negative (dashed blue line) directions. It is obviously easier to pitch down than it is to pitch up, due to the fact that there is more negative control availability. The disturbance vectors (red) are due to the variations $\pm\alpha_{max}$ relative to α_0 . An increase in alpha (solid red vector) pushes C_z further negative (up). The uncertainties δC_m and δC_z are shown by the rectangles at the tips of the disturbance vectors. The control vectors obviously dominate over the disturbance vectors in the pitch direction (including uncertainties). The $\pm\alpha_{max}$ variation has a small effect in the x and z directions, but there is no control demand along the x and z axes because the vehicle is not controlled along those directions. Our intention in this flight condition is to control the flight path through alpha.

The last figure shows the control versus disturbance partials in the pitch and normal force directions. The two red vectors are the disturbance partials are $(C_m\alpha)$ and $(C_z\alpha)$ calculated at two alpha points, at $(\alpha_0 + \alpha_{max})$ and at $(\alpha_0 - \alpha_{max})$. The red rectangles at the tips of the disturbance vectors represent the uncertainties in $C_m\alpha$ and $C_z\alpha$. The control partial is obviously stronger than the disturbance partial in the pitch direction.

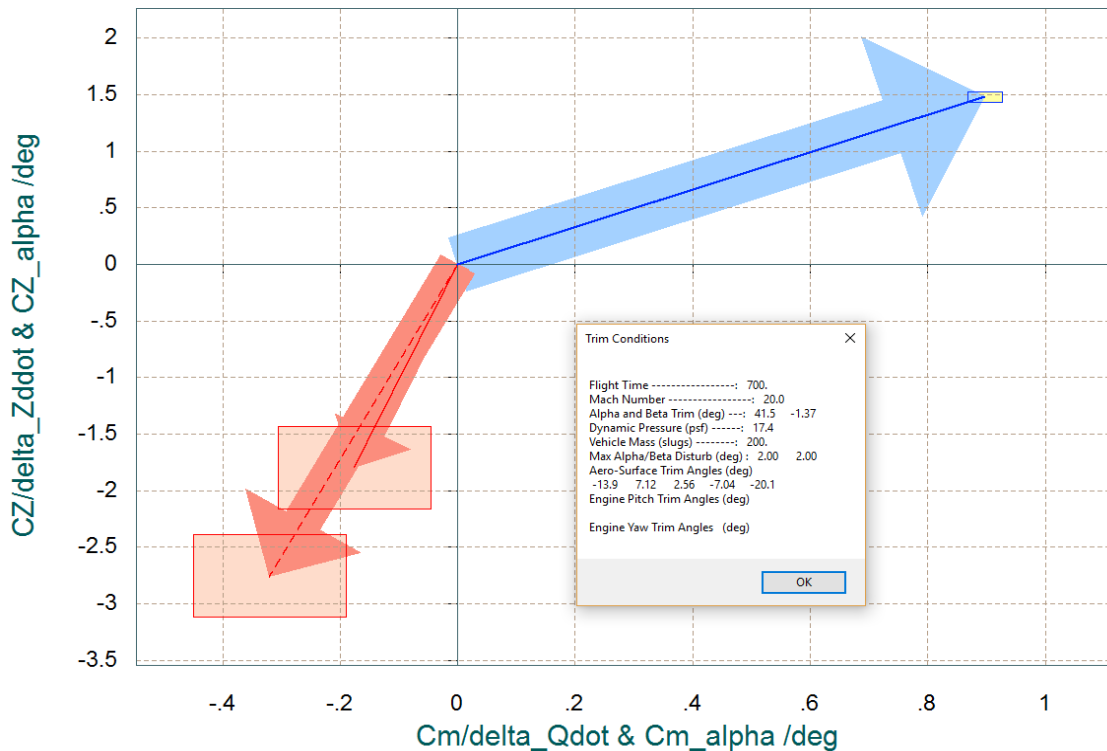
Comparison between Maximum Pitch Control Moment and Axial X-Force (Blue & Green)
Against Disturbances due to Maximum Alpha Variation (red), Non-Dimensional



Comparison between Maximum Pitch Control Moment and Normal-Z Force (Blue & Green)
Against Disturbance due to Maximum Alpha Variation (red), Non-Dimensional

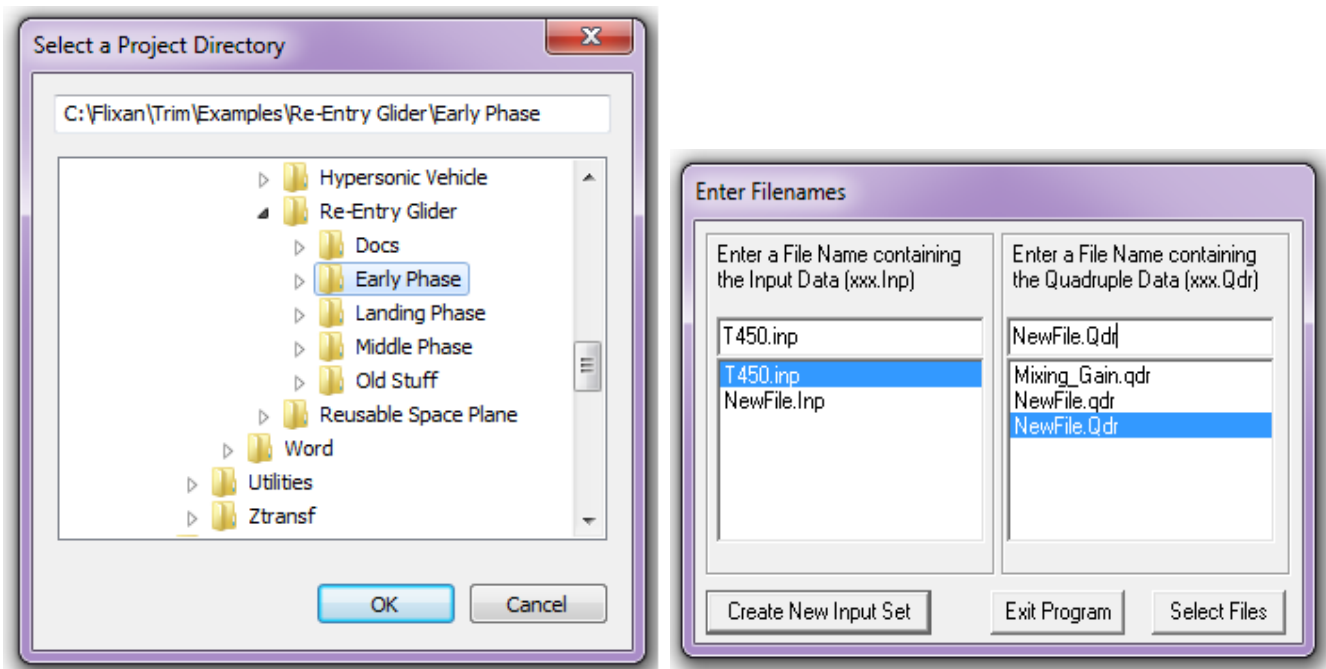


Comparison Between Control Moment and Normal Force Partial {Cm/delt_Q & CZ/delt_Z}
(Blue & Green) Against Moment/ Force Partial {Cm/alpha & CZ/alpha} (Red Vectors)

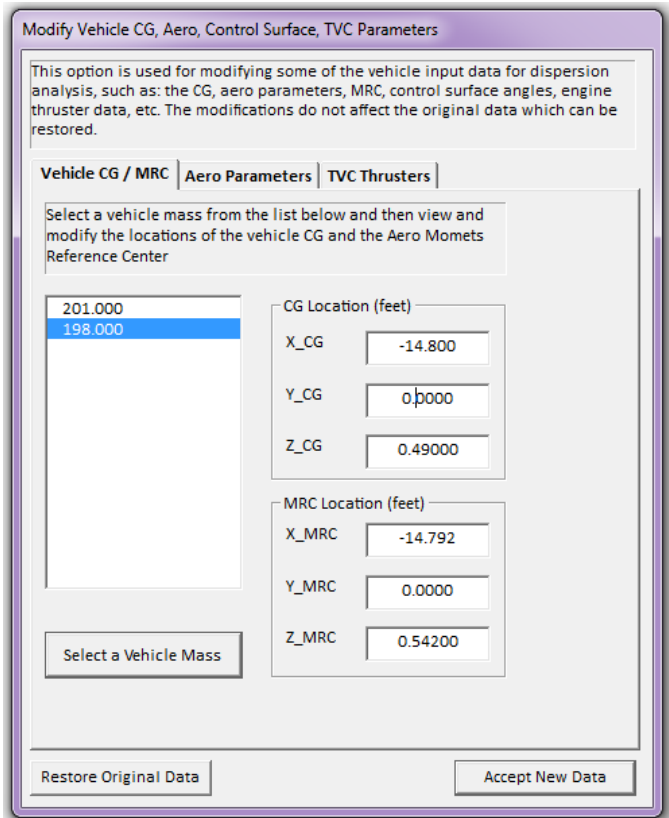
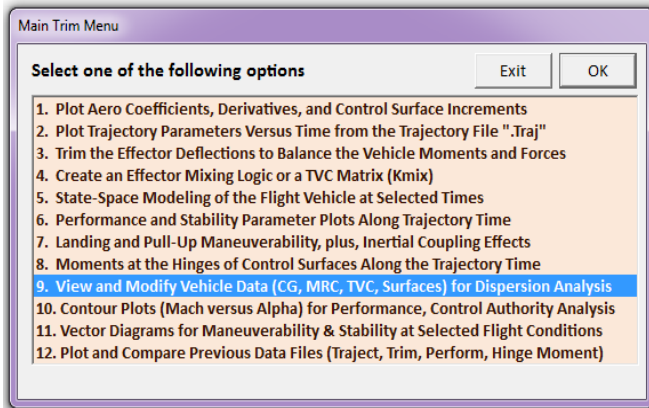


1.4 Creating an Early Re-Entry Dynamic Model

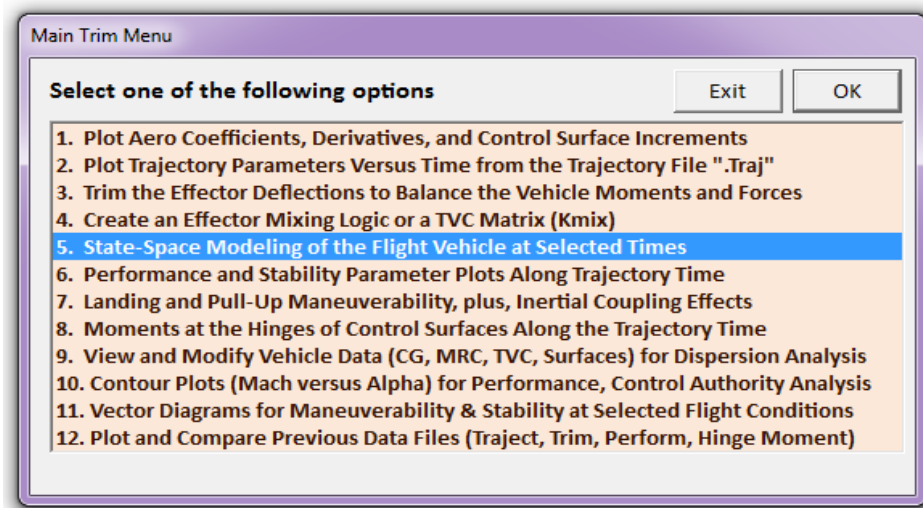
We will now use the Flixan and Trim programs to create a dynamic model for our re-entry vehicle at $t=450$ (sec), which is a time point where the surfaces are effective but not much, and the RCS is also needed to control the vehicle attitude. The vehicle at this point is controlled by both: RCS and the 4 aero-surfaces. The Body-Flap is scheduled open-loop for trimming and it is not active in the flight control loop. Restart the Flixan program and select the "Early Phase" directory and the same files as before. Make the file "T450.Inp" to be the Flixan input data file that will include the vehicle data plus other Flixan related model building data.

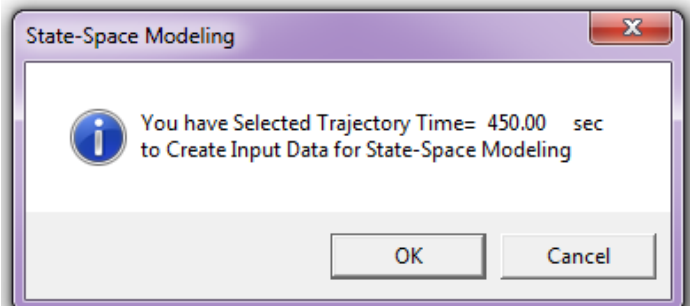
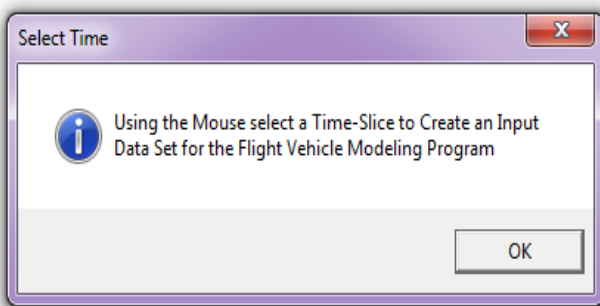
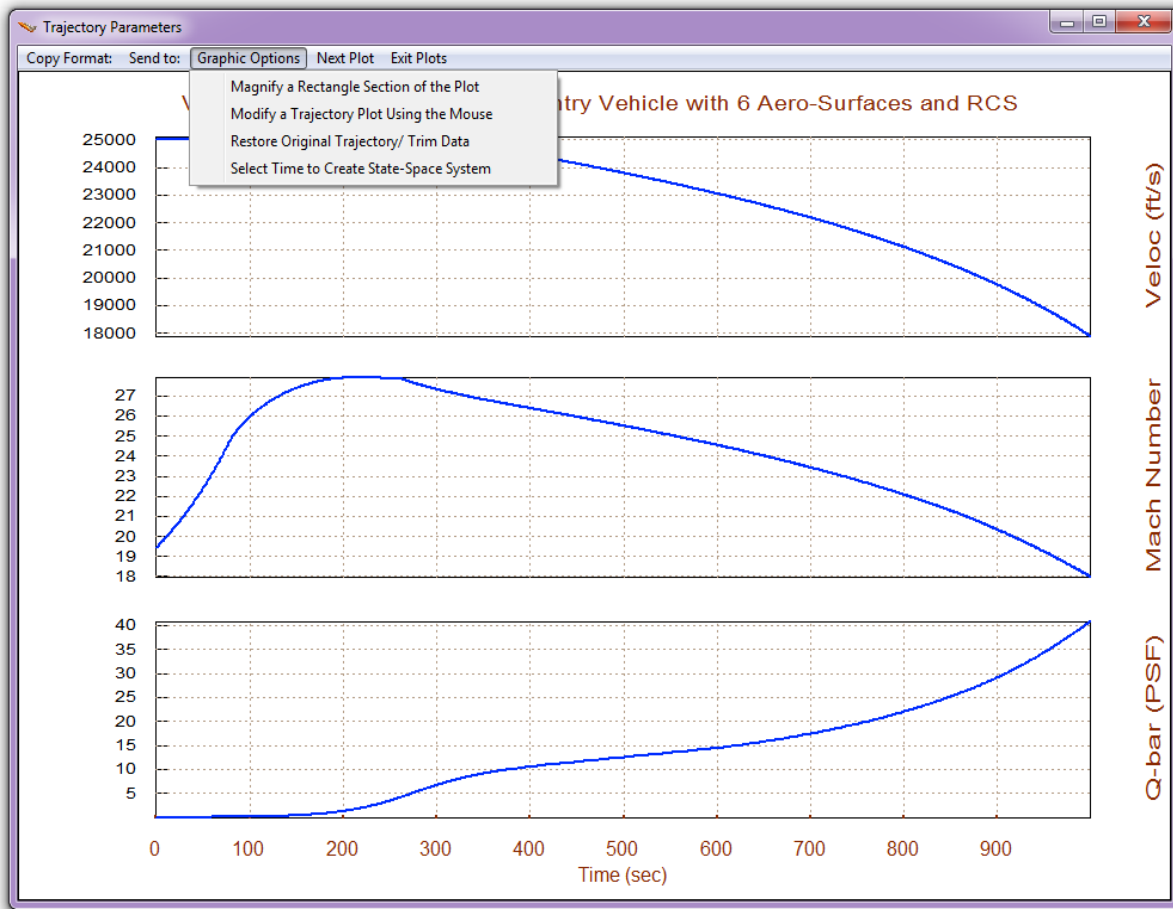
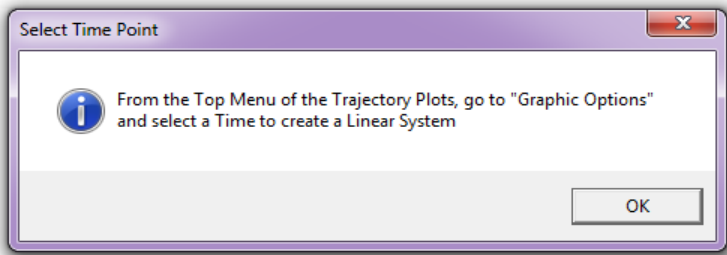


We want our control design and analysis to be based on a vehicle model that has a nominal YCG at zero and not shifted. So we must modify the mass properties, set the YCG at zero, and re-trim before creating the vehicle model. From the Trim main menu select option (9) to modify the YCG. This modification is temporary and it does not affect the mass properties file. From the following dialog select a vehicle mass and change the YCG value to 0. Repeat for both mass values and click on "Accept the New Data". When you return to the main menu, select option (3) to re-trim the effectors at YCG=0. Trim only the 3 moments and do not select an initialization file. The modified trim file "X_mod.Trim" where we disabled the jets was for trimming purposes only. Now we want all effectors to be active for control, except of course for the body-flap. With the YCG centered the left and right aero-surface deflections will be equal, otherwise, they are very different. The original mass-properties can be restored from file XRV.Mass by returning to this dialog and clicking on "Restore Original Data".



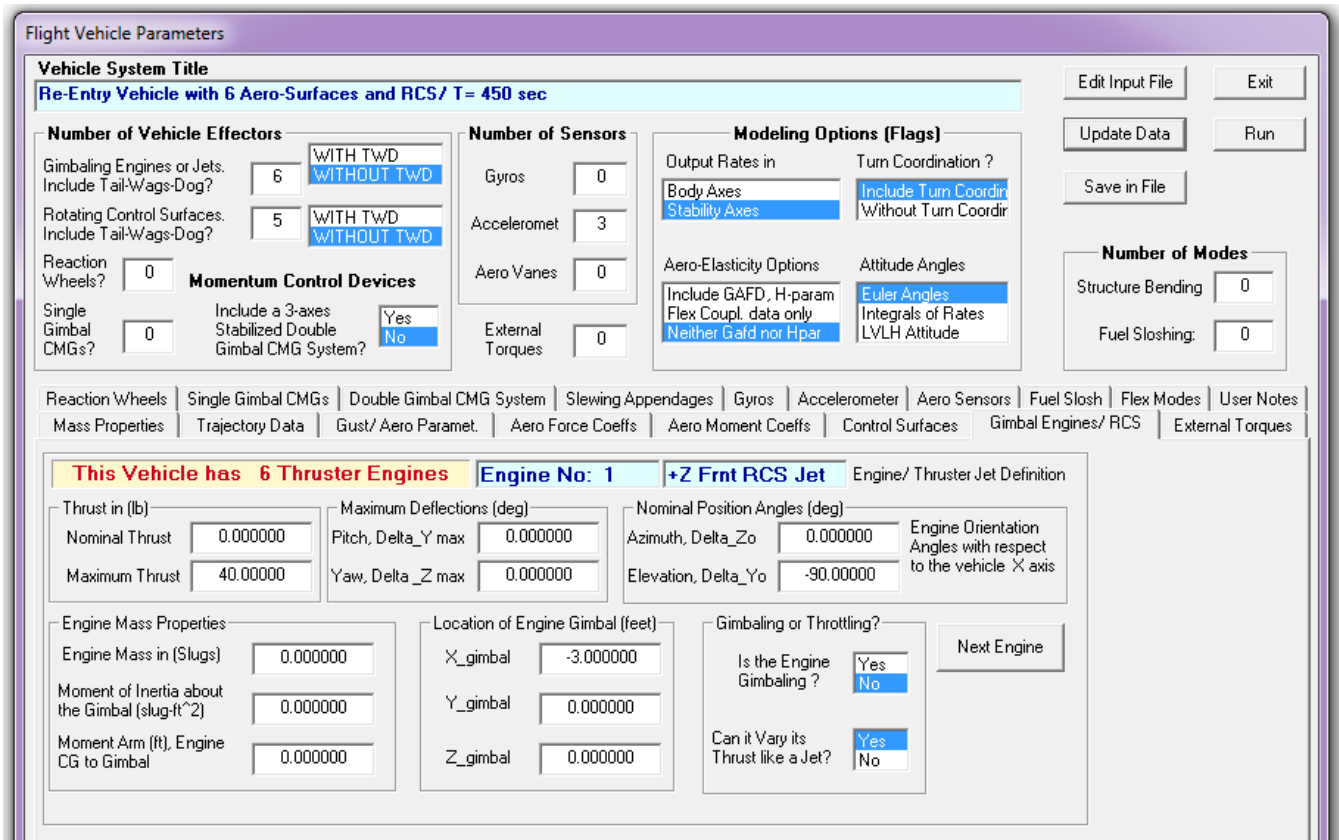
So now let us resume the analysis, return to the Trim main menu and select option (5) to create a state-space dynamic model. A dialog reminds the user how to select a flight time for the dynamic model, click "OK". From one of the trajectory plots go the top menu bar, and choose "Graphic Options", and then from the vertical pop-up menu click on "Select Time to Create State-Space System". Then using the mouse click at time t=450 sec, along the x axis, and confirm that you have selected the correct time by clicking "OK". Otherwise, click "Cancel" and try again.





The program is now ready to create a dynamic model at time=450 sec. The dialog below shows the flight vehicle data prepared by Trim and extracted from the data files. The user can modify some of the data or titles using this dialog before saving it. Some of the flags were changed from their default values. For example, the output rates were changed to stability rather than the body axis, meaning that the roll and yaw rates are measured with respect to the velocity vector V_0 rather than the vehicle x

axis. The turn-coordination flag was also included, meaning that the turn-coordination cross-coupling logic will be included in the vehicle dynamic model. Click on the *"Update Data"* button when the dialog modifications are complete. Do not run it yet because there is more work to be done and more data to be included in file T450.inp. Instead, click on *"Save in File"* and the vehicle data will be saved in file *"T450.inp"*, under the title *"Re-Entry Vehicle with 6 Aero-Surfaces and RCS/ T= 450 sec"*. The file *"T450.inp"* will be processed by Flixan to generate the systems for control design and analysis using Matlab/ Simulink. In addition to the vehicle data this input file contains also system interconnection and modification data related to this analysis that will be processed by Flixan. The systems and matrices generated by Flixan will be saved in file *"T450.Qdr"*.



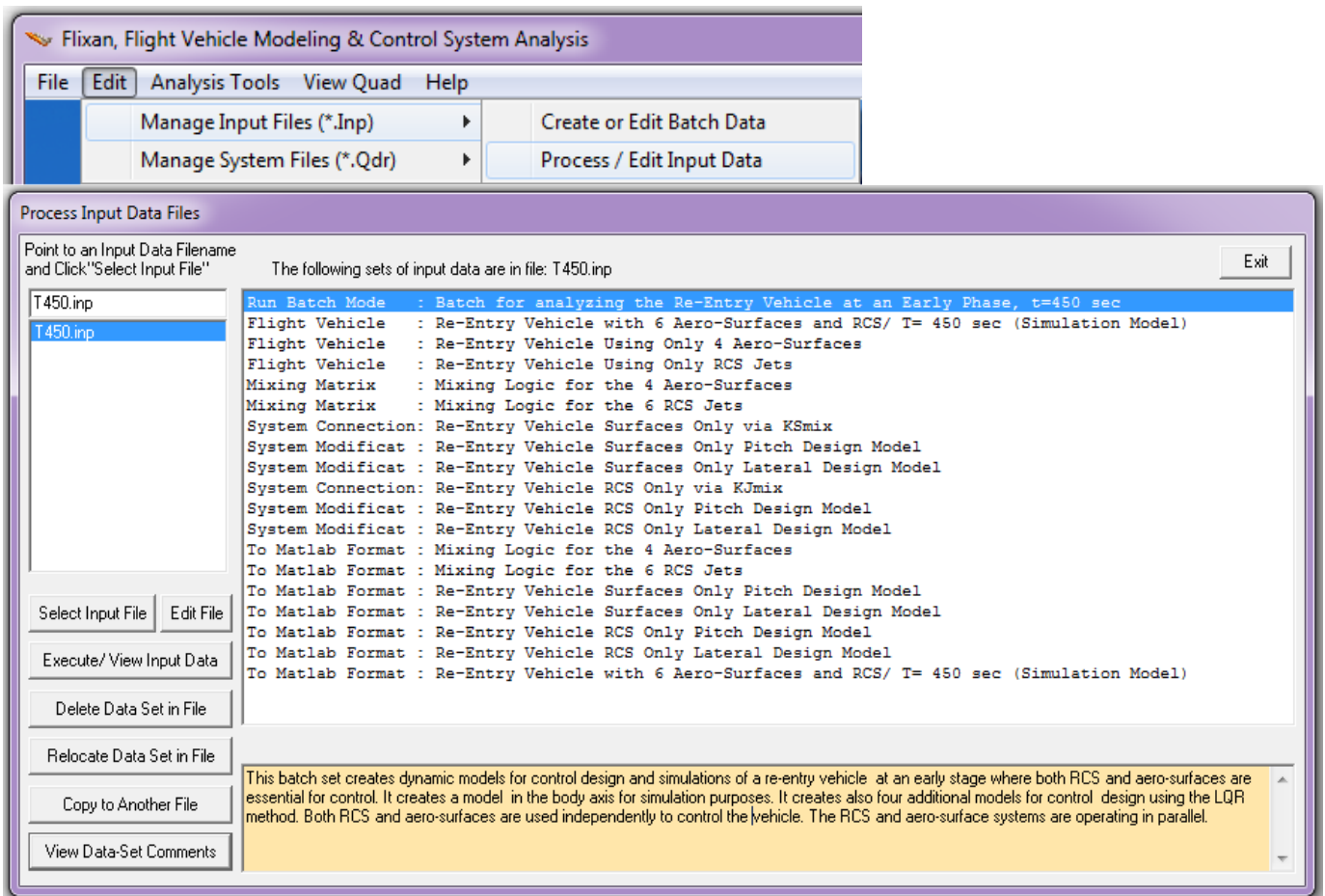
Let us now take a look in file *"T450.inp"* and see what it consists of before processing it in Flixan. This file has already been prepared and it contains several sets of data. Each set is processed by a Flixan utility which create systems and matrices that will be used for control analysis in the next section using Matlab. The flight control system consists of two separate systems operating independently from each other, an aero-surfaces FCS and a reaction control system (RCS) using jets. Notice that the body-flap is not included in the vehicle data because it is used for trimming only and not for control.

1. The first data-set in this file is a batch set for processing the remaining data-sets in batch mode. This is faster because it processes all the sets together instead of processing each set interactively. Its title is *"Batch for analyzing the Re-Entry Vehicle at an Early Phase, t=450 sec"*.

2. Below the batch there is a flight vehicle data set that generates the vehicle simulation model at 450 sec. Its title is "*Re-Entry Vehicle with 6 Aero-Surfaces and RCS/ T= 450 sec (Simulation Model)*". Its output rates are in the body axis.
3. The next set generates the same vehicle model but it includes only the 4 aero-surfaces. The RCS jets have been taken out. The output rates are in stability axis and the turn coordination logic is included. Its title is "*Re-Entry Vehicle Using Only 4 Aero-Surfaces*". This model will be used for generating the aero-surfaces mixing-logic matrix, and also for creating design models for aero-surfaces control.
4. Similarly, the next set generates a similar vehicle model but it includes only the 6 RCS jets. The aero-surfaces are not included. The output rates are also in stability axis and the turn coordination logic is included in the plant model. Its title is "*Re-Entry Vehicle Using Only RCS Jets*". This model will be used for generating the RCS mixing-logic matrix, and also for creating design models for RCS control.
5. The next data-set generates the (4 x 3) mixing logic matrix that converts the FCS demands (roll, pitch, yaw) to 4 surface deflection commands. The data-set title is "*Mixing Logic for the 4 Aero-Surfaces*" and the matrix name is KSmix.
6. Similarly, the next data-set generates the (6 x 3) mixing logic matrix that converts the FCS demands (roll, pitch, yaw) to 6 jet throttle commands. The data-set title is "*Mixing Logic for the 6 RCS Jets*" and the matrix name is KJmix.
7. The next set is a systems interconnection that combines the system created in step 3 with the matrix KSmix created in step-5 to create a new system "*Re-Entry Vehicle Surfaces Only via KSmix*". The new system inputs are roll, pitch and yaw demands. Its outputs are the same as those in step-3.
8. Similarly, the next set is a systems interconnection that combines the system created in step 4 with the matrix KJmix created in step-6 to create a new system "*Re-Entry Vehicle RCS Only via KJmix*". The new system inputs are roll, pitch and yaw demands. Its outputs are the same as the system's in step-4.
9. The next two data-sets are system modification sets. Their purpose is to split the system created in step-7 (using aero-surface control) and to create two separate systems for LQR design. Their titles are "*Re-Entry Vehicle Surfaces Only Pitch Design Model*" and "*Re-Entry Vehicle Surfaces Only Lateral Design Model*".
10. Similarly, the next two sets are also system modification sets. Their purpose is to separate the system created in step-8 (using the RCS jets) and to create two separate systems for LQR design. Their titles are "*Re-Entry Vehicle RCS Only Pitch Design Model*" and "*Re-Entry Vehicle RCS Only Lateral Design Model*".
11. The next two data sets convert the mixing-logic matrices KSmix and KJmix to Matlab (*.Mat) matrix format that can be loaded into Matlab.
12. The last 5 data-sets in the input data file convert the systems created to Matlab function (*.m) format so they can be loaded to Matlab for linear analysis. The simulation model is saved in file "*veh_sim.m*". The design plants using aero-surfaces are saved in files "*Pdes_surf.m*" and "*Ldes_surf.m*", and the design plants using RCS jets are saved in files "*Pdes_RCS.m*" and "*Ldes_RCS.m*".

Processing the Batch Using Flixan

The Flixan data-sets that will be used for the preparation of the vehicle models and the batch set for quick data processing have already been created in file "T450.Inp". This file has been moved to folder "C:\Flixan\Trim\ Examples\Re-Entry Glider\Early Phase\Mat Anal T450", where the control analysis will be performed using Matlab. The user must process this file in Flixan as follows. Start Flixan and select the project directory that contains the input data file. Then go to "Edit", "Manage Input Files" and then "Process/ Edit Input Data". When the following dialog appears, select the input data file "T450.Inp" from the left menu and click on "Select Input File". The menu on the right lists the titles of the data sets which are included in this file. On the left side of each title there is a short label defining the type of the data-set. It also identifies which program utility will process the data-set. On the top of the list there is a batch created to process the whole file. In order to process the batch, highlight the first line with title: "Batch for analyzing the Re-Entry Vehicle at an Early Phase, t=450 sec", and click on "Execute/ View Input Data". Flixan will process the input file and save the systems and matrices in file "T450.Qdr". It will also create the matrices and system functions for Matlab analysis. The same process can be used to create models, design and analyze other flight condition along the trajectory.



1.5 Control Design and Analysis during Early Re-Entry

There are several control approaches to consider in combining the aero-surfaces and RCS jets together. One approach might be to allow the aero-surfaces control system to be operating in the inner loop and the RCS to provide an outer loop control and acting as a back-up system. In this example, however, we will use two separate control systems operating in parallel, which are also capable controlling the vehicle independently from each other. One system is using the 4 aero-surfaces and the other is using the 6 RCS jets. The vehicle begins its descent trajectory from orbit by firing its orbital maneuvering engines to slow it down and placing it to a shallow re-entry flight path angle $\gamma=-1^\circ$. During this early phase the flight control system attempts to control the angle of attack, initially at $\alpha=41^\circ$ and gradually decreasing it to smaller alphas. This angle is optimal for heat protection.

The design models already include the mixing matrices so the input to the pitch plant model is pitch acceleration demand. The state-vector was modified from its original definition in files `pdes_rcs.m` and `pdes_surf.m`. The velocity and altitude states (δV and δh) were not included because during this phase we are not interested to control these variables which affect mainly the phugoid mode. The integral of the angle of attack was included in the state-vector, so the control state vector consists of: (θ , q , α , α -integral). In the lateral direction the vehicle is expected to perform roll maneuvers about its velocity vector V_0 . The design models are in the stability axes, that is, roll and yaw are defined relative to the velocity vector V_0 which is at $\alpha=41^\circ$. Now why do we want our design models to be in stability axis rather than in the body axis? It would make more sense to design the gains relative to the body axis since the rate and acceleration measurements are coming in the body axis. The reason is that in the lateral axes the vehicle is commanded to roll about the velocity vector V_0 . This minimizes the sideslip angle β transient. So it makes sense to optimize our LQR gains based on the stability model and command a roll directly in the stability axis. A roll command about the velocity vector corresponds to a simultaneous roll and yaw command in the body axis. This reduces the beta transients. The lateral design model state vector is augmented and it consists of (p_{stab} , r_{stab} , β , p_{stab} -integral, and β -integral). The inputs are roll and yaw demands.

LQR Design

The following Matlab script "Init.m" loads the four LQR design models, the simulation model, and the two mixing-logic matrices. It performs the four LQR designs for aero-surfaces and RCS, and generates four state-feedback matrices. Two lateral ($KJpr$ and $KSpr$), and two pitch (KJq , and KSq).

```
d2r=pi/180; r2d=180/pi;
[Apj, Bpj, Cpj, Dpj] = pdes_rcs;           % Load Pitch RCS Jet Design Model
[Aps, Bps, Cps, Dps] = pdes_surf;        % Load Pitch aero-surf Design Model
[Alj, Blj, Clj, Dlj] = ldes_rcs;         % Load Lateral RCS Jet Design Model
[Als, Bls, Cls, Dls] = ldes_surf;       % Load Lateral aero-surf Design Model
[Ave, Bve, Cve, Dve] = vehi_sim;        % Simulation Model 6-dof
load KSmix.mat -ascii;                  % Load Surfaces Mix Logic (4 x 3)
load KJmix.mat -ascii;                  % Load RCS Jets Mix Logic (6 x 3)
```

```

alfa0=41.5; V0=24124.0; Thet0=40.3; ge=32.174; % Additional Vehicle Parameters
calfa=cos(alfa0*d2r); salfa=sin(alfa0*d2r); % for Body to Stability Transform

% Convert Lateral State Vector from Body to Stability Axes, Outputs=States
Al2= Clj*Alj*inv(Clj); B12= Clj*B1j; % for the Jets
Cl2= Clj*inv(Clj); D12= D1j;

% Lateral LQR Design Using Only the RCS Jets
[Al5,B15,Cl5,D15]= linmod('LRdes5x'); % 5-state model {p,r,bet,pint,betint}
R=[1,1]*20; R=diag(R); % CS LQR Weights R=[1,1]*20
Q=[1 1 0.1 0.5 0.005]*3; Q=diag(Q); % CS LQR Weights Q=[1 1 0.1 0.5 0.005]*3
[KJpr,s,e]=lqr(Al5,B15,Q,R); % Perform LQR design on Jets

% Convert Lateral State Vector from Body to Stability Axes, Outputs=States
Al2= Cls*Als*inv(Cls); B12= Cls*B1s; % Transform from Body to Stability
Cl2= Cls*inv(Cls); D12= D1s; % for the Surfaces

% Lateral LQR Design Using Only the Aero-Surfaces
[Al5,B15,Cl5,D15]= linmod('LRdes5x'); % 5-state model {p,r,bet,pint,betint}
R=[1,1]*20; R=diag(R); % CS LQR Weights R=[1,10]*2
Q=[1 1 0.1 0.2 0.002]*2; Q=diag(Q); % CS LQR Weights Q=[1 1 1 0.04 0.04]*0.4
[KSpr,s,e]=lqr(Al5,B15,Q,R); % Perform LQR design on Jets

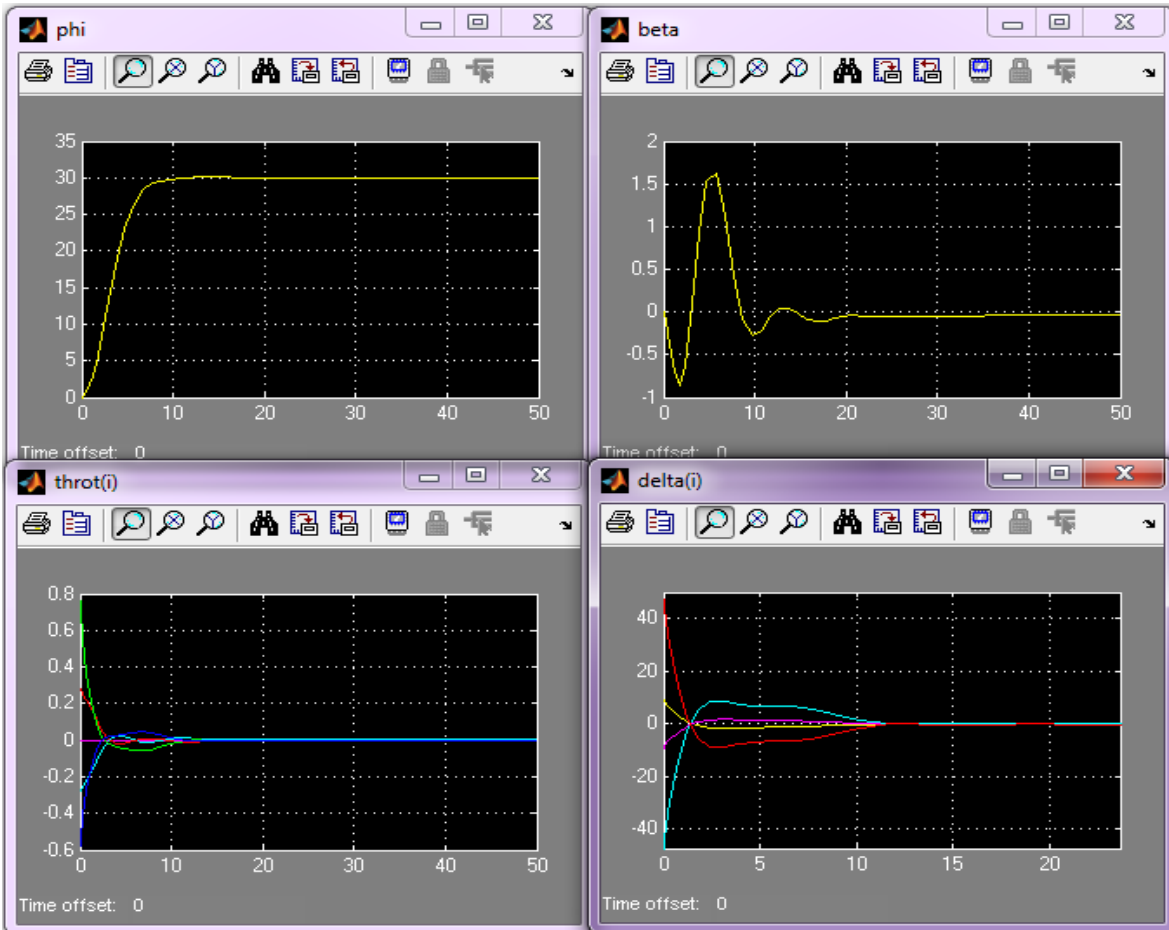
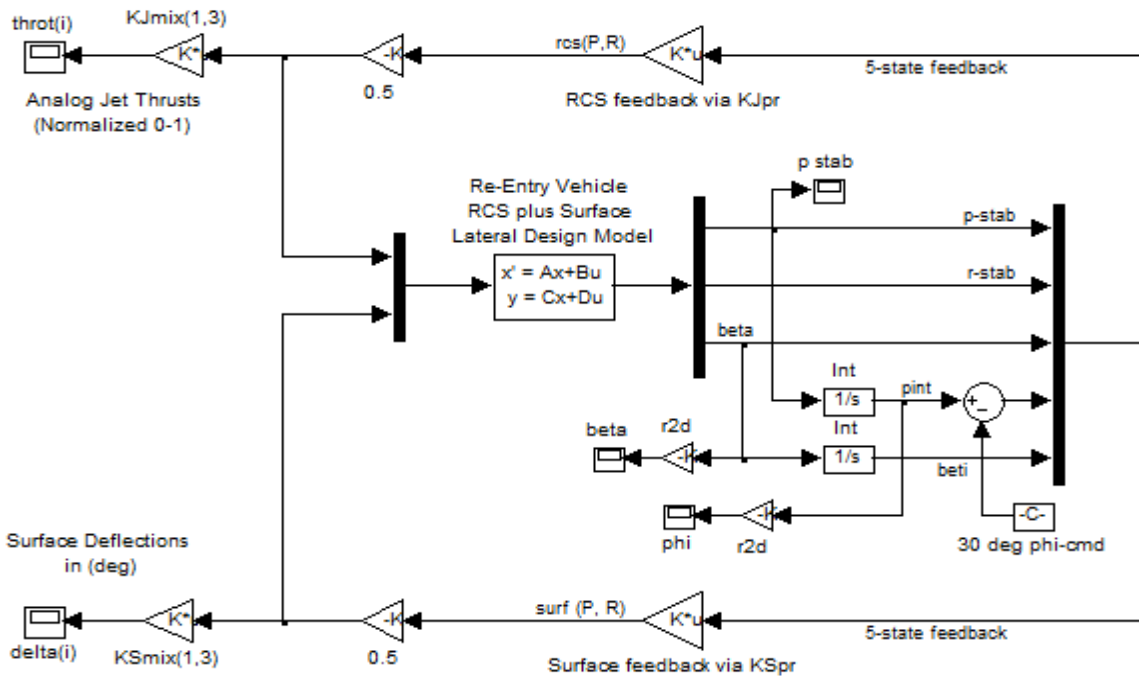
% Pitch LQR Design Using Only the RCS Jets
Apd=Apj; Bpd=Bpj; Cp4=Cpj; Dpd=Dpj;
[Ap4,Bp4,Cp4,Dp4]= linmod('Pdes4x'); % 4-state des model {theta,q,alfa,alf_int}
Ap5= Cp4*Ap4*inv(Cp4); Bp5= Cp4*Bp4; % Convert to
Output=State={theta,q,alfa,alf_int}
Cp5= Cp4*inv(Cp4); Dp5= Dp4;
R=4; Q=[0.05 0.5 1 1]; Q=diag(Q); % RCS LQR Weights {theta,q,alfa,alf_int}
[KJq,s,e]=lqr(Ap5,Bp5,Q,R); % Perform LQR design on Surf

% Pitch LQR Design Using Only the 4 Aero-Surfaces
Apd=Aps; Bpd=Bps; Cp4=Cps; Dpd=Dps;
[Ap4,Bp4,Cp4,Dp4]= linmod('Pdes4x'); % 4-state des model {theta,q,alfa,alf_int}
Ap5= Cp4*Ap4*inv(Cp4); Bp5= Cp4*Bp4; % Convert to
Output=State={theta,q,alfa,alf_int}
Cp5= Cp4*inv(Cp4); Dp5= Dp4;
R=2; Q=[0.05 0.5 1 1]; Q=diag(Q); % AS LQR Weights {theta,q,alfa,alf_int}
[KSq,s,e]=lqr(Ap5,Bp5,Q,R); % Perform LQR design on Surf

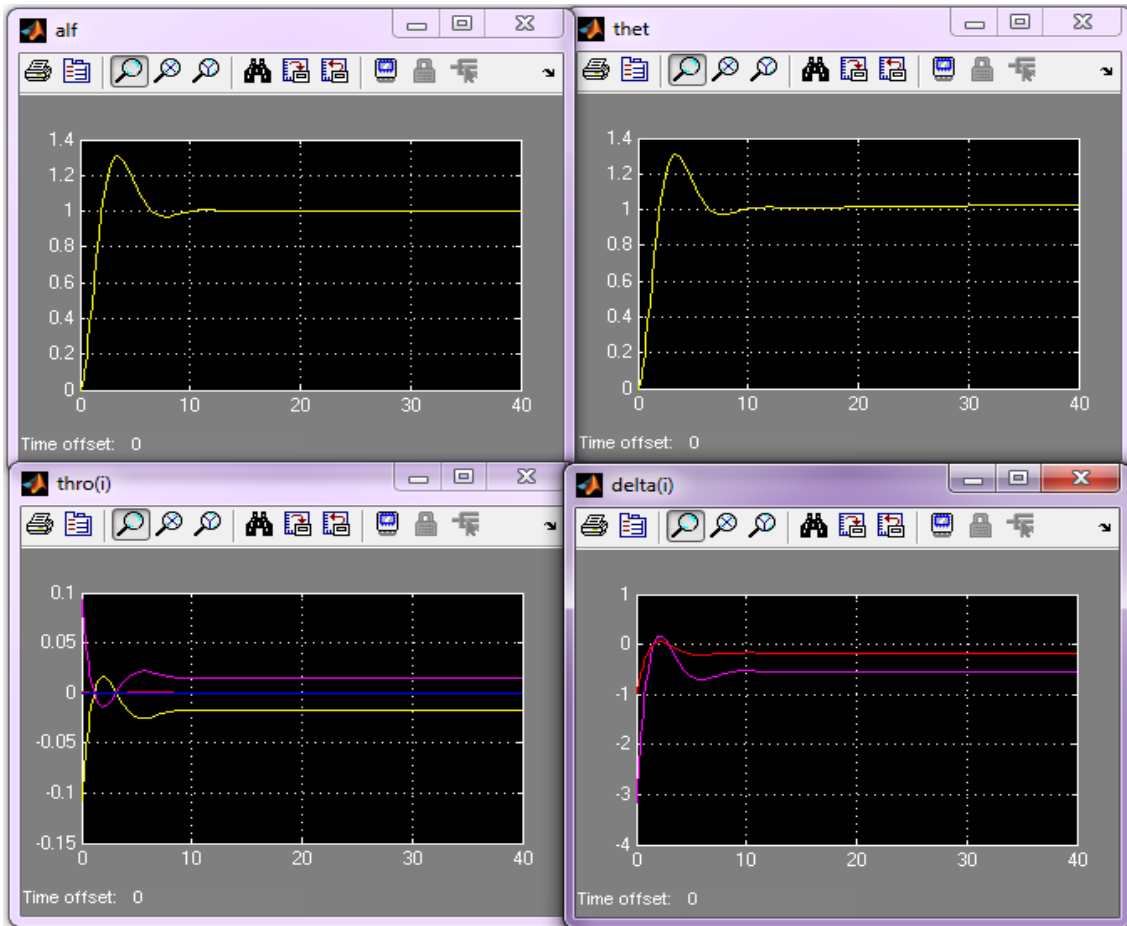
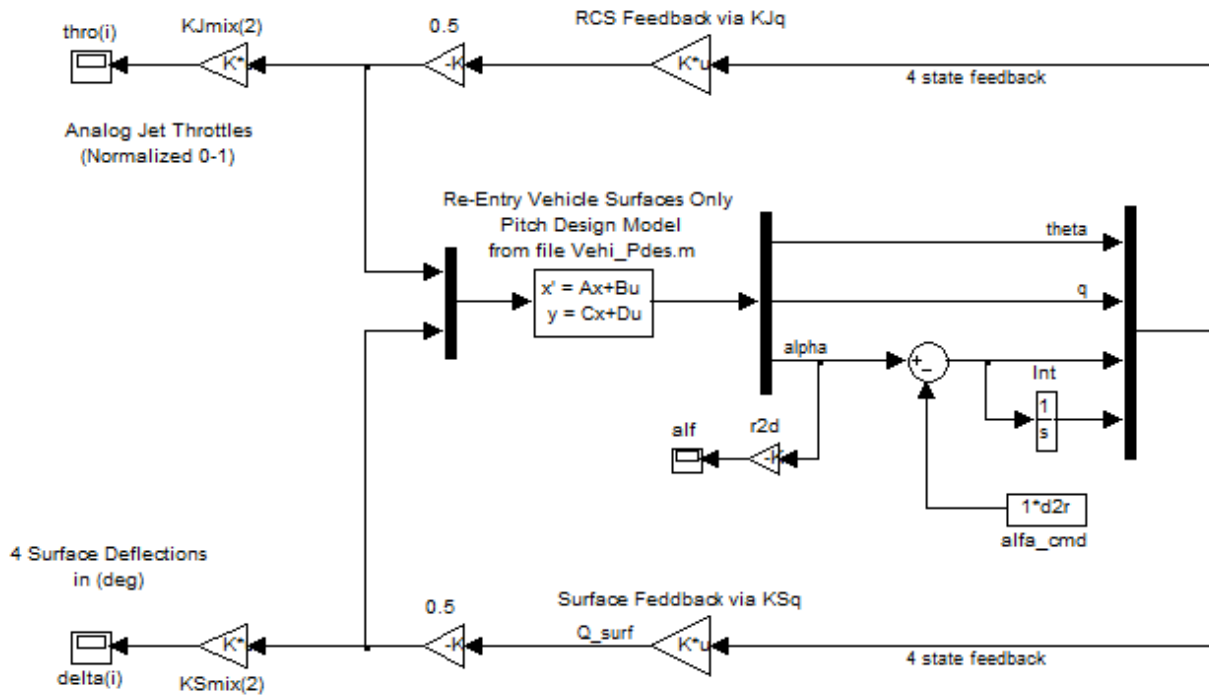
```

The two simple simulation models in files "*Sim_Later_Simple.mdl*" and "*Sim_Pitch_Simple.mdl*", shown below, are used to evaluate the pitch and lateral LQR designs and to adjust the LQR weights. They use the design models and they include both the RCS and the aero-surface state-feedback loops operating in parallel. Each loop is contributing half of the amount that it should be contributing if the other loop was absent. Since the mixing-logic matrices are included in the vehicle systems their inputs are acceleration demands (δP , δQ , δR) coming from the state-feedback matrices. The mixing-logic matrices in the models are used to convert the control demands to effector deflections which must be taken into consideration while adjusting the LQR weights. We would typically like to keep the surface deflections below $\pm 30^\circ$ during a maneuver and the throttles below ± 1 .

Lateral LQR Early Reentry Evaluation Model RCS and Aero-Surf Loops Operating in Parallel



Pitch LQR Early-Reentry Evaluation Model RCS and Aero-Surface Loops Operating in Parallel



Simulation Model

The Matlab simulation model is in file "*Simul_6dof.mdl*", see figure (1.5.1). The vehicle dynamic model is shown in detail in Figure (1.5.2). It uses the vehicle state-space system "*Re-Entry Vehicle with 6 Aero-Surfaces and RCS/ T= 450 sec (Simulation Model)*" which was generated by Flixan and saved in file "*vehi_sim.m*". This system does not include the two effector mixing matrices (KJmix & KSmix), as the design plants, so the matrices are included in the Simulink subsystem. The gust input is a low-pass shaped gust impulse of 30 (ft/sec) velocity. The direction of gust is defined relative to the vehicle in the input data file "T450.Inp", and it excites both pitch and yaw, perpendicular to the X-axis and at 45° between +Y and +Z axes (typical). Its output rates and attitudes are in the body axis. The controller, however, was designed using the stability axis models and it expects to see rates about the stability axis. For this reason we have included a transformation in the flight control system block that converts the (p & r) body rates to stability rates (p-stab & r-stab) to produce the lateral state-vector required by the LQR state-feedback. The state-feedback signals "Surface(P,Q,R)-demands" are converted to surface deflections (rad) after the multiplication with matrix KSmix which closes the surfaces feedback loop. Similarly, the state-feedback signals "Jet(P,Q,R)-demands" are converted to throttling inputs (0 to ±1) after being multiplied with matrix KJmix which closes the RCS jets loop.

6-dof Simulation Model Using Throttling Jets & Aero-Surfaces in Parallel

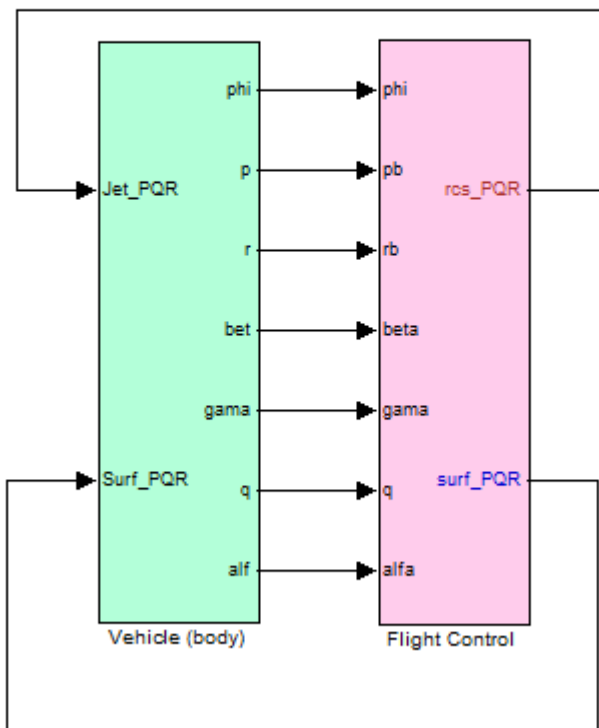


Figure 1.5.1 Early Re-Entry Simulation Model in File: "*Simul_6dof.mdl*"

Vehicle Simulation Model

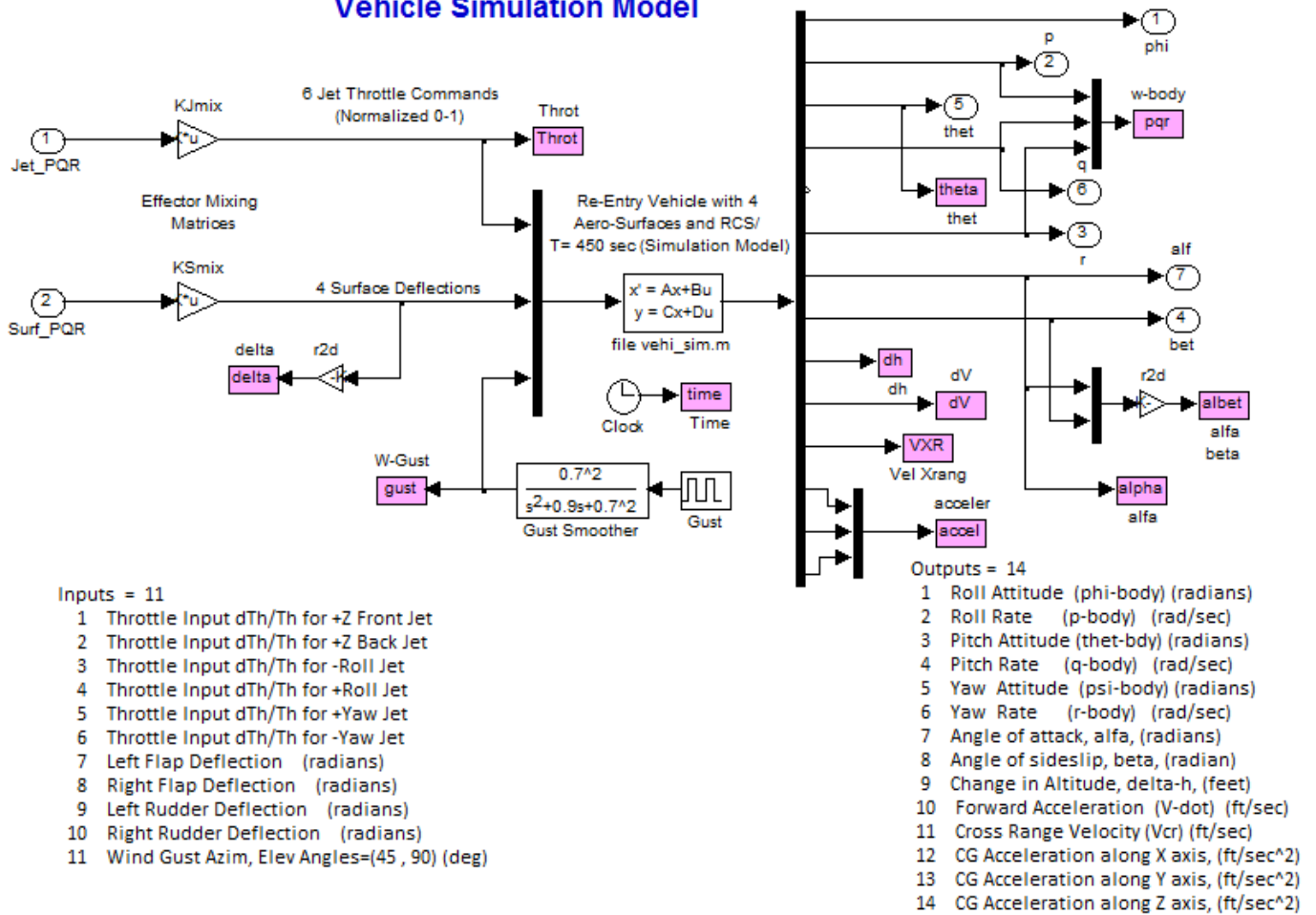


Figure 1.5.2 Early Re-Entry Simulation Model, Vehicle Block (Green)

The flight control subsystem is shown in Figure (1.5.3). In the upper left hand corner there is a transformation block that converts the body rates to stability rates which are needed for the lateral state-feedback. The lateral FCS receives a roll command from guidance (30° in this case) about the velocity vector V_0 . The state-feedback is converted to two sets of roll and yaw demands. One set for the RCS jets (shown in red) and another set for the aero-surfaces (shown in blue).

Similarly, the pitch FCS receives a step in α -command from guidance (1° in this case), and the state-feedback is converted to two sets of pitch demands. One set for the RCS jets (shown in red) and another set for the aero-surfaces (shown in blue). The signals are finally re-shuffled to two sets of (roll, pitch, yaw) demands. A set for the RCS jets (red) and a set for the aero-surfaces (blue) which close the two parallel loops. Some of the signals are saved for plotting using the script file pl.m. Notice that the throttle inputs to the jets are continuous and not the "on-off" type, which are more typical for RCS. This type of modification in the simulation is not difficult to achieve, as already shown in other examples.

Flight Control System

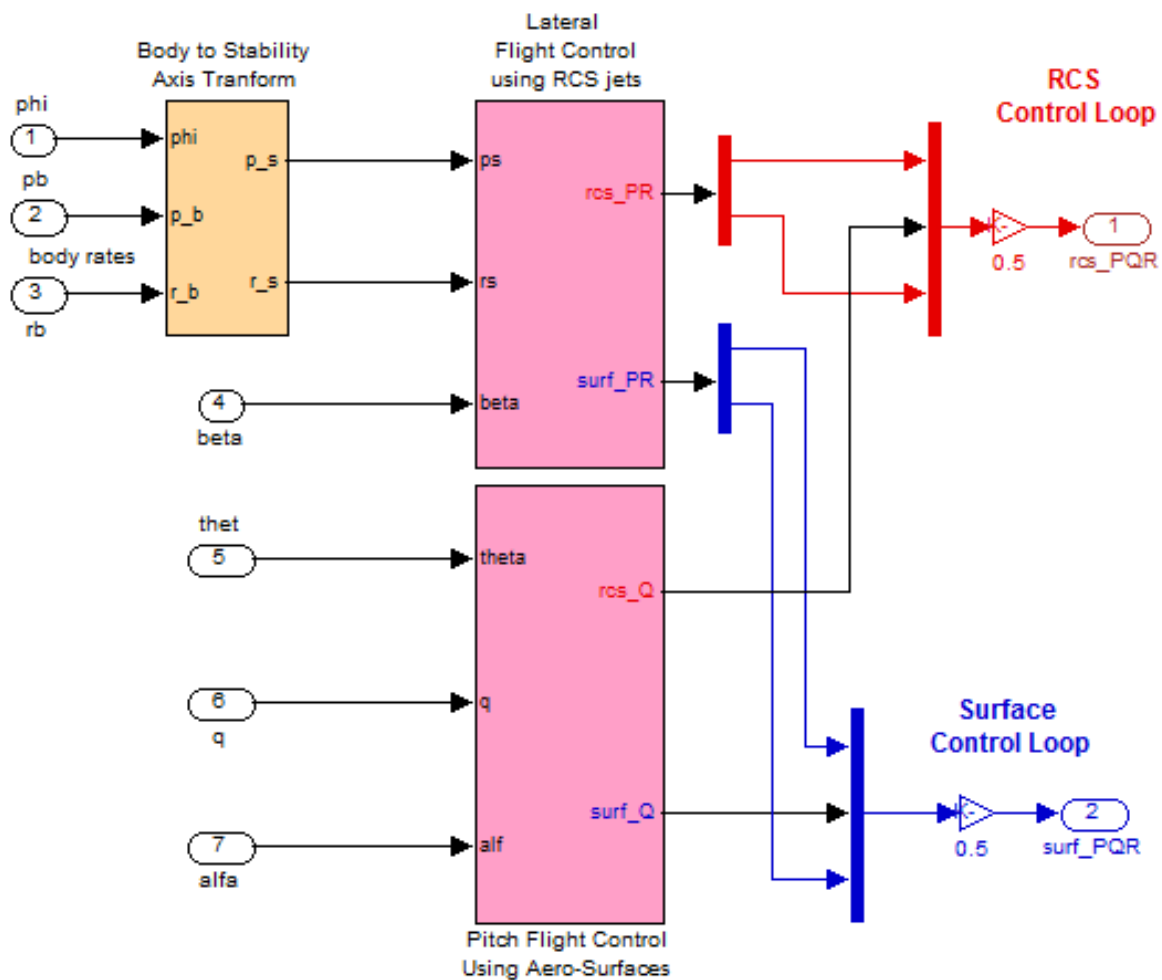
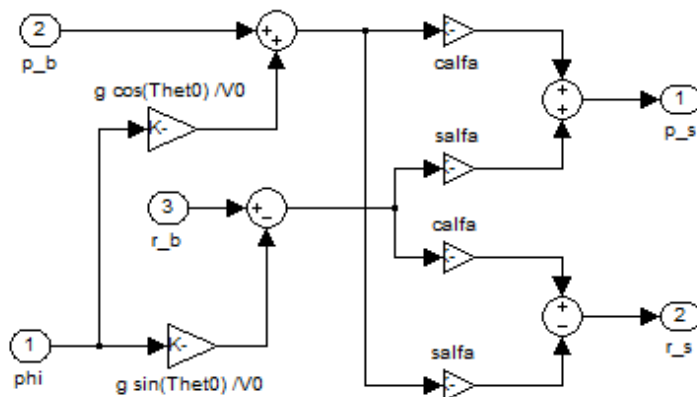
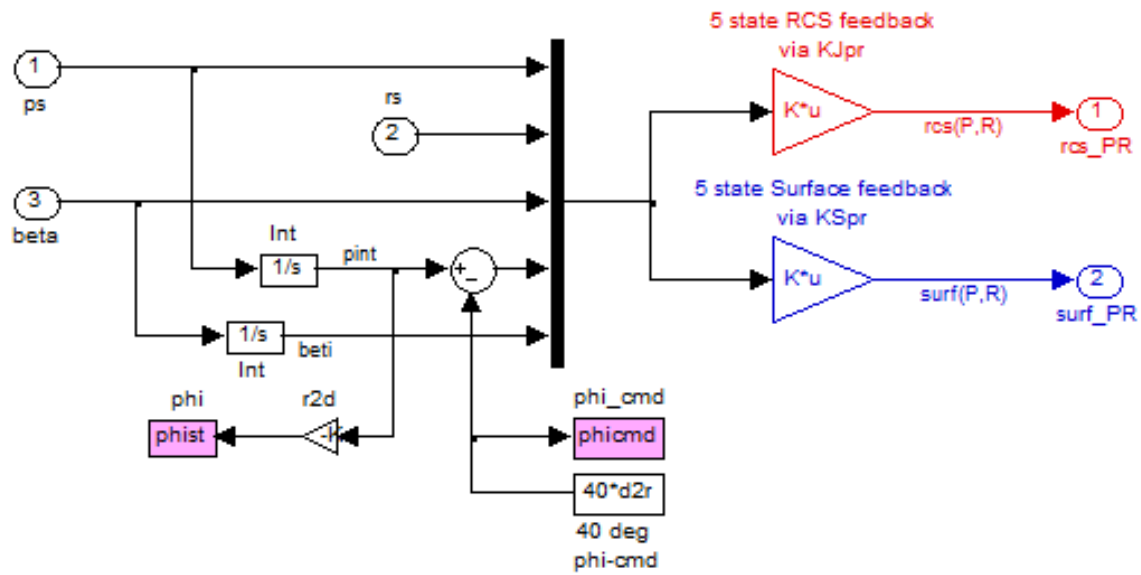


Figure 1.5.3 Early Re-Entry Flight Control System Block

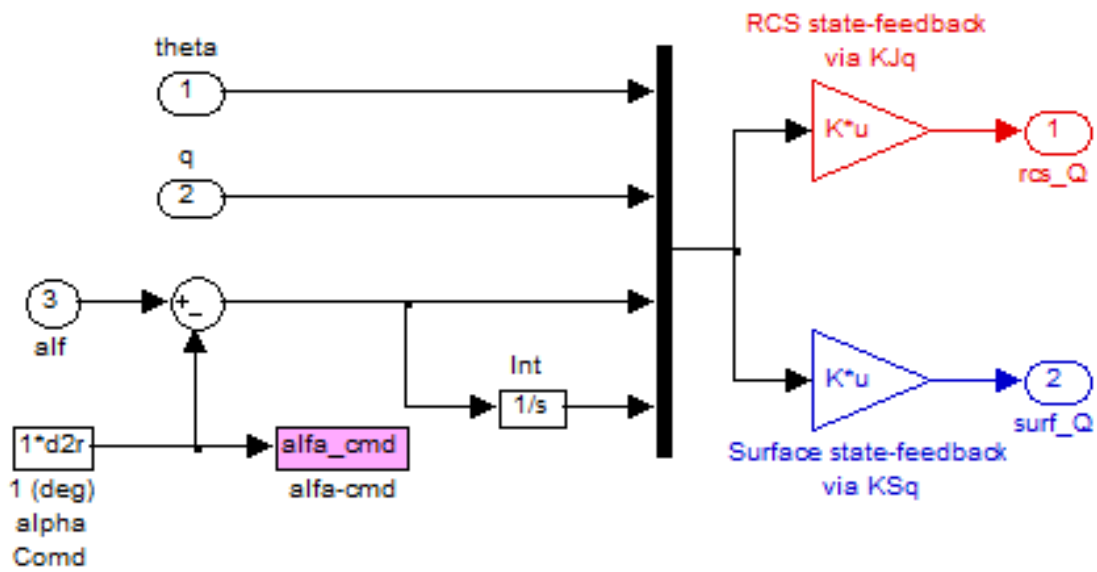
Body to Stability Axes Transformation



Lateral Flight Control System

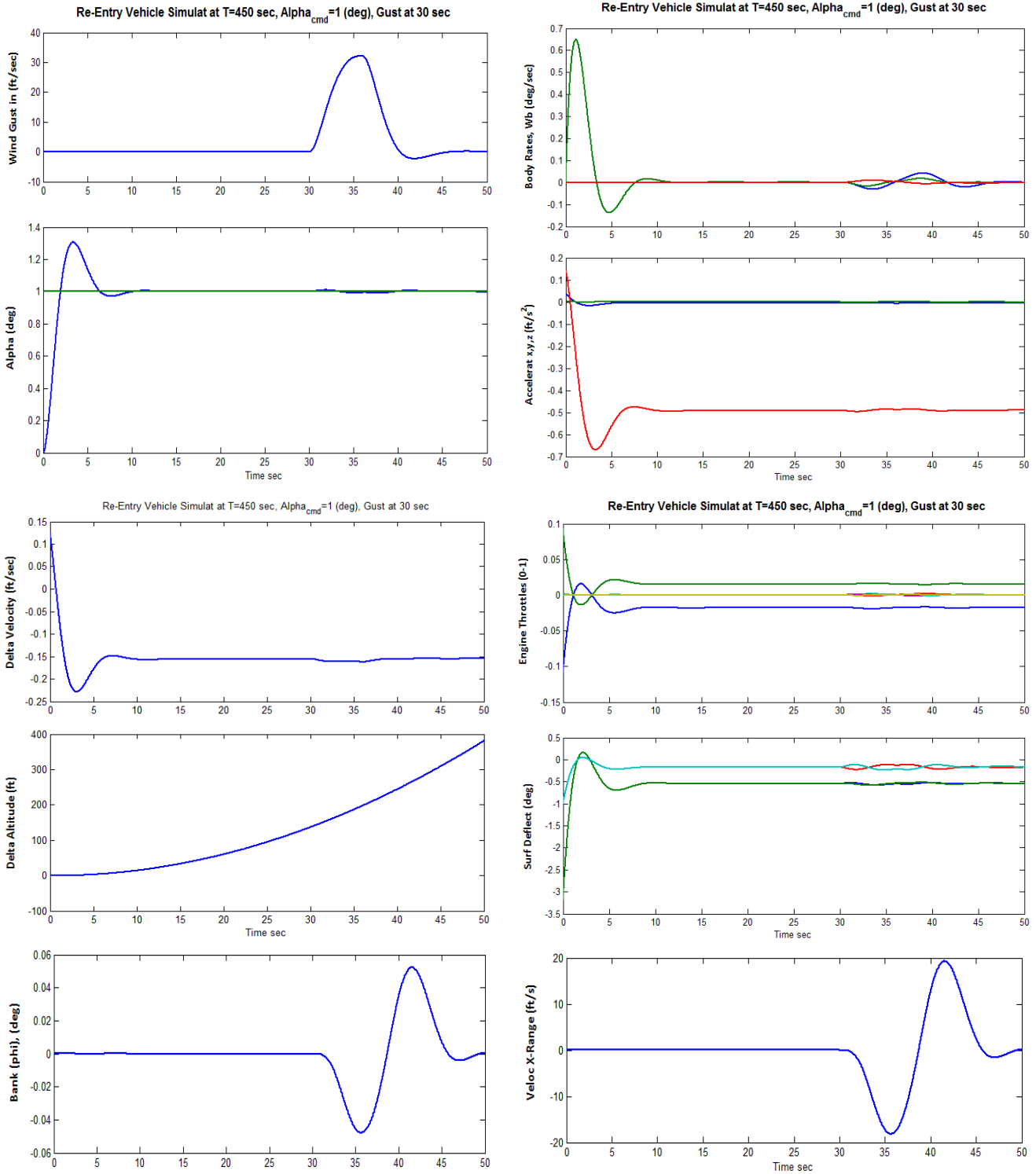


Pitch Flight Control System



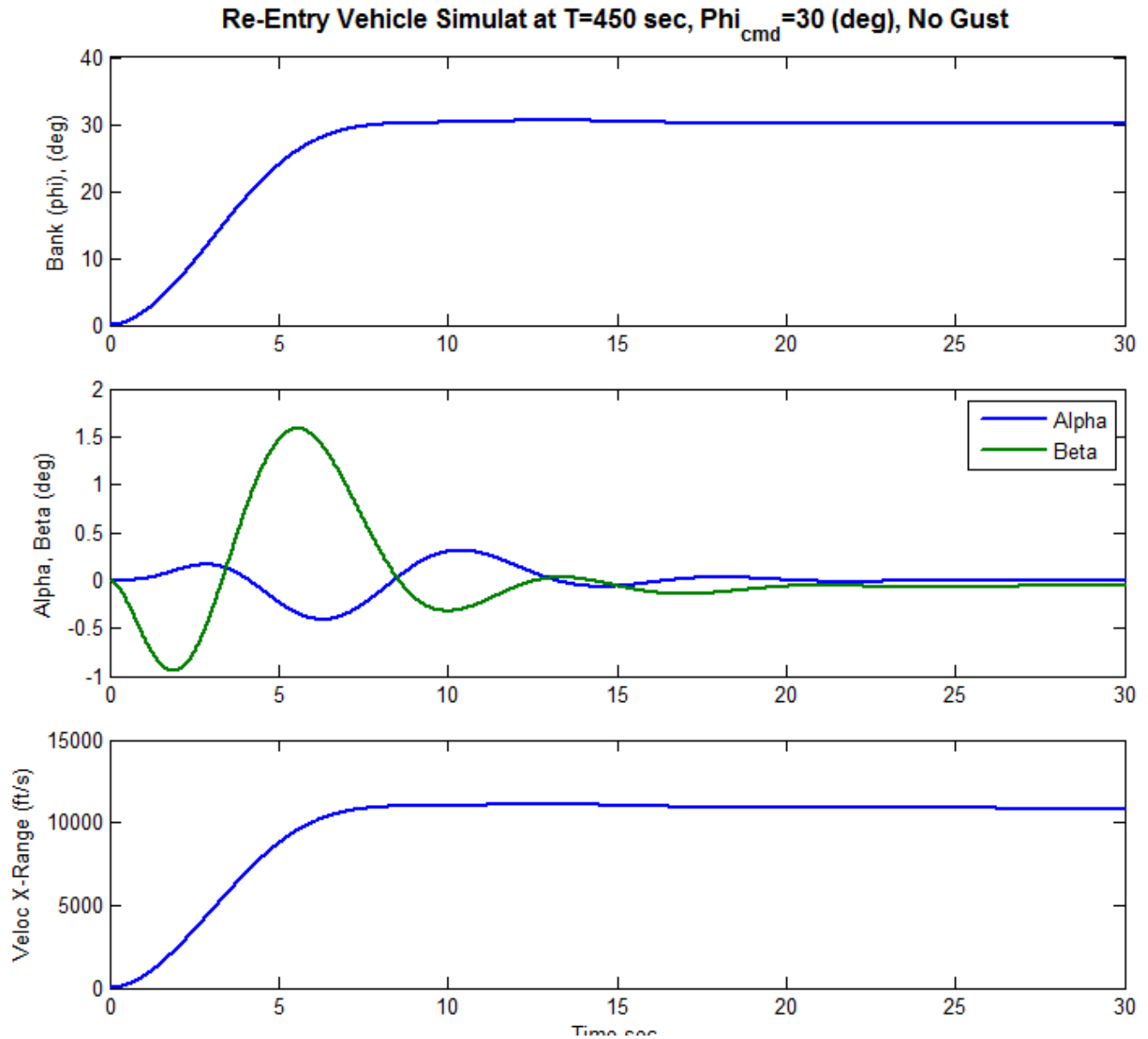
Case A, Gamma-Command with Gust Simulation

In this case the vehicle is commanded to 1° change in the angle of attack. This change is performed by a combination of surface deflection plus RCS firing. It causes a drop in velocity and an increase in altitude. Further down at t=30 sec it gets hit by a gust that causes a transient in beta.

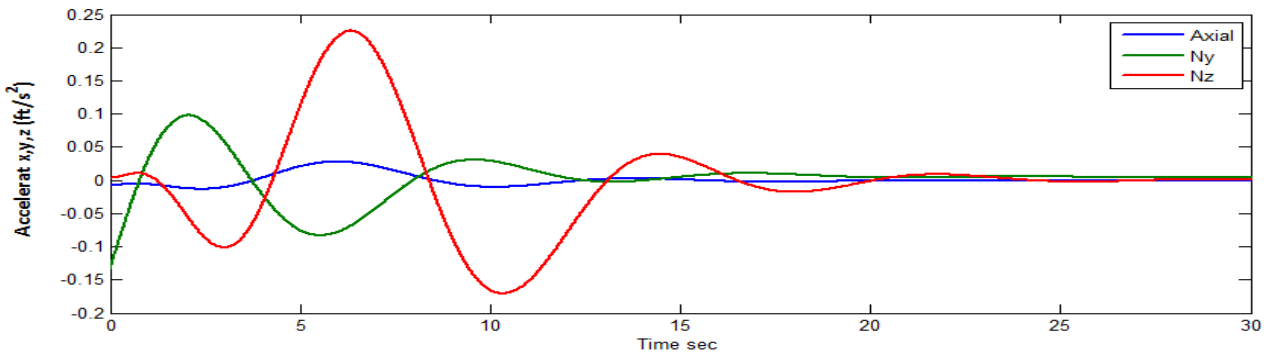
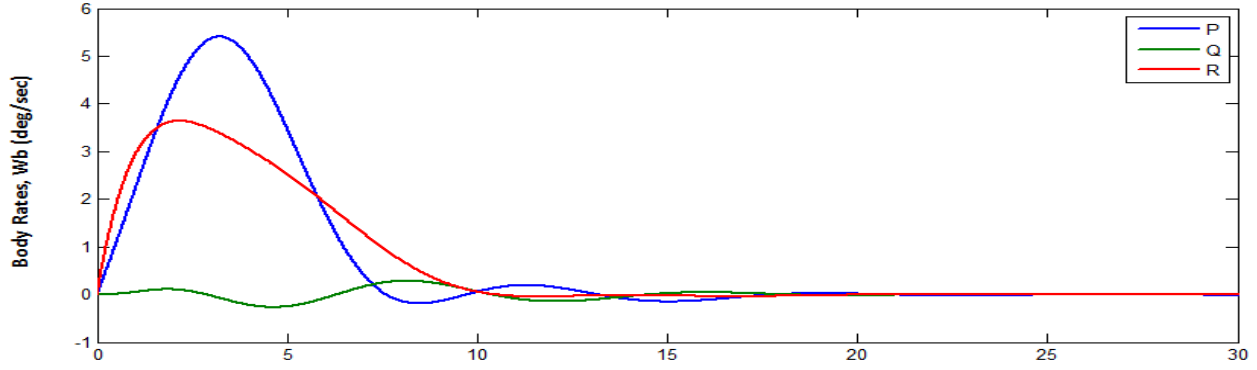


Case B, Phi-Command Simulation

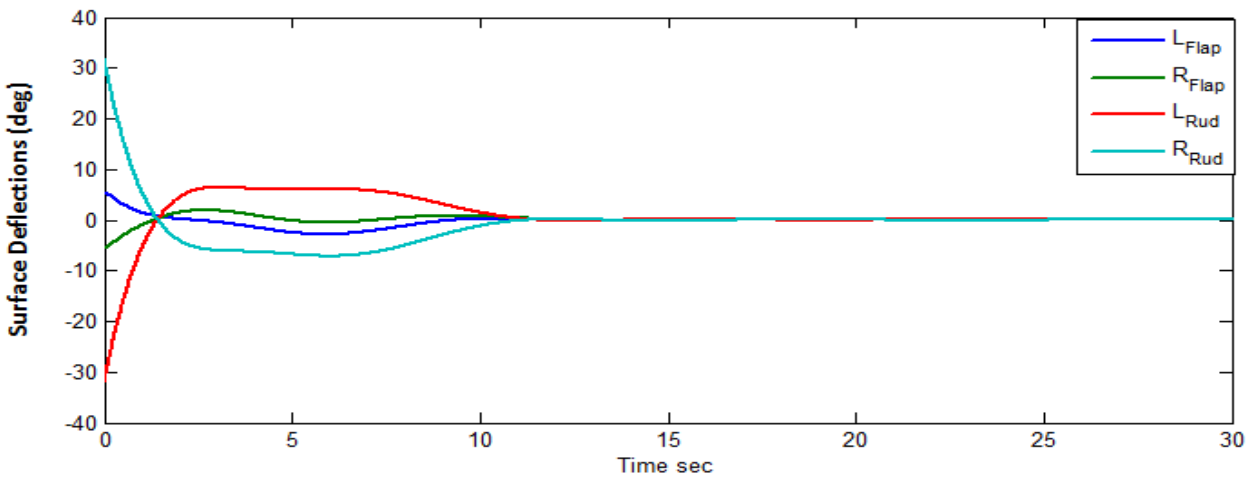
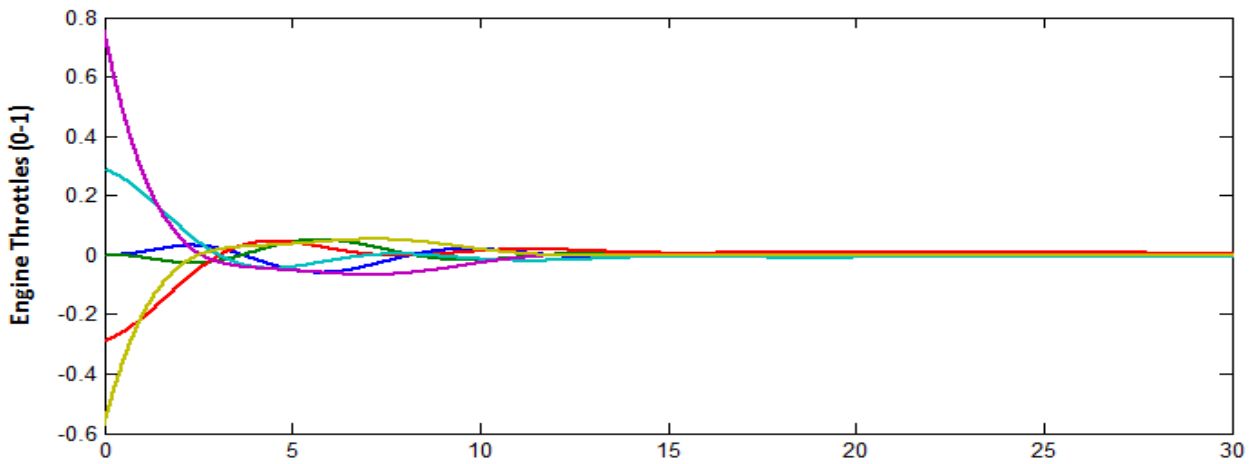
In this case the vehicle is initially commanded to perform a 30° roll maneuver about its velocity vector V_0 . The vehicle performs the roll maneuver in 7 sec, using a combination of aero-surfaces and RCS. The peak transient in beta is about 1.6°. The roll and yaw body rates are both responding to the ϕ -stability command. Both the RCS and the aero-surface control systems are equally contributing towards the maneuver, the RCS by differential throttling and the surfaces by differential deflections (mainly the 2 rudders). The steady bank angle also causes a steady cross-range velocity.



Re-Entry Vehicle Simulat at T=450 sec, $\Phi_{cmd}=30$ (deg), No Gust



Re-Entry Vehicle Simulat at T=450 sec, $\Phi_{cmd}=30$ (deg), No Gust



Stability Analysis

The Simulink model used for analyzing stability in the frequency domain is "Anal_6Dof.mdl", shown in Figure (1.5.4). This model is similar to the simulation except that it allows the user to open one loop at a time and to calculate the frequency response (with the other loops closed). The Matlab file "anal.m" uses this Simulink model to calculate the frequency response of the system across the open input and output and it plots the Nichols, and Bode plots.

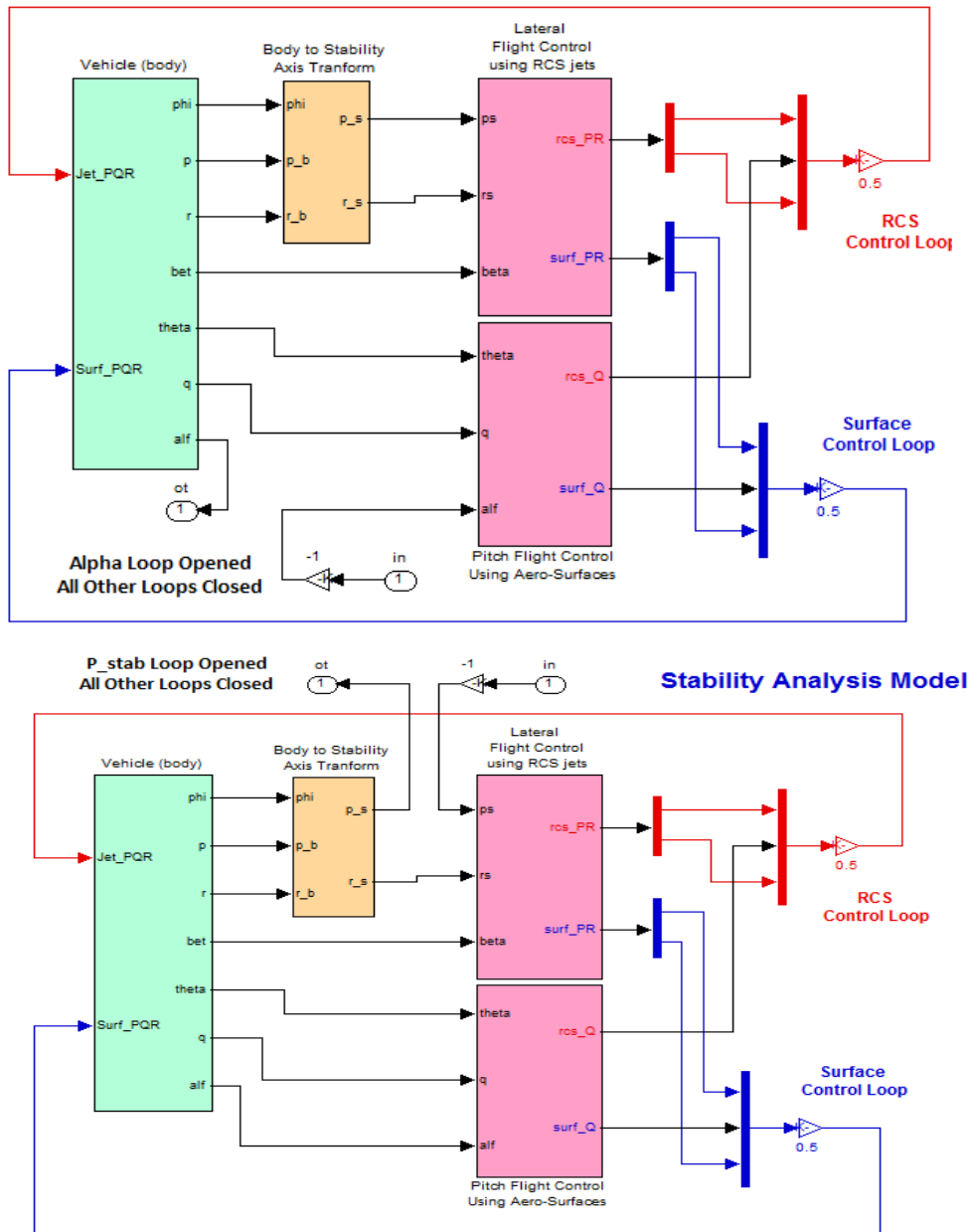
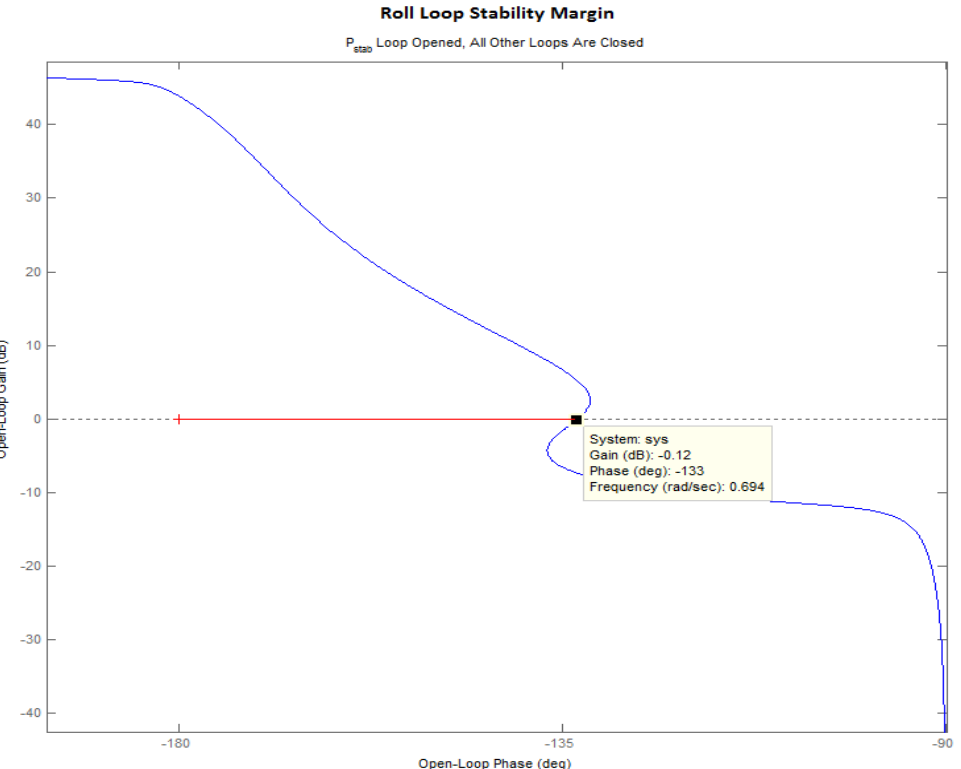
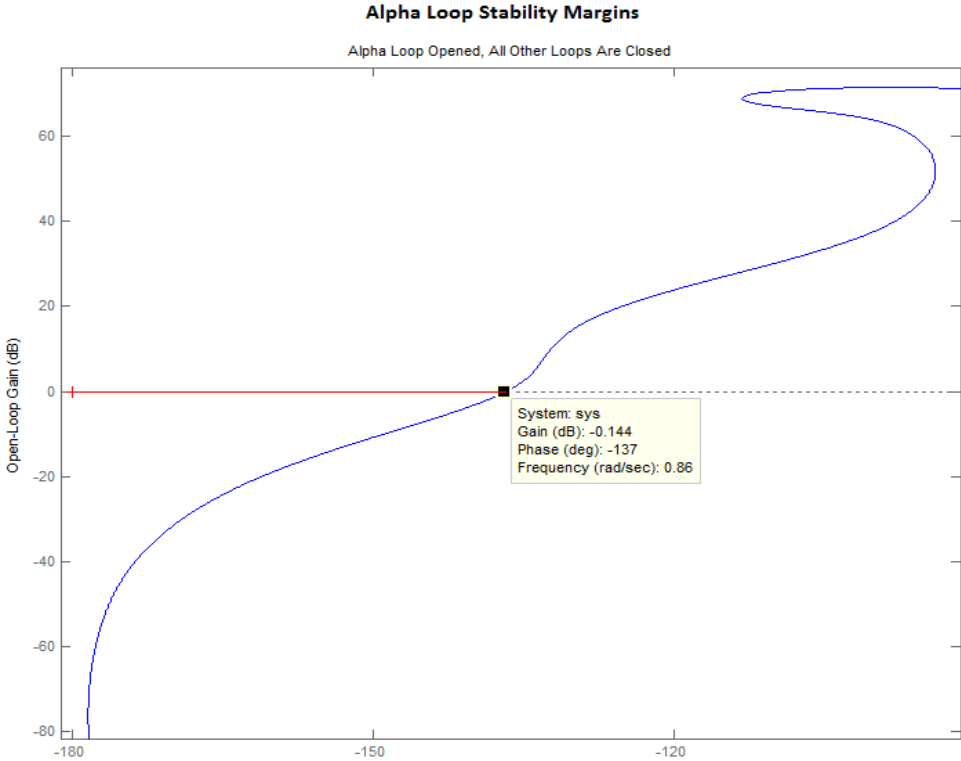


Figure 1.5.4 Simulink Model "Anal_6Dof.mdl" used for analyzing stability

The Figure (1.5.5) below shows the Nichols plots for the two control loops. They determine the phase and gain margins for dynamic stability. The first plot is calculated across the opened alpha loop and it shows the phase margin of the alpha-control loop. The second plot is calculated with the $p_{\text{stability}}$ loop opened and the alpha loop closed and shows the phase margin of the roll control loop.



2.0 Mid-Phase

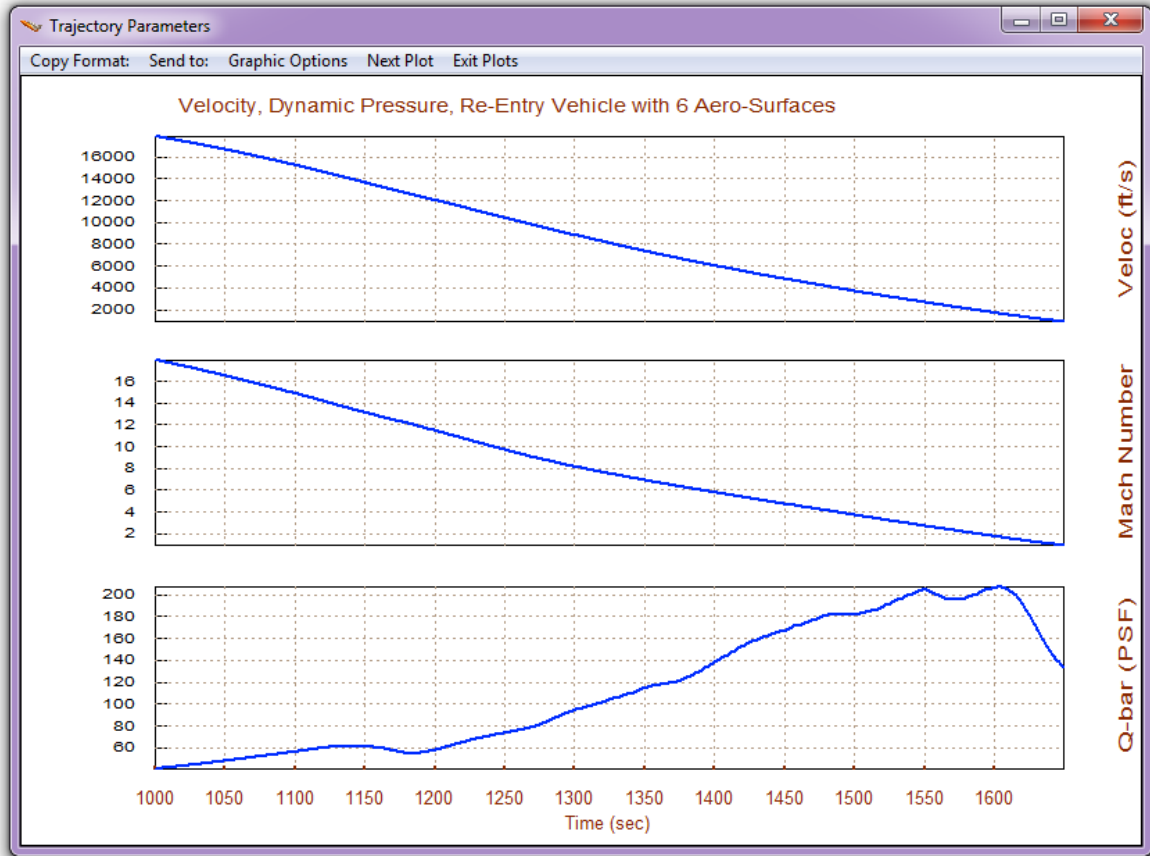
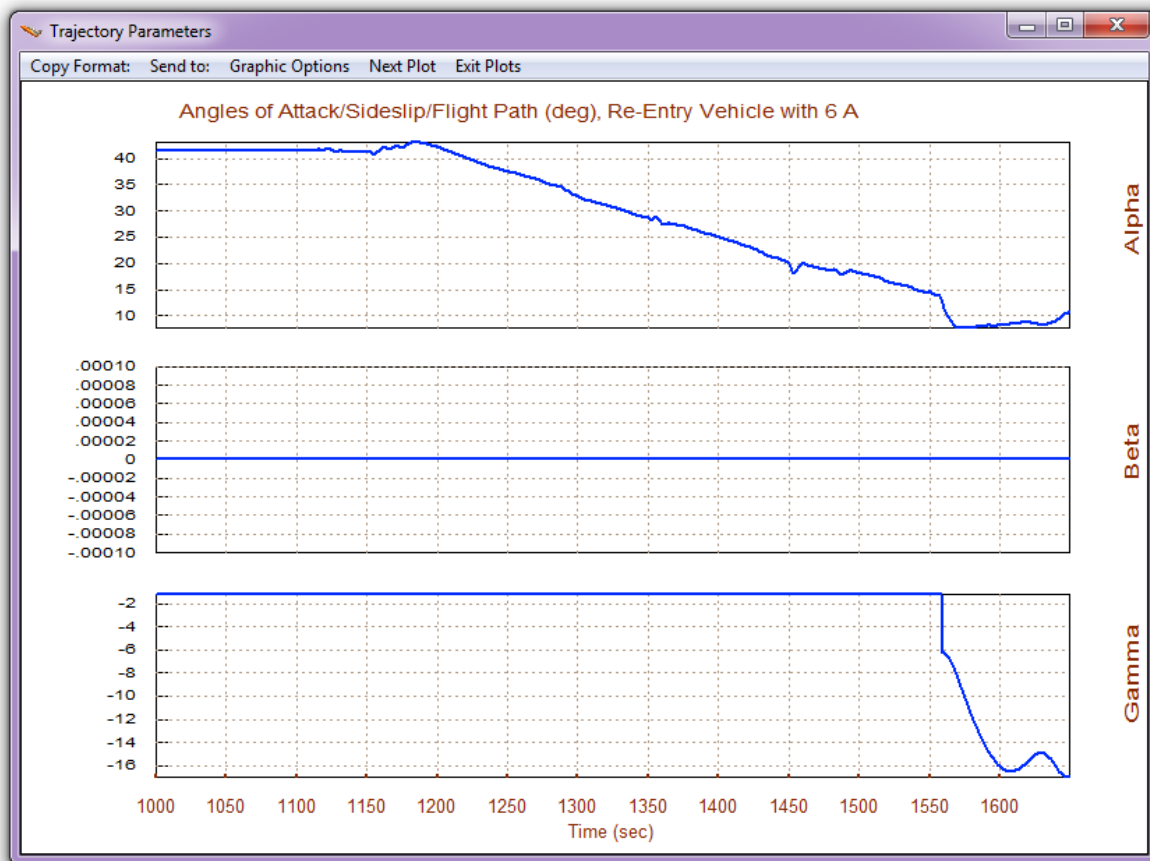
In the mid-phase of the entry trajectory the dynamic pressure is large enough to control the vehicle by using the aero-surfaces alone without any assistance from the RCS. There is an exception however, near the LCDP transitioning, where the RCS is necessary. Only the two Elevons, two Rudders, and the Body-Flap are used for trimming. The Speed-Brake is not activated during this phase because energy is dissipated by roll maneuvers about the velocity vector. Guidance commands the amount of rolling necessary in order for the vehicle to dissipate the excess kinetic energy, arrive at the alignment circle with the proper speed and altitude, perform a roll maneuver, and to align itself with the runway. The aerosurfaces are scheduled open-loop by the flight control system as a function of speed and angle of attack and their positions are determined from the trim analysis. The flight control feedback commands are superimposed on the scheduled positions. The body-flap, however, is not used for flight-control but it is scheduled open-loop. Prior to reentry the vehicle fires its orbital maneuvering engines to slow down and it begins to fall towards the earth. The descent flight path angle is initially maintained at $\gamma=-1.2^\circ$. The angle of attack is initially controlled at steady 41° as in the previous phase in order to protect the vehicle from aero-heating. It is gradually reduced to approximately 10° towards the end of the mid-phase. The flight path angle is also coming down steeper at $\gamma=-16^\circ$ to maintain high speed as it approaches Mach 2 and the dynamic pressure increases to 200 psf.

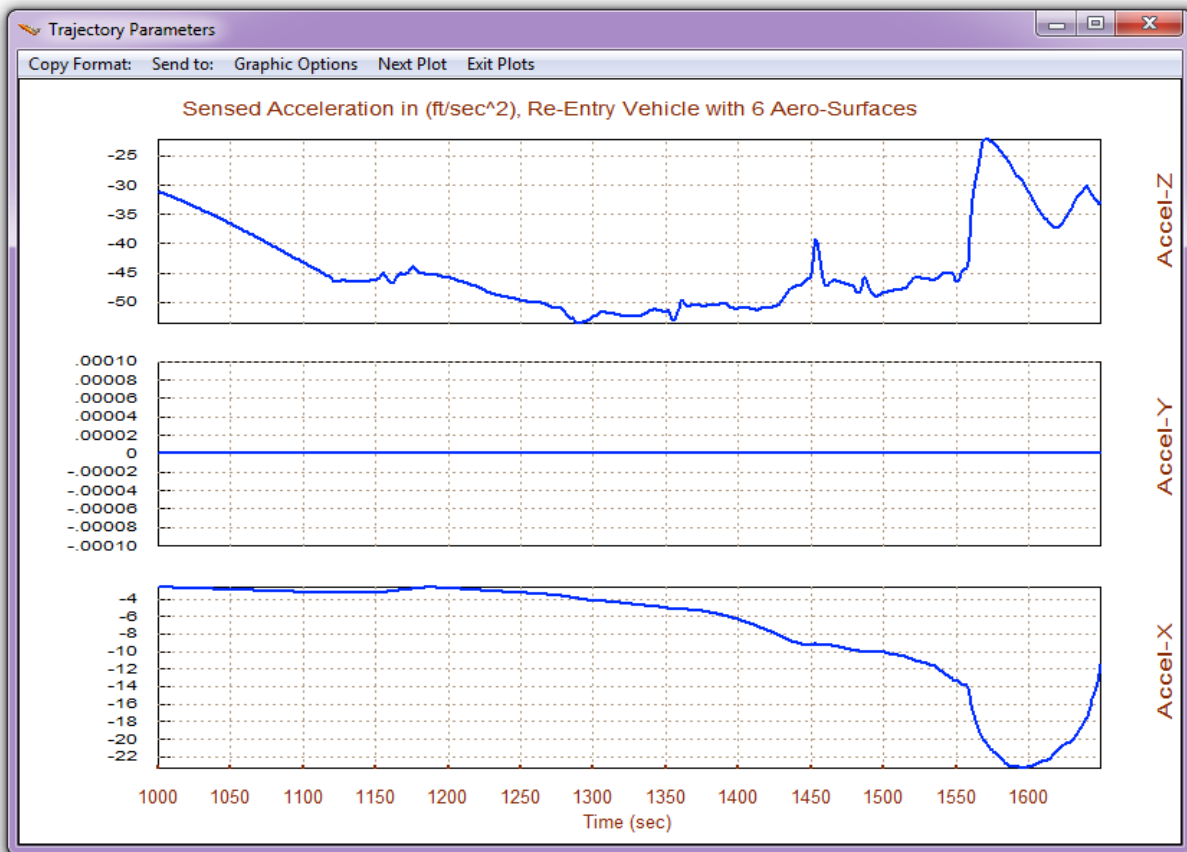
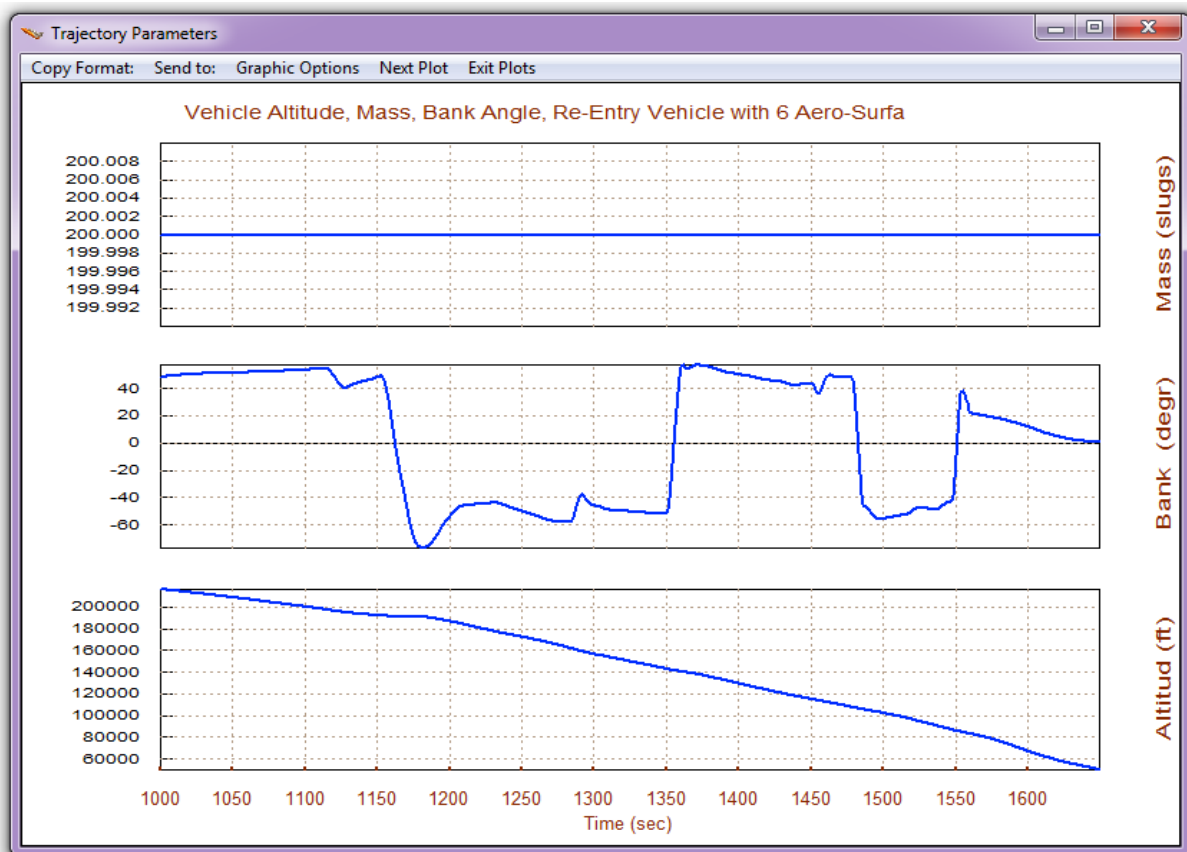
During most of the flight and mainly in the high Mach and high alpha regions the LCDP ratio is negative and it does not change much. This requires reversal in the roll control. As the vehicle transitions to smaller angles of attack, the LCDP ratio changes sign a few times and $C_n\beta$ -dynamic becomes negative. This changing in the LCDP ratio indicates that we cannot rely on the ailerons for roll control during this period and that we must also use RCS. Negative values of $C_n\beta$ -dynamic indicate lack of directional stability and the RCS is also required for yaw control during this period. This is because the terms (ω_ϕ) and (ω_D) in the transfer function that relates roll acceleration per roll control become uncertain and in the steady-state it may become unstable or change sign.

$$\frac{\dot{p}(s)}{\delta_{P_{FCS}}(s)} = \frac{L_{\delta p}}{I_{XX}} \left\{ \frac{s^2 + \omega_\phi^2}{s^2 + \omega_D^2} \right\} \quad \text{where}$$

$$\omega_\phi^2 = \frac{\cos \alpha_o}{I_{ZZ} L_{\delta p}} [N_\beta L_{\delta p} - L_\beta N_{\delta p}] \quad \text{and} \quad \omega_D^2 = \left[\frac{N_\beta \cos \alpha_o}{I_{ZZ}} - \frac{L_\beta \sin \alpha_o}{I_{XX}} \right]$$

A solution to the problem during this uncertain transitioning period is to activate the reaction control jets as an outer loop around the aileron and rudder loops. The data files for this mid-phase analysis are in directory "*C:\Flixan\Trim\Examples\Re-Entry Glider\Middle Phase*". The following figures show the trajectory variables versus time during the mid-phase period.



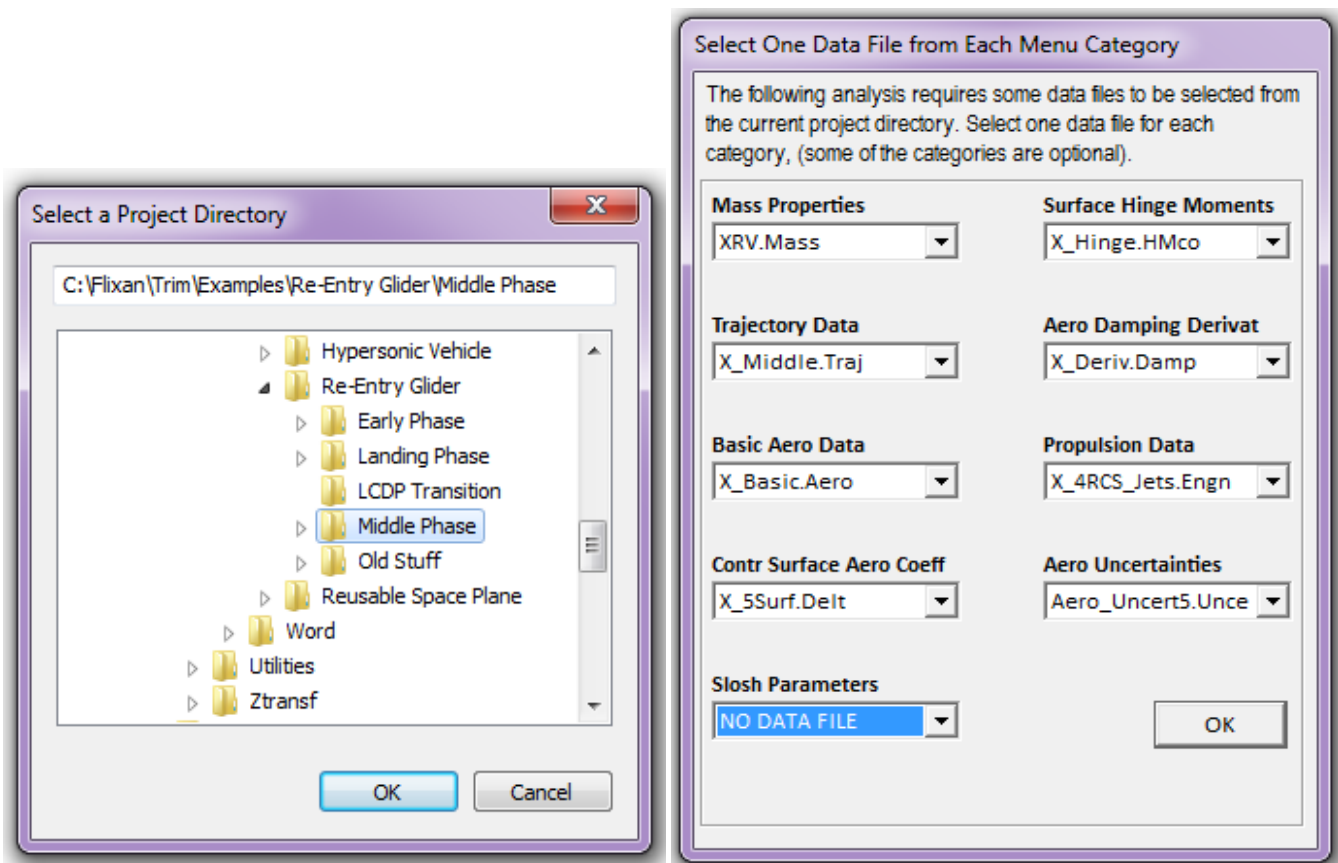


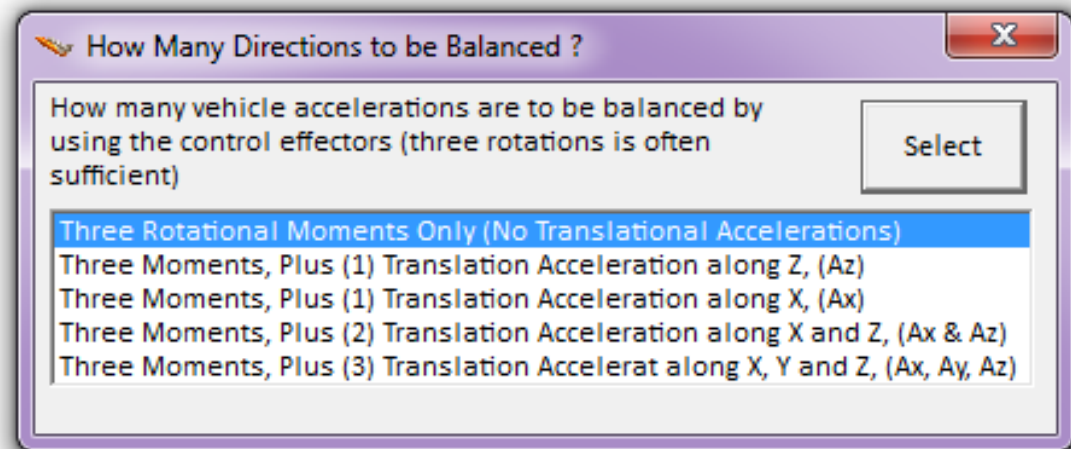
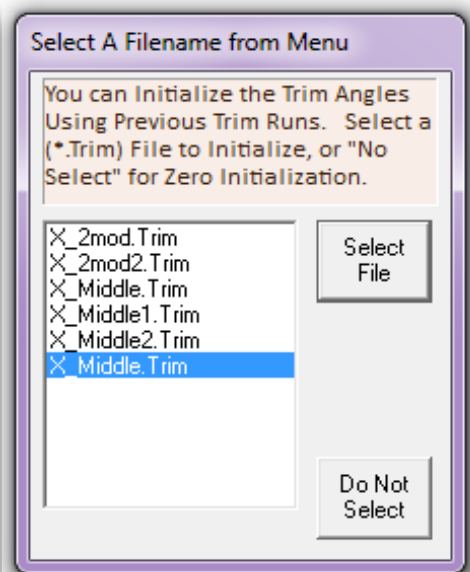
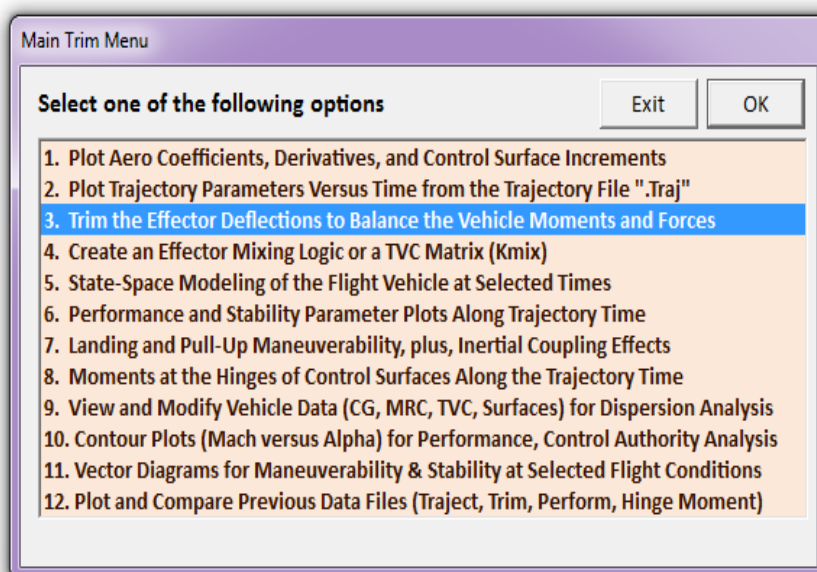
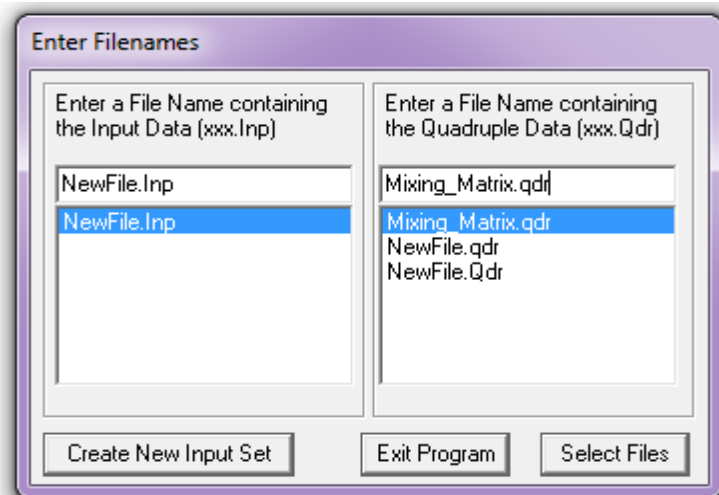
2.1 Mid-Phase Trimming

Trimming allows us to obtain open-loop scheduling commands for the aerosurfaces as a function of time. When the vehicle has multiple effectors there is a trade of possibilities that can be explored to optimize controllability, performance, and fuel efficiency. Flight control feedback provides additional deflections for vehicle stabilization, guidance, and reacting against wind disturbances.

Start the Trim program and select the mid-phase folder. From the filenames selection menu select the mid-phase trajectory file "X-Middle.Traj". The file "X_4RCS_Jets.Engn" contains four jets that will be assisting the surfaces in roll/yaw control. Although the surfaces alone are capable of trimming the moments the jets are included to improve lateral controllability. Plus the jets also need to be included in the dynamic models. In the aero-data files only the first 5 surfaces are included instead of 6. The speed-brake is not read. The Body-Flap is biased at -10° in the aero-coefficients file.

In the second filename selection menu make sure that you include the systems file "Mixing-Matrix.Qdr" which includes the aero-surface/RCS combination logic. It will be used in the up-coming sections. Do not select an initialization file for trimming, and in the menu that selects the directions to be balanced select the first option (3 moments only). Since the speed-brake is disabled and alpha is high, we do not have any axial or Nz control. Therefore, we must only trim the moments and not attempt to trim any axial or Nz forces.





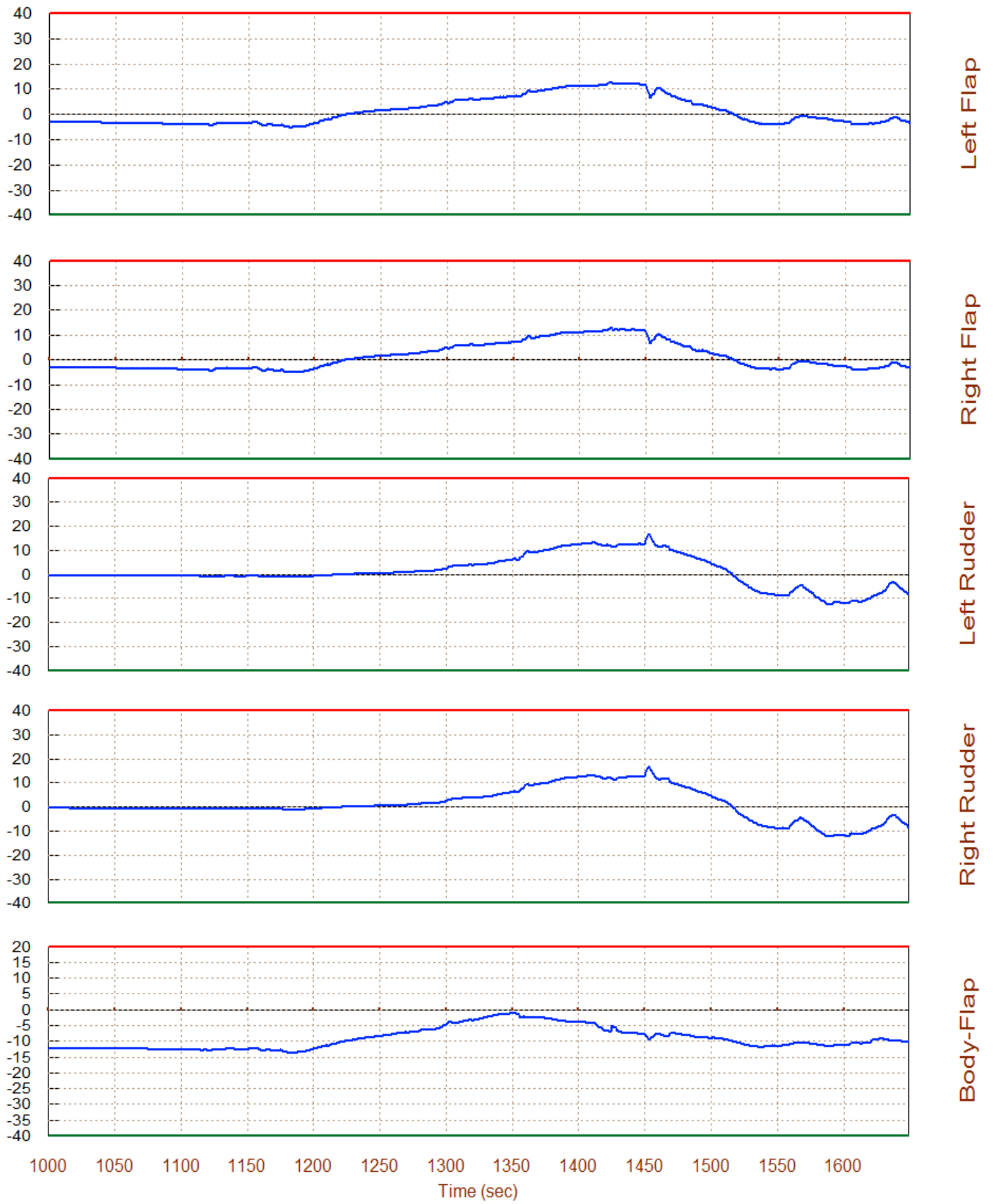
Surface & Engine Deflections/ Thrusts, Re-Entry Vehicle with 6 Aero-Surfaces



Notice that there is no throttling in the four jets. This is because the Y_{CG} was set to zero and, therefore, there is no need for trimming in the roll and yaw directions. Therefore, the roll and yaw are zero.

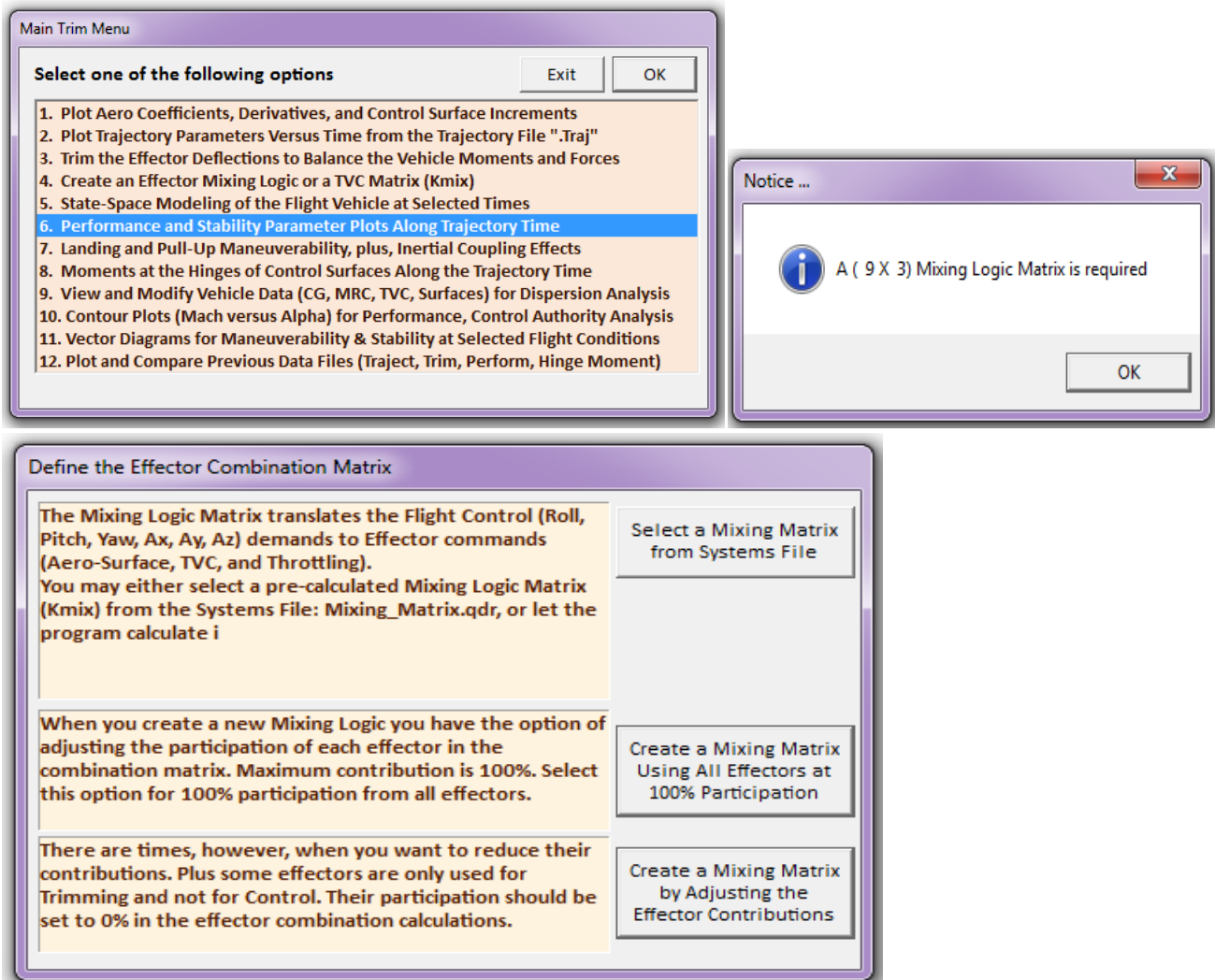
The positions of all 5 control surfaces vary as a function of the flight condition. Biasing the body-flap in the aerosurfaces file helps the other four aerosurfaces begin their trimming positions closer to zero.

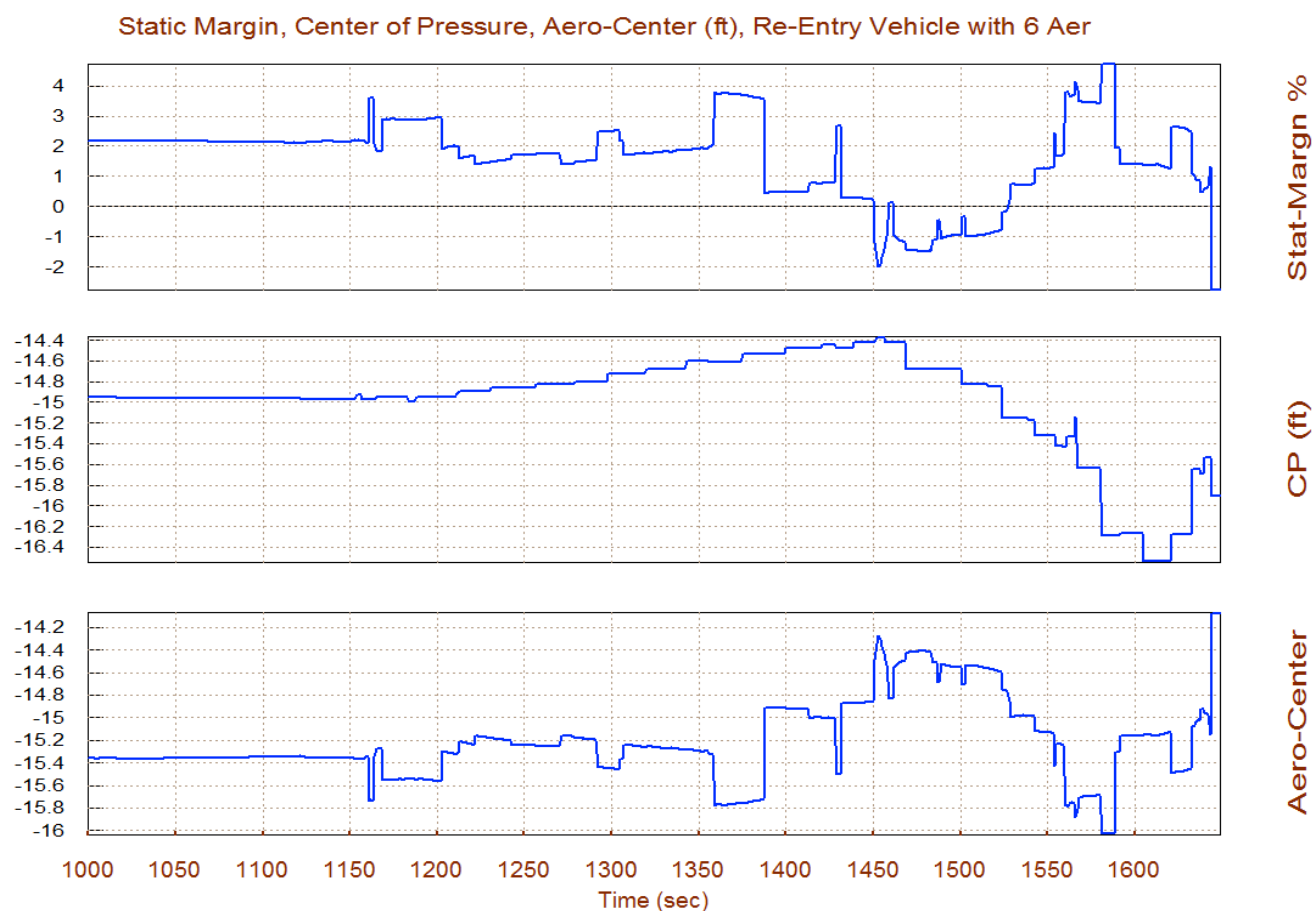
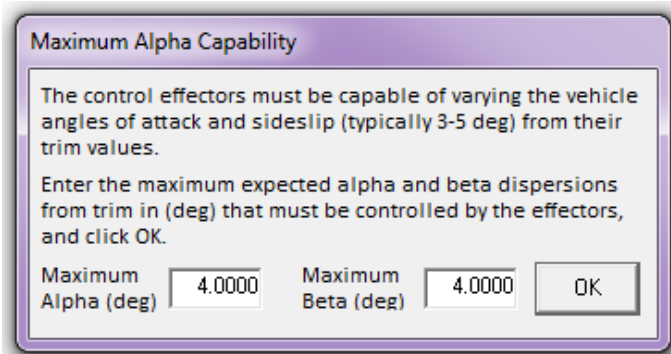
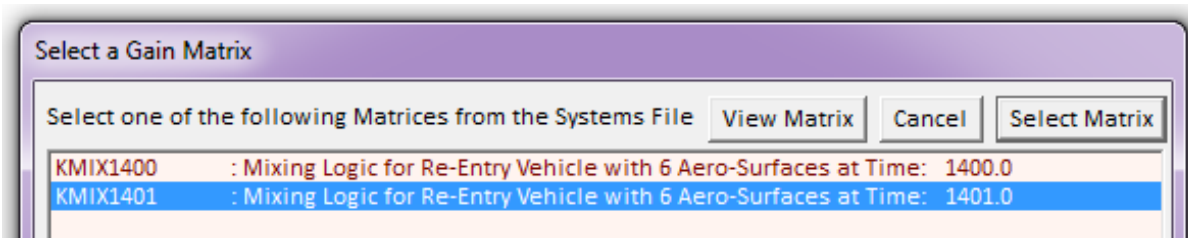
Surface & Engine Deflections/ Thrusts, Re-Entry Vehicle with 6 Aero-Surfaces



2.2 Performance Analysis along Trajectory

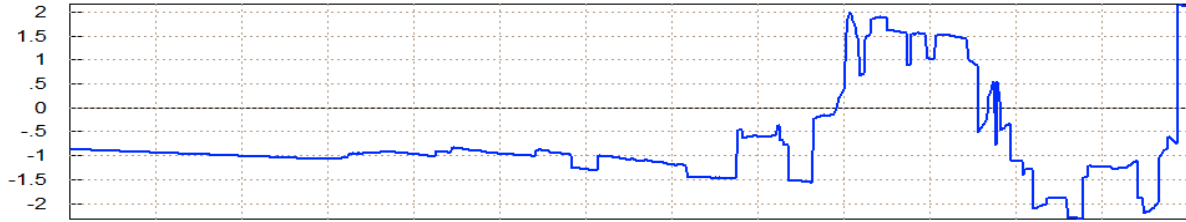
We will now analyze some critical performance parameters along the mid trajectory. Performance analysis requires knowledge on how the RCS and aero-surfaces combine together to provide the control moments. This information is included in the mixing-logic. This time we will not let the program calculate the mixing logic matrix because the LCDP ratio parameter is too small using this algorithm. Instead, we will use a pre-calculated constant matrix that allocates more authority to the rudders (differential deflection) and less authority to the two flaps in comparison with the matrix generated by the program which tends to use more differential flaps than differential rudders. The modified aerosurface/RCS combination ratio increases the magnitude of the LCDP, even though it is negative that implies reversal in the roll gain. This is acceptable, however, as long as its magnitude is not too small and it does not change too much. But it changes sign several times near the end of the mid-phase, and for this reason we must heavily rely on the RCS for stabilization in that period. From the Trim main menu select option (6) and in the mixing-logic matrix dialog click on the top option to "Select a Mixing Matrix from Systems File" to read the matrix from file "Mixing-Matrix.Qdr", and then select the second matrix from the menu, as shown. Enter also the maximum dispersion angles α_{max} and β_{max} .



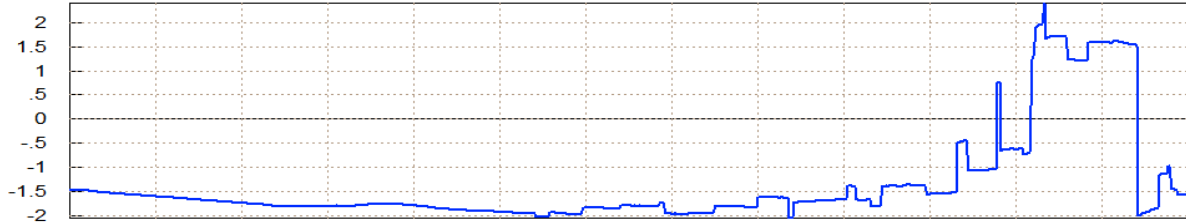


At flight times greater than 1500 seconds directional stability deteriorates significantly, $C_n\beta$ -dynamic becomes negative, and the LCDP ratio switches between negative and positive several times. This situation is not reliable for aileron and rudder control, and during this time period RCS is required.

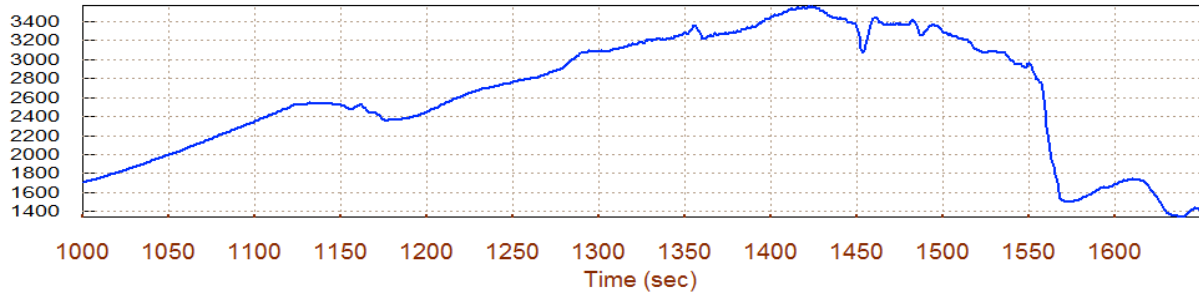
Short-Period (w/ Time-to-Double-Ampl-Inverse (/sec), Q_alpha_beta (deg-lb/ft^2)



Ptch T2-inv

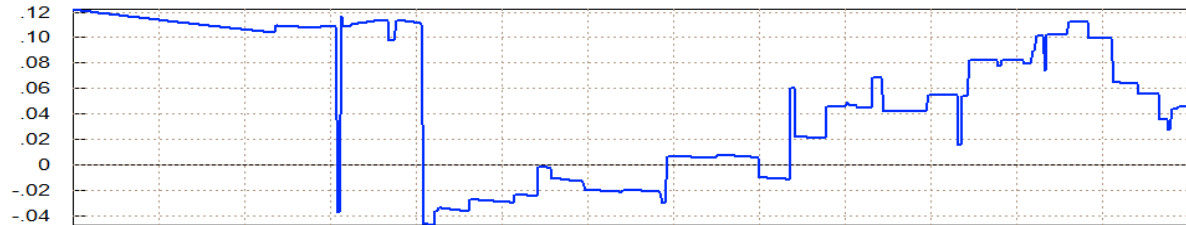


Yaw T2-inv

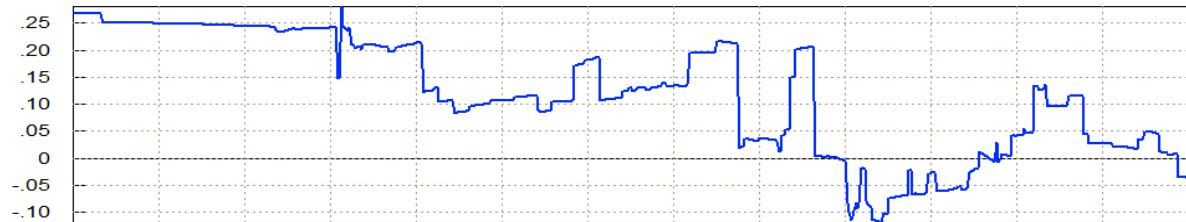


Q_alpha_beta

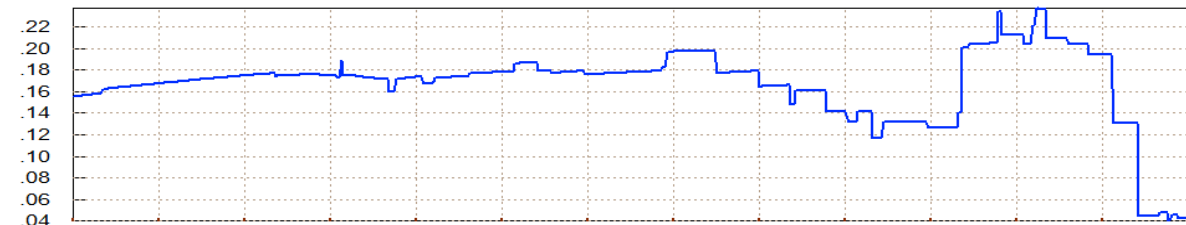
Rotation Control Authority (dQ/dQmax)<1 for 4 (deg) of Alpha & Beta Variation



Roll Effort

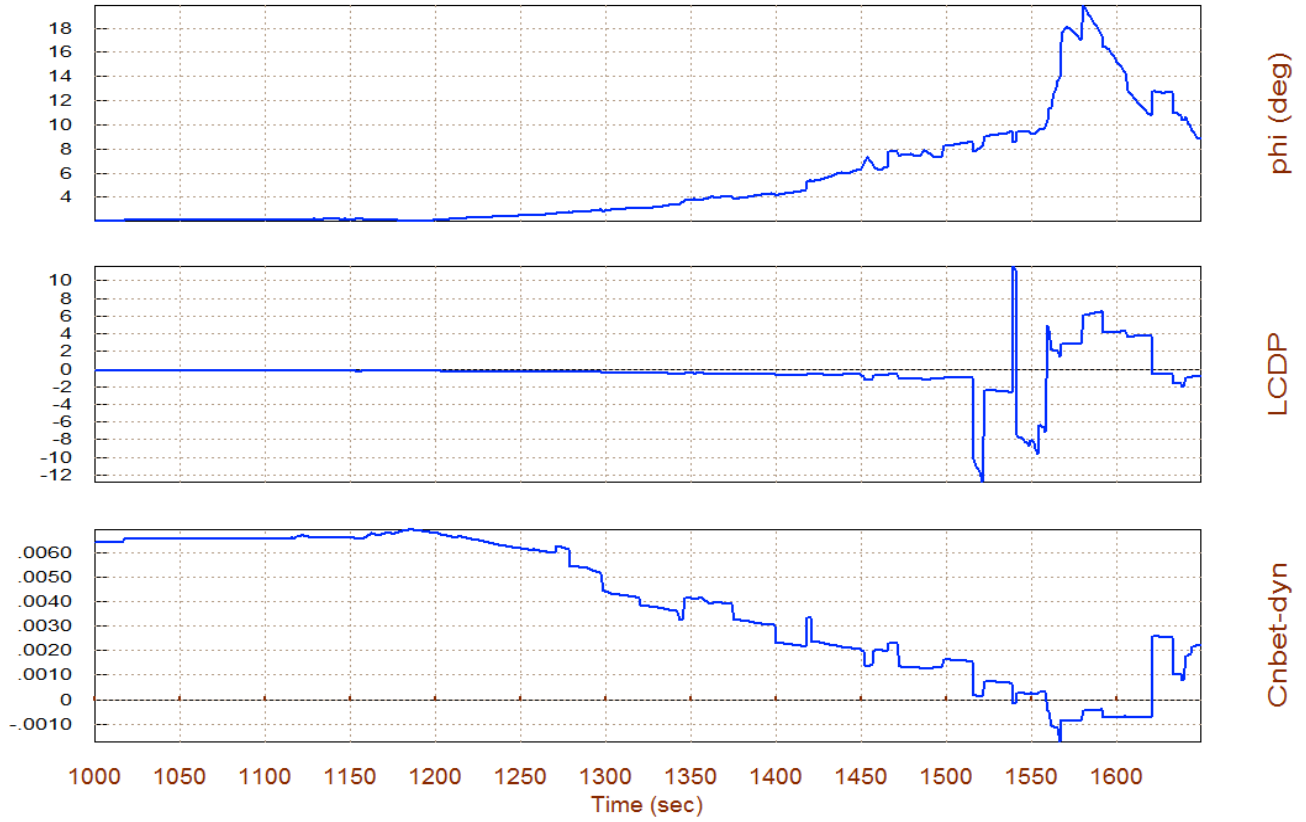


Pitch Effort

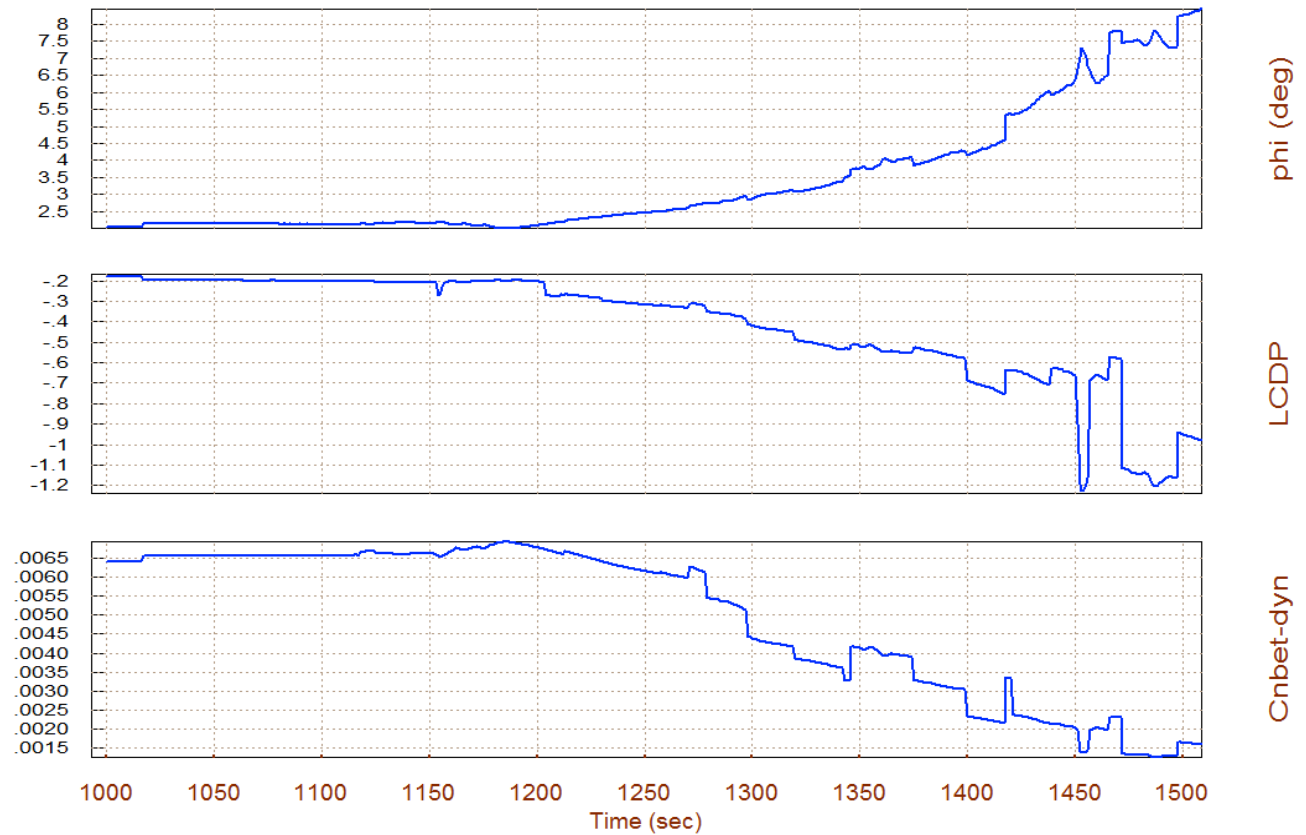


Yaw Effort

Bank Angle, LCDP Ratio, Cn_beta_dynam /deg, Re-Entry Vehicle with 6 Aero-Surface

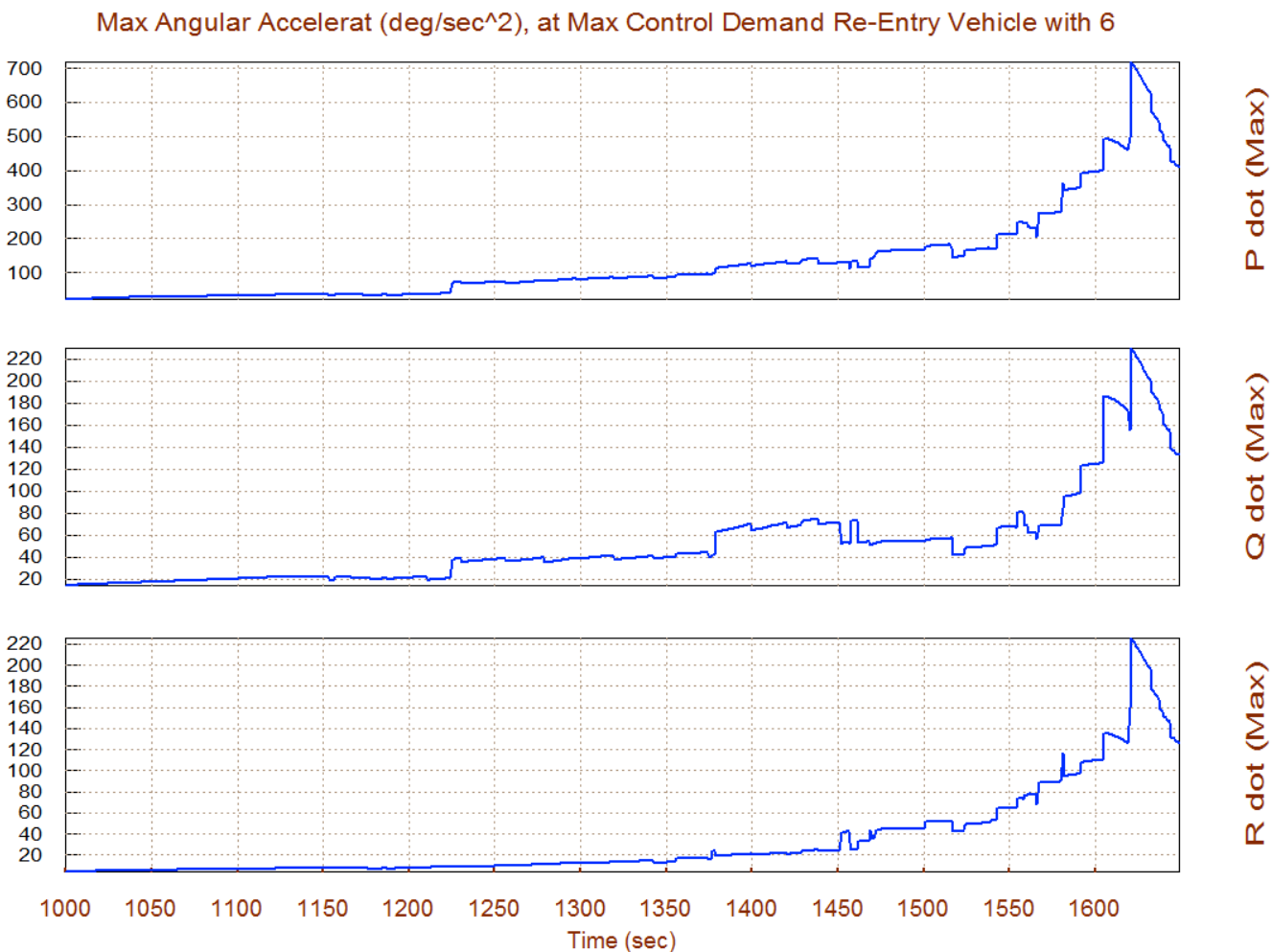


Bank Angle, LCDP Ratio, Cn_beta_dynam /deg, Re-Entry Vehicle with 6 Aero-Surface



The stability parameter (T2-inverse) that measures static-stability or time-to-double amplitude is initially negative in both: pitch and lateral directions. It means that they are both stable with short-period and Dutch-roll resonances at around 1.5 (rad/sec). Later on they become positive and change signs a few times. When unstable, however, their time-to-double amplitude is not shorter than 0.5 second. The (Q-alpha, Q-beta) loading parameter peaks at about 3,500 (psf-deg). The control authority is very good. The effort is less than 0.5 in all 3 directions. It means that wind-shear dispersions due to $(\alpha_{max}$ and $b_{max})=4^\circ$ do not saturate the controls, plus they have additional 50% control to spare.

The LCDP ratio begins at -0.2 and it remains negative for a long period. Then towards the end of the mid-trajectory it changes sign a few times. The Cn-beta-dynamic parameter also becomes negative towards the end which implies directional instability. The bank angle (phi) in the presence of a wind-shear due to (β_{max}) is not applicable here. It is only meaningful near landing. The following plot shows the max accelerations achieved in roll, pitch, and yaw when the controls are maximized.



2.3. Contour Plots Analysis

Now let us take a look at some key performance parameters using contour plots that allow us to have a broader perspective of vehicle performance over the entire Mach versus Alpha range. In general, the mixing logic matrix generated by the Flixan algorithm optimizes the control authority of the effector system, but it does not necessarily optimize all vehicle performance parameters. Sometimes we may have to trade-off between performance parameters, as we shall see in this case. Let us first analyze the contour plots performance by letting the program calculate its own mixing-logic matrix and then use a pre-calculated matrix from file "*Mixing_Matrix.qdr*" and repeat the analysis. Make sure that this matrix file is selected when you start Flixan. From the Trim menu select option (10) and from the dialog that selects an effector combination matrix select the third option to allow the program create a mixing matrix with adjustable contributions from each effector. Use the menu on the right to set zero participation for the 4 thrusters and also the body-flap, since the body-flap is only used for trimming and not flight control. We removed the jets because we want to check the vehicle performance using only aerosurfaces. Then click on the button in the upper right hand corner to continue.

Enter Filenames

Enter a File Name containing the Input Data (xxx.Inp)

Enter a File Name containing the Quadruple Data (xxx.Qdr)

NewFile.Inp
T1550.Inp
NewFile.Inp

Mixing_Matrix.qdr
Mixing_Matrix.qdr
NewFile.qdr
T1550.Qdr
NewFile.Qdr

Create New Input Set Exit Program Select Files

Main Trim Menu

Select one of the following options

Exit OK

1. Plot Aero Coefficients, Derivatives, and Control Surface Increments
2. Plot Trajectory Parameters Versus Time from the Trajectory File ".Traj"
3. Trim the Effector Deflections to Balance the Vehicle Moments and Forces
4. Create an Effector Mixing Logic or a TVC Matrix (Kmix)
5. State-Space Modeling of the Flight Vehicle at Selected Times
6. Performance and Stability Parameter Plots Along Trajectory Time
7. Landing and Pull-Up Maneuverability, plus, Inertial Coupling Effects
8. Moments at the Hinges of Control Surfaces Along the Trajectory Time
9. View and Modify Vehicle Data (CG, MRC, TVC, Surfaces) for Dispersion Analysis
10. Contour Plots (Mach versus Alpha) for Performance, Control Authority Analysis
11. Vector Diagrams for Maneuverability & Stability at Selected Flight Conditions
12. Plot and Compare Previous Data Files (Traject, Trim, Perform, Hinge Moment)

Define the Effector Combination Matrix

The Mixing Logic Matrix translates the Flight Control (Roll, Pitch, Yaw, Ax, Ay, Az) demands to Effector commands (Aero-Surface, TVC, and Throttling). You may either select a pre-calculated Mixing Logic Matrix (Kmix) from the Systems File: *Mixing_Matrix.qdr*, or let the program calculate it

When you create a new Mixing Logic you have the option of adjusting the participation of each effector in the combination matrix. Maximum contribution is 100%. Select this option for 100% participation from all effectors.

There are times, however, when you want to reduce their contributions. Plus some effectors are only used for Trimming and not for Control. Their participation should be set to 0% in the effector combination calculations.

Select a Mixing Matrix from Systems File

Create a Mixing Matrix Using All Effectors at 100% Participation

Create a Mixing Matrix by Adjusting the Effector Contributions

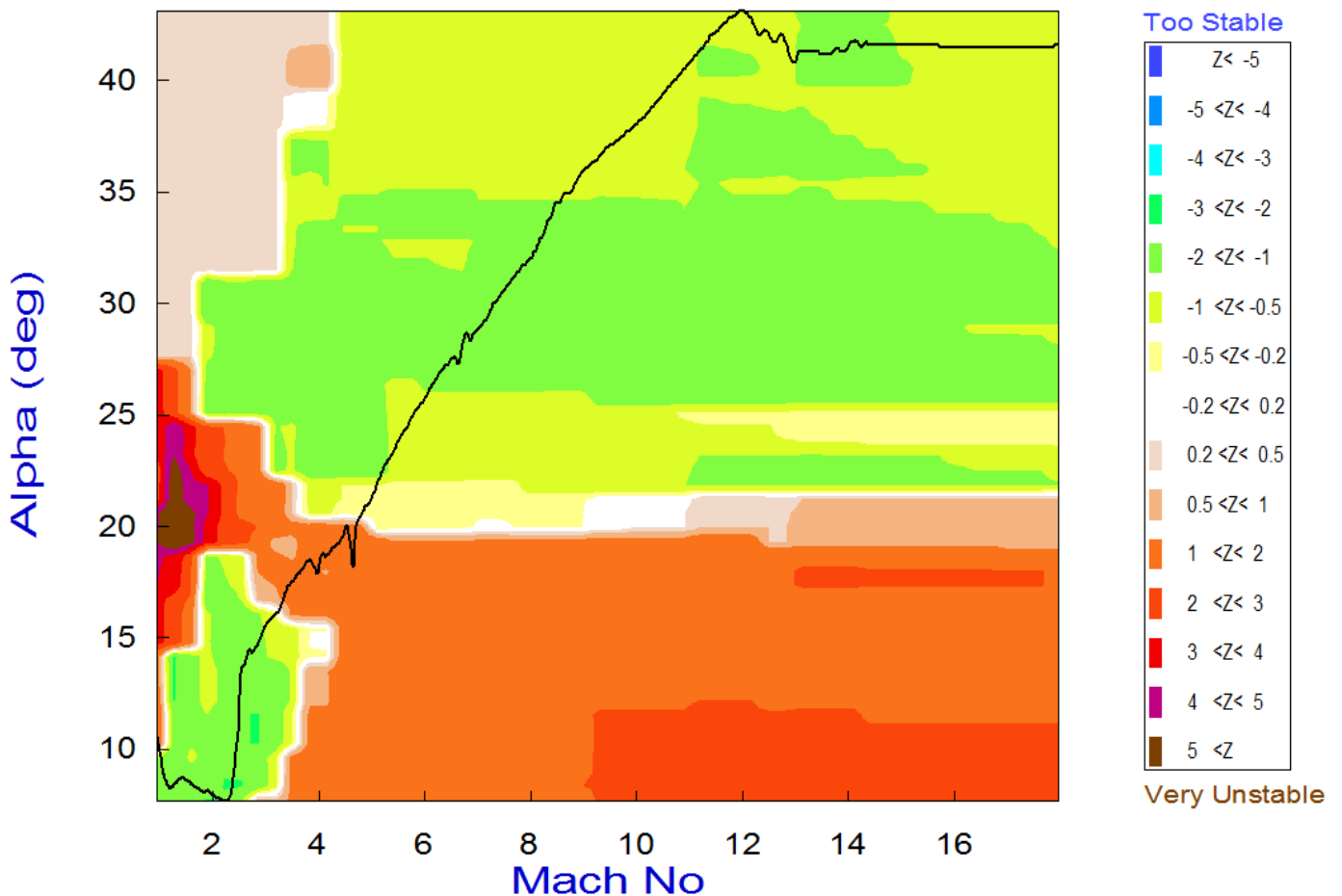
	Effector	Participation %
1	Throttle 1	0
2	Throttle 2	0
3	Throttle 3	0
4	Throttle 4	0
5	Left Flap	100
6	Right Flap	100
7	Left Rudder	100
8	Right Rudder	100
9	Body-Flap	0
10		
11		
12		
13		
14		

Adjust the Effectors Participation and Click Here

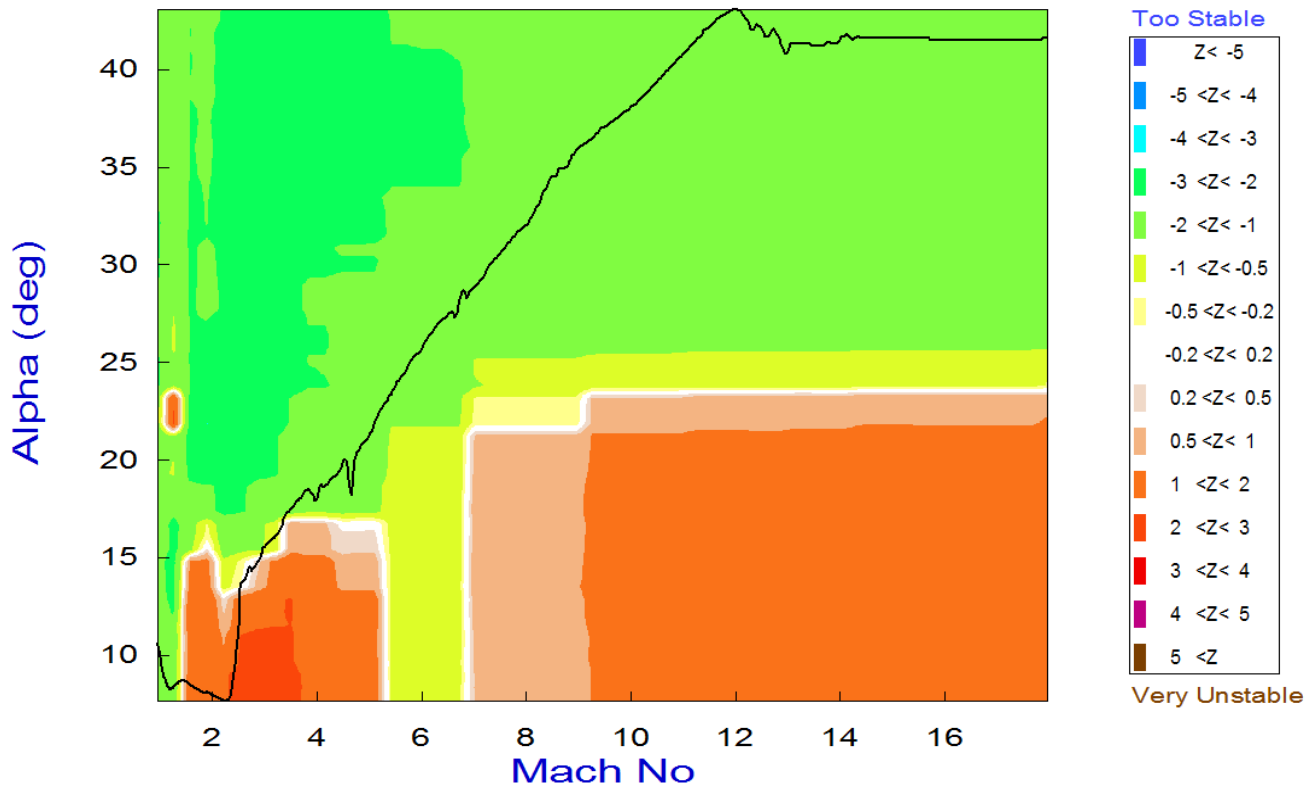
The first contour plot shows the pitch stability parameter (T2-inverse) versus Mach and alpha. The trajectory is shown by the black line that travels across the Mach versus alpha field. It begins in the upper right-hand side where both alpha and Mach are high and it ends near the lower left-hand corner at Mach 10. The trajectory passes through regions which are mostly stable, although it briefly crosses a mildly unstable region.

The second plot shows the lateral stability parameter (T2-inverse) where the results are similar. The third contour plot shows the LCDP ratio which does not look very good. It is red through most of the high Mach, high alpha region, which indicates a "sluggish" and uncertain roll controllability. The next three contour plots show the control authority in roll, pitch, and yaw, and they look very good in all 3 axes.

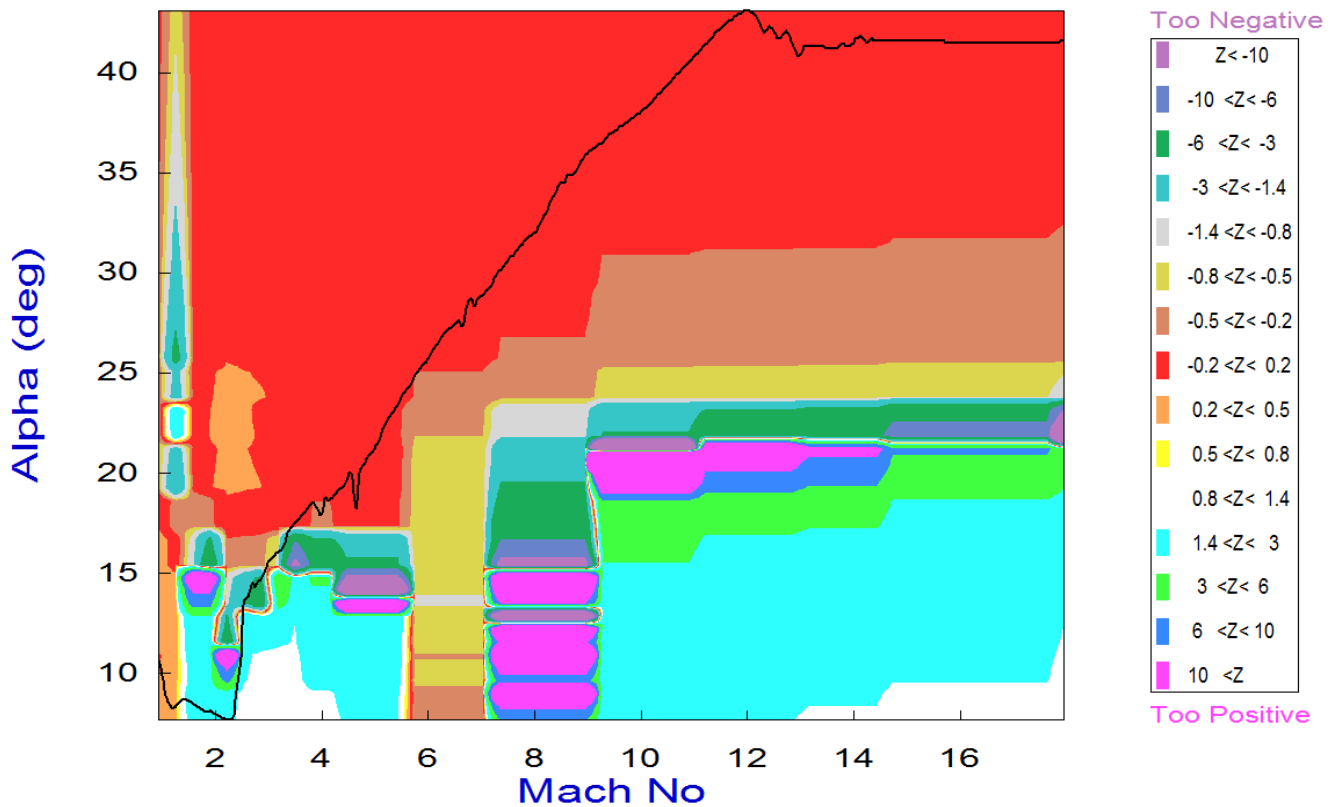
Pitch Stability Contour Plot (Mach vs Alpha)



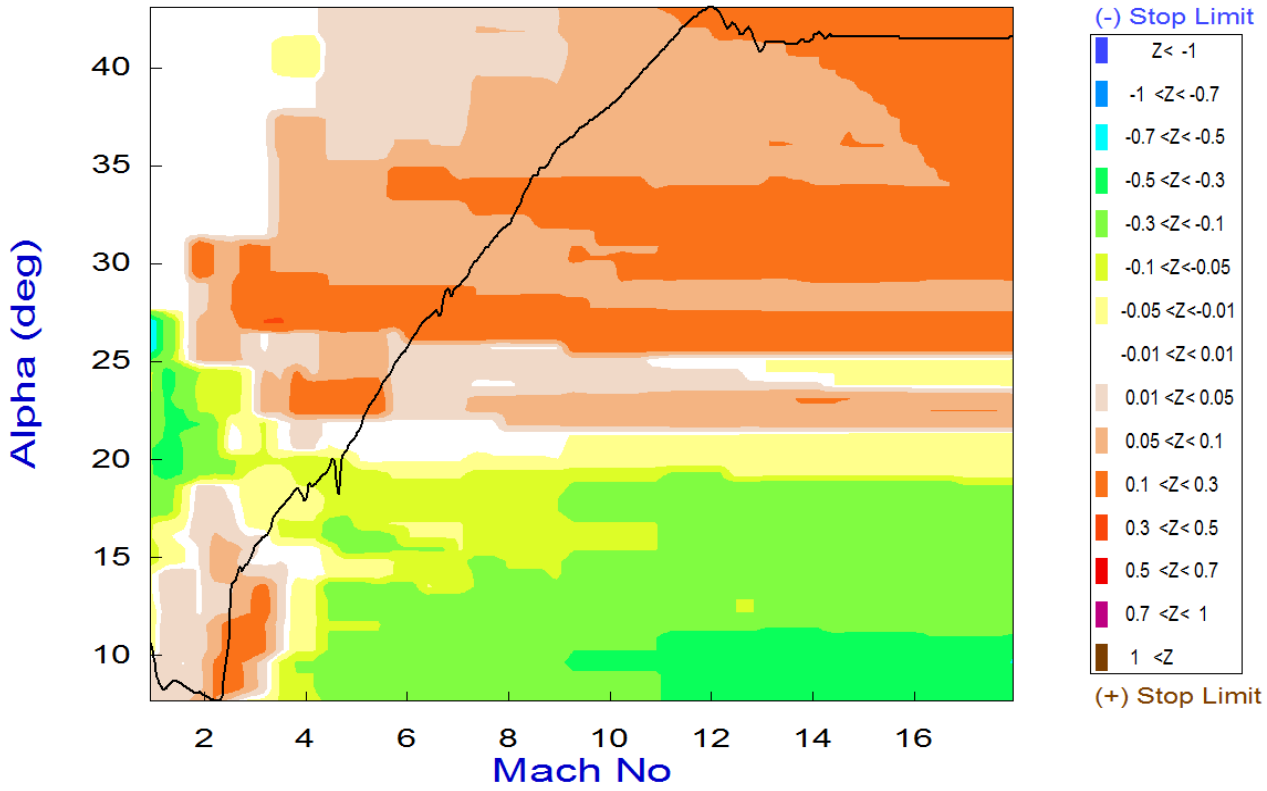
Lateral Stability Contour Plot (Mach vs Alpha)



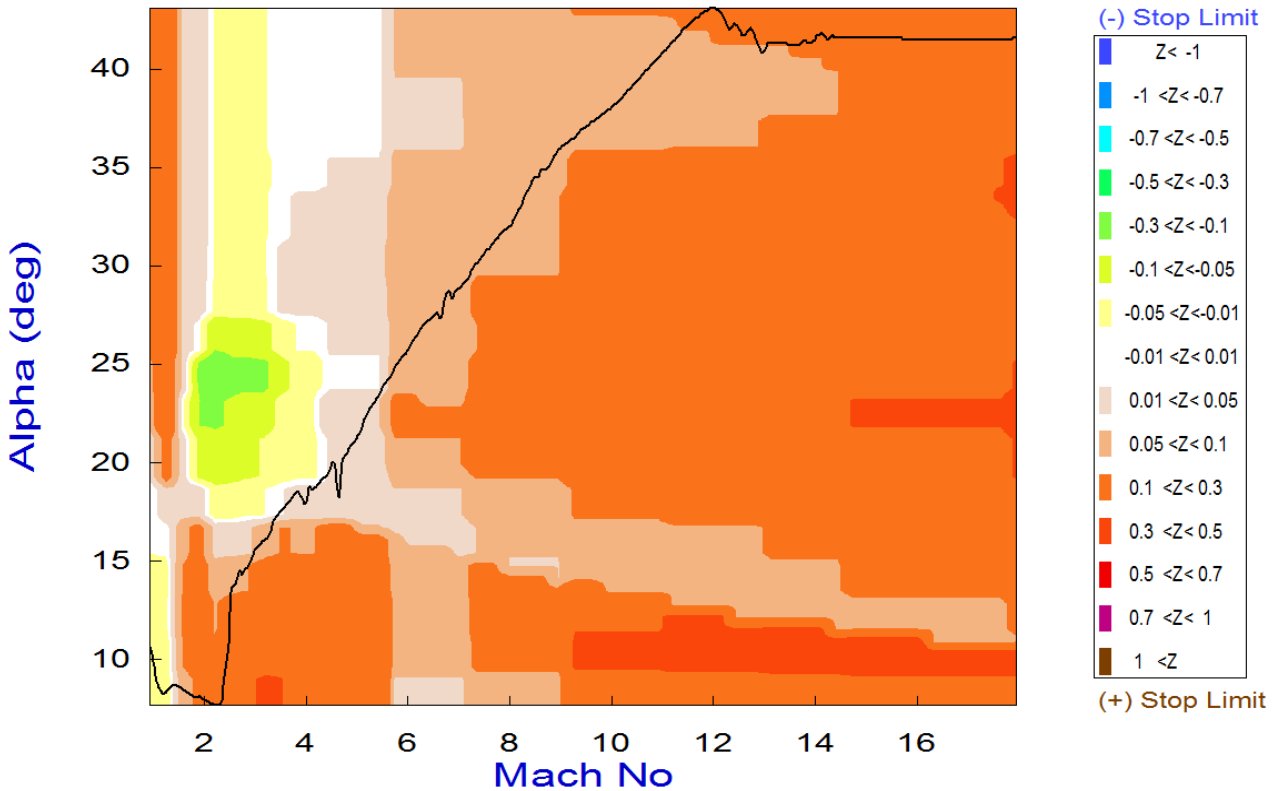
Roll Departure (LCDP) Contour Plot (Mach vs Alpha)



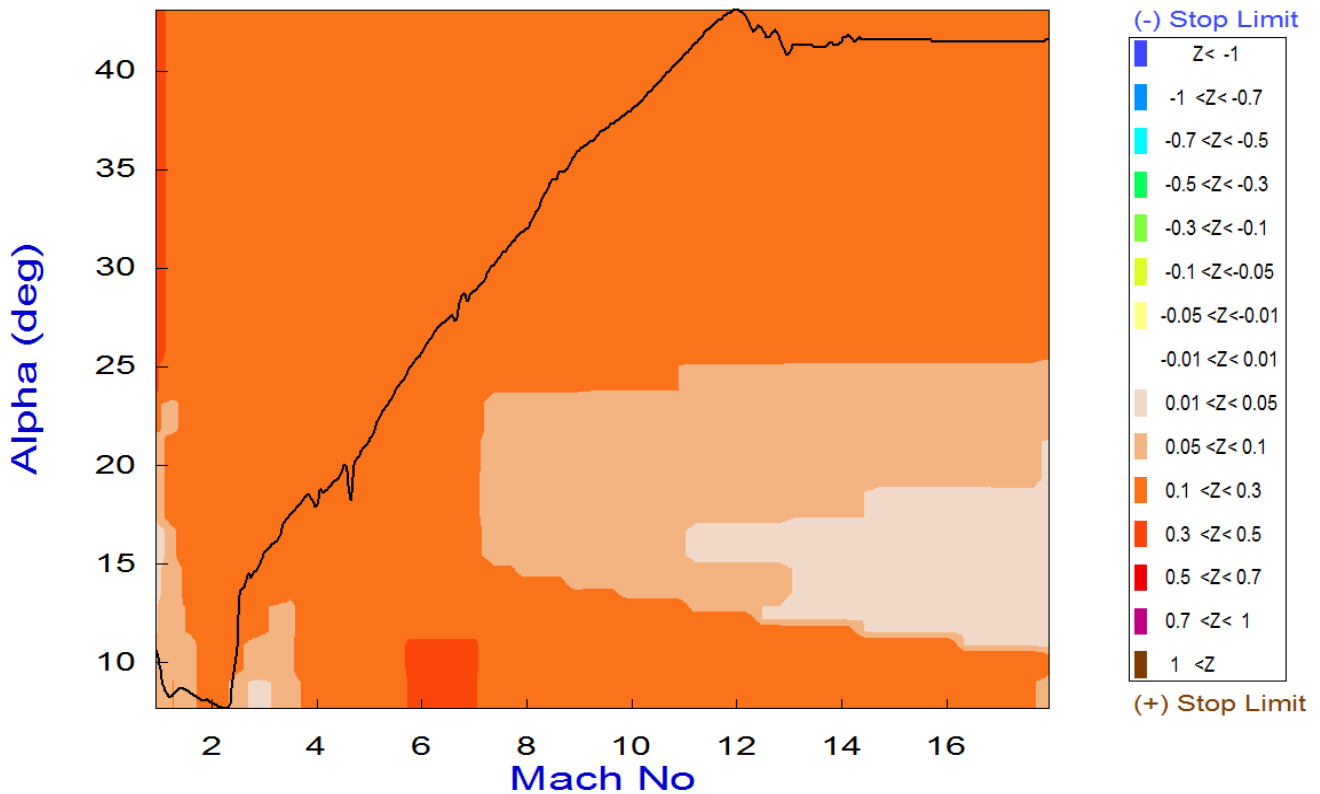
Pitch Control Effort Contour Plot (Mach vs Alpha)



Yaw Control Effort Contour Plot (Mach vs Alpha)

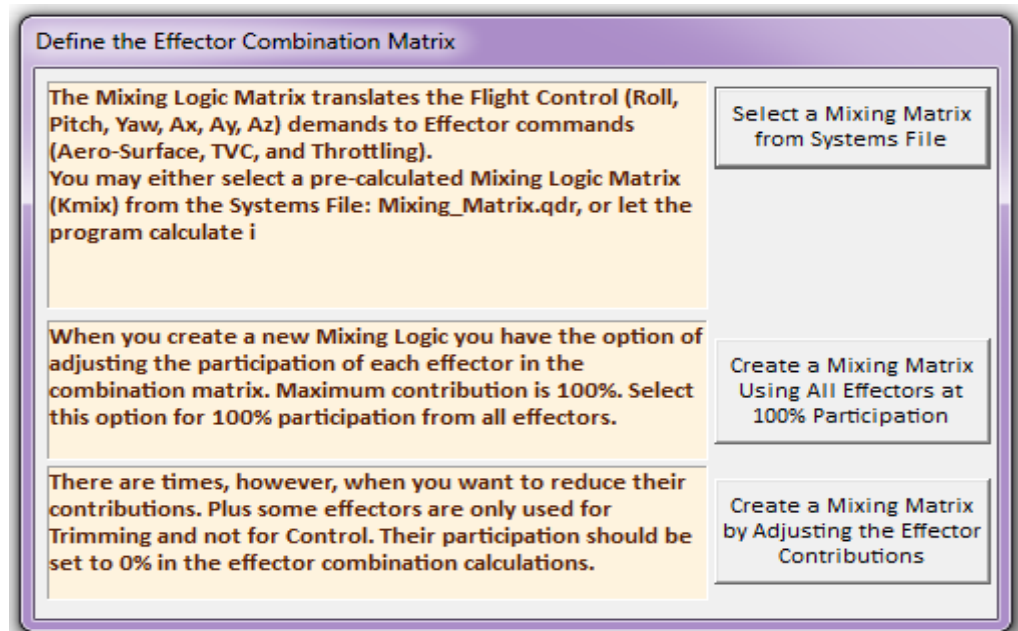


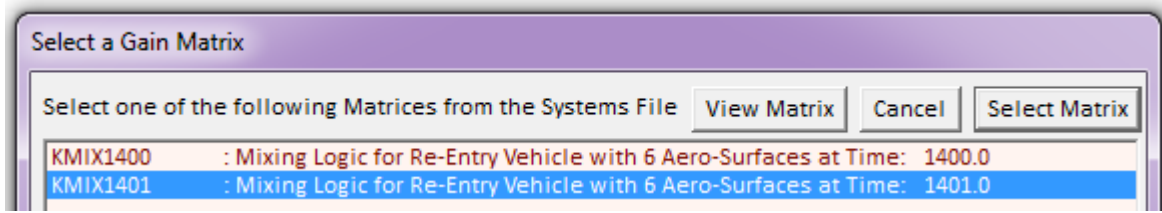
Roll Control Effort Contour Plot (Mach vs Alpha)



Using a Pre-Calculated Mixing-Logic Matrix

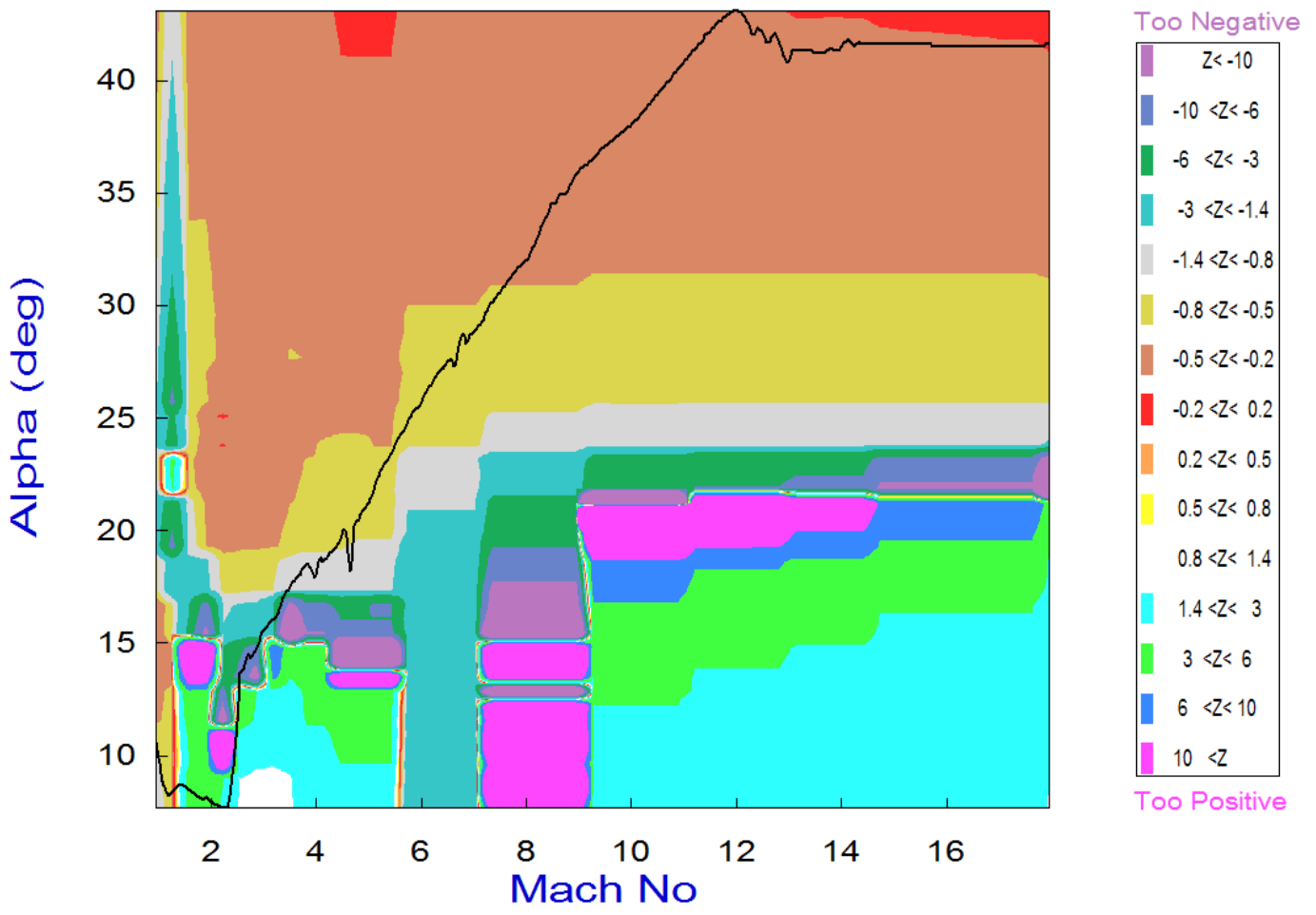
Now let us return to the Trim menu and select again option (10), but this time instead of letting the program calculate its own mixing-logic we will use a pre-calculated matrix instead. From the effector combination menu choose the first option "Select a Mixing Matrix from Systems File" to read a previously prepared matrix that de-emphasizes the contributions of the two Elevons in the roll direction and it uses more rudder instead. It includes also the two roll jets to help in the roll axis. From the matrix selection menu select the second matrix "Kmix1401".



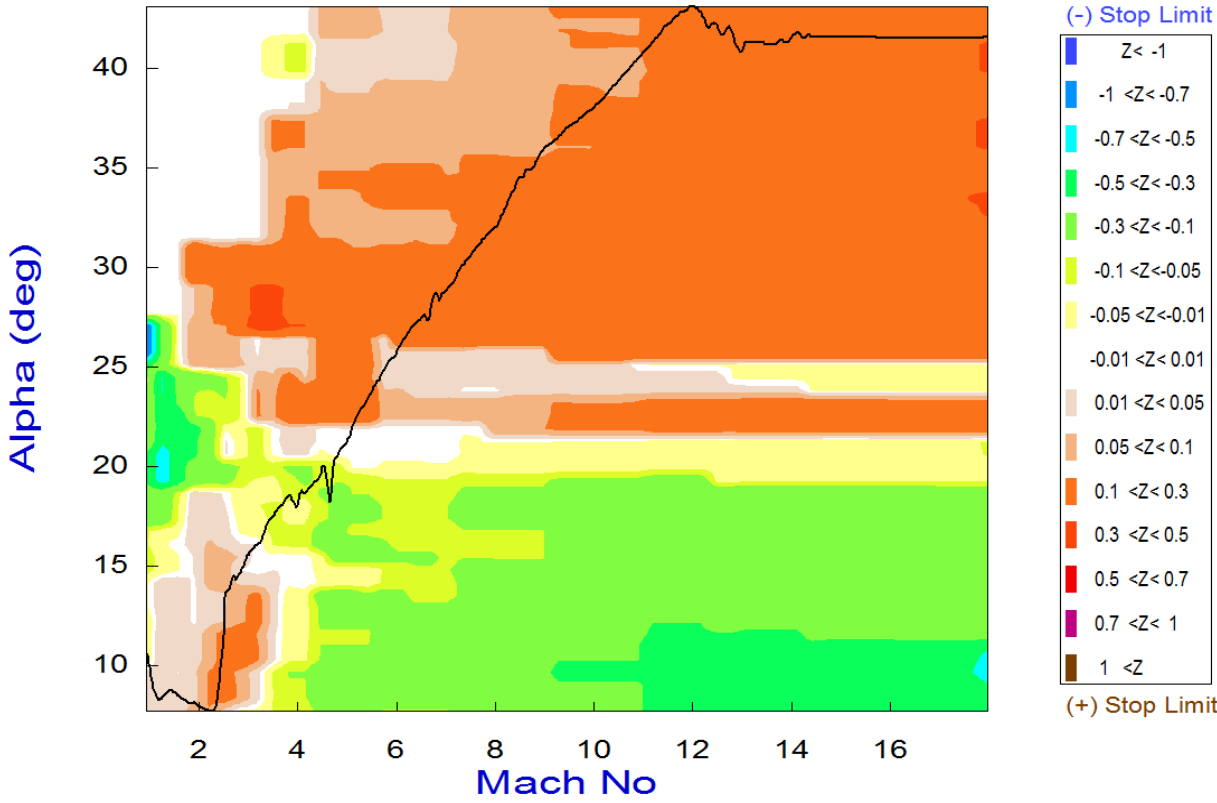


The pitch and lateral stability did not change very much with the new mixing matrix. The LCDP ratio, however, has changed considerably. It has become more negative (dark colors) in the high Mach and high alpha region. It is no longer in the red "sluggish" and uncertain roll control region (± 0.2) but it has shifted further negative (brown, dark yellow, grey regions). It requires, however, a reverse roll control which is okay until we get below Mach #3, where we have to rely on the RCS for roll control because the LCDP becomes unpredictable for a period. When it gets below Mach #1, the LCDP becomes positive and we can use the aero-surfaces again for lateral control, as we shall see in the next phase.

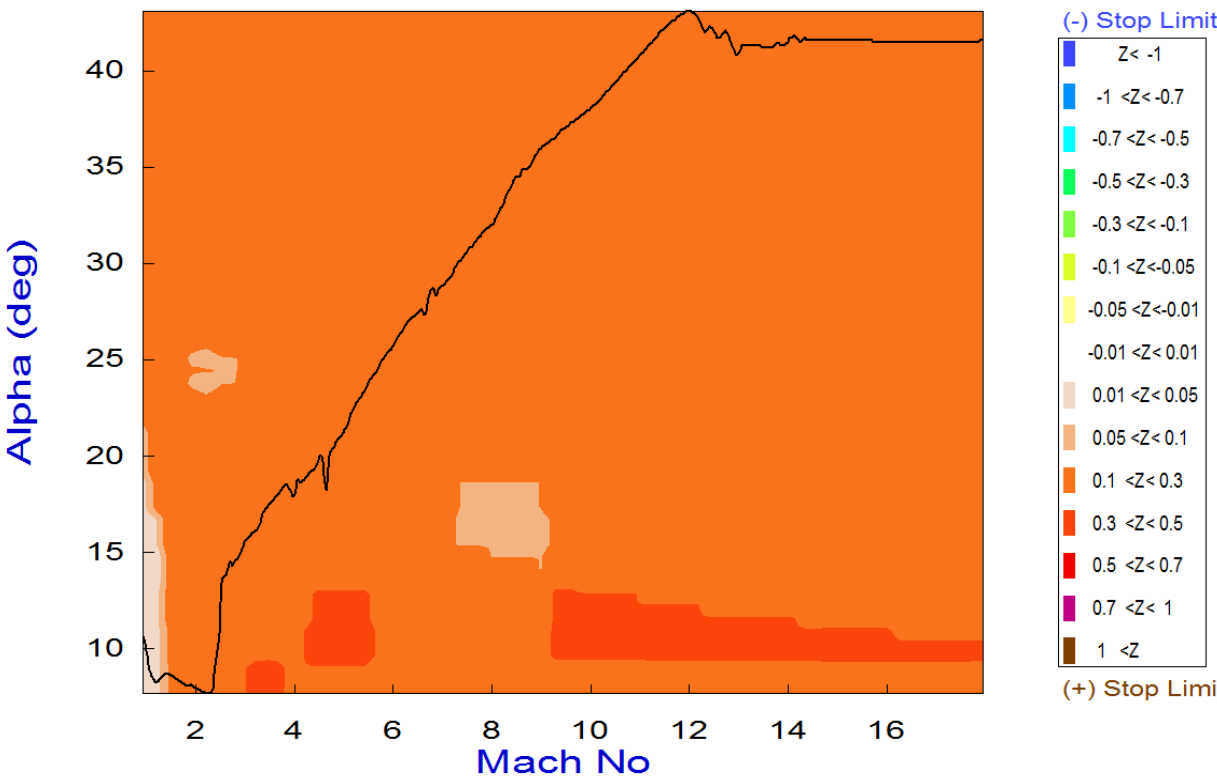
Roll Departure (LCDP) Contour Plot (Mach vs Alpha)



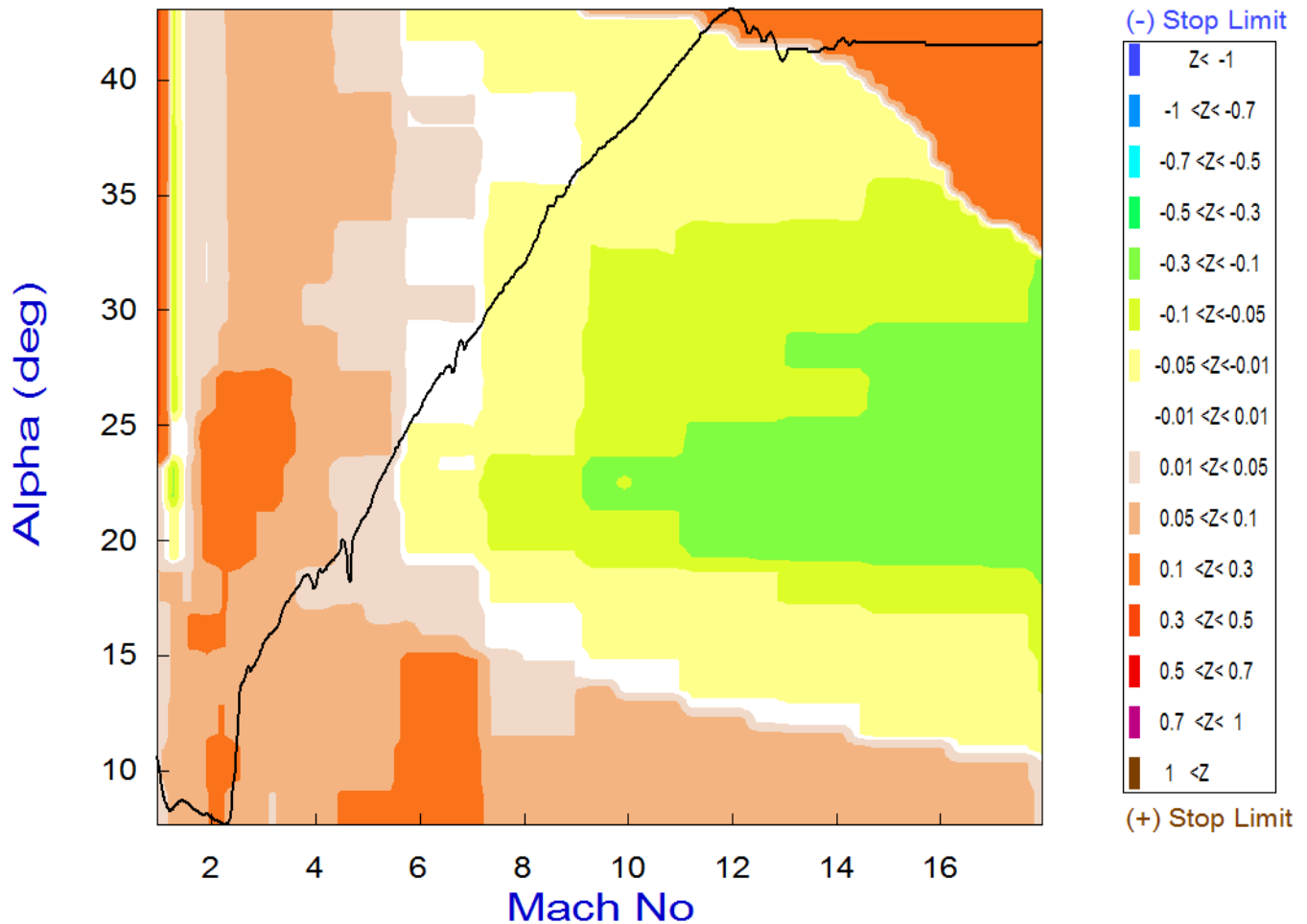
Pitch Control Effort Contour Plot (Mach vs Alpha)



Yaw Control Effort Contour Plot (Mach vs Alpha)



Roll Control Effort Contour Plot (Mach vs Alpha)



The modification in the effector combination matrix however, and the LCDP improvement did not come without a cost. Although the pitch control authority did not change, and the roll authority improved, the control authority in the yaw direction was slightly degraded with the user supplied mixing matrix, but it is still within the acceptable region.

2.3. Vector Diagrams Analysis

Vector diagrams are 2-dimensional plots used for analyzing the vehicle controllability at a specified flight condition. We compare the control capability of the effectors system against the effects on the vehicle of a wind disturbance that is defined by dispersions in the angles of attack, sideslip, and also airspeed variations. From the Trim menu select option (11), and then an arbitrary flight condition at $t=1320$ sec, near the middle of the mid-phase trajectory that corresponds to Mach 8. Define the disturbance angles (α_{max} and β_{max})= 4° , and select the (9x3) effector combination matrix "Kmix1403" from file "Mixing_Matrix.Qdr", as before.

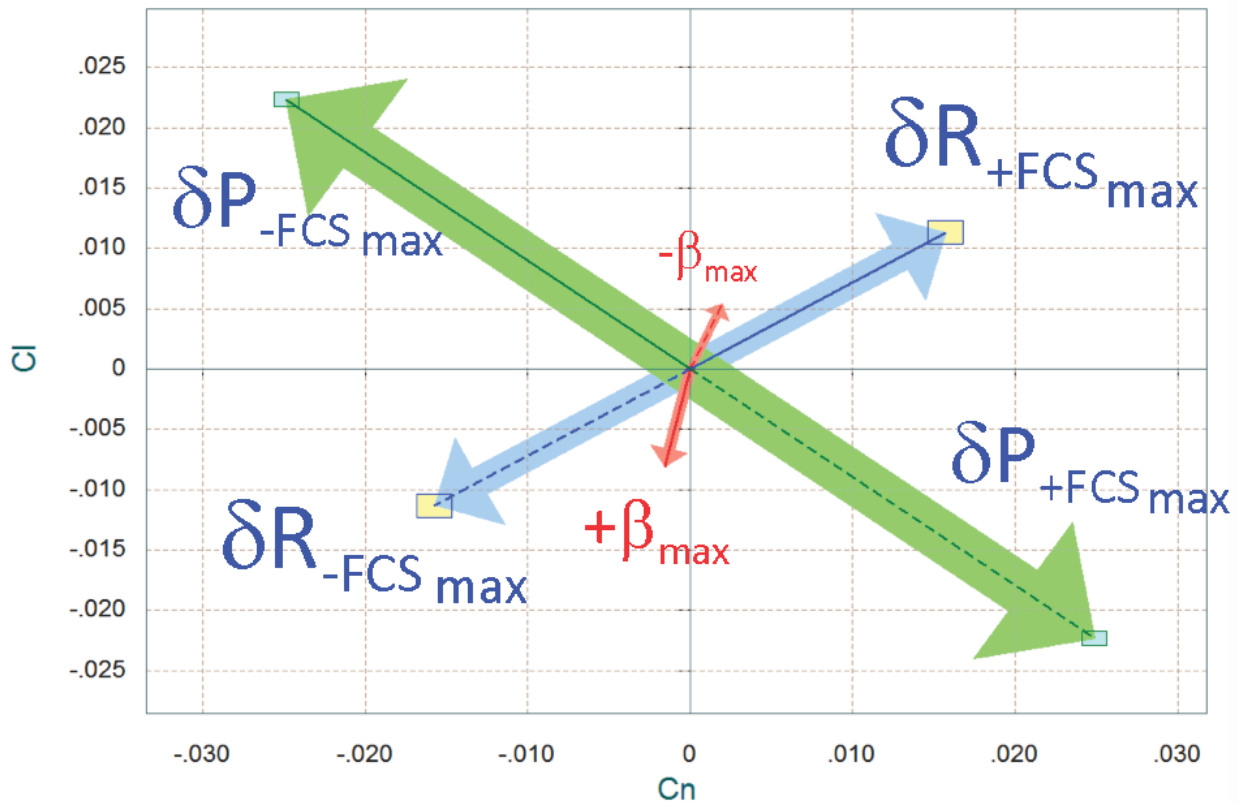
The first set of vector diagrams shows the roll and yaw moments, non-dimensional (C_l & C_n), produced when the roll and yaw FCS demands are maximized (before saturating the effectors). The solid blue vector corresponds to max positive yaw FCS demand ($+\delta R_{FCS_Max}$) and the dashed blue vector to max negative yaw demand ($-\delta R_{FCS_Max}$). Similarly, the green vectors correspond to the roll FCS demands ($\pm\delta P_{FCS_Max}$). There is a significant amount of control cross-coupling in both directions but fortunately the controls are nearly orthogonal to each other. The CY versus C_n diagram shows the effects of the yaw control on the side-force. Positive yaw produces negative side-force due to negative rudder deflections. The two red vectors show the roll and yaw moments generated by the variations in the angles of attack and sideslip ($\pm\alpha_{max}$ and $\pm\beta_{max}$) from their trim positions. Positive β_{max} produces negative moments and side-force C_y . The rectangles at the tips of the control vectors represent the uncertainties in the control moments. The uncertainties are obtained from file "*Aero_Uncert5.Unce*".

The next two figures are moment and acceleration partials vector diagrams showing the variation in roll and yaw moments and accelerations per acceleration demands in roll and yaw in (rad/sec^2). The blue vector in the top diagram represents moments per yaw demand $\{C_n\delta R, C_l\delta R\}$, and the green vector is moments per roll demand $\{C_n\delta P, C_l\delta P\}$. The red vectors pointing downward are the scaled $\{C_n\beta, C_l\beta\}$ partials. They are two because they are calculated at the two extreme values of ($\pm\alpha_{max}$ and $\pm\beta_{max}$). Notice that $C_l\beta$ is negative due to the dihedral caused by the V-tail and it is bigger in magnitude than $C_n\beta$. The red rectangle centered at the tip of the $\{C_n\beta, C_l\beta\}$ vector is due to the uncertainties in the two partials. Similarly the yellow and cyan rectangles at the tips of the yaw and roll control partials are due to the uncertainties in $\{C_n\delta R, C_l\delta R\}$, and $\{C_n\delta P, C_l\delta P\}$. The uncertainties are obtained from file "*Aero_Uncert5.Unce*".

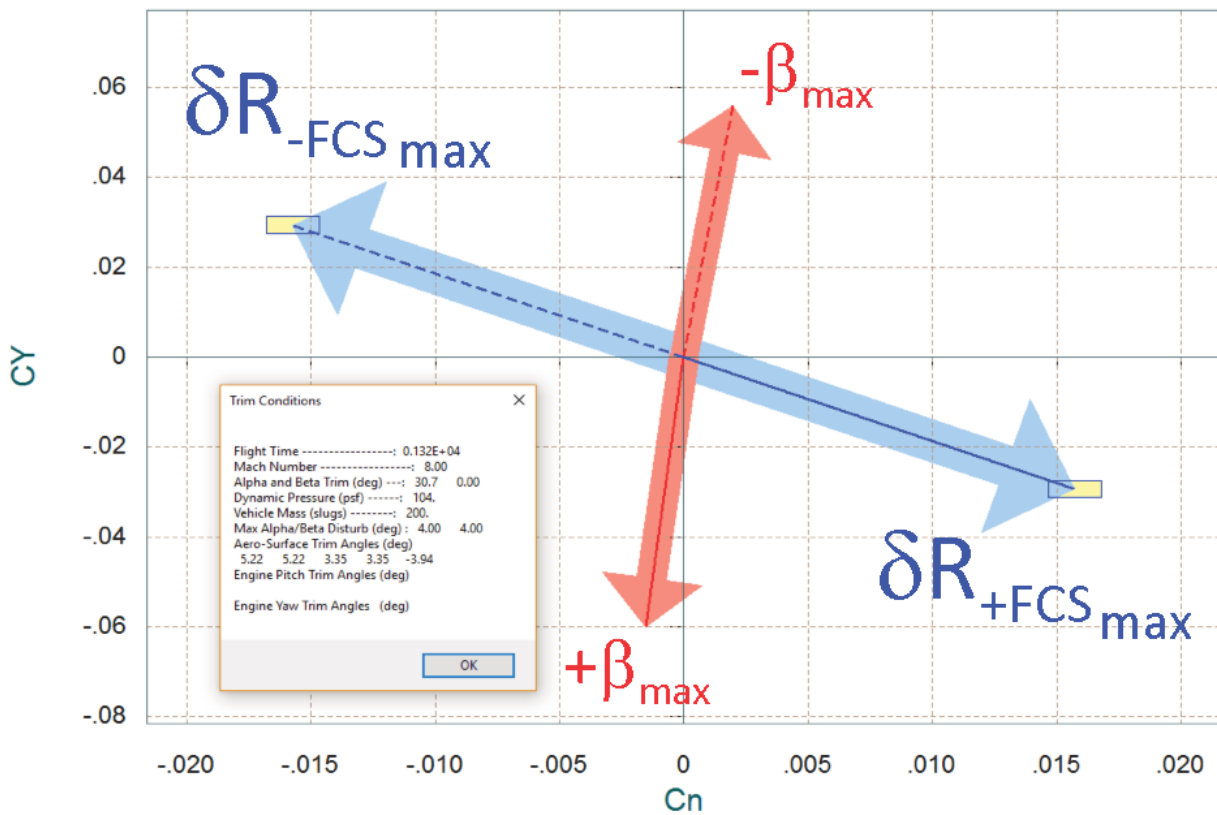
The bottom figure shows the partials of accelerations per acceleration demands in roll and yaw. The green vector is $\{\dot{P}/\delta P_{FCS}, \dot{R}/\delta P_{FCS}\}$, and the blue vector is $\{\dot{P}/\delta R_{FCS}, \dot{R}/\delta R_{FCS}\}$. The axis units are in $(\text{rad}/\text{sec}^2)/(\text{rad}/\text{sec}^2)$. Ideally they should be unit vectors, decoupled, and pointing in their corresponding direction (green vector along the +vertical axis and blue vector along +horizontal), but perfect diagonalization of the plant is not necessary. In this case, both vectors couple into each other's directions. However, they are orthogonal to each other, which is a good property because we have control authority in both axes. We sacrificed some of those good properties with our modified mixing-logic matrix in order to gain an improvement in the LCDP.

The last set of vector diagrams shows the pitch moment C_m , axial and normal (non-dimensional) forces (C_x & C_z), produced when the pitch FCS demand is maximized in both directions. The forces at trim C_{x0} and C_{z0} are both negative due to negative acceleration. The pitch control is twice more effective in the negative than it is in the positive direction. Positive pitch demand produces positive z-force (down) due to negative (up) Elevon deflection. An increase in alpha from α_0 to $+\alpha_{max}$ produces negative z-force (up). The pitch moment produced by maximizing the control demands is obviously stronger than the pitch moment produced by the $\pm\alpha_{max}$ variations.

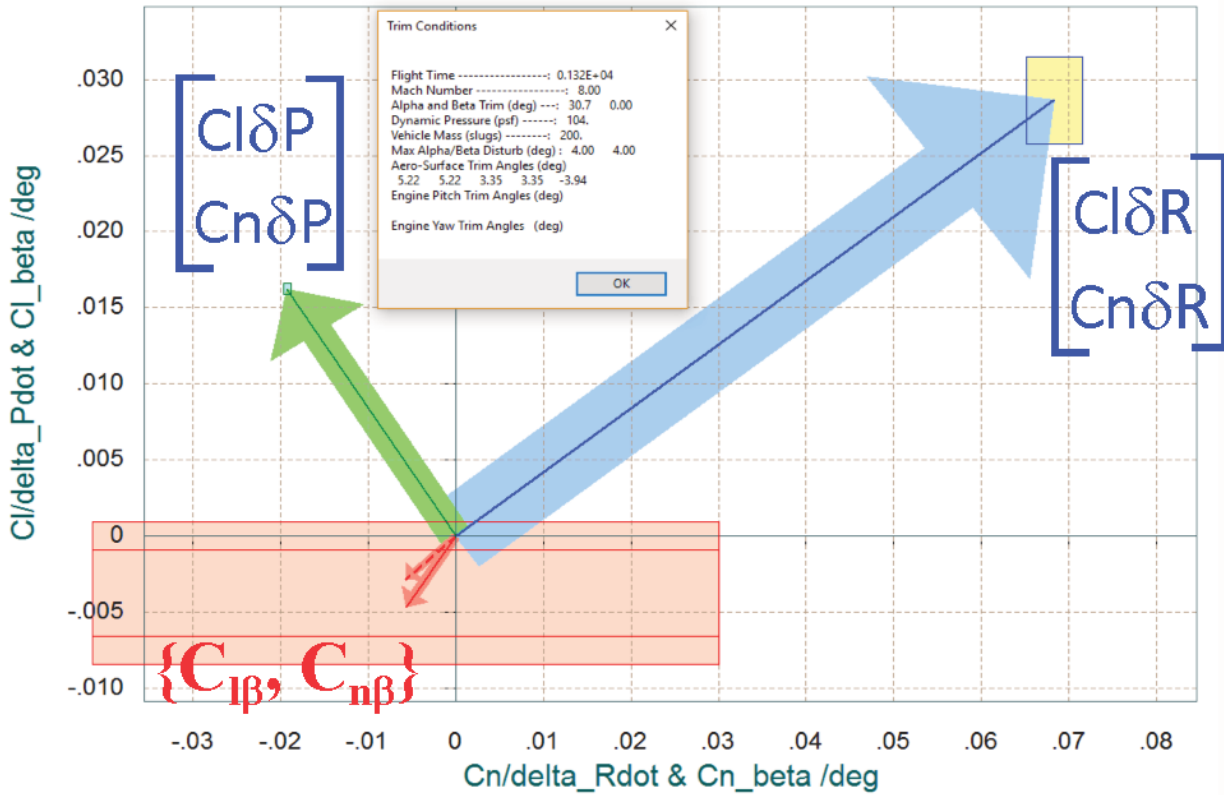
Comparison between Maximum Roll & Yaw Control Moments (Green & Blue) versus Moments due to Maximum Alpha/ Beta Dispersions (Red), Non-Dimensional



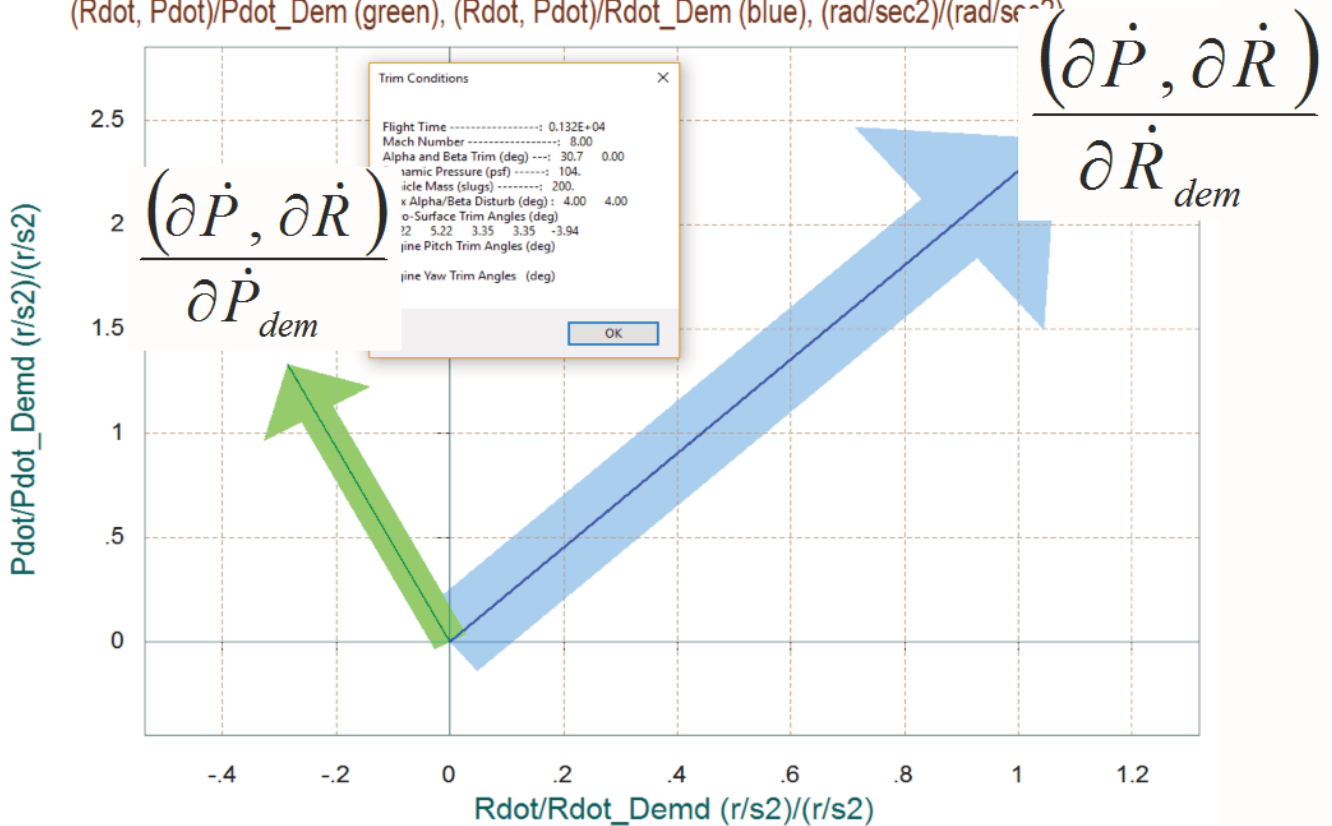
Comparison Between Maximum Yaw Control Moment C_n and Side-Force C_Y (Green & Blue) Versus Disturbance due to Maximum Beta Variation (red), Non-Dimensional



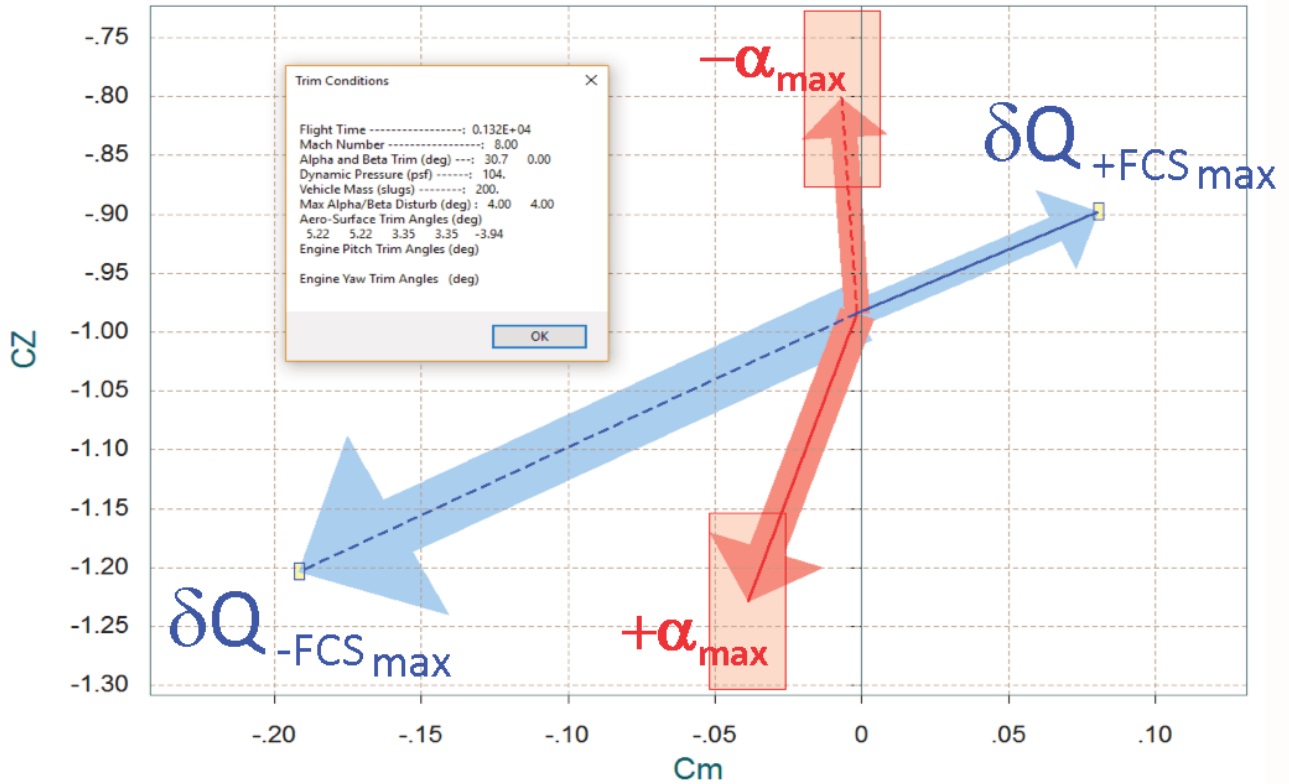
Comparison Between Yaw & Roll Control Moment Partial {Cn/delta_R and Cl/delta_P} (Blue and Green Vectors) Against Partial: {Cn_beta and Cl_beta} (Red Vectors)



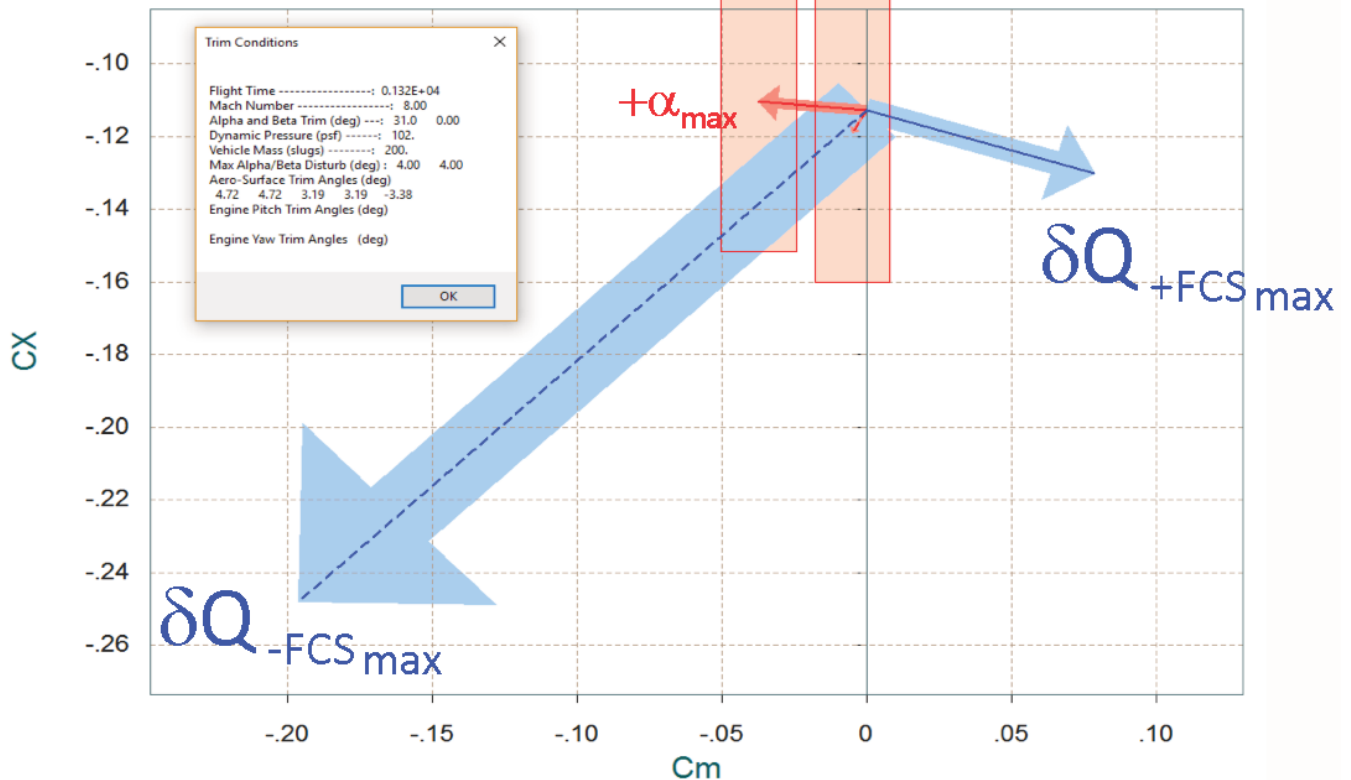
Partials of Roll and Yaw Accelerations per Roll and Yaw Control Accelerat Demands (Rdot, Pdot)/Pdot_Dem (green), (Rdot, Pdot)/Rdot_Dem (blue), (rad/sec2)/(rad/sec^2)



Comparison between Maximum Pitch Control Moment and Normal-Z Force (Blue & Green) Against Disturbance due to Maximum Alpha Variation (red), Non-Dimensional



Comparison between Maximum Pitch Control Moment and Axial X-Force (Blue & Green) Against Disturbances due to Maximum Alpha Variation (red), Non-Dimensional



2.4. Flight Control Design and Analysis

We will now select a flight condition to analyze further, create dynamic models, design control laws, and analyze stability. The flight condition chosen was at $t=1550$ sec, because this is the time period when the LCDP ratio changes sign, which implies the possibility of sluggish roll control using aero-surfaces alone. The $C_n\beta$ -dynamic parameter also becomes very small and negative, which implies directional divergence. At earlier times the Mach number and the angle of attack are high, and the LCDP ratio is consistently negative. Plus the $C_n\beta$ -dynamic parameter is positive and it does not change much. Reversing the roll control gain in this earlier time period takes care of the roll and yaw axis stabilization in the aero-surfaces control law. In the next section we will see that during the approach and landing phase those two parameters are also consistent and they do not change and, therefore, there is no problem in controlling the lateral directions using aero-surfaces alone during approach and landing. In this transitioning period, however (between $t=1500$ to 1600), we cannot fully rely on the aero-surfaces to control the lateral directions and it is safer to use the RCS jets as a primary system. In the longitudinal direction we do not have this problem and we can still use the aero-surfaces for pitch control.

We will use this vehicle model generated by Flixan to perform preliminary LQR control designs for the pitch and lateral axes. The control analysis is performed in directory "*C:\Flixan\Trim\Examples\Re-Entry Glider\Middle Phase\Matan_T1550*". The file "*T1550.Inp*" includes the vehicle input data plus the mixing matrices and system reduction data. Let's take a look at the input data file and describe what is in it.

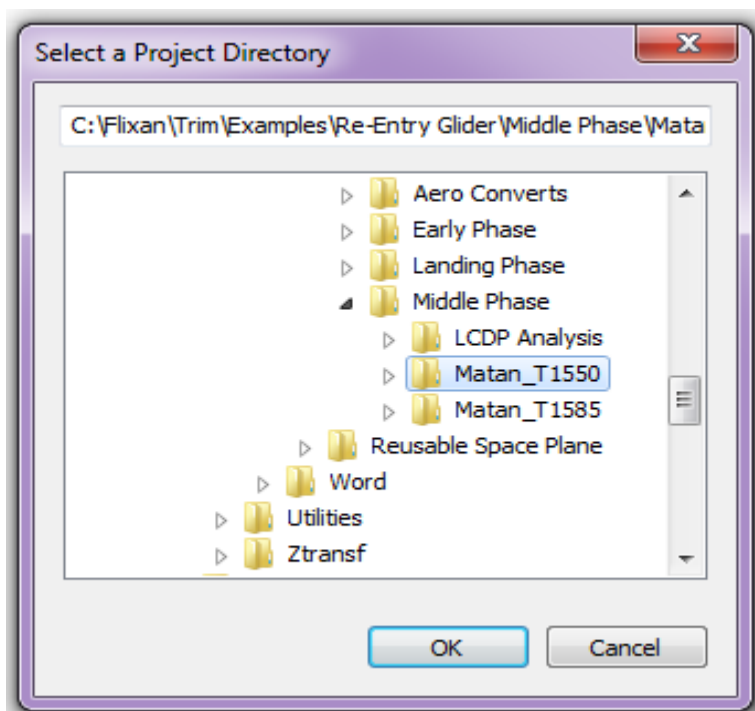
1. On the top of the file there is a batch set "*Batch for analyzing a Re-Entry Vehicle in the Mid-Phase at t=1550 sec*" which processes the remaining data-sets. It generates three types of vehicle models, design plants, mixing-logic matrices, and converts the data to Matlab.
2. The first vehicle system is a simulation model with rates defined in the body-axes. Its title is "*Re-Entry Vehicle with Aero-Surfaces and RCS Jets, T=1550 sec (Simulation Model)*". The body axes definition flag in the flight vehicle data is located below the title and comments. It includes the first 4 aero-surfaces plus the four RCS jets (defined as throttling). The four jets provide a maximum of ± 100 (lb) each. The first two generate roll torques and the other two yaw torques. Pitch thrusters are not included because only the aero-surfaces are used for pitch control. This simulation system is saved in Matlab file "*Vehicle_Sim.m*".
3. The second system is a design model that includes only the 4 aero-surfaces. The jets are not included. Its output rates are defined in the stability axis where roll is measured about the velocity vector. Its title is "*Re-Entry Vehicle with Aero-Surfaces Only, T=1550 sec (Stab Axis)*". It is used for control design using aero-surfaces, mainly in the pitch axis but also for the lateral control backup.
4. The next system is also a design model for the lateral axis that includes only the four jets, no surfaces. Its output rates are also defined in the stability axis. Its title is "*Re-Entry Vehicle with*

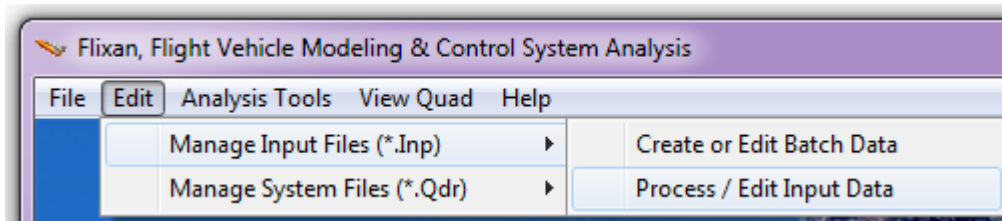
RCS Jets Only, T=1550 sec (Stab Axis)". The "Stability Axes" definition flag is located in the flight vehicle data below the title and comments. Notice that the "Turn Coordination" flag is also set in the two stability axis design models.

5. The next two data-sets in file "T1550.Inp" are used to create two separate mixing logic matrices. The first set "*Mixing Logic for the 4 Control Surfaces*" generates a matrix KSmix that combines the 4 aero-surfaces to generate 3-axes moments. The second set "*Mixing Logic for the 4 RCS Jets*" generates a matrix KJmix that combines the jets to generate the roll, pitch, and yaw moments. These matrices, however, are not the ones used in the control analysis.
6. The next three sets of data generate design plants for LQR control synthesis. A pitch design plant that uses aero-surfaces "*Re-Entry Vehicle Pitch Design Model Using Aero-Surfaces Only*", and two lateral plants. A lateral plant that uses RCS jets "*Re-Entry Vehicle Lateral Design Model Using RCS Only*", and another back-up plant that uses aero-surfaces "*Re-Entry Vehicle Lateral Design Model Using Aero-Surfaces Only*". The three design systems are saved in separate Matlab files "*Pdes_as.m*", "*Ldes_rcs.m*", and "*Ldes_as.m*" respectively.

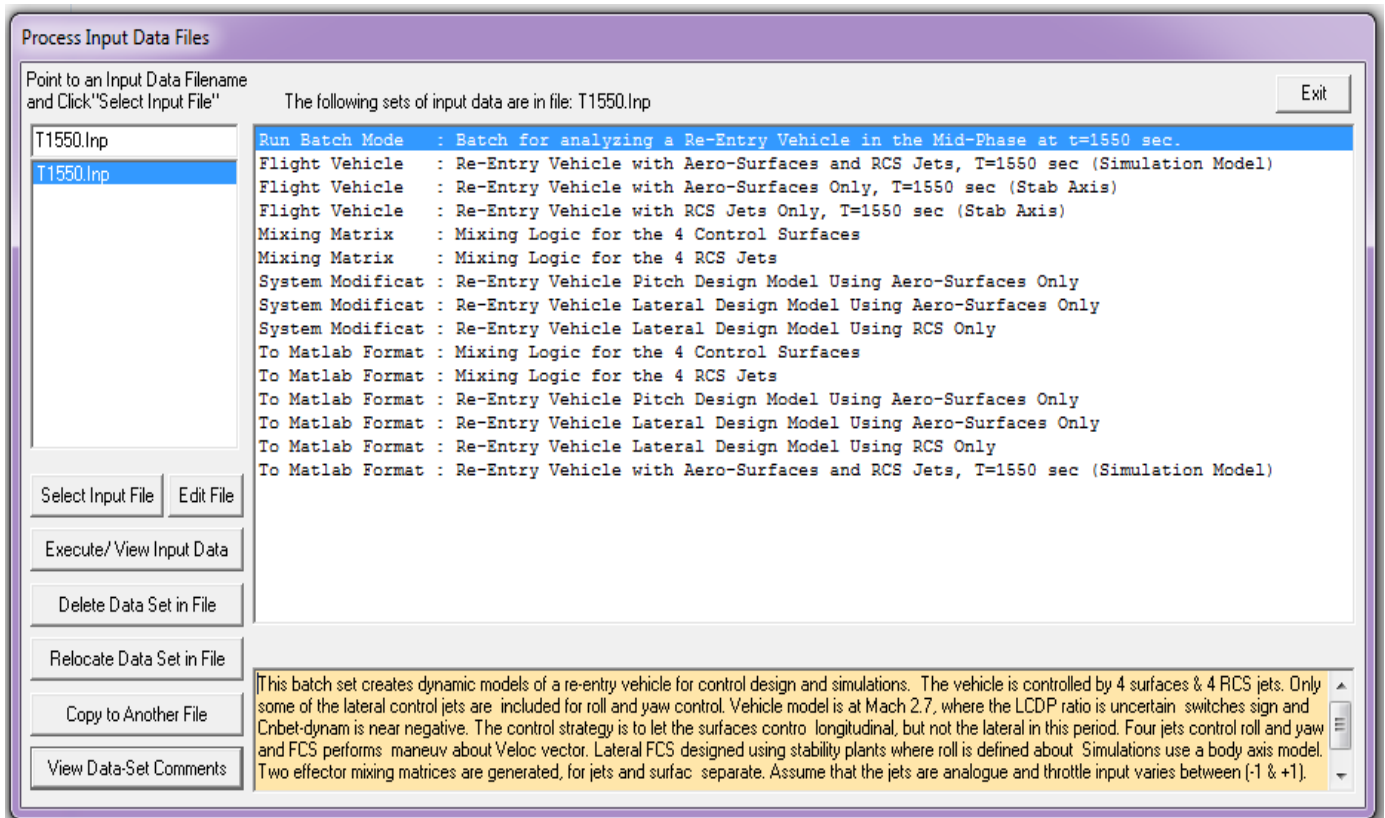
Processing the Input File Using Flixan

The Flixan data-sets that will be used for the preparation of the vehicle models and the batch set for processing the input file have already been created in file "T1550.Inp". This file was moved to folder "C:\Flixan\Trim\Examples\Re-Entry Glider\Middle Phase\Matan_T1550", where the control analysis will be performed using Matlab. The user may process this file by starting Flixan and selecting the project directory that contains the input data file. Then go to "Edit", "Manage Input Files" and then "Process/Edit Input Data".





When the following dialog appears, select the input data file "T1550.Inp" from the left menu and click on "Select Input File". The menu on the right lists the titles of the data sets which are included in this file. On the left side of each title there is a short label defining the type of the data-set. It also identifies which program utility will process the data-set. Each data-set may be processed separately. On the top of the list there is a batch that processes the whole file. To process the batch highlight the first line with title: "Batch for analyzing a Re-Entry Vehicle in the Mid-Phase at t=1550 sec", and click on "Execute/ View Input Data". Flixan will process the input file and save the systems and matrices in file "T1550.Qdr". It will also create the matrices and system functions for Matlab analysis. The same process can be used to create models, design and analyze other flight condition along the trajectory.



Initialization File Init.m

The models created may be loaded into Matlab by running the following initialization file "*init.m*", which loads the simulation model, the design models, and the two mixing matrices. This file also performs some transformations, augments the state-vectors, and performs LQR designs for the pitch and lateral systems. Some additional parameters for this flight condition are also loaded, such as: $\{\Theta_0, V_0, \alpha_0, \text{ and } g\}$ because they are needed for the transformation of the rates from body to stability axis.

```
% File Init.m for Initialization and Perform Control Design
d2r=pi/180; r2d=180/pi;
[Ave, Bve, Cve, Dve] = vehicle_sim;           % Simulation Model 6-dof
[Aps, Bps, Cps, Dps] = pdes_as;              % Load Pitch aero-surf Design Model
[Avls, Bvls, Cvls, Dvls]= ldes_as;           % Load Lateral aero-surf Design Model
[Avlj, Bvlj, Cvlj, Dvlj]= ldes_rcs;          % Load Lateral RCS Jet Design Model
load KSmix.mat -ascii;                       % Load Surfaces Mix Logic (4 x 3)
load KJmix.mat -ascii;                       % Load RCS Jets Mix Logic (4 x 3)

alfa0=14.5; VO=2649.4; Thet0=13.3; ge=32.174; % Additional Parameters for Sim
calfa=cos(alfa0*d2r); salfa=sin(alfa0*d2r);  % for Body to Stability Transform

% Pitch LQR Design Using the 4 Aero-Surfaces, States: {gamm_int,gamma,q,alfa}
[Ap4,Bp4,Cp4,Dp4]= linmod('Pdes4x');        % 4-state des model {gami,gama,q,alfa}
Ap5= Cp4*Ap4*inv(Cp4); Bp5= Cp4*Bp4;       % Convert to Output=State={gami,gama,q,alfa}
Cp5= Cp4*inv(Cp4); Dp5= Dp4;
R=4; Q=[2 5 2 2]*5; Q=diag(Q);             % LQR Weights {gami,gama,q,alfa}
[Kq,s,e]=lqr(Ap5,Bp5,Q,R)                  % Perform LQR design on Surf
save Kq.mat Kq -ascii

% Lateral LQR Design Using Only the RCS Jets
Alj= Cvlj*Avlj*inv(Cvlj); Blj= Cvlj*Bvlj;   % Transform Vector from Body to Stability
Clj= Cvlj*inv(Cvlj); Dlj= Dvlj;            % for the RCS Jets
[A15,B15,C15,D15]= linmod('LRdes5x');       % 5-state model {p,r,bet,pint,betint}
R=[1,1]*4; R=diag(R);                      % RCS LQR Weights R=[1,10]*2
Q=[2 0.2 0.2 1 0.01]*1; Q=diag(Q);        % RCS LQR Weights Q=[1 1 1 0.04 0.04]*0.4
[KJpr,s,e]=lqr(A15,B15,Q,R)                % Perform LQR design on Jets
save KJpr.mat KJpr -ascii

% Lateral LQR Design Using Only the Aero-Surfaces
Als= Cvls*Avls*inv(Cvls); Bls= Cvls*Bvls;  % Transform Vector from Body to Stability
Cls= Cvls*inv(Cvls); Dls= Dvls;           % for the Surfaces
[A15,B15,C15,D15]= linmod('LSdes5x');       % 5-state model {p,r,bet,pint,betint}
R=[1,1]*2; R=diag(R);                      % AS LQR Weights R=[1,10]*2
Q=[2 0.2 0.2 1 0.01]*0.8; Q=diag(Q);      % AS LQR Weights Q=[1 1 1 0.04 0.04]*0.4
[KSpr,s,e]=lqr(A15,B15,Q,R)                % Perform LQR design on Surfaces
save KSpr.mat KSpr -ascii
```

Lateral Design

A question may be asked, why do we want our lateral design models to be in the stability axis rather than in the body axis? It would make more sense to design the gains relative to the body axis system since the rate and acceleration measurements are coming in the body axis. The reason is that in the lateral axes the vehicle is commanded to roll about the velocity vector V_0 for minimizing sideslip beta

transients and lateral loads, and in the stability model the roll-rate is defined about V_0 . So if we optimize our LQR gains based on the stability model we should be able to command rotations about the stability axis directly, thus minimizing the sideslip transients.

There are two lateral design models generated by Flixan. The primary one is "Re-Entry Vehicle Lateral Design Model Using RCS Only" which is loaded into Matlab from file "Ldes_rcs.m" and uses only RCS jets. There is also a lateral system "Re-Entry Vehicle Lateral Design Model Using Aero-Surfaces Only" that uses the aero-surfaces and it is loaded into Matlab from file "Ldes_as.m". The second control system that uses aero-surfaces is considered to be a back-up. Both systems should be capable of controlling the vehicle independently from each other, however, in this analysis we are considering operating them both in parallel. Notice that only the output rates in the original design plants are defined in stability axes. The states are in the body axis because the C matrix is not the identity and they must be transformed before used for design. The lateral design systems state-vector is easily converted to stability axes by a matrix transform, as shown in file "init.m". Also, the original design models consist of 3 states (p_s , r_s , and β). These models are augmented by including two additional variables in the state-vector (p_s -integral & β -integral). This augmentation is created by two Simulink models "LRdes5x.mdl" and "LSdes5x.mdl", and the effector mixing matrices $KJmix$ and $KSmix$ respectively are included in the augmentation models (columns 1 and 3 only corresponding to roll and yaw).

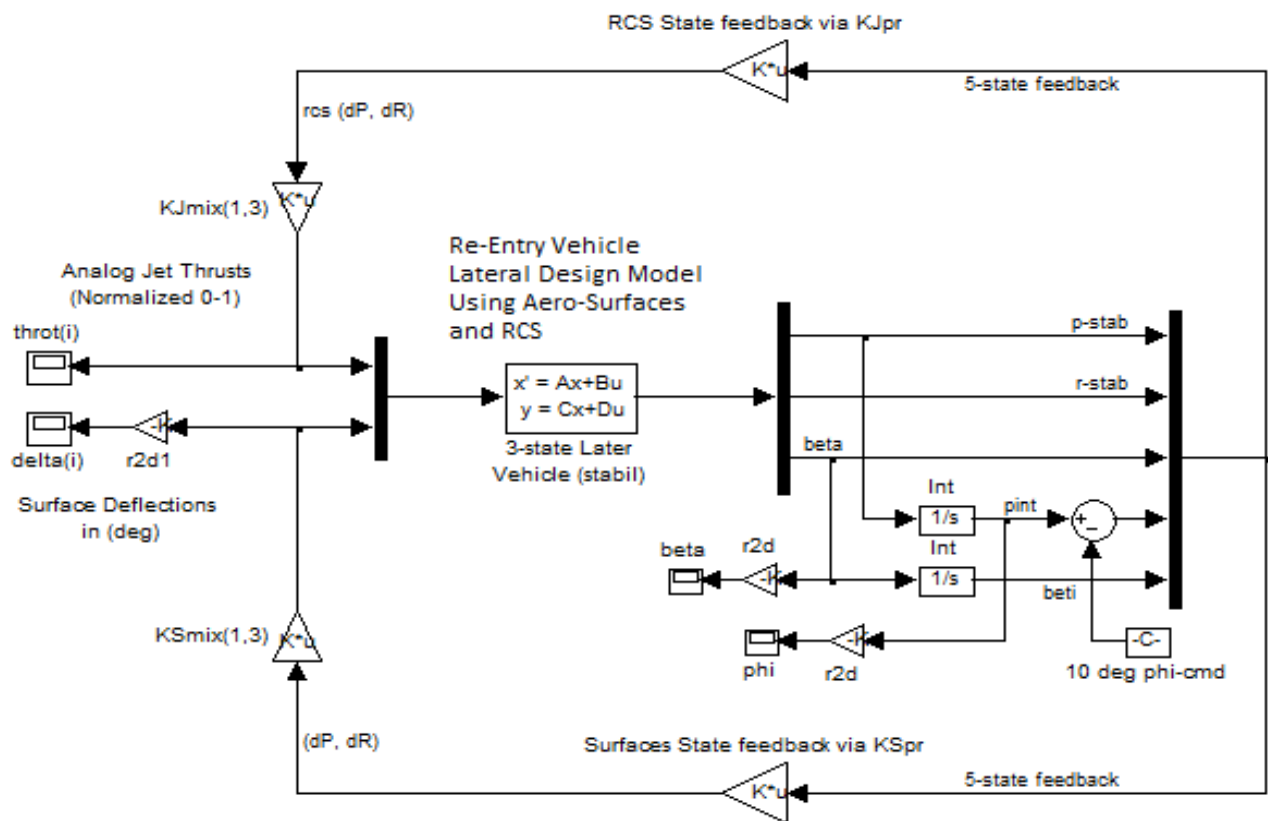
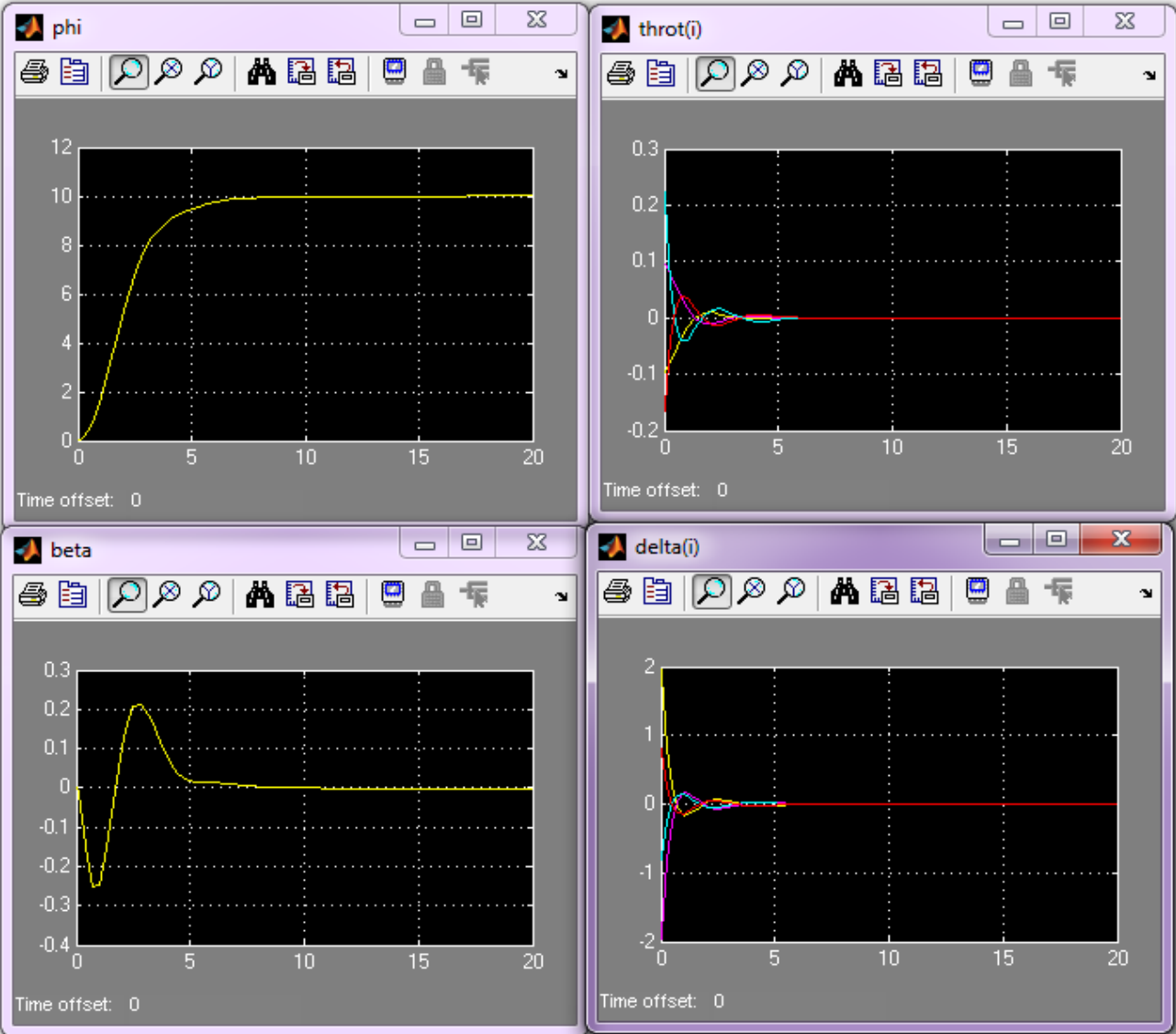


Figure 2.4.1 Lateral Simulation Model in File "Sim_Simple.mdl" for evaluating the Lateral LQR Control Design

Figure (2.4.1) is a closed-loop simulation model "Sim_Later_Simple.Mdl" used for preliminary evaluation of the lateral LQR design and for adjusting the LQR weight matrices. Both control loops are operating in parallel in this model via state-feedback matrices K_{Jpr} and K_{Spr} and via mixing matrices K_{Jmix} and K_{Smix} , for RCS jets and aero-surfaces respectively. The state-feedbacks are (2x5) matrices. Matrix "KSpr" converts the 5-state vector to roll and yaw surface acceleration demands which are then converted to surface deflections by matrix "KSmix". Matrix "KJpr" converts the 5-state vector to roll and yaw jet acceleration demands which are then converted to jet throttle commands by matrix "KJmix". This system is commanded to perform a 10° roll about the velocity vector V_0 , and it performs the maneuver with a very small transient in β , and by using a combination of surface deflection and jet throttling, as shown below. The throttle commands are continuous (analog) signals and must vary between zero and ± 1 . If a throttle bigger than one is required, this is an indicator that the jet thrusts in the vehicle model must be increased. Only the throttle inputs are applied to the models, the actual jet thrusts are internal. In the current model the 4 jet thrusts generate up to ± 100 (lb) each.



Longitudinal Design

In the longitudinal direction during this flight condition we are attempting to control the flight-path angle. So the control input is a (γ_{command}) from guidance. In this case it makes no difference as to whether we use a stability or a body axis model to design the FCS gains, because the pitch states are the same in both models. The design plant for the longitudinal LQR design is "Re-Entry Vehicle Pitch Design Model Using Aero-Surfaces Only" which is loaded from file "pdes_as.m", and uses only the 4 aero-surfaces. An augmented design plant is constructed using the file "Pdes4x.Mdl". Its state-vector consists of (γ , q , α , & α -integral). The flight-path angle is constructed by combining pitch attitude and angle of attack ($\gamma = \theta - \alpha$). The augmented design plant also includes the surfaces mixing logic matrix "KSmix" which transforms the pitch demand feedback signal to 4 aero-surface deflections. Figure (2.4.2) is a closed-loop simulation model "Sim_Pitch_Simple.Mdl" used for preliminary evaluation of the pitch LQR design and for adjusting the LQR weight matrices. Only the middle column of matrix (KSmix) is used in this model because it consists of only pitch states. The (1x4) state-feedback matrix Kq is created by the LQR method and it closes the feedback loop.

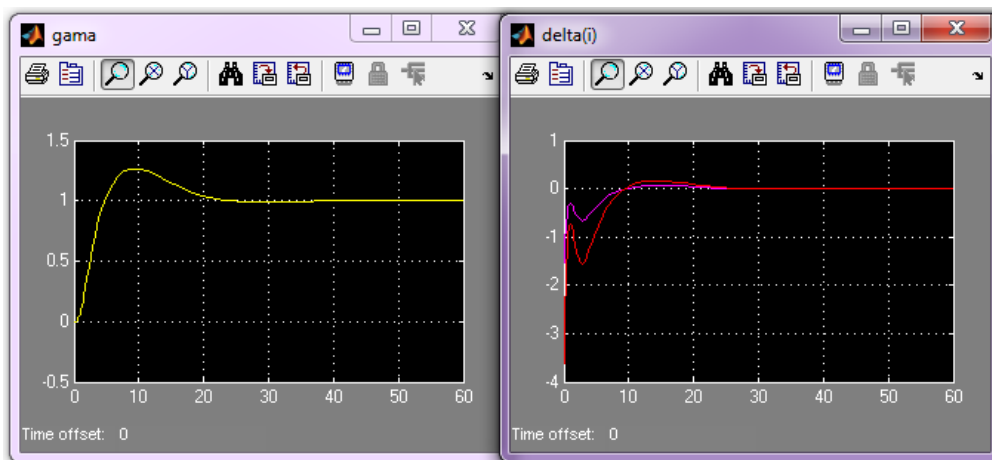
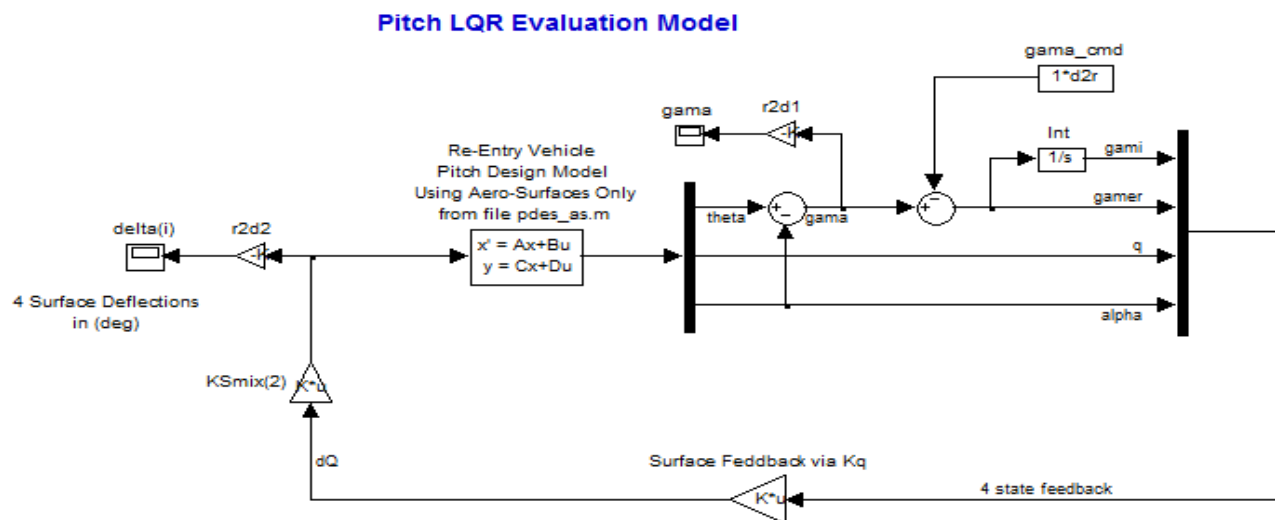


Figure 2.4.2 Simple Longitudinal Simulation Model in File "Sim_Pitch_Simple.mdl" that Uses Only Aero-Surfaces Control

Simulation Model

The Matlab simulation model for this flight condition is in file "Simul_MidPhase.Mdl", and shown figure (2.4.3). It uses the body-axis vehicle model "Re-Entry Vehicle with Aero-Surfaces and RCS Jets, $T=1550$ sec (Simulation Model)" which was generated by Flixan and it was saved in file "vehicle_sim.m". This simulation model controls the flight-path angle in the pitch direction and in the lateral direction it controls the roll angle about the velocity V_0 . There is a transformation that converts the body axis roll and yaw rates to rates about the velocity V_0 . This is because the controller expects stability axes rates because it was designed using a stability model. The vehicle model is shown in detail in Figure (2.4.3b). It includes actuator models and the two effector combination matrices KJ_{mix} and KS_{mix} at its input. It receives roll, pitch, and yaw acceleration demands which are converted to surface deflections and throttle inputs (0 to ± 1). It includes also a gust input shaped by a low-pass filter to produce a smooth gust impulse of 30 (ft/sec) velocity. The direction of gust is defined relative to the vehicle in the input data file "T1550.Inp", and it excites both pitch and yaw, perpendicular to the X-body and at 45° between +Y and +Z axes (typical). The body to stability axis transformation is shown in detail in a separate figure. It includes also turn-coordination terms (linearized) because the turn-coordination flag was turned-on in the design plant model. It means that the controller assumes that the vehicle includes a turn-coordination logic. Notice that the (α, β) variables in the state-feedback were replaced with normal and lateral accelerations (N_z, N_y) respectively.

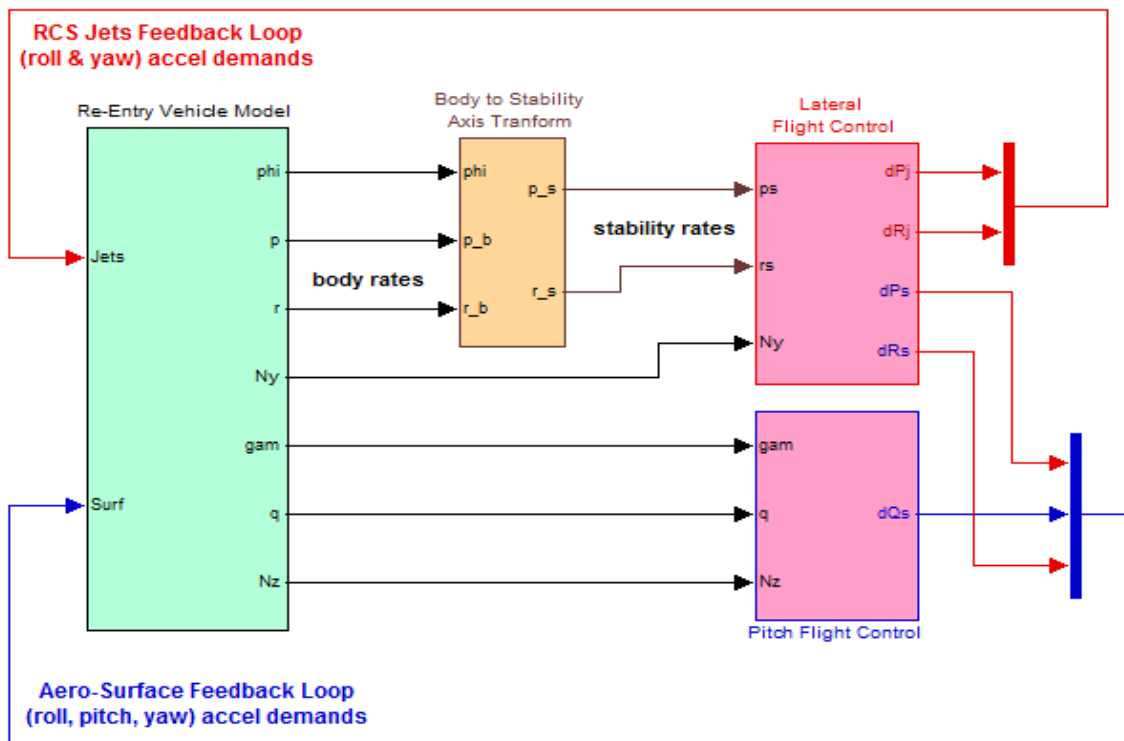


Figure 2.4.3 Gamma and Phi Control Simulation Model in file "Simul_MidPhase.Mdl" Using a Combination of Aero-Surfaces plus Throttling Jets

Vehicle Simulation Model

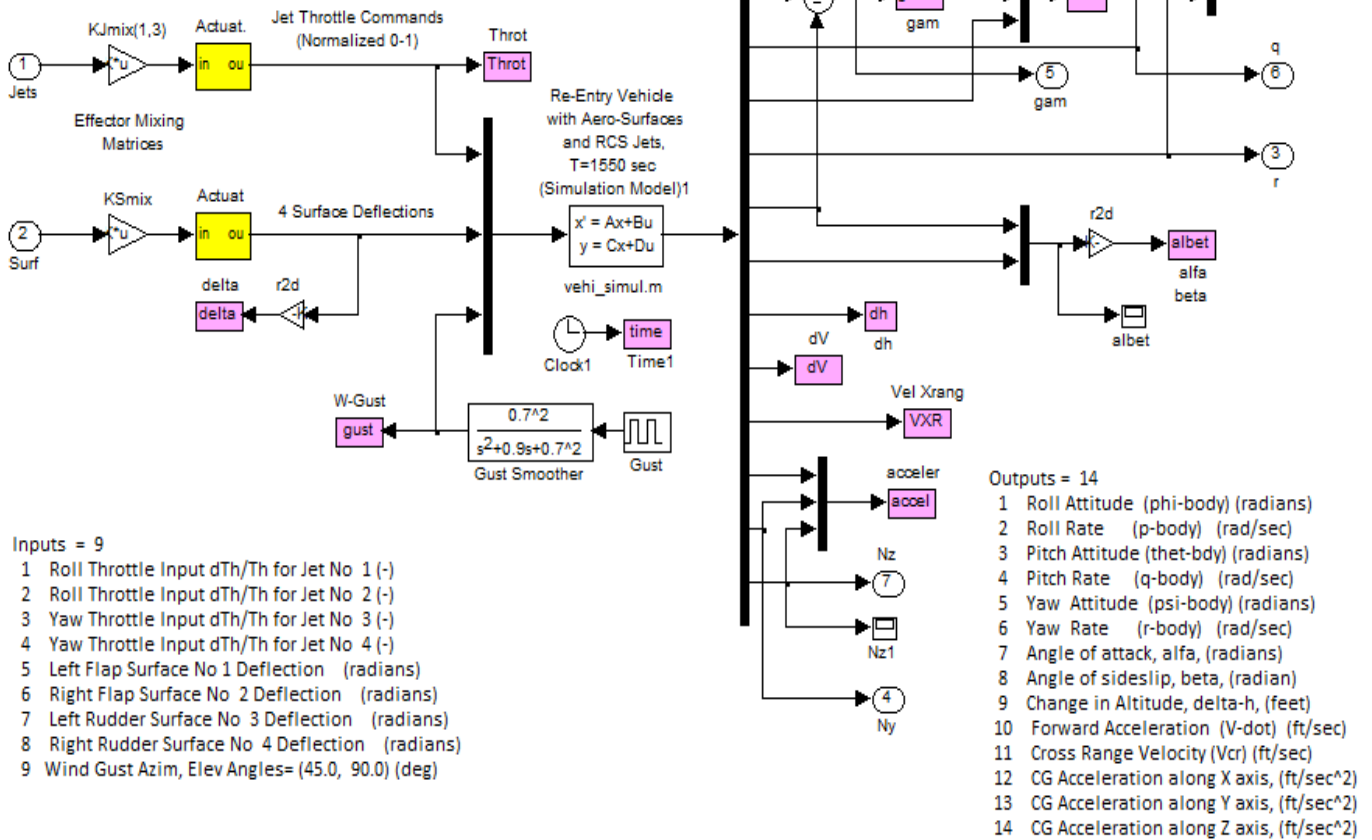
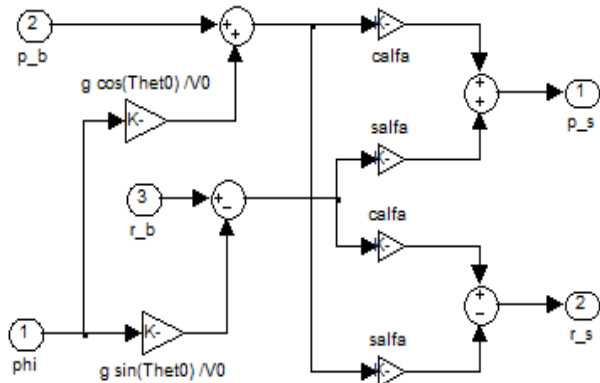


Figure 2.4.3b Vehicle Dynamics Sub-System in File: "Simul_6dof.mdl"

Body to Stability Axes Transformation



Pitch Flight Control System (Gamma_Control Mode)

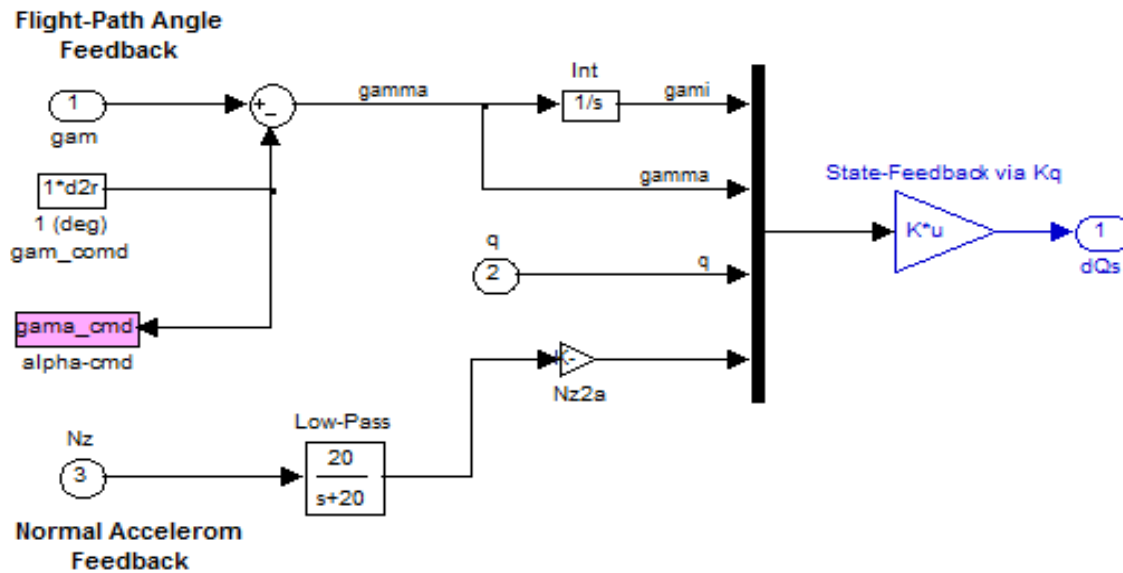


Figure 2.4.3c Pitch FCS Uses Aero-Surfaces to Control (γ) and uses pitch rate (q) plus Normal Accelerometer Feedback (Nz)

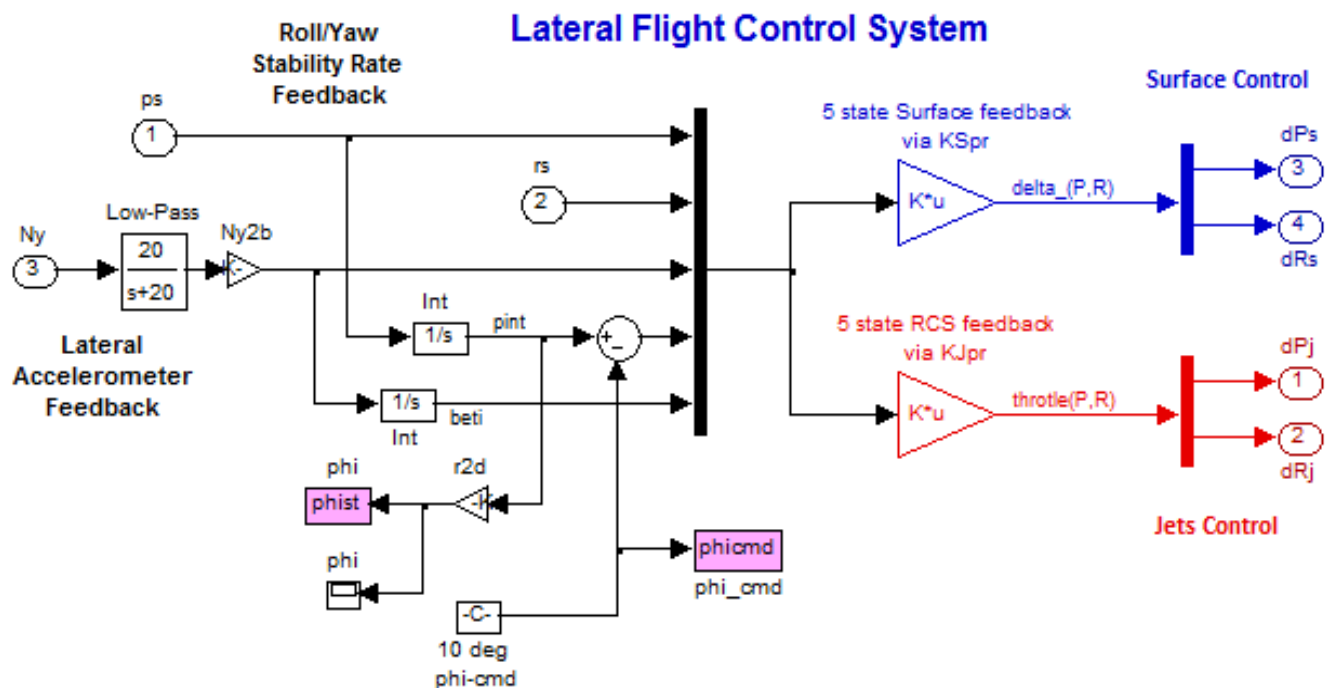


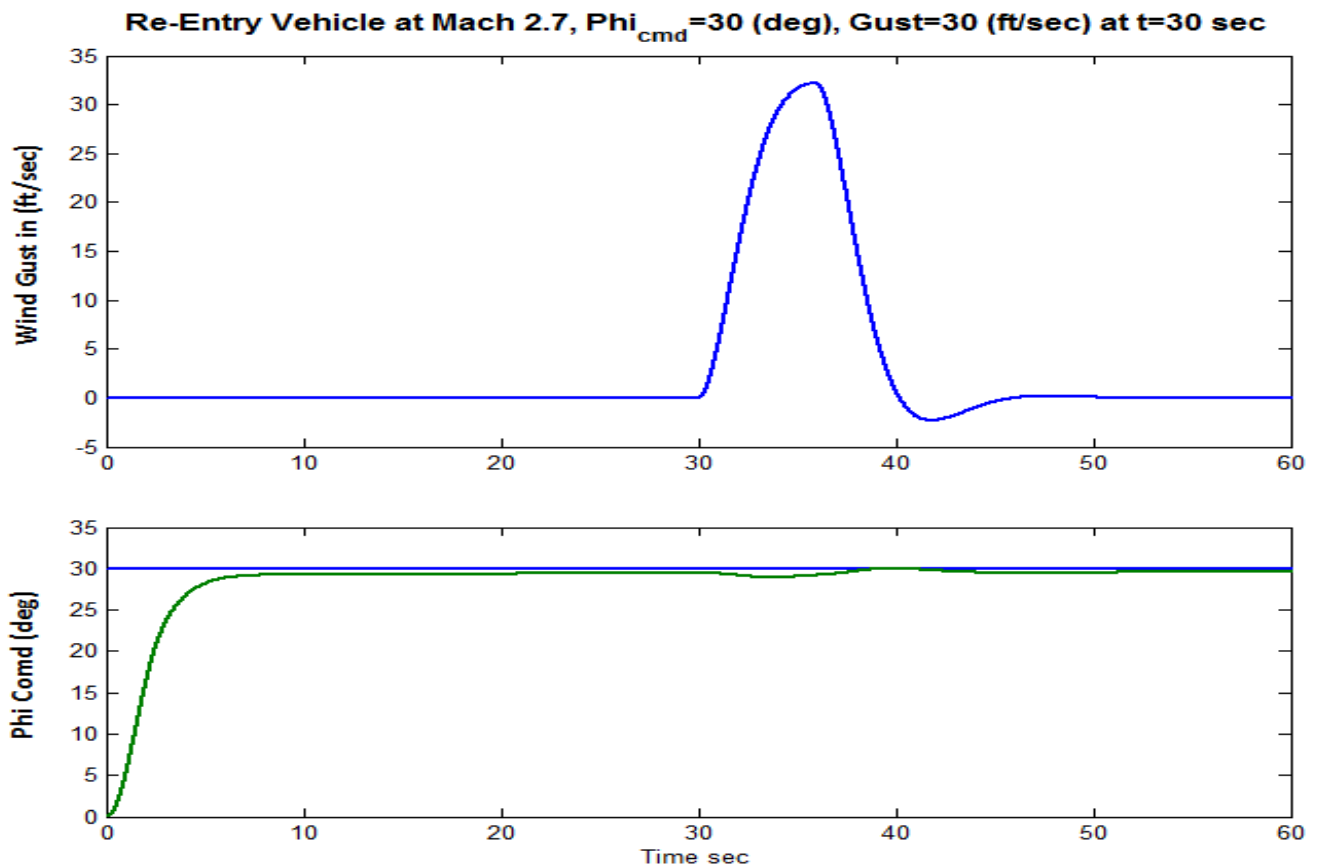
Figure 2.4.3d Lateral FCS Uses Both RCS plus Aero-Surfaces to Control (ϕ) and uses roll/yaw stability rates plus Lateral Accelerometer Feedback (Ny)

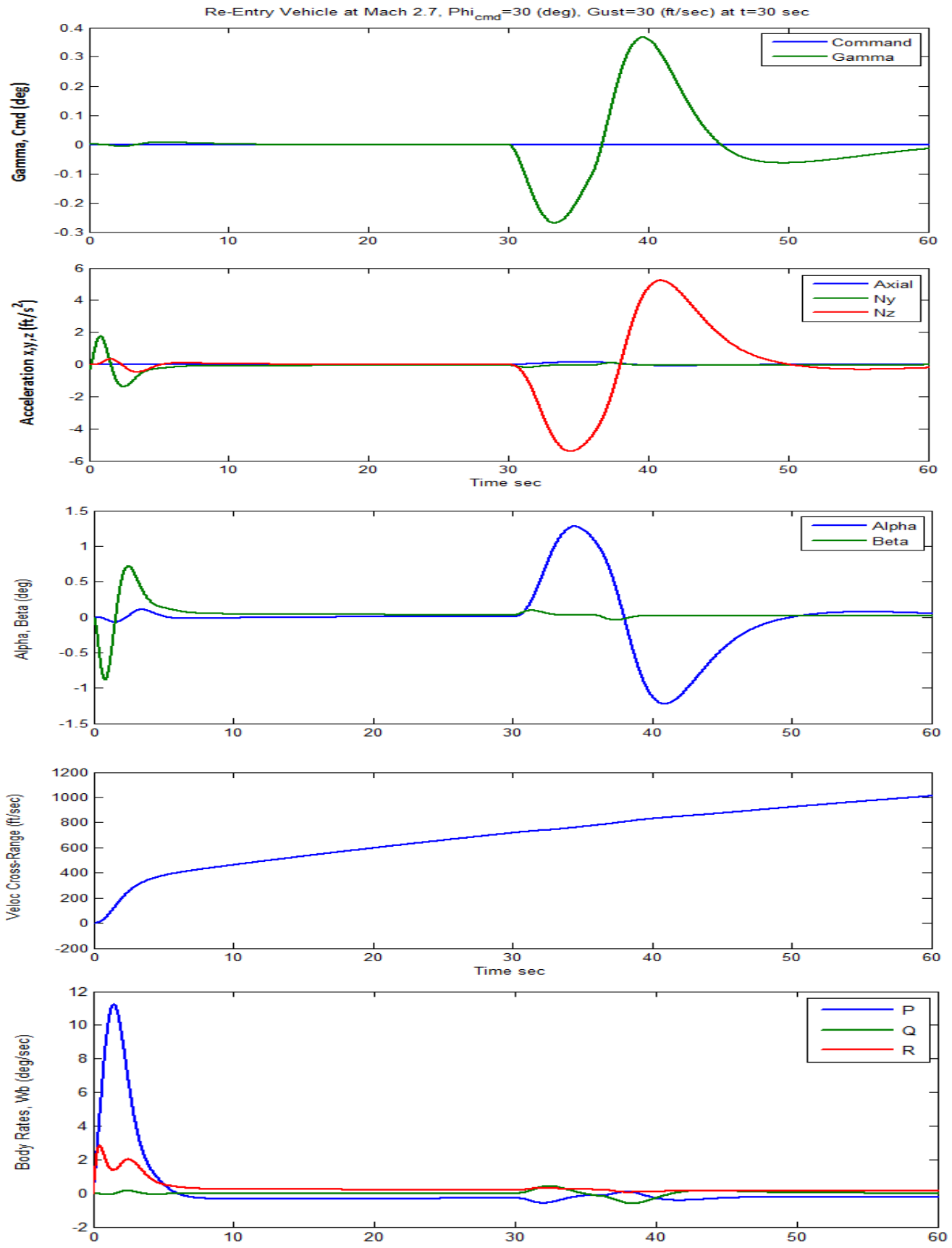
Simulation Results

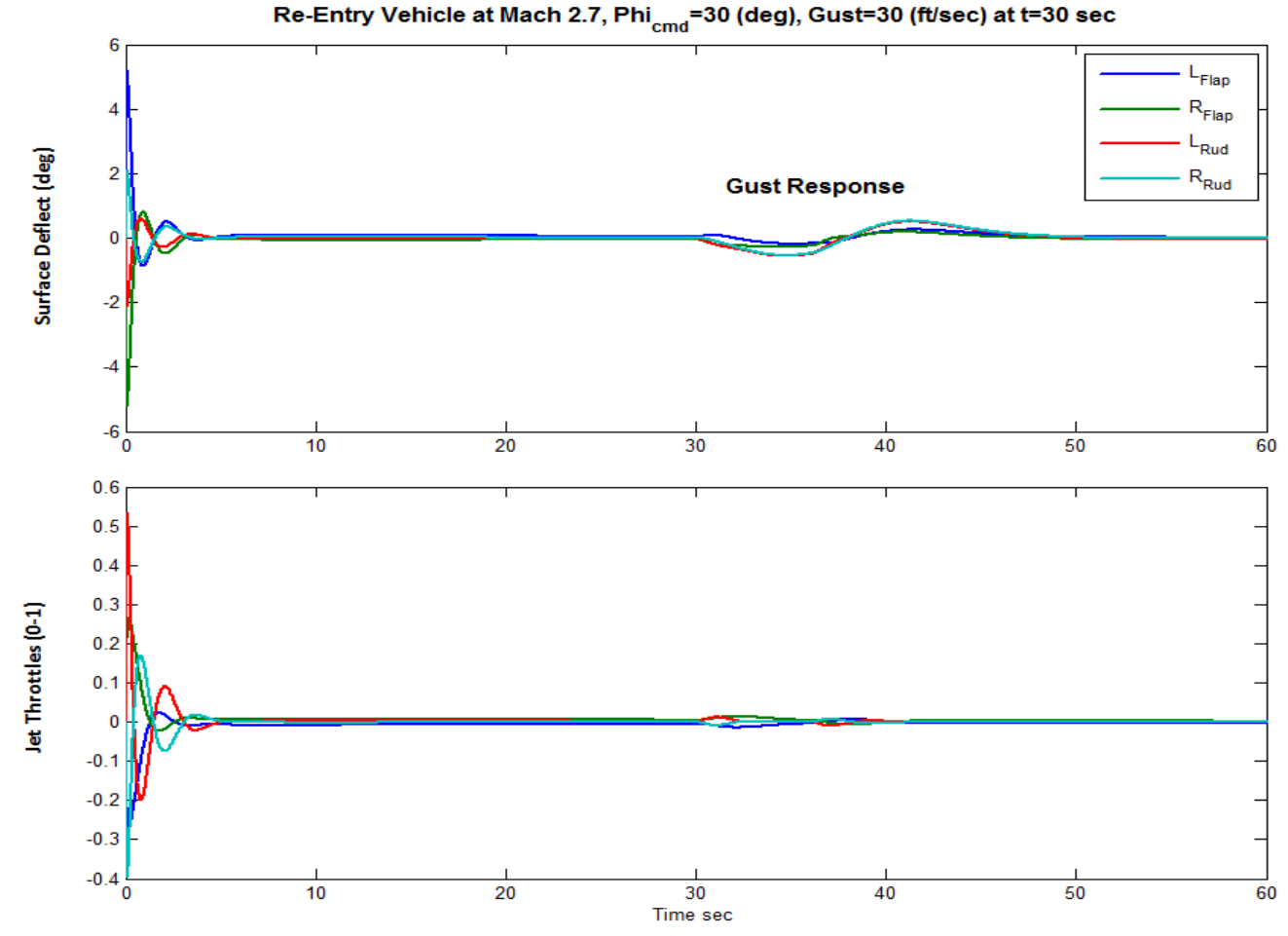
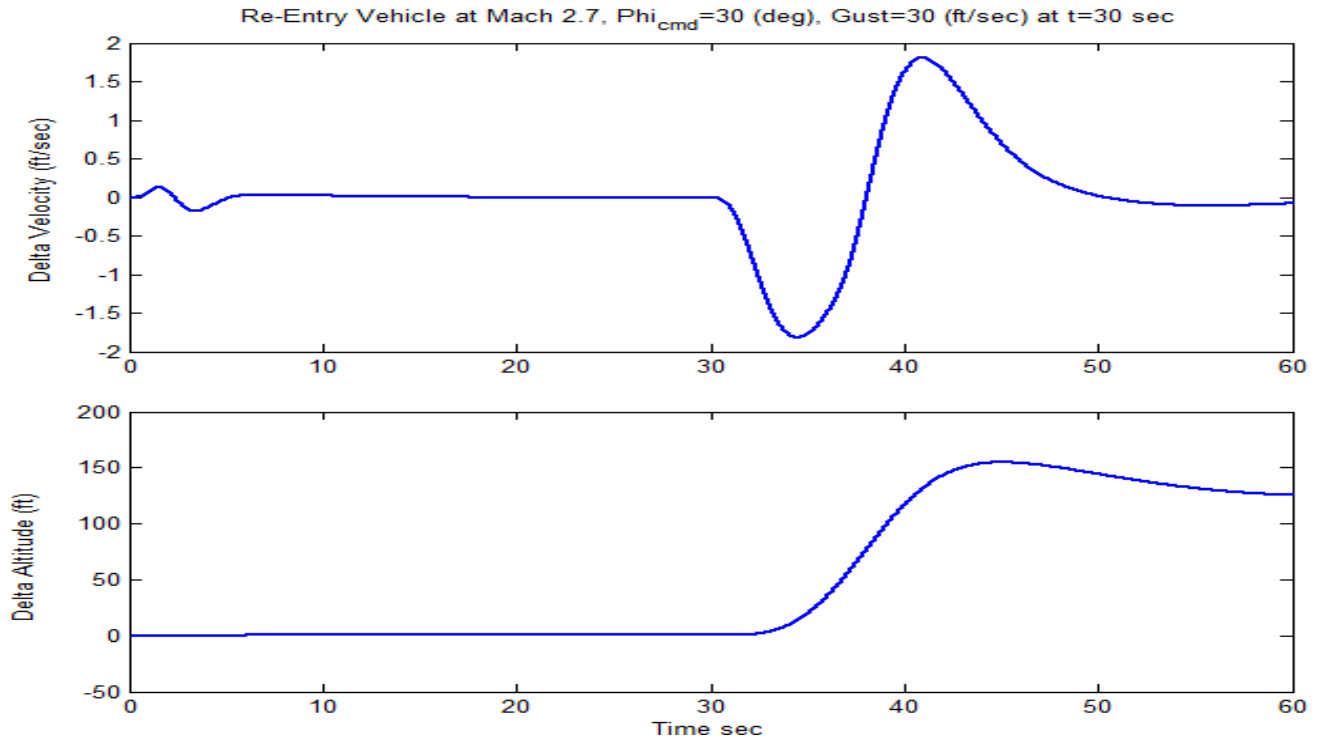
The simulation model described is set up to accept three inputs: a gamma command, a roll command (ϕ_{cmd}) about the velocity vector V_0 , and a wind-gust disturbance (W_{gust}). We will perform two simulation runs using this model. The first run is excited by a roll step command applied at $t=0$ sec, and a wind velocity impulse of 30 (ft/sec) applied at $t=30$ sec. The second run is excited by a gamma step command applied at $t=0$ sec, without a gust.

Case A, Phi-Command with Gust

A 30° roll step command is applied at $t=0$ sec, and a wind velocity impulse of 30 (ft/sec) applied at $t=30$ sec. The vehicle performs the roll maneuver about the velocity vector V_0 with a very small transient in beta, as expected. The gust direction is towards the vehicle with a $-z$ component causing a temporary increase in altitude, a $-z$ acceleration (red), and a velocity transient. All 4 surfaces deflect in unison to compensate against the pitch transient created by the gust at $t=30$ sec. The jets respond to the lateral commands and vehicle motion. Initially they respond to the roll command by throttling up and down to generate the roll and yaw torques required to rotate the vehicle. Both body rates (p & r) are responding together to rotate the vehicle about the velocity vector. The FCS gains are adjusted to prevent the jets from violating their throttle limits (± 1). A throttle value of (± 1) corresponds to a thrust ± 100 (lb) as defined in the vehicle data.

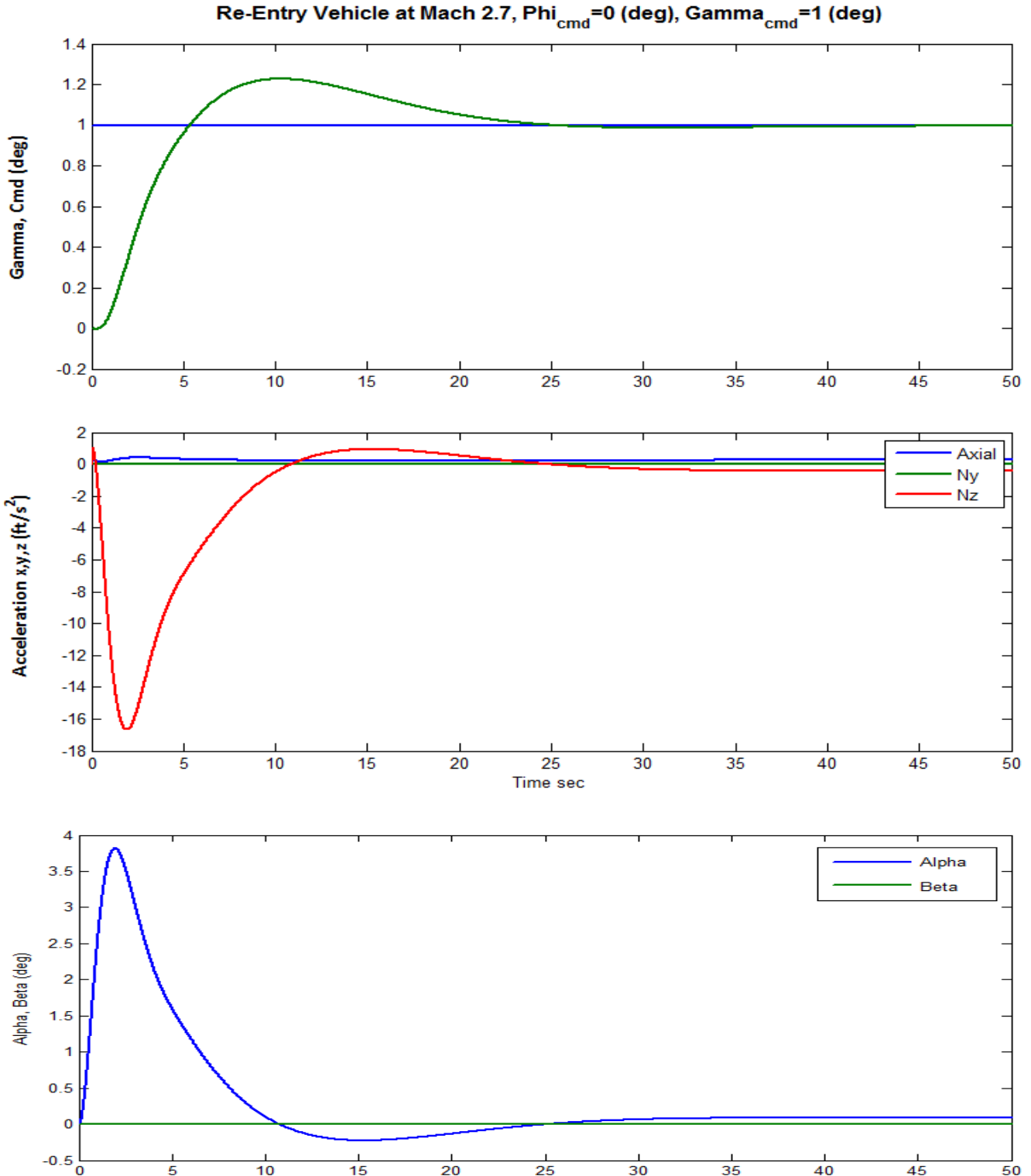


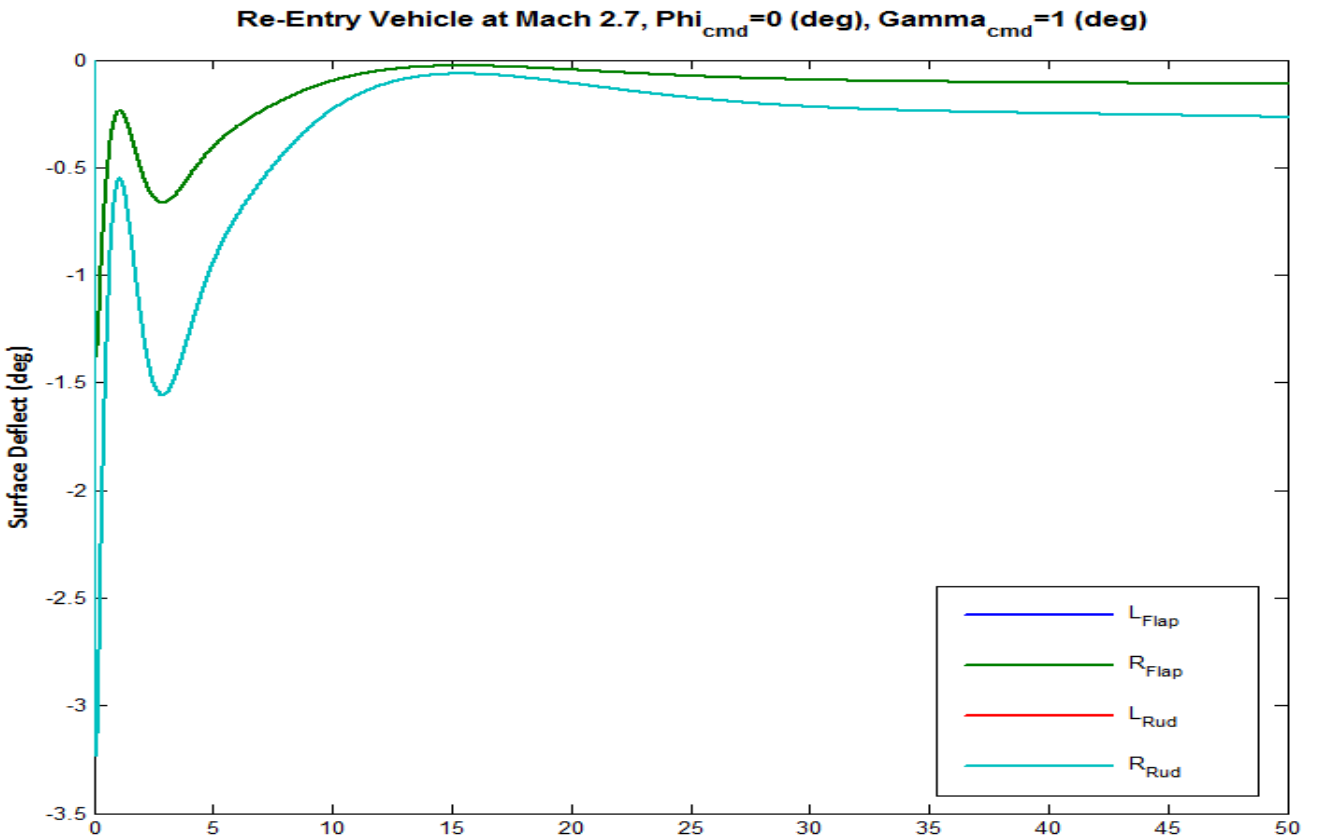
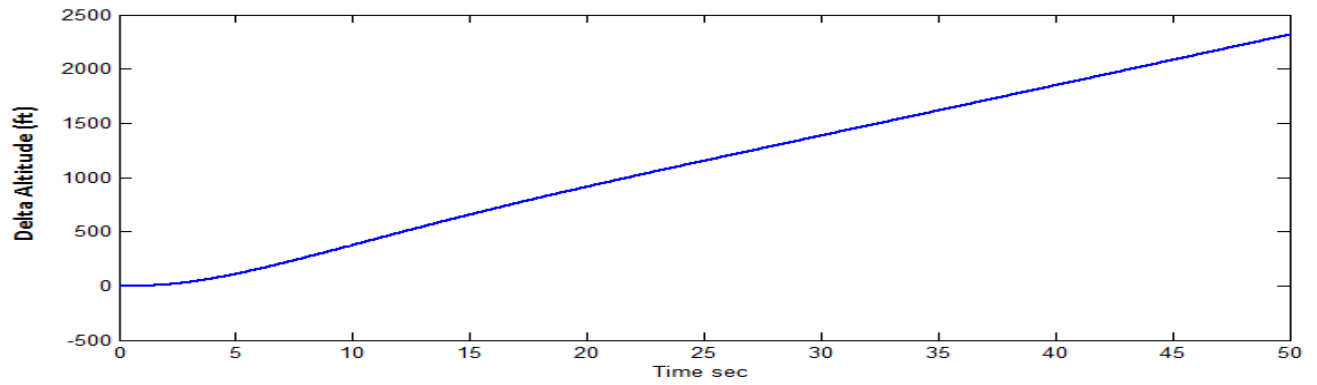
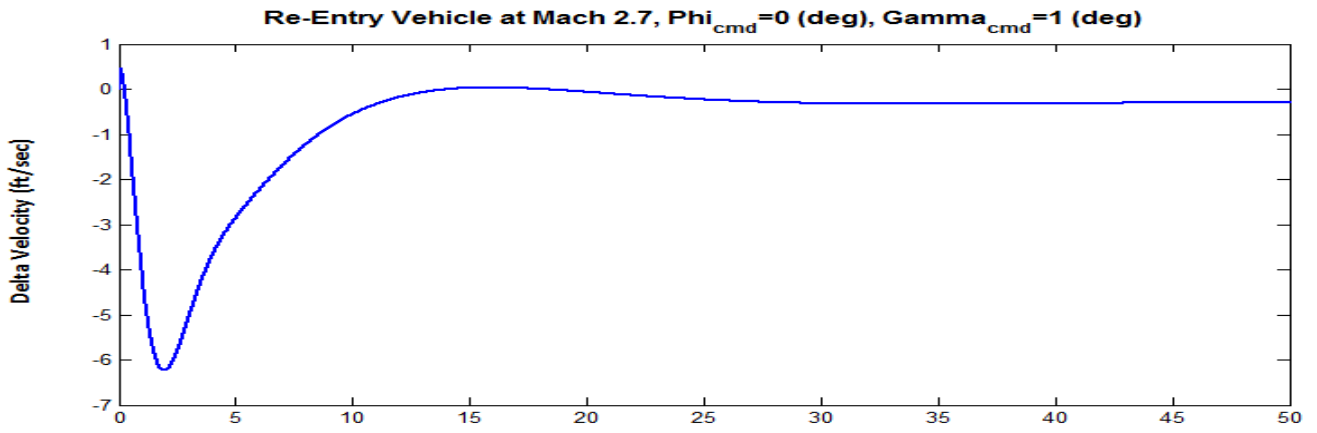




Case B, Flight-Path Change Command (No Gust)

In this case the vehicle is commanded to perform one degree change in gamma. Both flaps and elevons momentarily deflect in the negative direction for the vehicle to pitch up and to generate a positive alpha. This helps it create a positive flight-path angle and to start climbing in altitude.





Stability Analysis

The Simulink model used for analyzing open-loop stability in the frequency domain is "*Stab_Anal.Mdl*", shown in Figure (2.4.4) below, and it is very similar to the simulation model. It has several loops but the analysts is mainly interested in checking stability in the two commanded loops which are: the (γ) loop and the (p_s) loop. One loop is opened at a time and calculating its frequency response across the open ends, while the remaining loops are closed, as shown in Figure (2.4.4) below.

The Matlab file "*Frequ.m*" shown below uses this Simulink model to calculate the frequency response of the system between the open input and output and it plots the Nyquist, Nichols, and Bode plots, as shown in Figures (2.4.5 & 2.4.6). These plots are used for evaluating the phase and gain margins in analyzing stability.

```
% Frequency Response Analysis "Frequ.m"
init                                     % Initialize gains
label='Gamma Loop Opened, all other loops are Closed'
[As,Bs,Cs,Ds]= linmod('Stab_Anal');    % Frequ Response Model
sys=ss(As,Bs,Cs,Ds);                   % Perform Linearization
w=logspace(-5,4,8000);                  % and Frequ domain analysis
figure(1); Bode(sys,w); title(label); grid on
figure(2); Nichols(sys,w); title(label)
figure(3); Nyquist(sys,w); title(label)
```

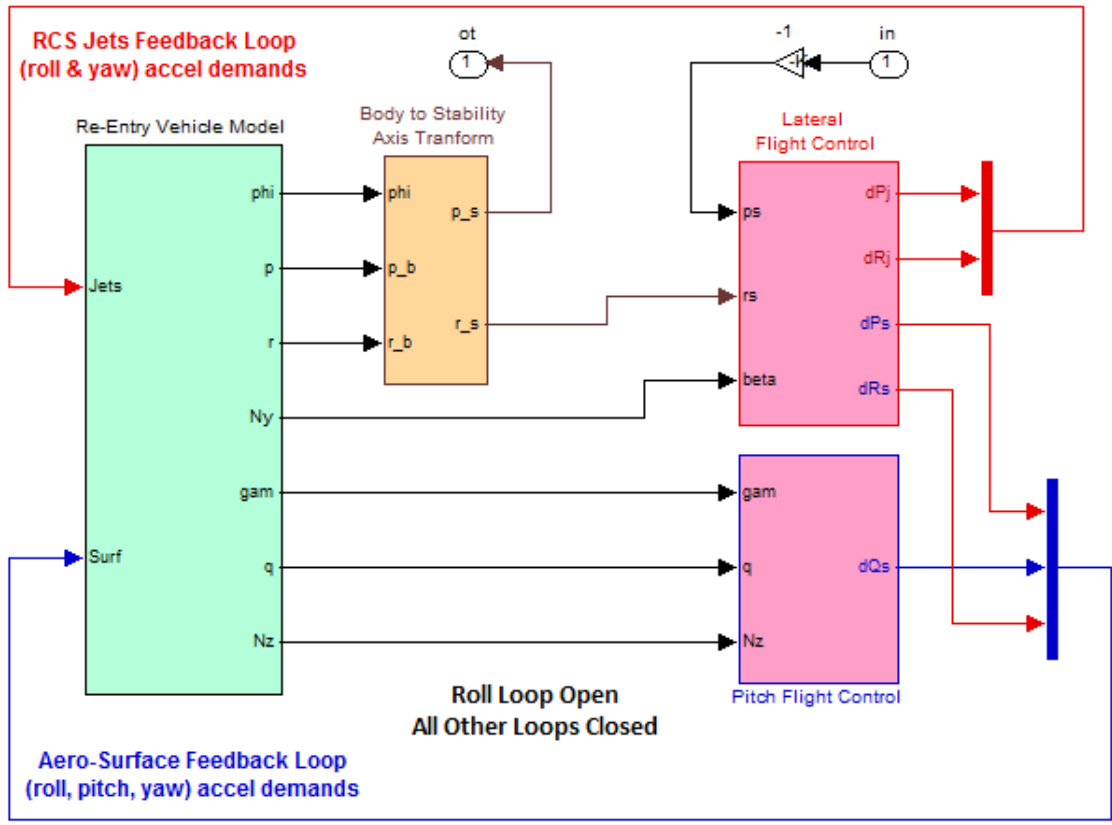
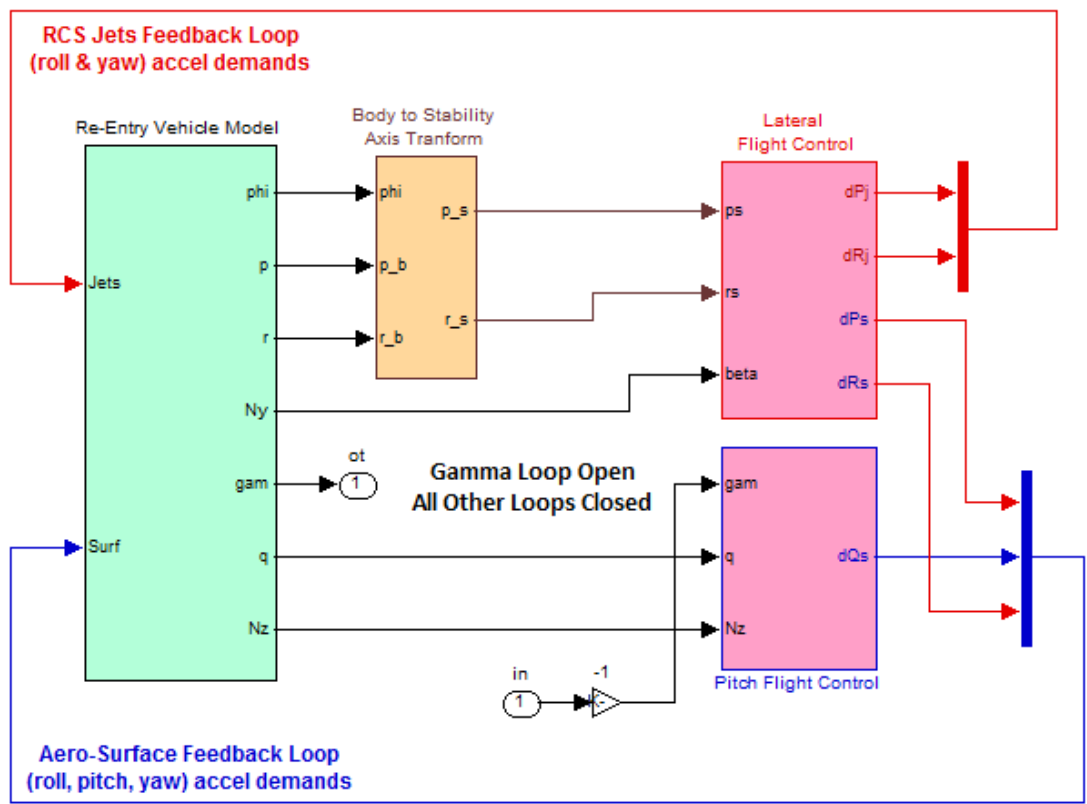
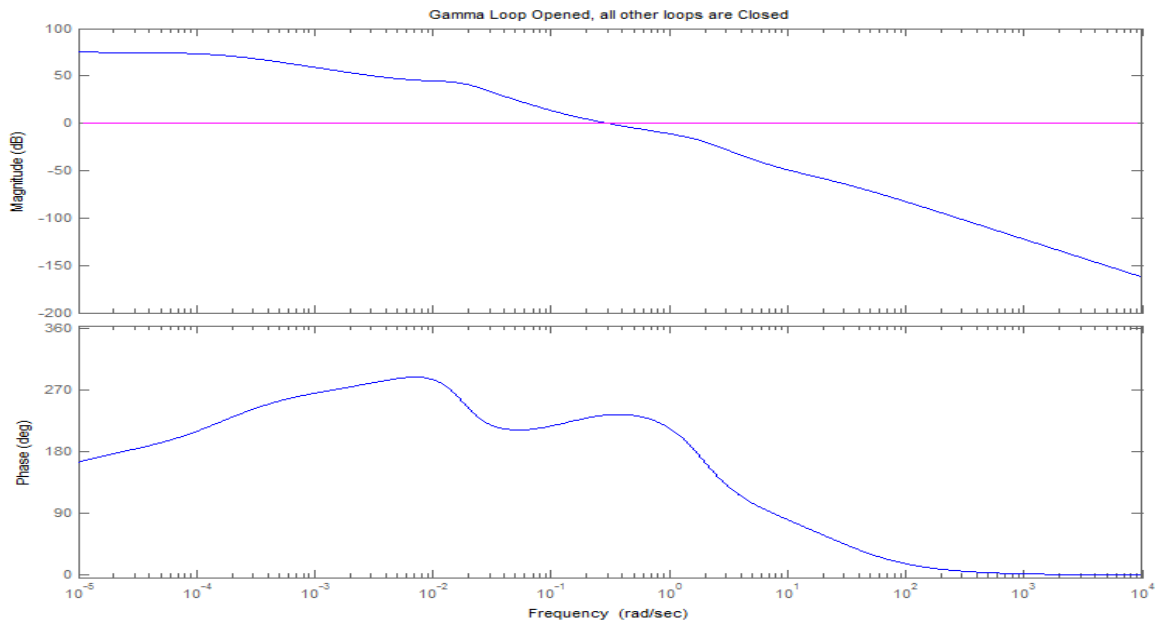


Figure 2.4.4 Simulink Model "Anal_6Dof.mdl", used for Stability Analysis



Gamma Loop Stability Margins

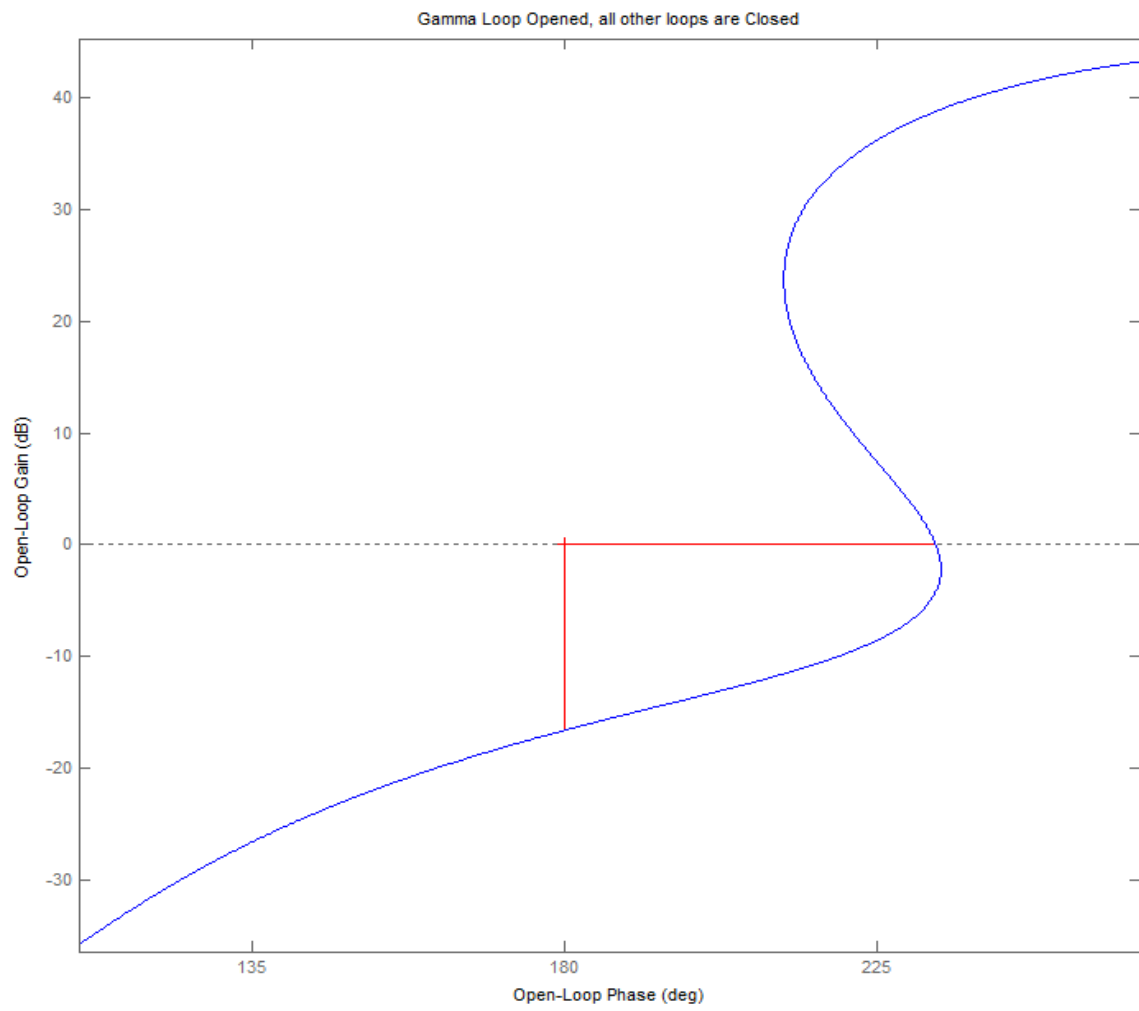
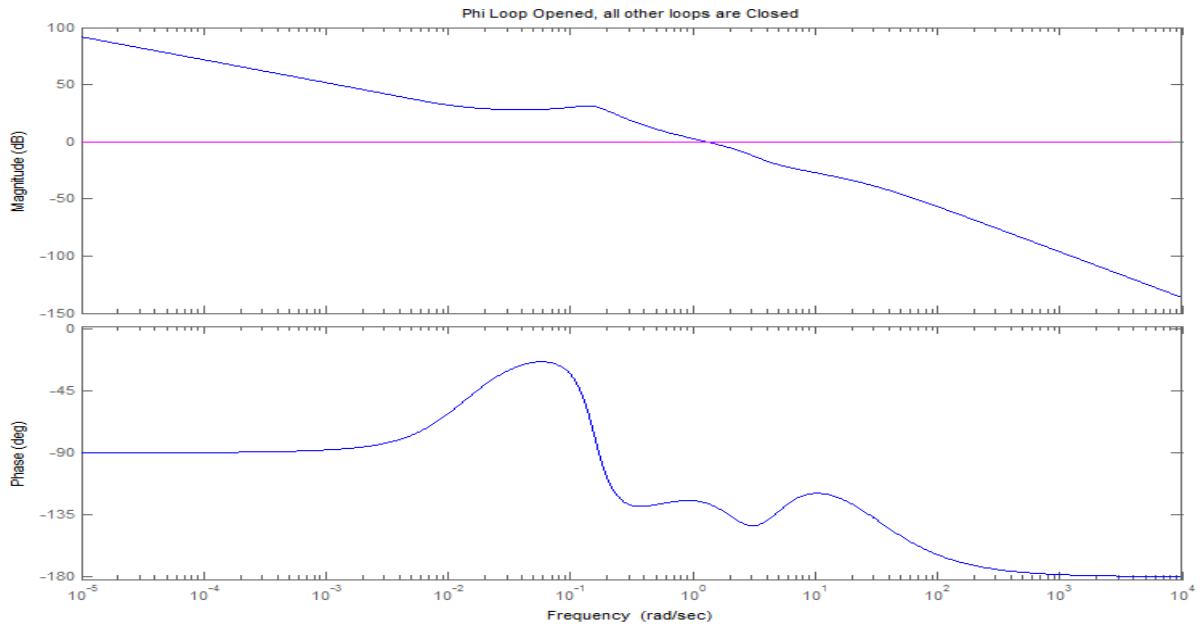


Figure 2.4.5 Gamma Control Loop Bode and Nichols, showing Stability Margins



Roll Axis Stability

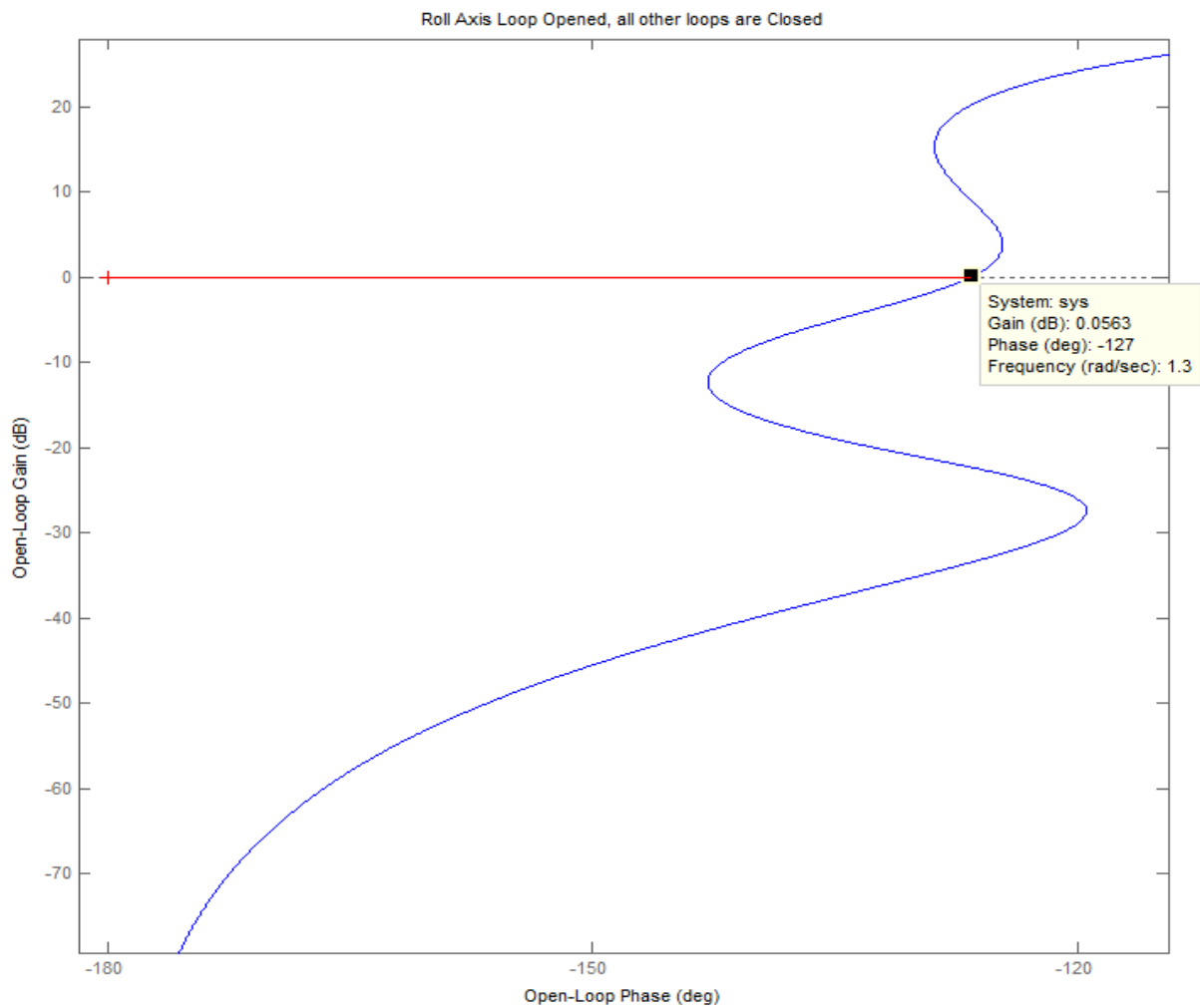


Figure 2.4.6 Phi Control Loop Bode and Nichols, showing Stability Margins

3.0 Approach and Landing Phase

The approach and landing phase begins below Mach 1 at trajectory times between 1650 and 1890 sec. The angle of attack is positive and the flight-path angle gets steeper to -21° . The max dynamic pressure is 200 psf. The vehicle banks 40° for the final maneuver to align itself with the runway. In this final period the vehicle no longer dissipates its extra energy by roll-maneuvering but it uses the speed-brake to control speed. The flight control system now controls 5 variables. In addition to roll, pitch, and yaw, it controls also the vehicle altitude by controlling vertical acceleration N_z using a combination of flaps and body-flap, and also its speed by adjusting the opening of the speed-brake.



In the final segment of the trajectory, which is in file "*X_Land.Traj*", we must trim the vehicle along the 5 controlled directions (roll, pitch, yaw, A_x , A_z) and to determine the trim deflections of the 6 aerosurfaces. This will tell us if we have sufficient control authority to fly along the trajectory. The basic aero coefficients file is the same as before, but the aerosurface coefficients file "*X_6Surf.Delt*" this time contains all 6 aerosurfaces, including the speed-brake. The bias positions are different from the previous phases. Notice that the speed-brake has only positive deflections. The analysis files for the landing phase are in folder "*C:\Flixan\ Trim\ Examples\Re-Entry Glider\Landing Phase*". The mass properties file is the same "*XR.V.Mass*". We have introduced some lateral asymmetry by shifting the YCG towards the right by a small amount of 0.1 (ft), because we want to make sure that we have sufficient control authority to land with a small CG offset. So let us begin the Flixan program, choose the landing project folder, and select the data files for this final phase. In the input/system filenames selection menu choose the default "NewFile" names, as shown below. Begin by selecting option-2 from the Trim main menu to plot the trajectory variables, as shown below.

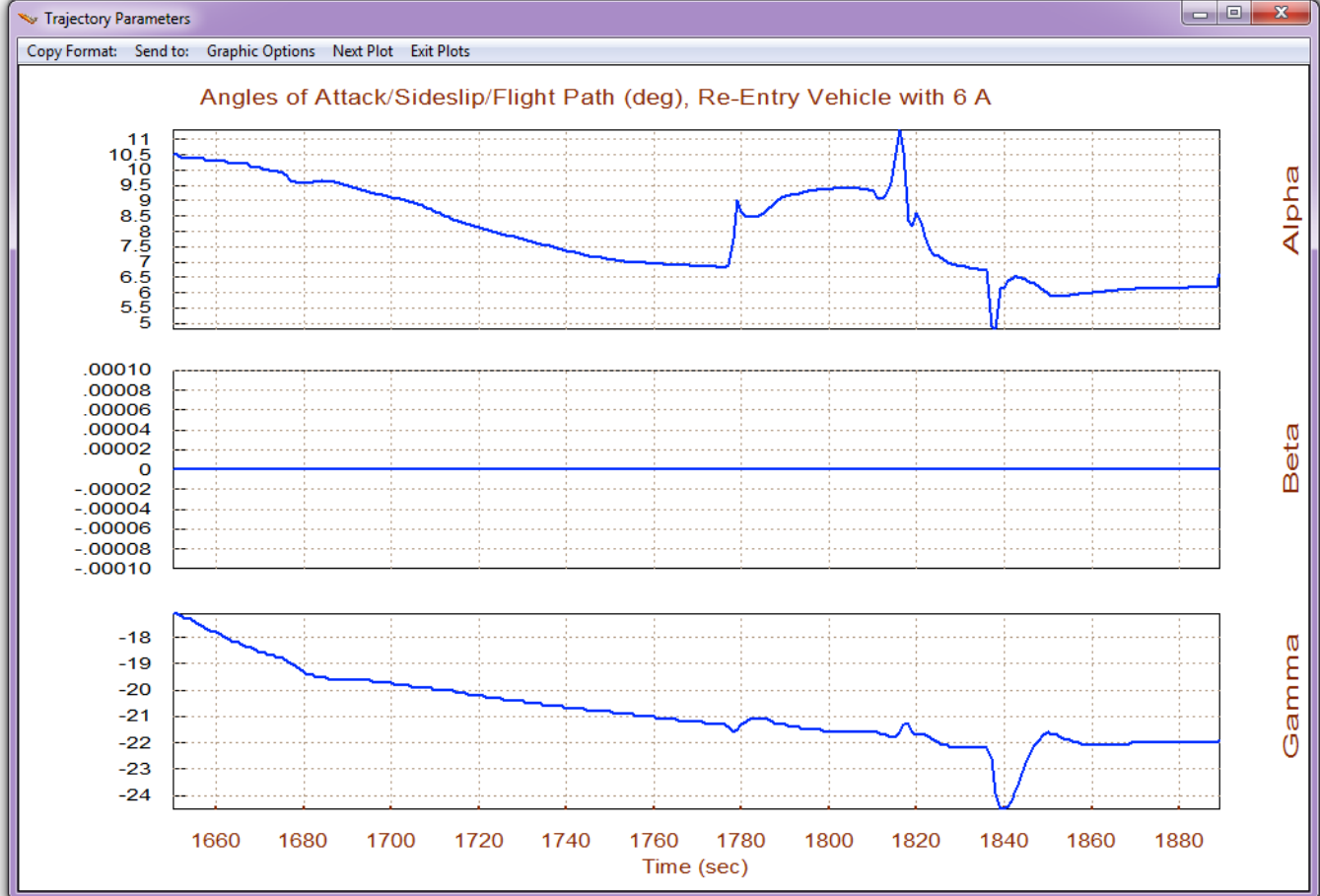
Select One Data File from Each Menu Category

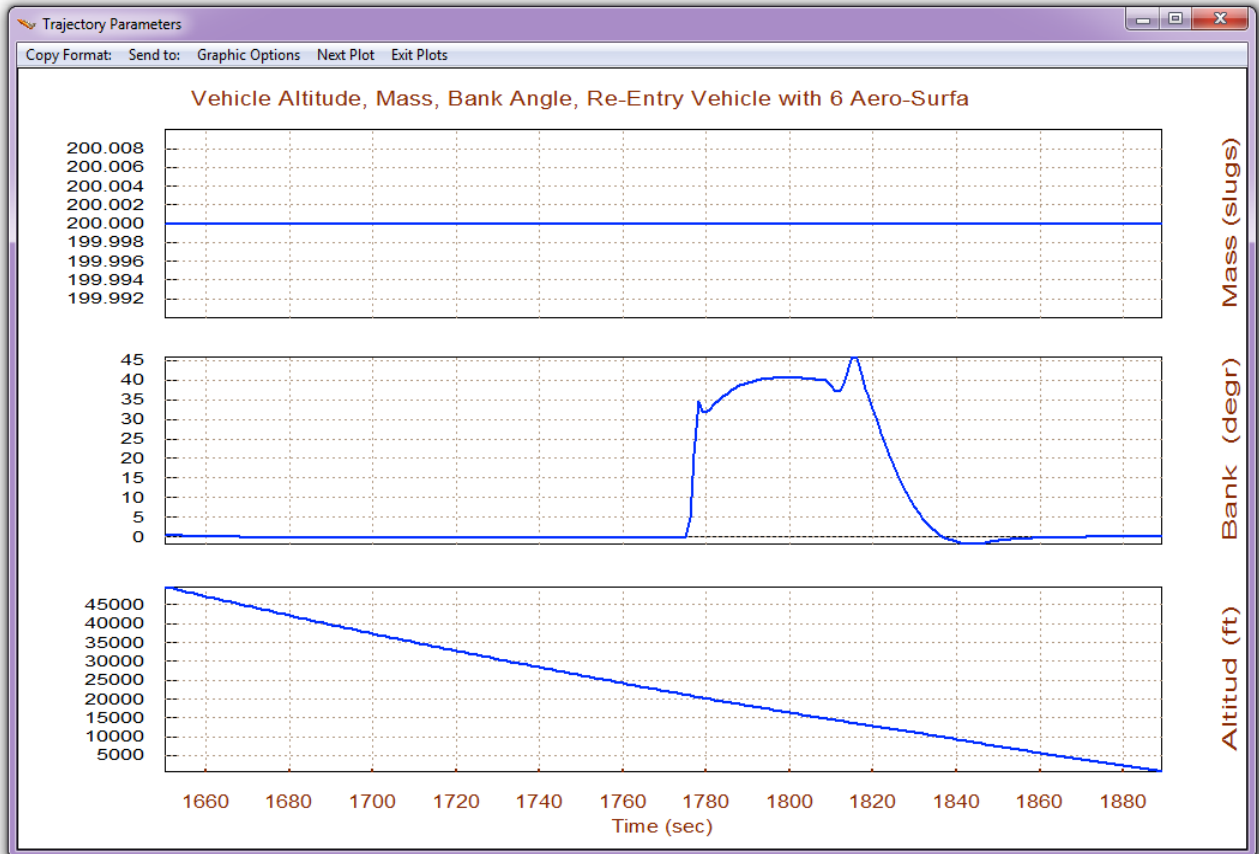
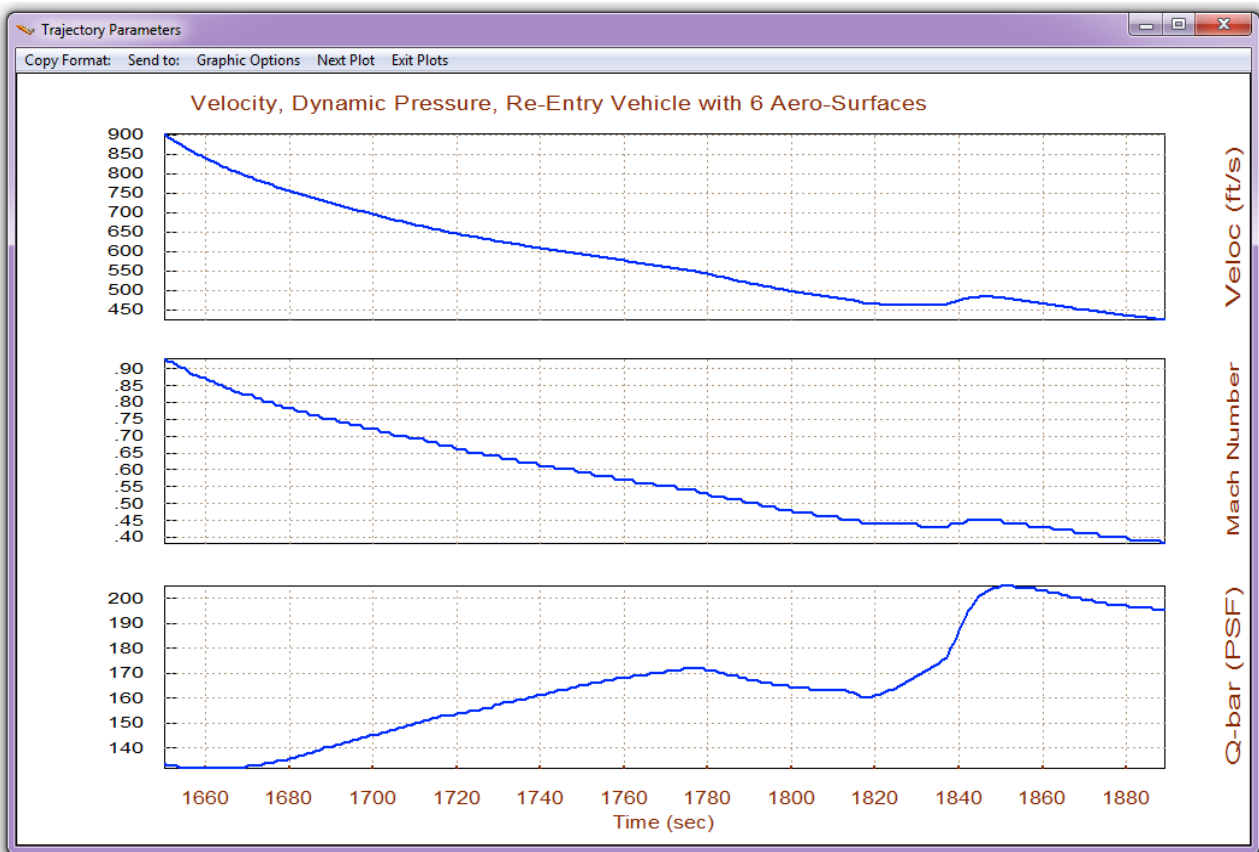
The following analysis requires some data files to be selected from the current project directory. Select one data file for each category, (some of the categories are optional).

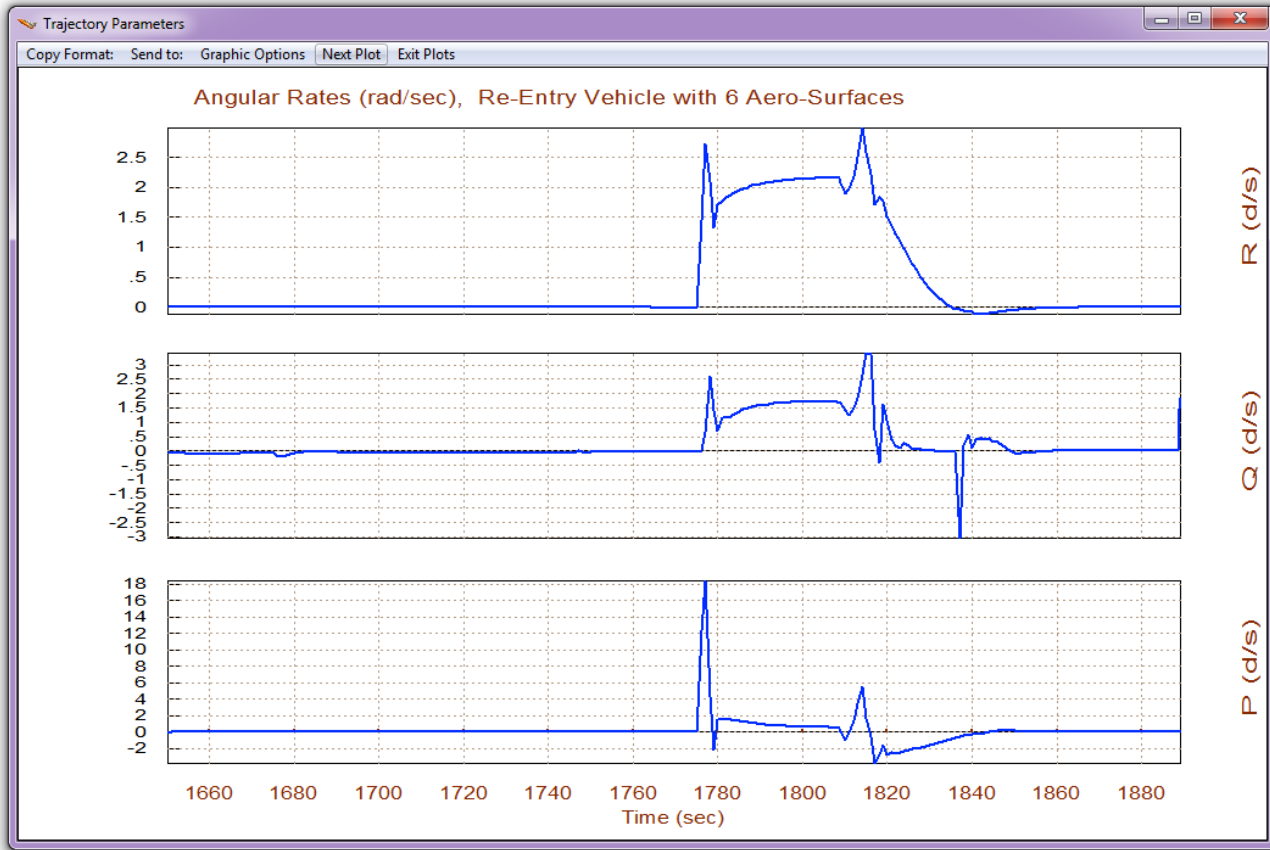
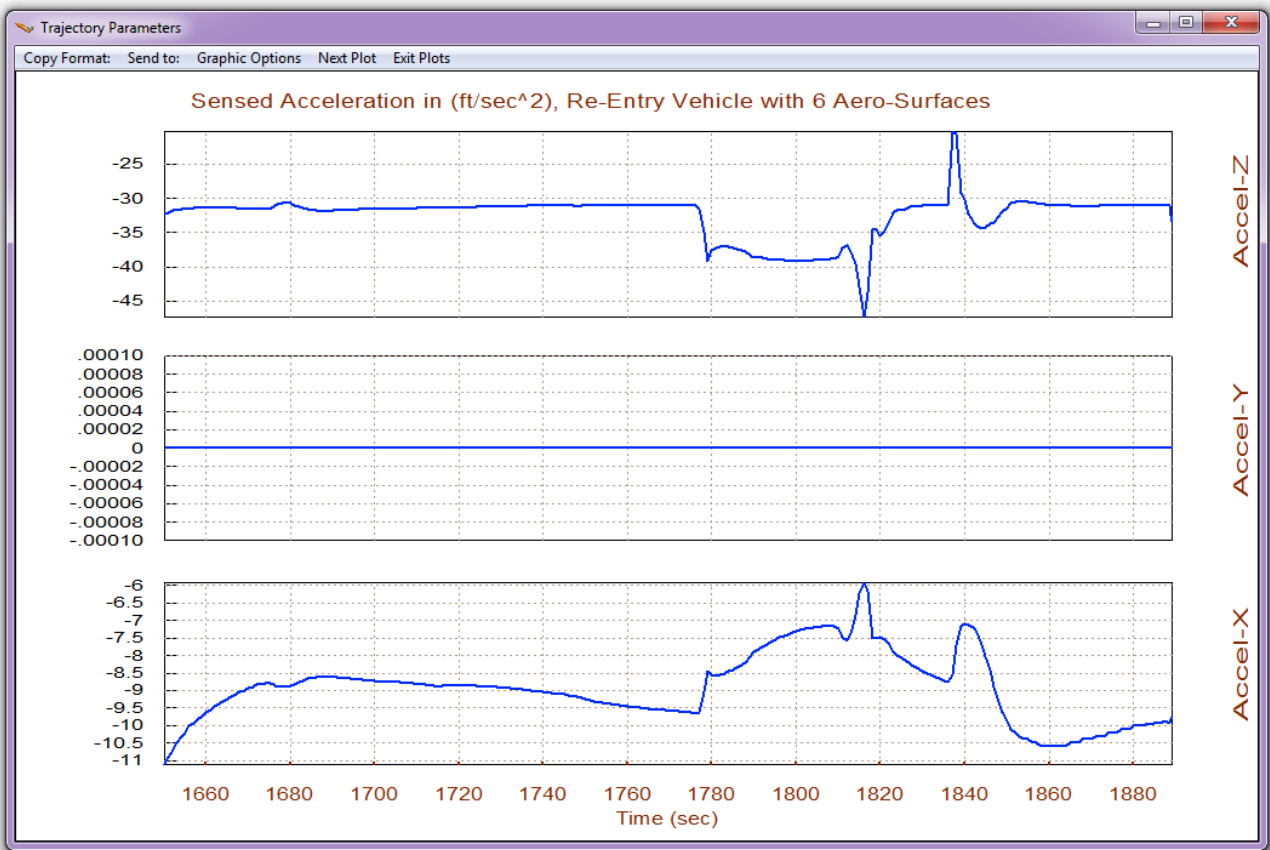
Mass Properties XRV.Mass	Surface Hinge Moments X_Hinge.HMco
Trajectory Data X_Land.Traj	Aero Damping Derivat X_Deriv.Damp
Basic Aero Data X_Basic.Aero	Propulsion Data NO DATA FILE
Contr Surface Aero Coeff X_6Surf.Delt	Aero Uncertainties Aero_Uncert6.Unce
Slosh Parameters NO DATA FILE	OK

Enter Filenames

Enter a File Name containing the Input Data (xxx.Inp)	Enter a File Name containing the Quadruple Data (xxx.Qdr)
<input type="text" value="NewFile.Inp"/> <input type="text" value="T1860.inp"/> <input type="text" value="NewFile.Inp"/>	<input type="text" value="Kmix.qdr"/> <input type="text" value="Kmix.qdr"/> <input type="text" value="NewFile.qdr"/> <input type="text" value="T1860.Qdr"/> <input type="text" value="NewFile.Qdr"/>
Create New Input Set	Exit Program Select Files

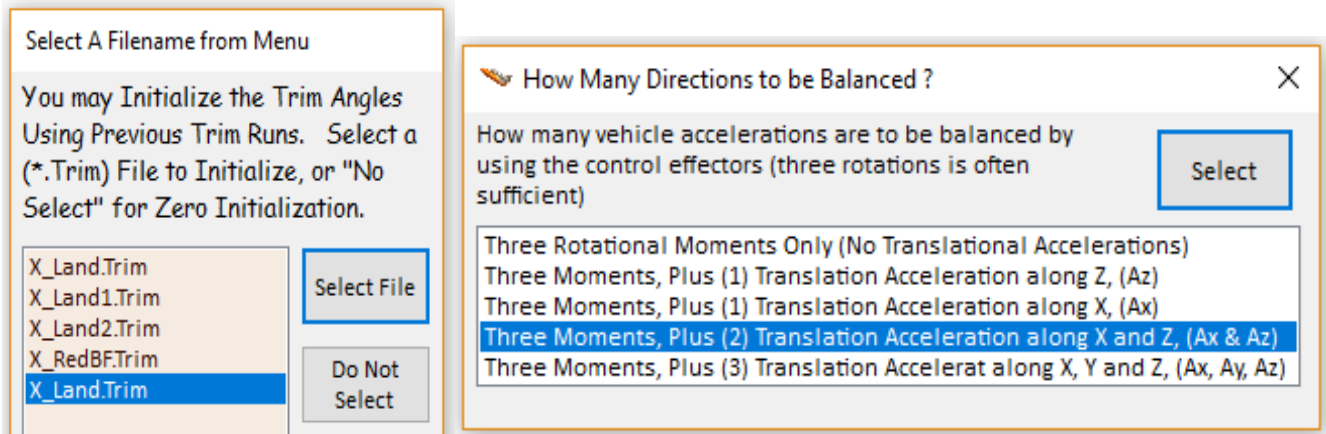




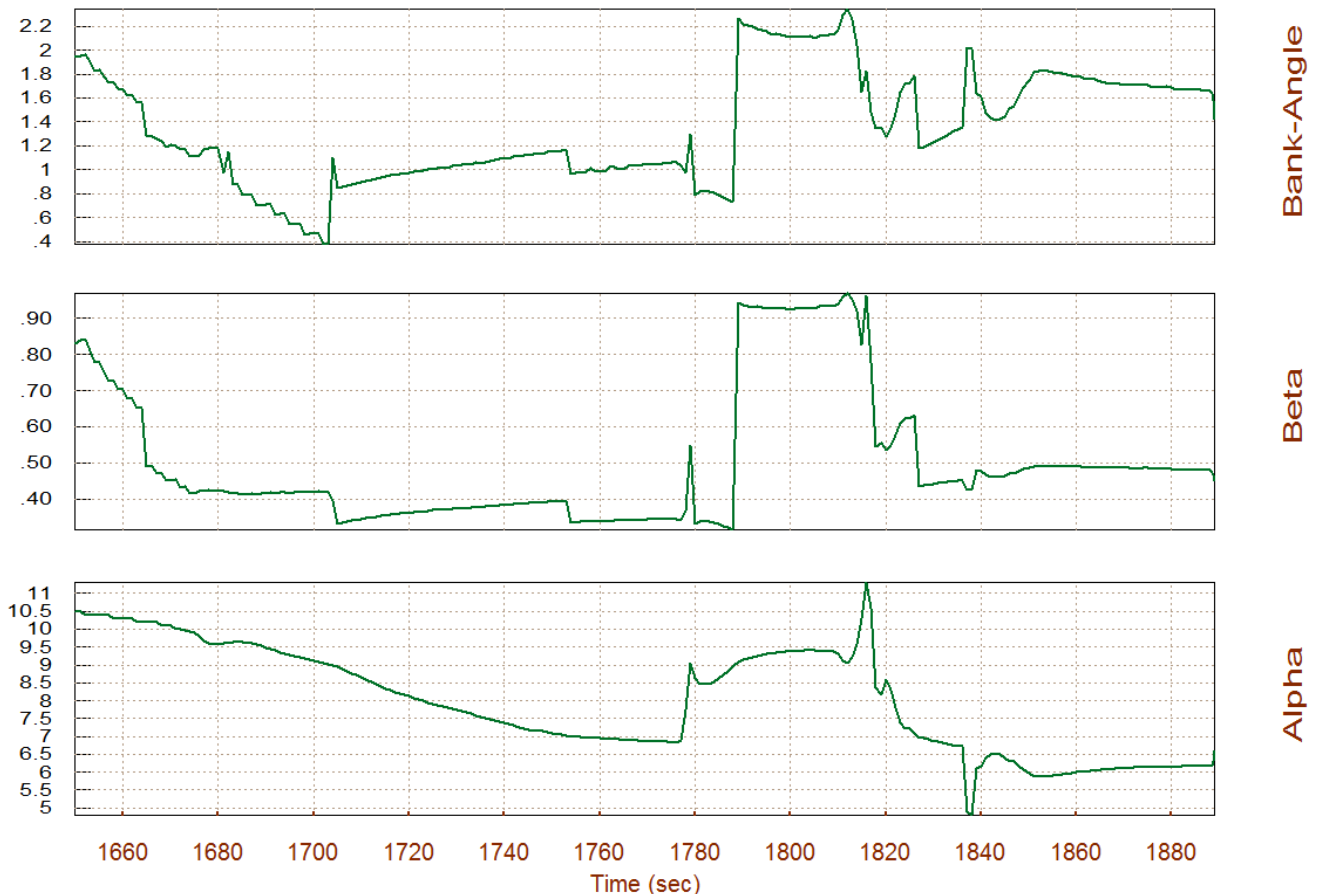


3.1 Trimming

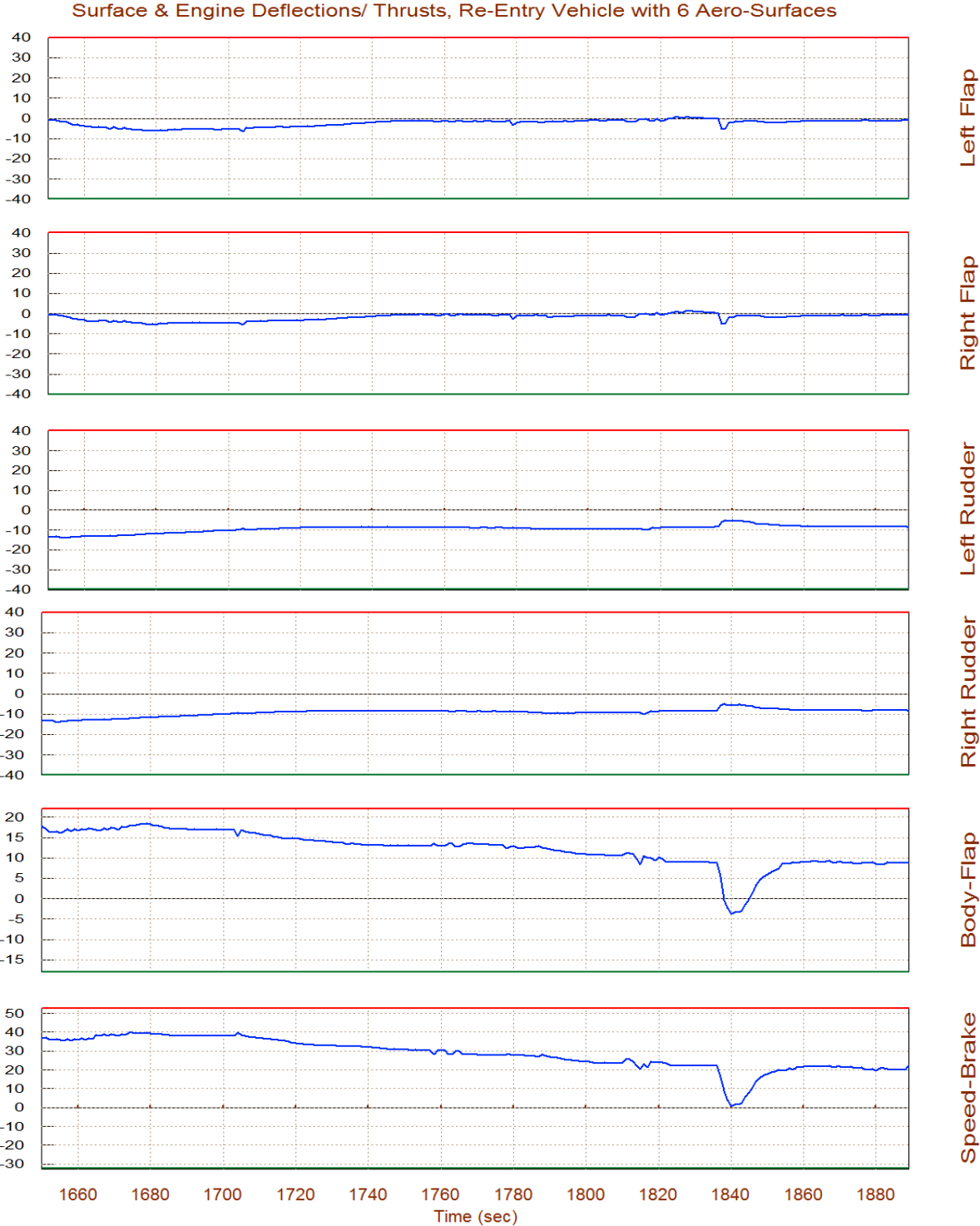
Return to the Trim main menu and choose option-3 to trim the 6 aerosurfaces. In the following menu do not select a filename to initialize the Trim program since it is the first time and there isn't one yet. In the following menu we now select the 4th option to trim along 5 control directions: all 3 moments plus normal and axial accelerations. The next plot shows that the YCG offset causes a small sideslip beta, plus a couple of degrees of banking towards the right.



Alpha, Beta, and Bank Angle (phi), Assuming Effectors are Trimmed (deg)

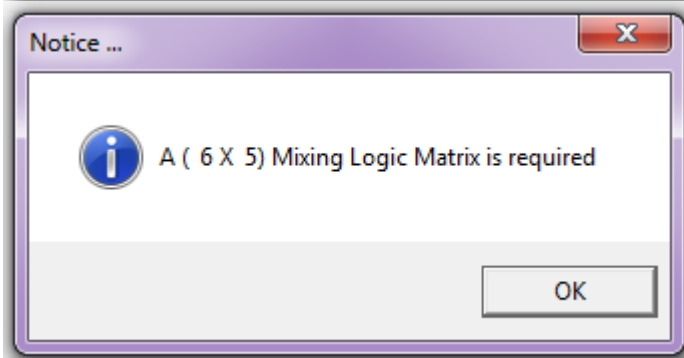
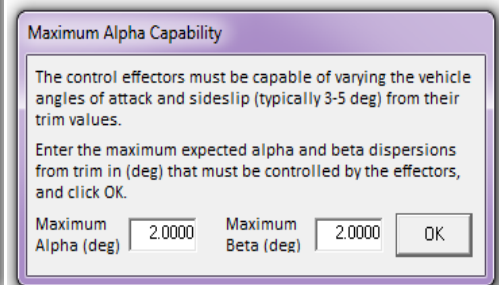
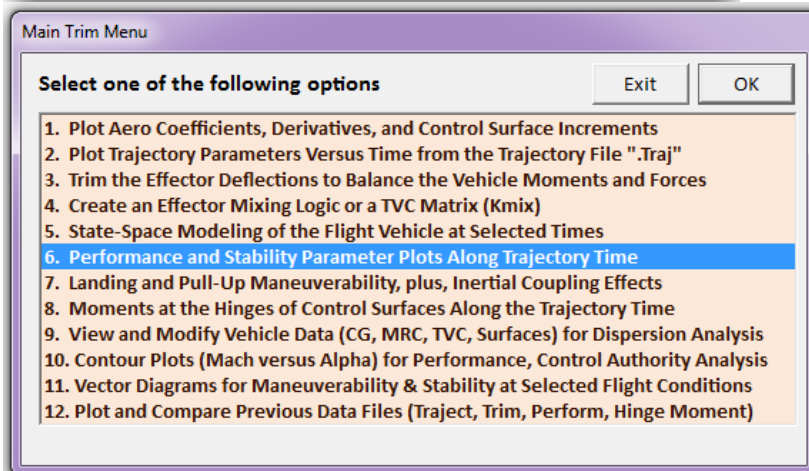
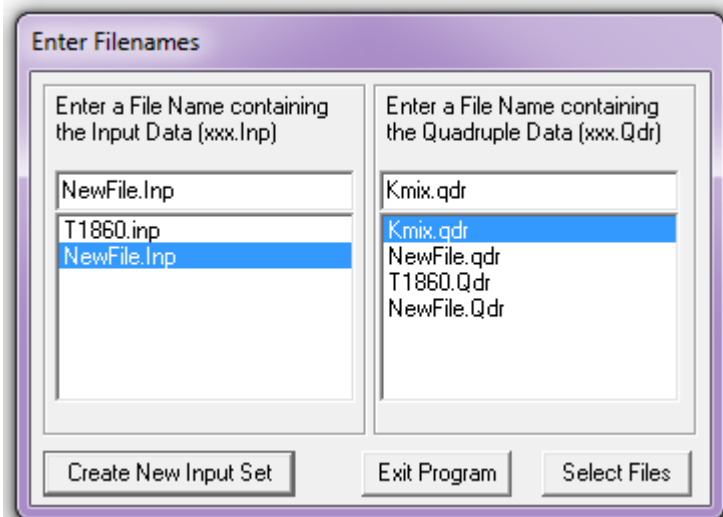


The next two plots show the deflections of the 6 aero-surfaces which are trimming the vehicle in 5 directions along the trajectory. The speed brake opening adjusts the acceleration to match the axial acceleration defined in the trajectory. Notice that it is partially opened at 40° to allow space for modulating drag. Notice also the symmetric negative deflections of the two V-tail rudders which provide the necessary positive alpha. The trim deflections of the aerosurfaces are acceptable and there is no need for any trimming adjustments for now.



3.2 Performance Analysis along the Trajectory

Make sure that the file Kmix.Qdr containing the aerosurfaces mixing matrix is selected before starting the Trim program. Return to the Trim main menu and select option (6) to check the performance parameters along the trajectory using the previously calculated trim deflections. Enter 2° for α_{max} and β_{max} which define the dispersions in this phase due to wind-shear. Then from the dialog that selects the effector combination logic choose the first option to select a matrix already created in file Kmix.Qdr, and select matrix Kmix_1861 from the next menu.



Define the Effector Combination Matrix

The Mixing Logic Matrix translates the Flight Control (Roll, Pitch, Yaw, Ax, Ay, Az) demands to Effector commands (Aero-Surface, TVC, and Throttling). You may either select a pre-calculated Mixing Logic Matrix (Kmix) from the Systems File: Kmix.qdr, or let the program calculate it

When you create a new Mixing Logic you have the option of adjusting the participation of each effector in the combination matrix. Maximum contribution is 100%. Select this option for 100% participation from all effectors.

There are times, however, when you want to reduce their contributions. Plus some effectors are only used for Trimming and not for Control. Their participation should be set to 0% in the effector combination calculations.

Select a Mixing Matrix from Systems File

Create a Mixing Matrix Using All Effectors at 100% Participation

Create a Mixing Matrix by Adjusting the Effector Contributions

Select a Gain Matrix

Select one of the following Matrices from the Systems File

View Matrix Cancel Select Matrix

KMIX_1860 : Mixing Logic for Re-Entry Vehicle with 6 Aero-Surfaces at Time: 1860.0

KMIX_1861 : Mixing Logic for Re-Entry Vehicle with 6 Aero-Surfaces at Time: 1860.1

Matrix Name: KMIX_1861 Save Changes Exit

Mixing Logic for Re-Entry Vehicle with 6 Aero-Surfaces at Time: 1860.1 Matrix Title

Inputs Outputs Matrix Description

This Mixing Logic Matrix eliminates the independent use of Az control but it attempts to use only pitch to control normal accelerat indirectly. This increases controllability in the remaining directions.

Select an Input or Output variable from the menu above and press Edit. Then you may type in a new description for that variable in the field above.

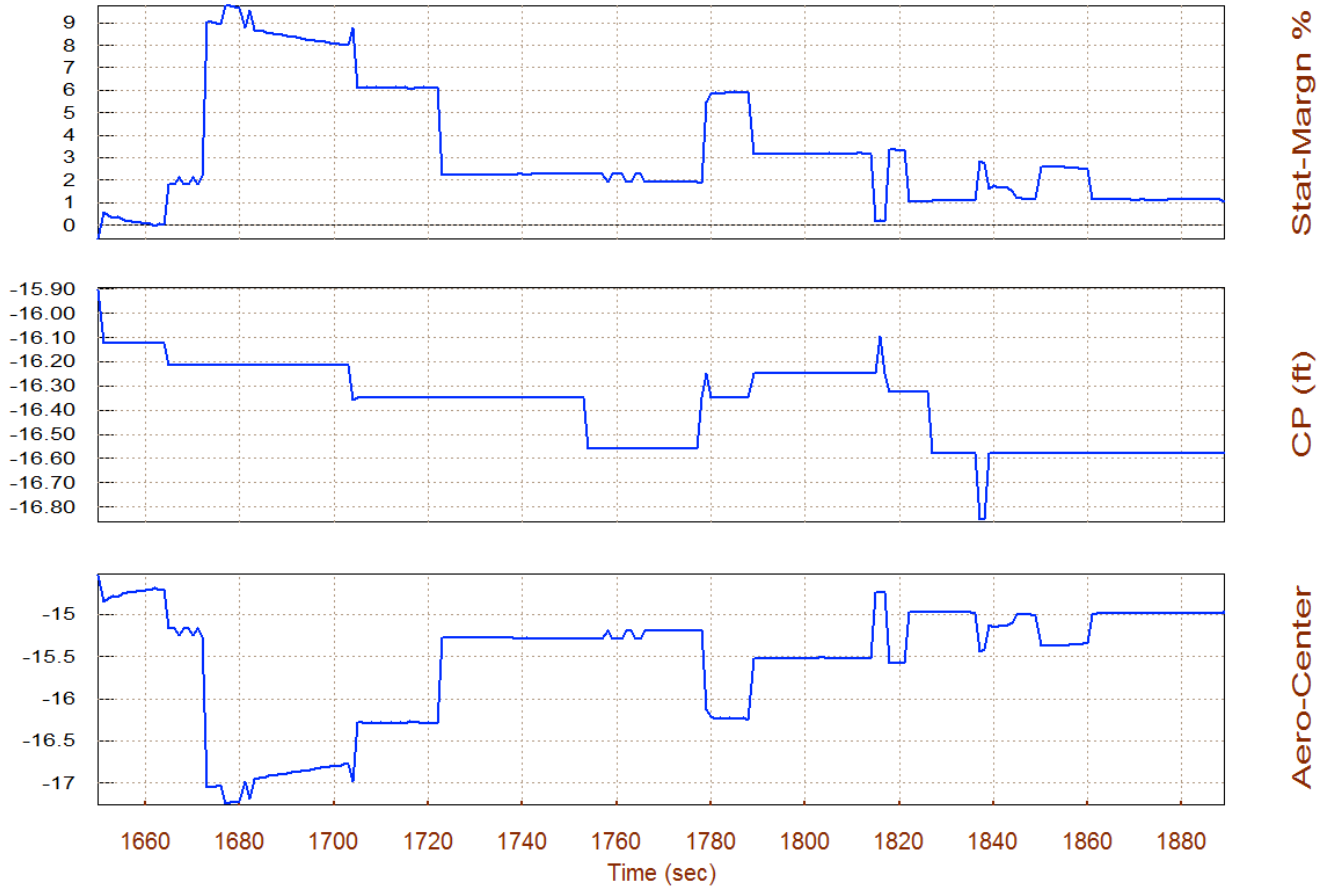
Repeat to change other Inputs, Outputs, or Matrix Elements. Then click on "Save Changes" to save the new values and titles or Exit the dialog.

Matrix Element: (1, 1)= 0.50000000E-01 0.50000000E-01

To Create a New Matrix, Click on the Elements, Enter New Values and Push on "Save Changes"

The 5th column of this aero-surface mixing-logic matrix that controls z-acceleration is set to zero. The matrix controls only roll, pitch, yaw, plus axial acceleration. Even though the 6 aero-surfaces are capable to provide control in all 5 directions, however, there is no need to independently control pitch and Az. We included the z-axis in trimming but we are not controlling it independently of pitch. It reduces control authority if you spread the control in too many directions.

Static Margin, Center of Pressure, Aero-Center (ft), Re-Entry Vehicle with 6 Aer

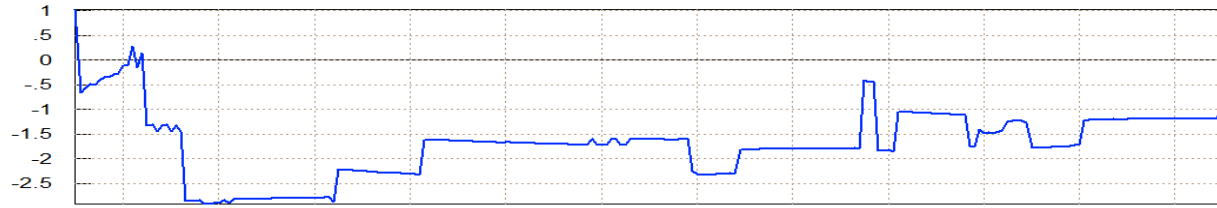


The static-margin and the pitch T2-inverse parameters are telling us that overall the pitch axis is statically stable with a short period resonance of about 1.5 to 2.5 (rad/sec). Initially, for the first 15 seconds, it is neutrally stable to unstable with 1 sec time to double amplitude. The lateral axis is also statically stable with an average Dutch-Roll resonance of 2 (rad/sec). The (Q-alpha, Q-beta) load for a wind disturbance of (α_{max} and β_{max})=2°, is below 1800 (psf-deg), which is also acceptable.

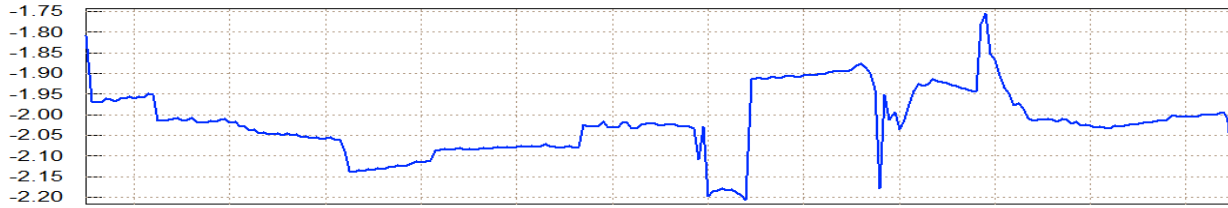
The $C_n\beta$ -dynamic parameter is positive indicating that the vehicle is directionally stable in this phase. The LCDP ratio is also consistently positive which indicates that dynamic roll controllability is satisfactory without any undesirable roll-reversals. It momentarily drops below 0.25 during the bank maneuver. The bank angle “phi” parameter near landing with a cross-wind $\beta_{max}=2^\circ$ is 7°. It is a little higher than expected. We like to see it below 5°.

The control authority plots (3-rotational plus x-translational) show that the vehicle has the control authority required to trim against the α_{max} and β_{max} disturbances not only about the three moments (roll, pitch, and yaw) but also along the x direction, with plenty of margins left to respond against gusts, guidance commands, and maneuvering. The control efforts are less than 0.5 in all 4 directions.

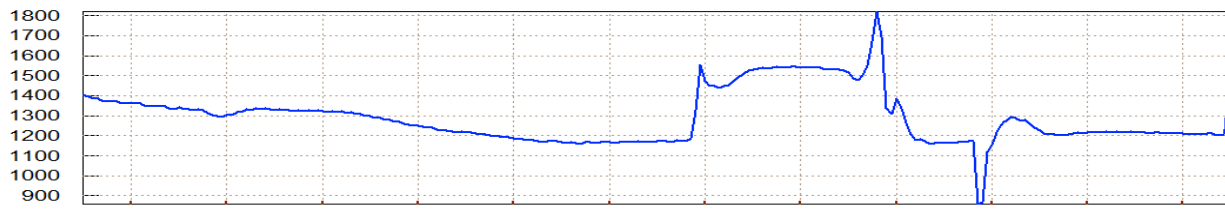
Short-Period (w/ Time-to-Double-Ampl-Inverse (/sec), Q_alpha_beta (deg-lb/ft^2)



Ptch T2-inv



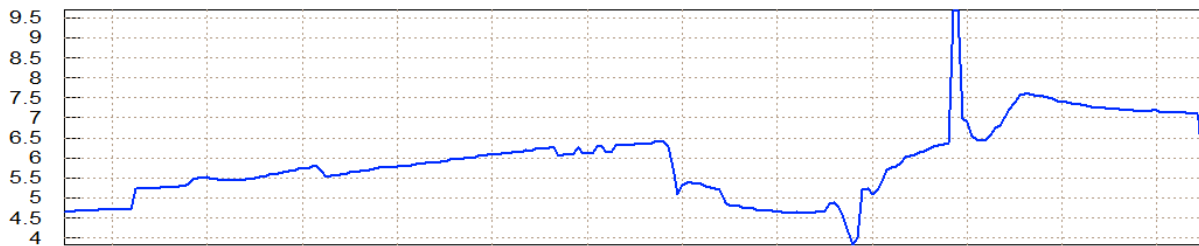
Yaw T2-inv



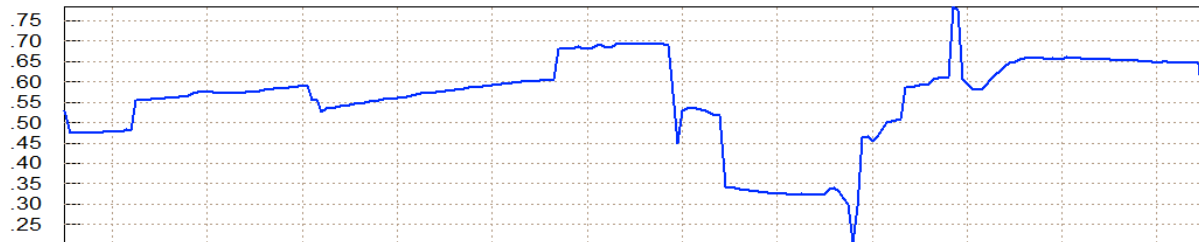
Q_alfabet

Time (sec)

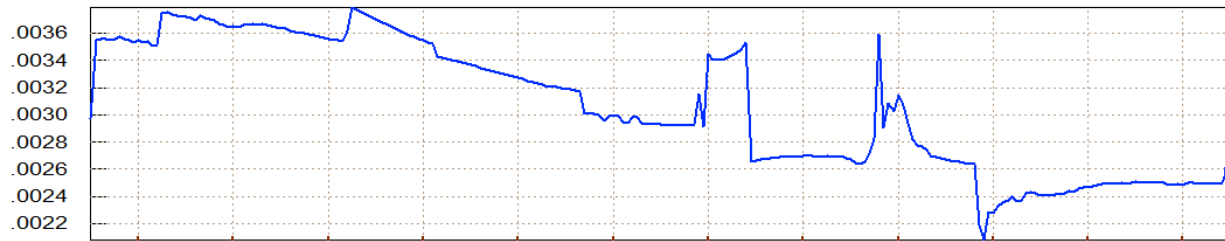
Bank Angle, LCDP Ratio, Cn_beta_dynam /deg, Re-Entry Vehicle with 6 Aero-Surface



phi (deg)



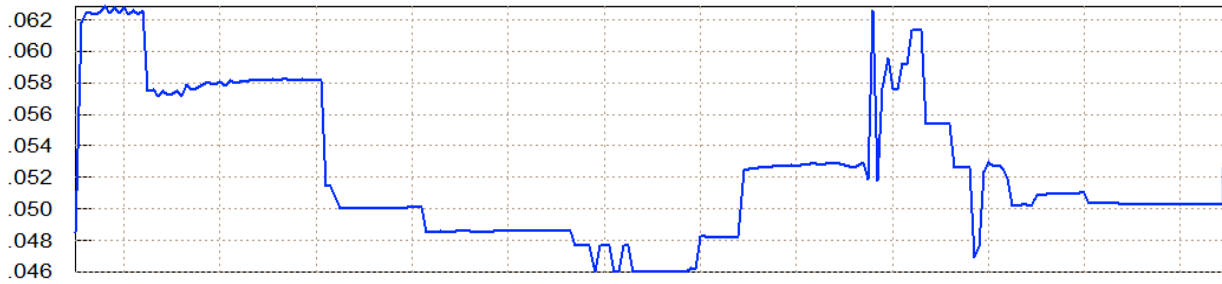
LCDP



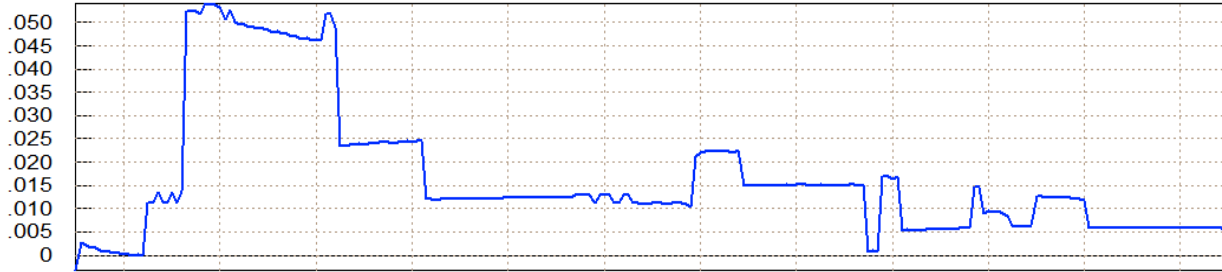
Cnbet-dyn

Time (sec)

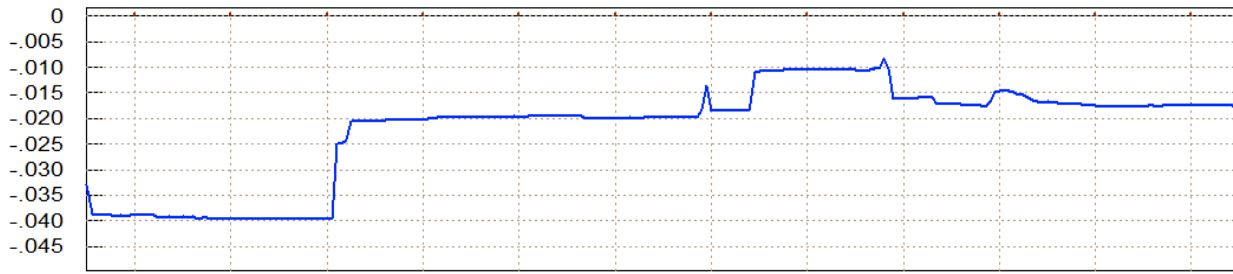
Rotation Control Authority (dQ/dQ_{max}) < 1 for 2 (deg) of Alpha & Beta Variation



Roll Effort



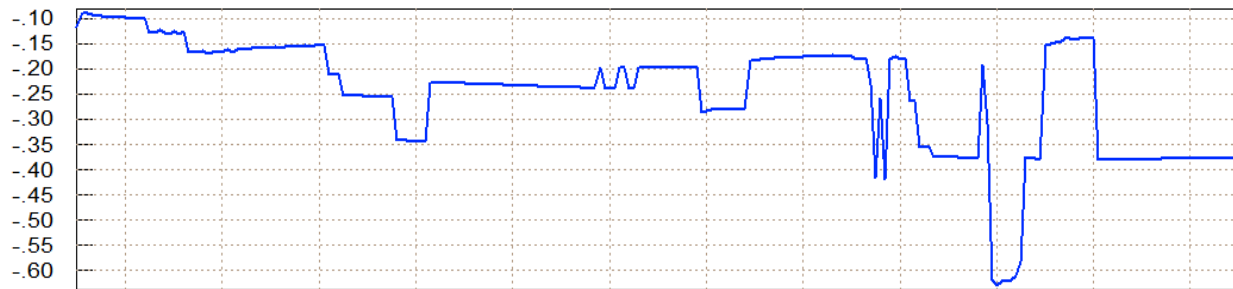
Pitch Effort



Yaw Effort

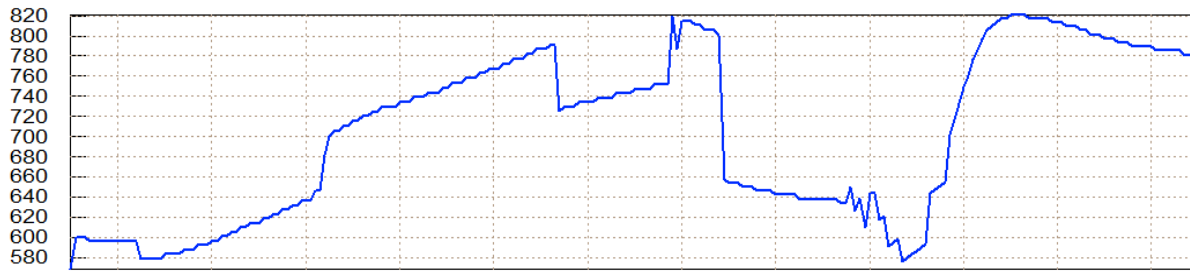
1660 1680 1700 1720 1740 1760 1780 1800 1820 1840 1860 1880
Time (sec)

Translation Control Authority (dX/dX_{max}) < 1 for 2 (deg) of Alpha/ Beta Variation

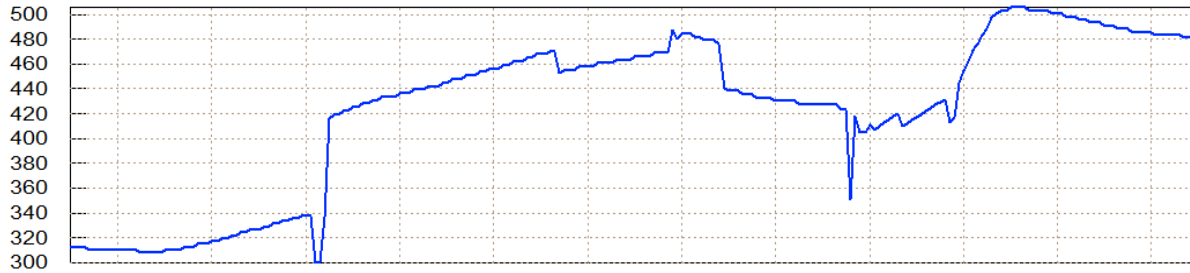


dX / dX_{max}

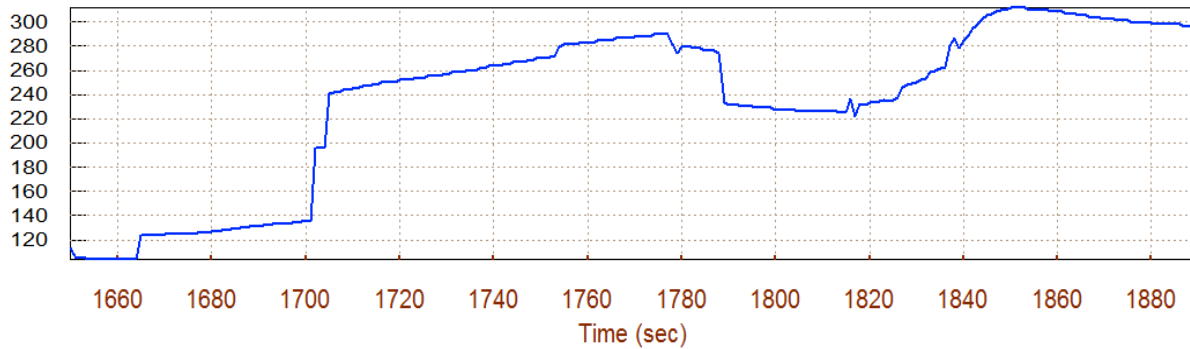
Max Angular Accelerat (deg/sec²), at Max Control Demand Re-Entry Vehicle with 6



P dot (Max)

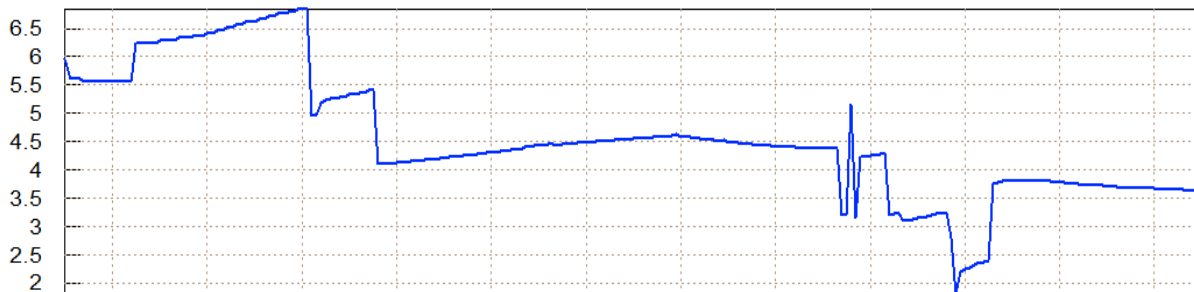


Q dot (Max)



R dot (Max)

Max Linear Accelerat. (ft/sec²), at Max Control Comd Re-Entry Vehicle with 6 Ae

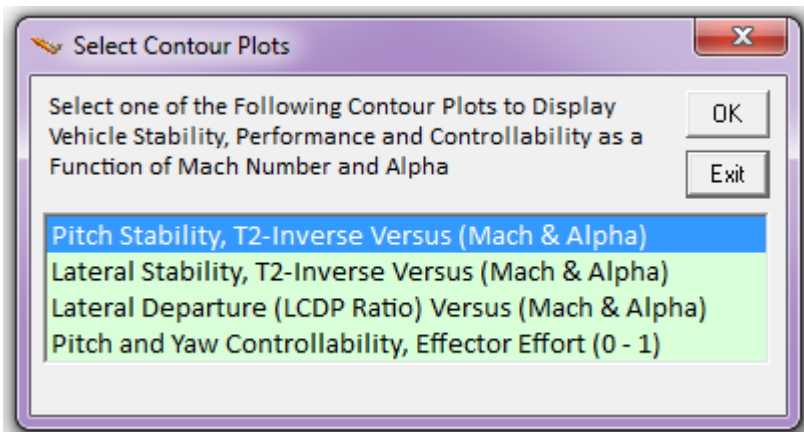
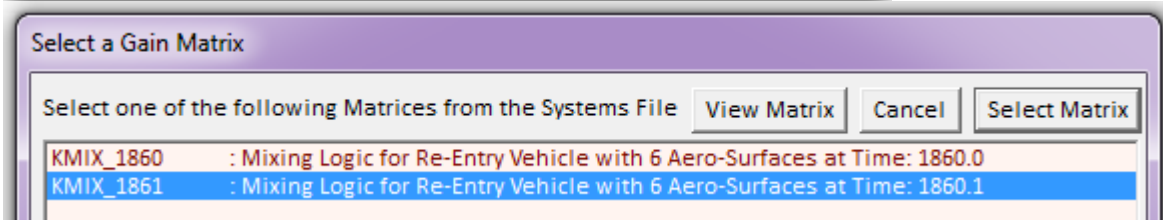
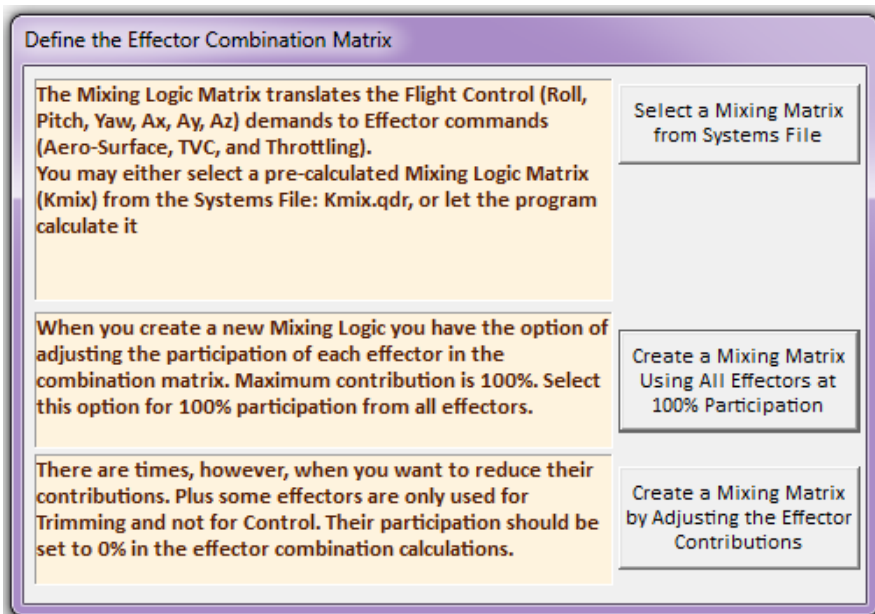


X-accel(Max)

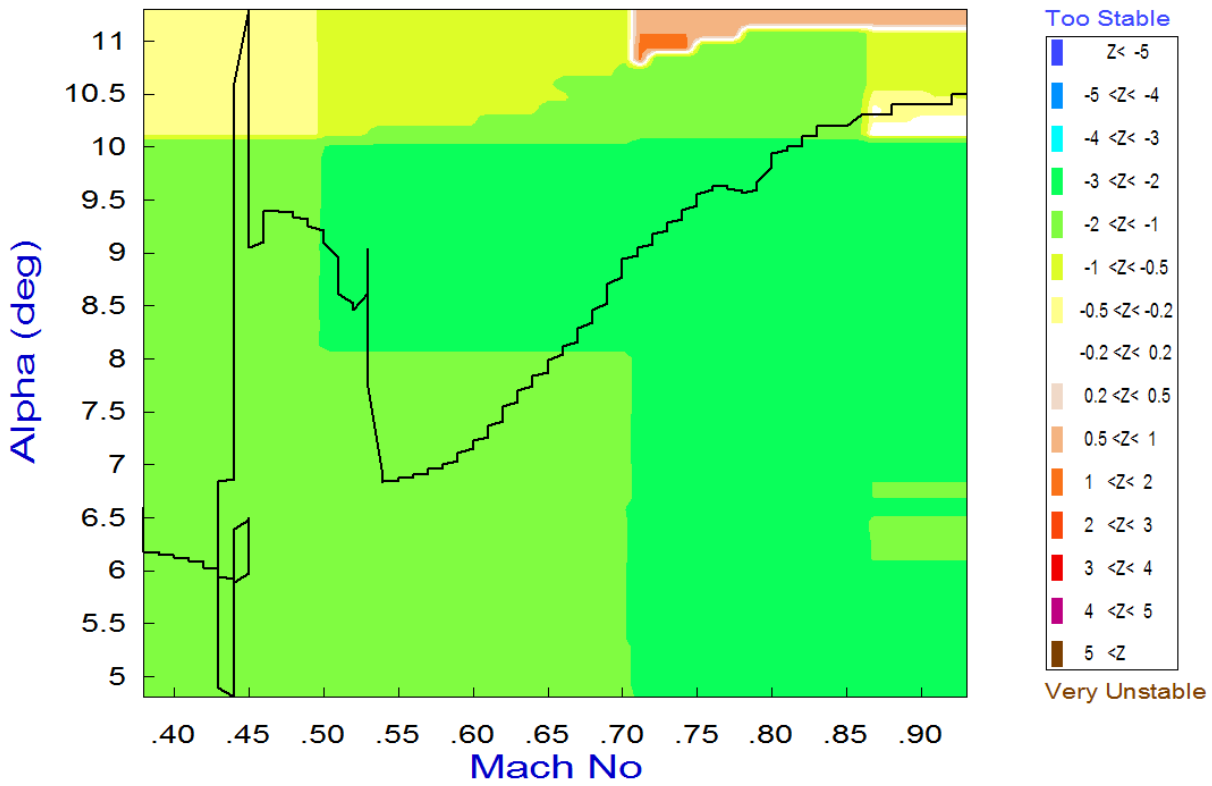
The last plots show the maximum accelerations that can be achieved by the effectors system before at least one of the effectors saturates. These values strongly depend on the effector mixing logic. In fact most performance parameters depend on the mixing logic matrix.

3.3 Performance Analysis Using Contour Plots

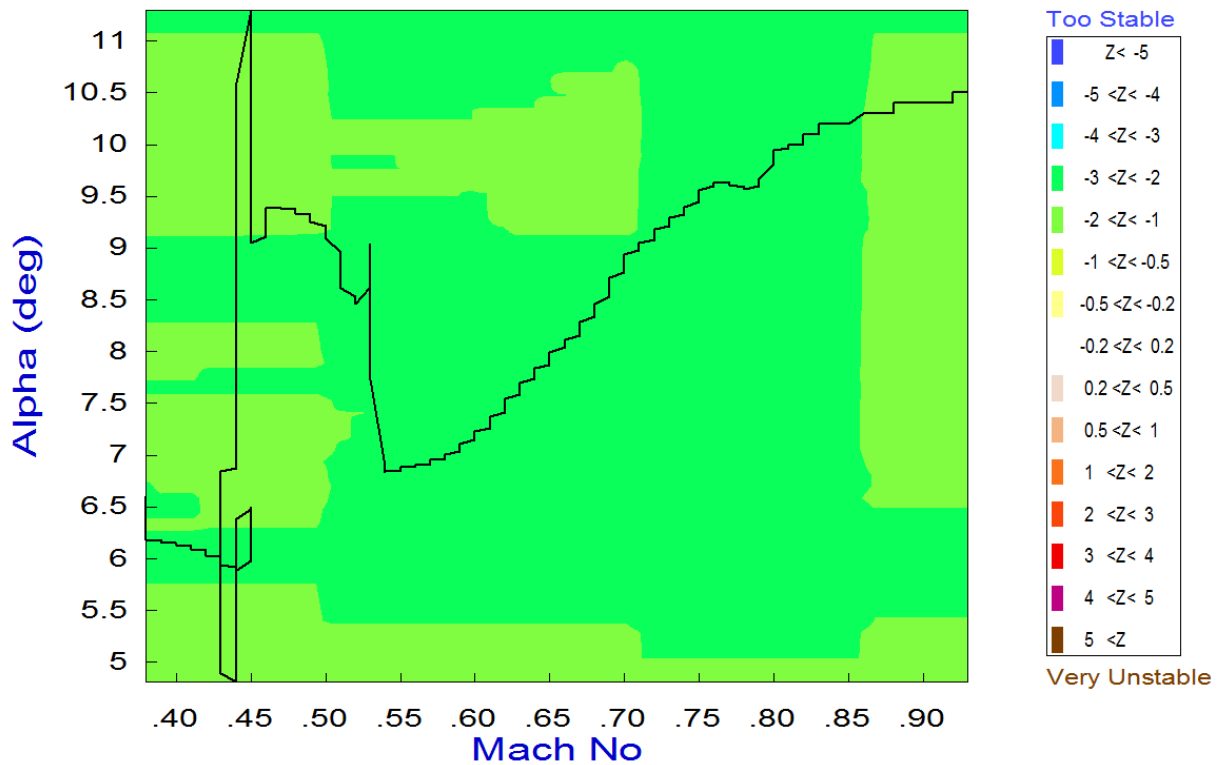
The contour plots are created by selecting option-10 from the Trim main menu. Select 2° for the α_{\max} and β_{\max} wind-shear disturbance, as before, and from the following dialog choose the first option to select the aerosurface mixing matrix Kmix_1861 from file Kmix.Qdr. The LCDP contour plot shows that the surface mixing matrix provides an acceptable LCDP ratio without reversals. The remaining plots are also acceptable.



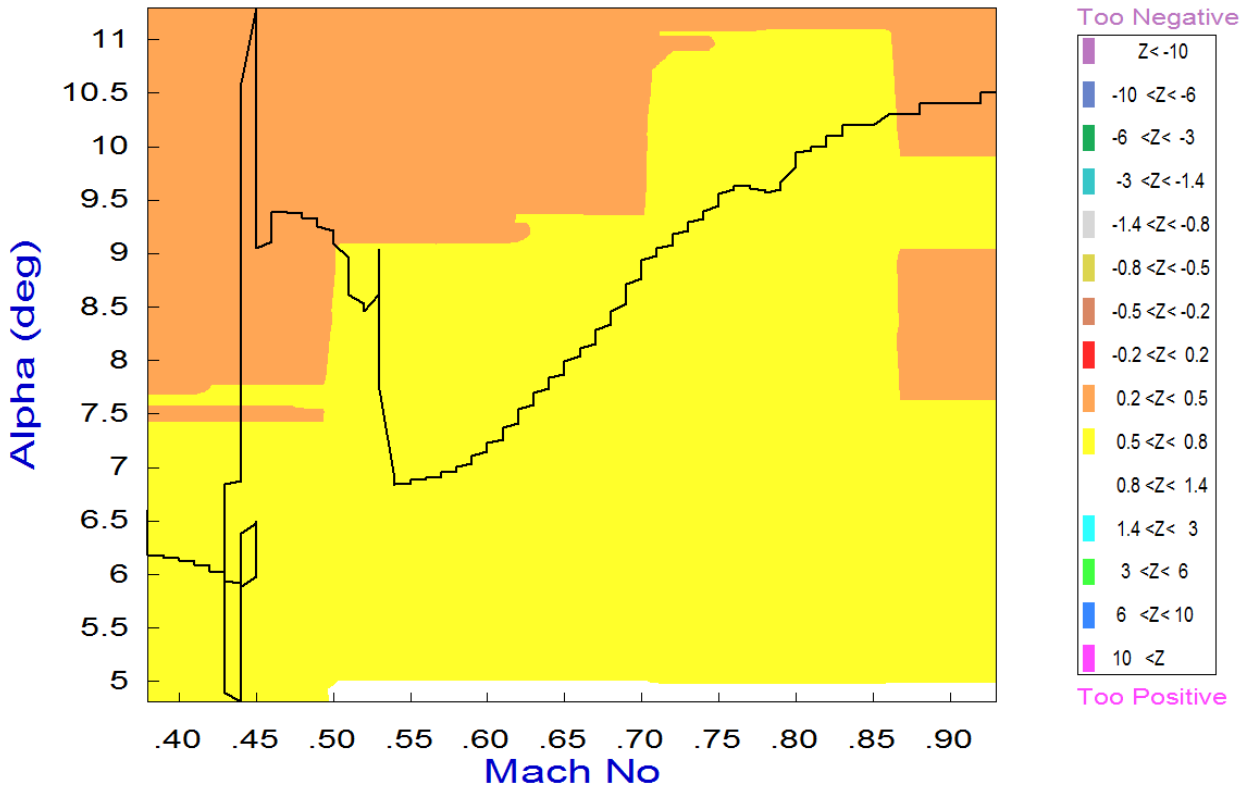
Pitch Stability Contour Plot (Mach vs Alpha)



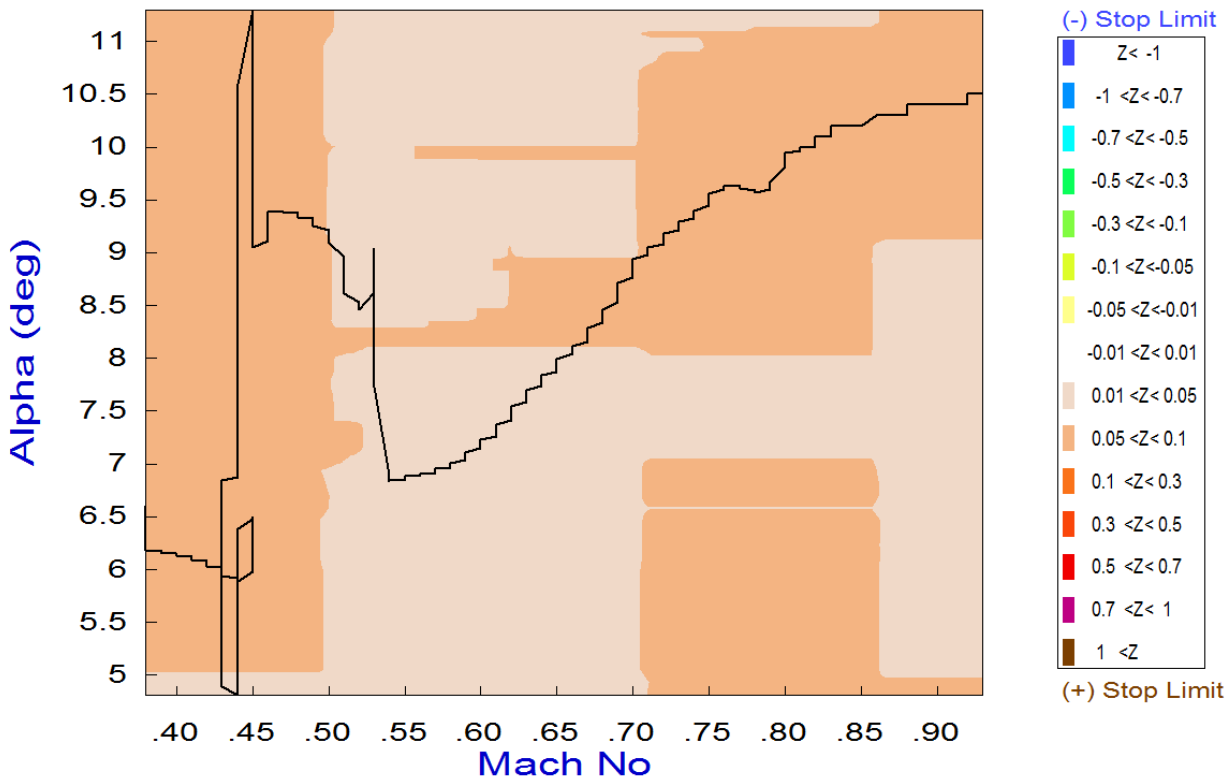
Lateral Stability Contour Plot (Mach vs Alpha)



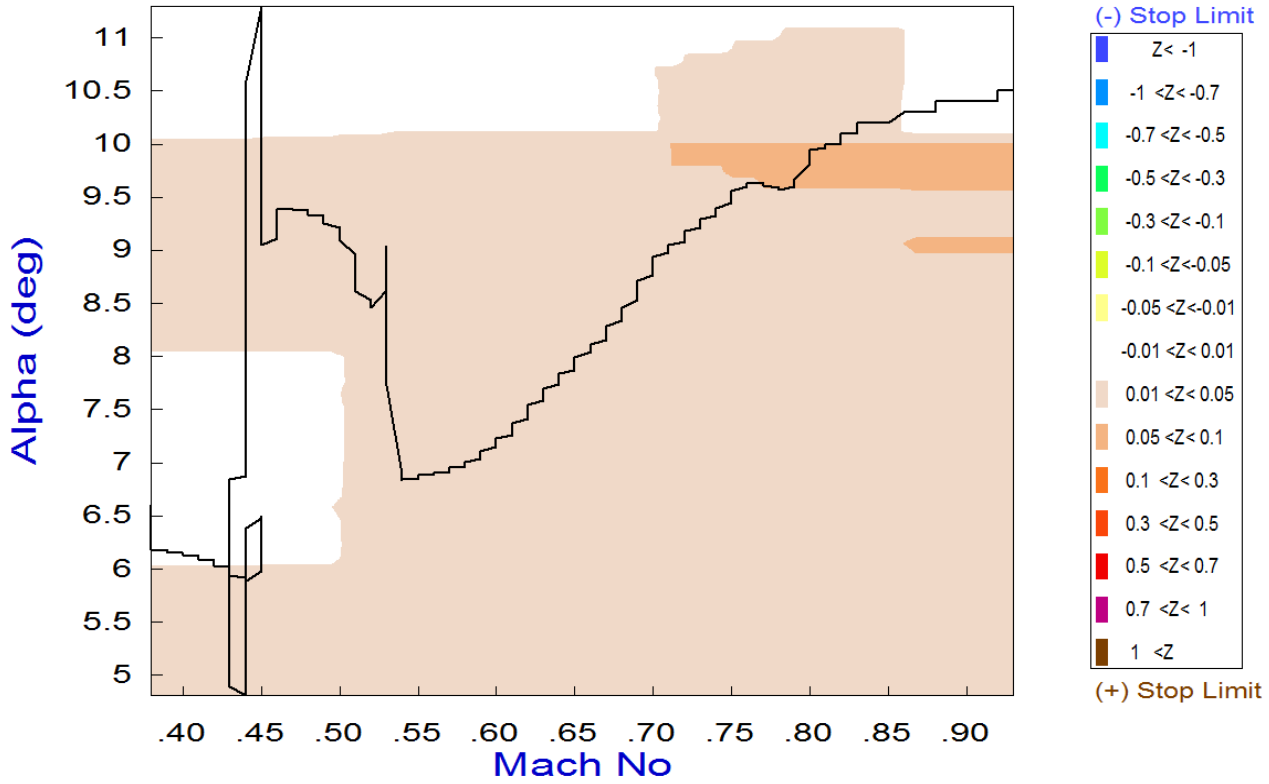
Roll Departure (LCDP) Contour Plot (Mach vs Alpha)



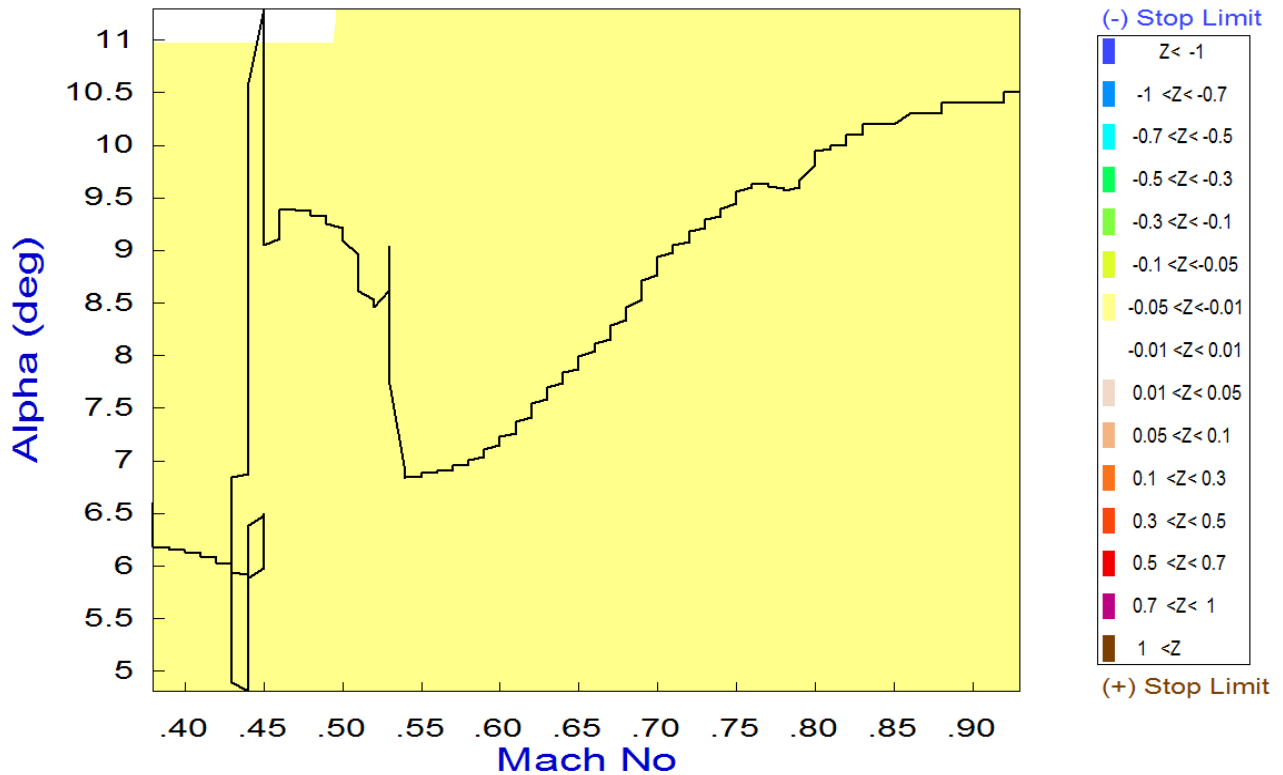
Roll Control Effort Contour Plot (Mach vs Alpha)



Pitch Control Effort Contour Plot (Mach vs Alpha)



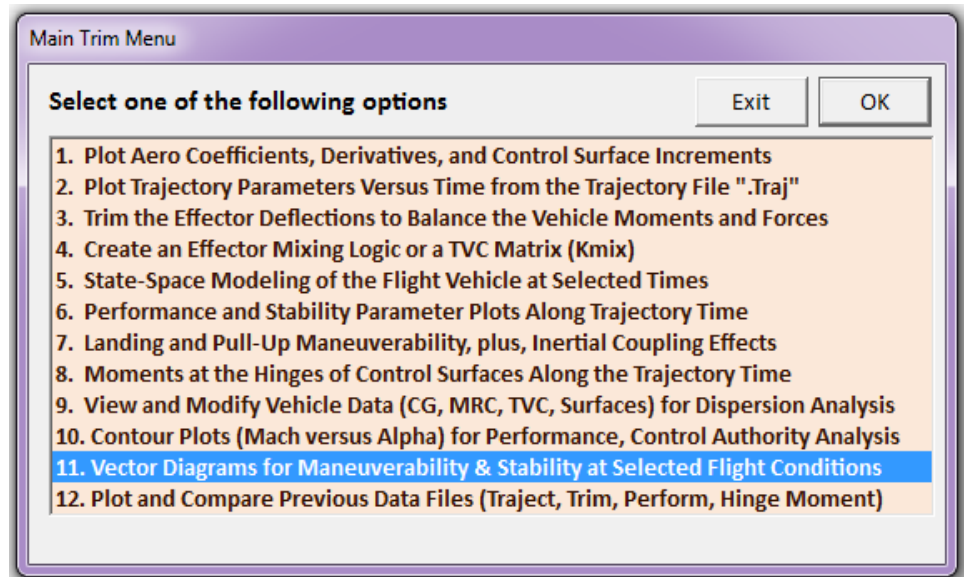
Yaw Control Effort Contour Plot (Mach vs Alpha)



3.4 Controllability Analysis Using Vector Diagrams

Vector diagrams are 2-dimensional plots used for analyzing the vehicle controllability at a specified flight condition. We compare the control capability of the effectors system against the effects on the vehicle of a wind disturbance that is defined by dispersions in the angles of attack, sideslip, and also airspeed variations. They also help us analyze the orthogonality of the control system, compare the acceleration magnitudes due to the controls and wind, and to determine if the controls are powerful enough and their directions are properly aligned to counteract the disturbance effects along the controlled directions, which in this case they are four: roll, pitch, yaw and axial acceleration. Since vector diagrams are limited to 2 directions we typically need several plots to check control authority in multiple directions. We will analyze a flight condition towards the end of the trajectory, near landing. We prefer this case because the speed-brake is active in controlling velocity during this period, plus we would also like to illustrate the advantage of using multiple aero-surfaces towards achieving independent control in more than three directions. In this approach and landing phase it is very important to control altitude and this is accomplished via N_z control. Theoretically it is not difficult to achieve control in multiple directions including axial and N_z . However, the control system must have the authority to counteract the aerodynamic disturbances in those directions otherwise there is no point in controlling them. Even though it is possible to control N_z independently of pitch, it does not benefit much because N_z can also be controlled by pitch control. By reducing the controllable degrees of freedom from 5 to 4 it improves the control authority in the remaining 4 DOFs.

From the Trim menu select option-11, and then a flight condition to analyze, at $t=1800$ sec, which is within the range where the speed-brake is partially deployed and it can provide variations in drag, and therefore speed control. Our flight control system during this period must be configured to independently control 3 rotations, plus axial acceleration. The following dialog consists of menus for selecting the vehicle mass, Mach number, alpha, and beta. Select the default values which correspond to this flight condition and click on "Select". The disturbances are defined by the maximum alpha and beta dispersions produced by the winds which are $\pm 2^\circ$ in this case. Select also the top option from the next dialog to read the (6x5) control surface combination matrix "Kmix_1861" from file Kmix.Qdr, as shown.



Select a Time from: (1650.0 to 1889.1) to Analyze Vehicle Controllability OK

1800

Select the following parameters

Select a Vehicle Mass, Mach Number, Alpha, and Beta from the lists below and click "Select" Select

Vehicle Mass (slug)	Mach Number	Angle of Attack (deg)	Angle of Sideslip (deg)
198.00	0.4000	10.0	0.00
201.00	0.4000	10.0	-5.00
198.00	0.6000	12.0	0.00
	0.8000	14.0	5.00
	0.9000	16.0	
	0.9500	18.0	
	1.050	20.0	
	1.100	22.0	
	1.200	24.0	
	1.500	26.0	

Maximum Aero Disturbances


The control effectors must be capable of varying the vehicle angles of attack and sideslip (typically 3-5 deg) from their trim values.

Enter the worst expected alpha and beta dispersions in (deg), and also delta-velocity in (ft/sec) from trim that must be controlled by the effectors, and click OK.

Maximum Alpha (deg) Maximum Beta (deg) OK

Maximum Change in Velocity due to Wind in (feet/sec)

Notice

 A (6 X 5) Mixing Logic Matrix is required

OK

Define the Effector Combination Matrix

The Mixing Logic Matrix translates the Flight Control (Roll, Pitch, Yaw, Ax, Ay, Az) demands to Effector commands (Aero-Surface, TVC, and Throttling). You may either select a pre-calculated Mixing Logic Matrix (Kmix) from the Systems File: Kmix.qdr, or let the program calculate it

Select a Mixing Matrix from Systems File

When you create a new Mixing Logic you have the option of adjusting the participation of each effector in the combination

Create a Mixing Matrix

Select a Gain Matrix

Select one of the following Matrices from Systems File: Kmix.qdr Select Matrix

KMIX_1860	: Mixing Logic for Re-Entry Vehicle with 6 Aero-Surfaces at Time: 1
KMIX_1861	: Mixing Logic for Re-Entry Vehicle with 6 Aero-Surfaces at Time: 1

Cancel

View Matrix

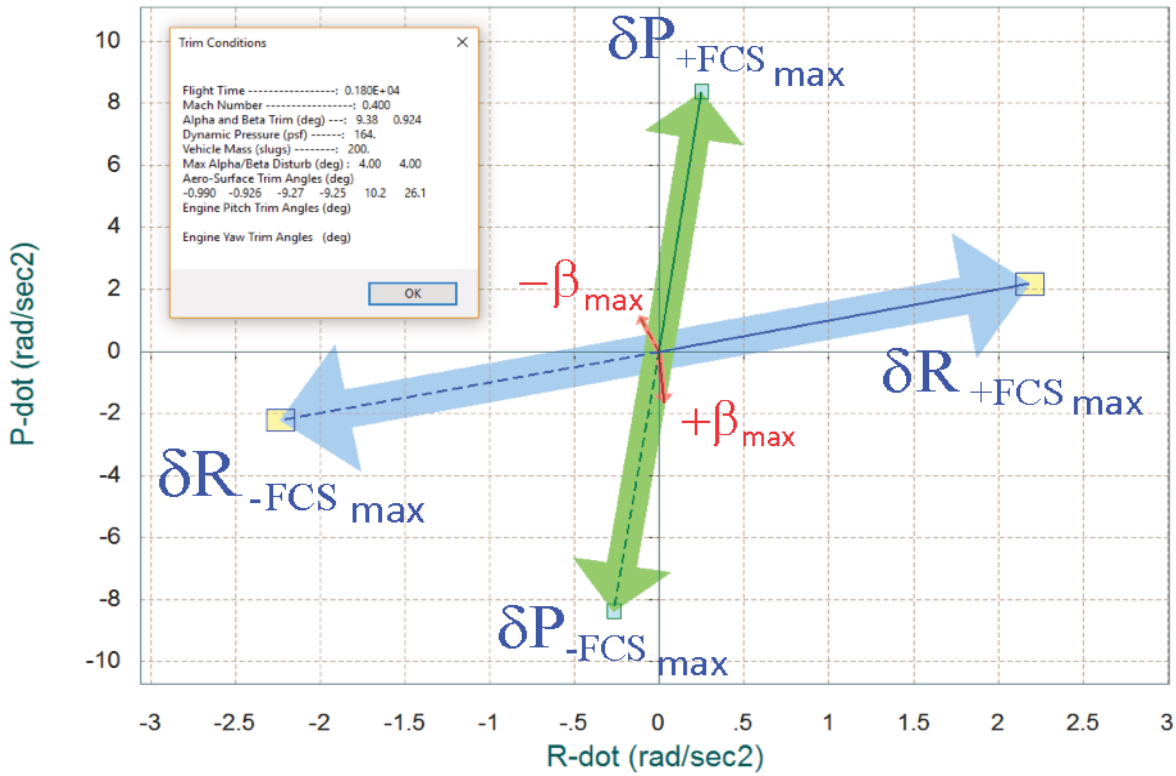
The vector diagram at the top of Figure 3.4.1 shows the roll and yaw angular accelerations in (rad/sec²) and the lateral acceleration in (g), produced when the roll and yaw control demands ($\delta P_{\pm FCS}$ and $\delta R_{\pm FCS}$) are maximized. The blue solid vector corresponds to max positive yaw FCS demand $\delta R_{+FCSMax}$ and the dashed blue vector corresponds to max negative yaw demand $\delta R_{-FCSMax}$. The effect is mainly in yaw but it also couples in the roll direction. Similarly, the green vectors are the accelerations produced by maximizing the roll demands ($\delta P_{\pm FCSMax}$) and they are mainly in roll but they also couple in the yaw direction. The blue vector at the bottom shows also the effect of maximizing the yaw demand $\delta R_{\pm FCSMax}$ in the lateral acceleration. The vehicle is trimmed with a small side-force due to the YCG offset. Positive yaw demand produces negative lateral acceleration, as expected. The two small red vectors in the top diagram show the roll and yaw accelerations produced by the dispersions in the angles of attack and sideslip $\pm\alpha_{max}$ and $\pm\beta_{max}$ from trim positions (α_0 and β_0). An increase in β produces positive yaw, and negative roll and lateral accelerations as expected. The rectangles at the tips of the control vectors capture the uncertainties in the aerosurface coefficients.

The vector diagrams in figure 3.4.2 show the acceleration results of maximizing the two longitudinal controls: pitch demand $\delta Q_{\pm FCS}$, and axial acceleration demand $\delta X_{\pm FCS}$ against the accelerations produced by the $\pm\alpha_{max}$ and $\pm\beta_{max}$ dispersions. The actual aerosurface deflections are determined by the mixing-logic matrix. The vehicle in this flight condition uses the speed-brake to modulate drag and to vary the negative acceleration. The blue and green vectors show the pitch, axial, and normal accelerations when the two control demands are maximized. The control vectors are identical in both: left and right diagrams, only the red dispersion vectors are different.

The solid blue vector in the top diagrams is the maximum accelerations produced due to $\delta Q_{+FCSMax}$, and the dashed blue vector is the accelerations due to $\delta Q_{-FCSMax}$. The pitch control produces positive and negative accelerations in the demanded pitch directions, but it also produces a significant amount of acceleration in the x and z directions. The vehicle is trimmed in pitch because the pitch acceleration is zero when the control $\delta Q_{FCS}=0$. It is, however, decelerating at trim, in both -x and -z directions. The trim accelerations are: $\ddot{x}_0 = -0.23 g$ and $\ddot{z}_0 = -1.2 g$. Unlike the lateral directions, the pitch vectors are not symmetrical because either positive or negative pitch demands ($\delta Q_{\pm FCSMax}$) produce more negative x-acceleration. A +pitch demand reduces the negative z-acceleration, reducing lift because the elevons rotate upwards to increase the pitching moment.

The green vectors in the top diagram and the blue vectors at the bottom show the pitch, x, and z accelerations when the axial acceleration demands ($\delta X_{\pm FCSMax}$) are maximized. This is mainly controlled by the speed-brake which is partially opened and the body-flap. The effect is mainly in the demanded x direction, and it can vary the x-acceleration between 0.13 g and 0.31 g. A small amount of pitching moment is also produced by the speed-brake control. The pitch control strongly affects also the z-acceleration. It can be varied from -1.8 g at $\delta Q_{-FCSMax}$ to -0.4 g at $\delta Q_{+FCSMax}$.

Comparison between Maximum Roll & Yaw Control Accelerations (Green & Blue)
Against Disturbance Accelerations due to Maximum Alpha/ Beta Dispesions (Red)



Comparison Between Maximum Yaw Control Accelerat & Side Acceleration (Green & Blue)
Versus Aero Disturbance due to Maximum Beta Variation (red)

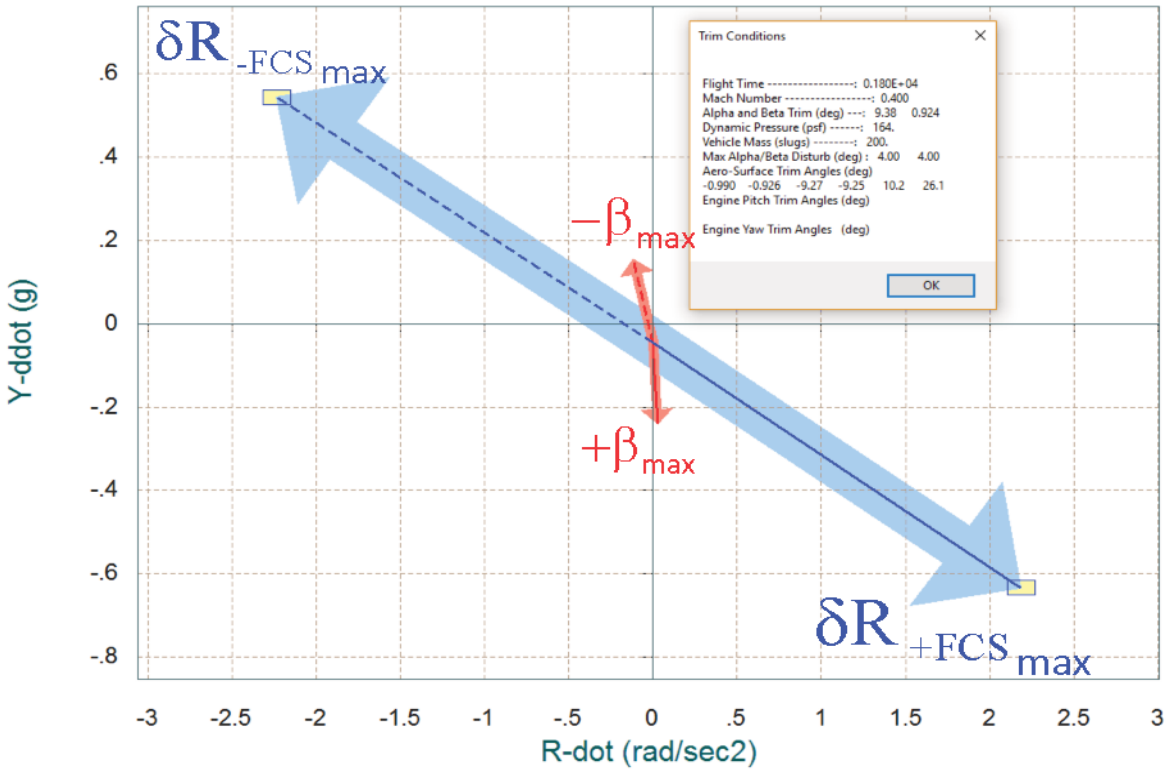


Figure 3.4.1 Roll, Yaw and Lateral Accelerations Produced by Maximizing the Roll and Yaw Control Demands, and also by the Wind Dispersion ($\pm\beta_{max}$)

The red vectors on the left side of Figure 3.4.2 show the accelerations produced by the variations in the angles of attack and sideslip (α_{max} and β_{max})= $\pm 4^\circ$, from their trim positions. The disturbance in this case is mainly due to the $\pm\alpha_{max}$ variations, positive α_{max} generates a negative pitching moment because the vehicle is stable in this flight condition. An increase in α produces more negative z-acceleration (upward). It also produces less negative x-acceleration. The rectangles show the possible vector variations due to the uncertainties in the aero-coefficients. The red vectors on the right side show the accelerations produced by an airspeed variation due to wind disturbance, $V_{max}=\pm 80$ (feet/sec) relative to nominal airspeed V_0 . The control vectors are the same as on the left side. It shows that an increase in airspeed due to head-wind produces more negative x and z accelerations (drag and lift), and a negative pitching moment because the vehicle is statically stable at this time.

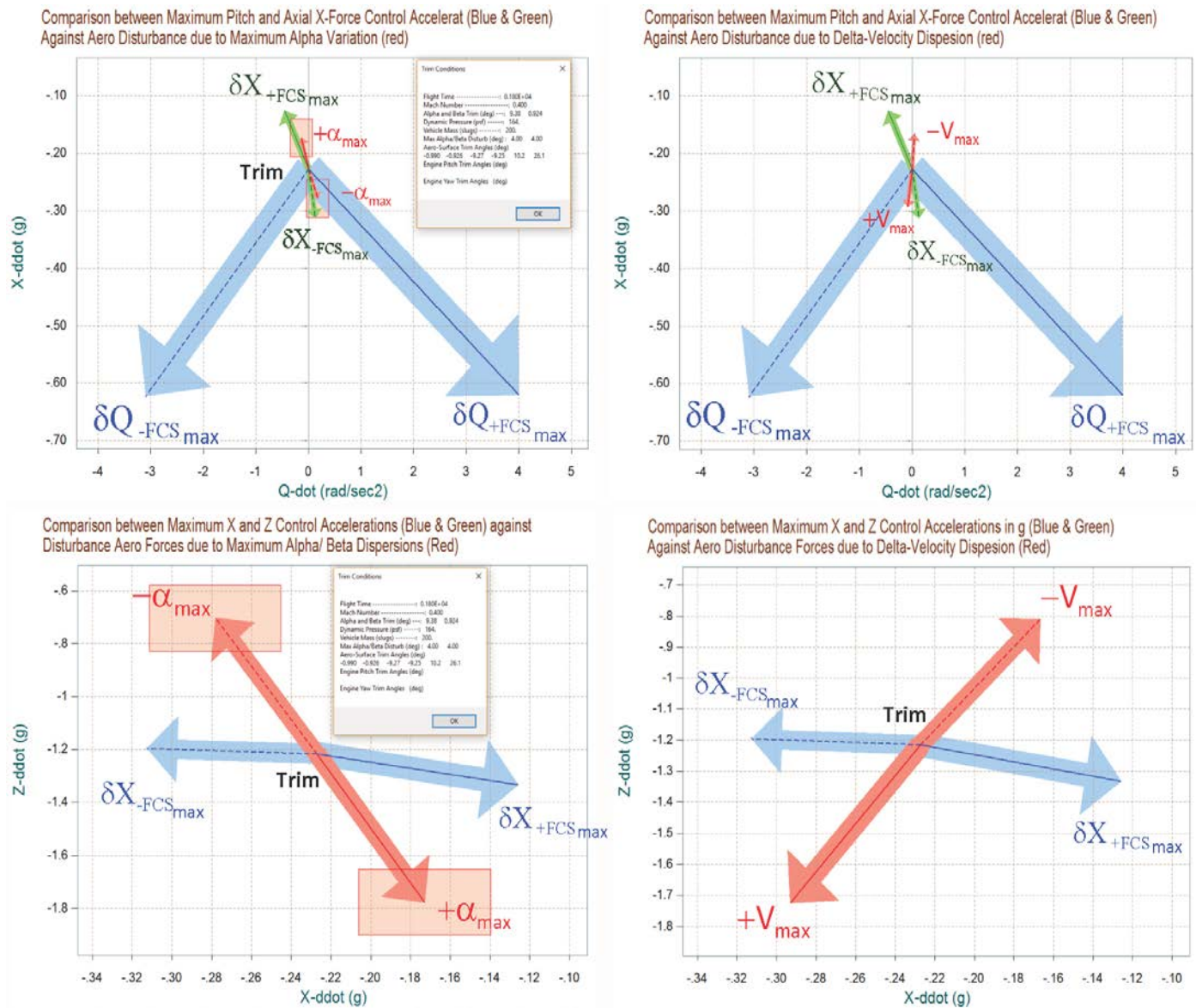
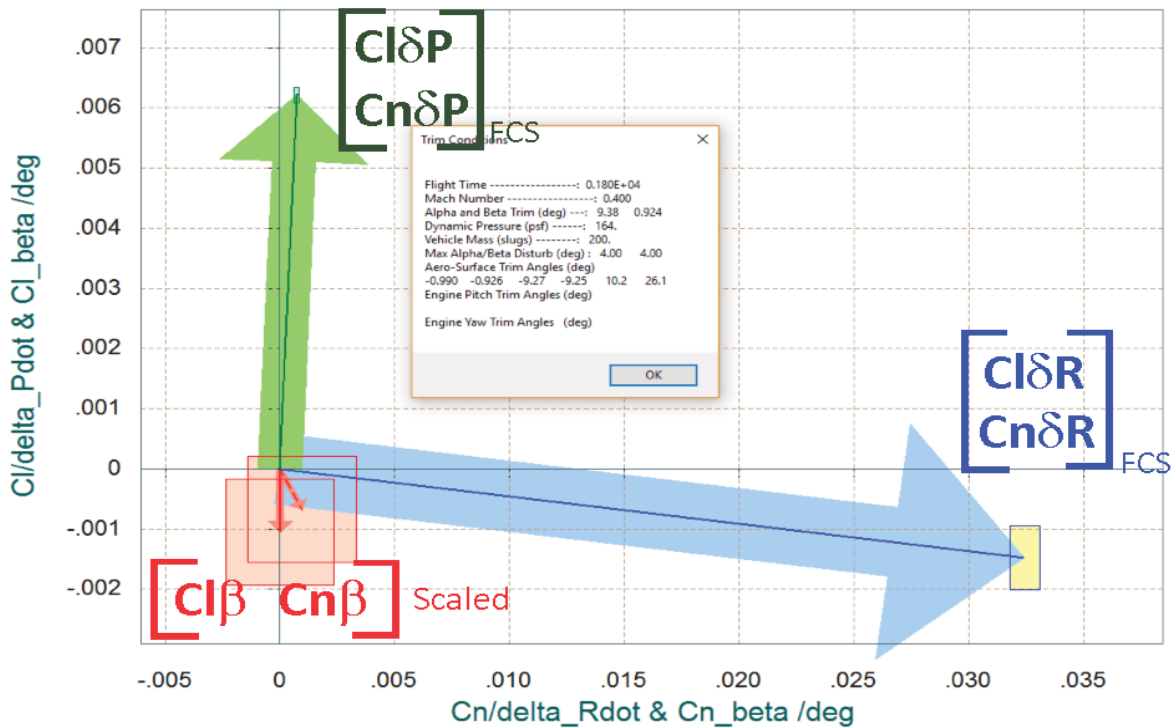


Figure 3.4.2 Pitch, Normal and Axial Accelerations produced by Maximized Pitch and Axial Control Demands, and also due to $\pm\alpha_{max}$ and $\pm V_{max}$ Variations

Comparison Between Yaw & Roll Control Moment Partial (Cn/delta_R and Cl/delta_P) (Blue and Green Vectors) Against Partial: {Cn_beta and Cl_beta} (Red Vectors)



Comparison Between Yaw Control Moment and SideForce Partial (Cn/delt_R, CY/delt_R) (Blue & Green), Against Moment and Force Partial: {Cn/beta , CY/beta} (Red Vector)

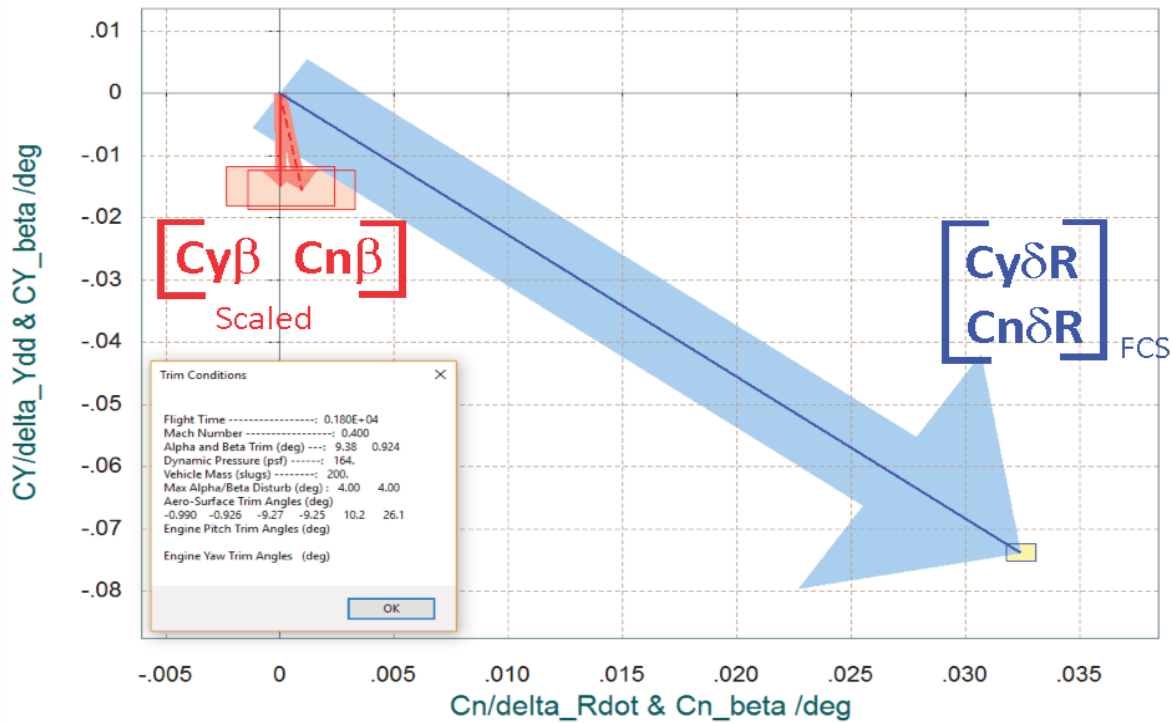


Figure 3.4.3 Lateral Moment and Force Partial

The vector diagrams in figure 3.4.3 show the roll and yaw moment partials per acceleration demands in roll and yaw in (rad/sec²) and the side-force partial per yaw demand. The blue vector is the moments partial per yaw control demand $\{C_n\delta R_{FCS}, Cl\delta R_{FCS}\}$ and it is mainly in the yaw direction. The green vector is the moments partial per roll control demand $\{C_n\delta P_{FCS}, Cl\delta P_{FCS}\}$ and it is mainly in roll. They both couple into each other's direction but they are almost orthogonal to each other. The bottom diagram also shows the partial of side-force per yaw demand ($C_Y\delta R_{FCS}$). The red vectors pointing downwards are the partials $\{C_n\beta, Cl\beta, C_Y\beta\}$. Notice that $Cl\beta$ is negative due to the dihedral and it is bigger in magnitude than $C_n\beta$. The red rectangles centered at the tips of the $\{C_n\beta, Cl\beta, C_Y\beta\}$ vectors are due to the uncertainties in the aero partials. Similarly, the yellow and cyan rectangles at the tips of the yaw and roll control partials $\{C_n\delta R, Cl\delta R\}$ and $\{C_n\delta P, Cl\delta P\}$, are due to the uncertainties in the aerosurface derivatives which are included in file "Aero-Uncert6.Unce".

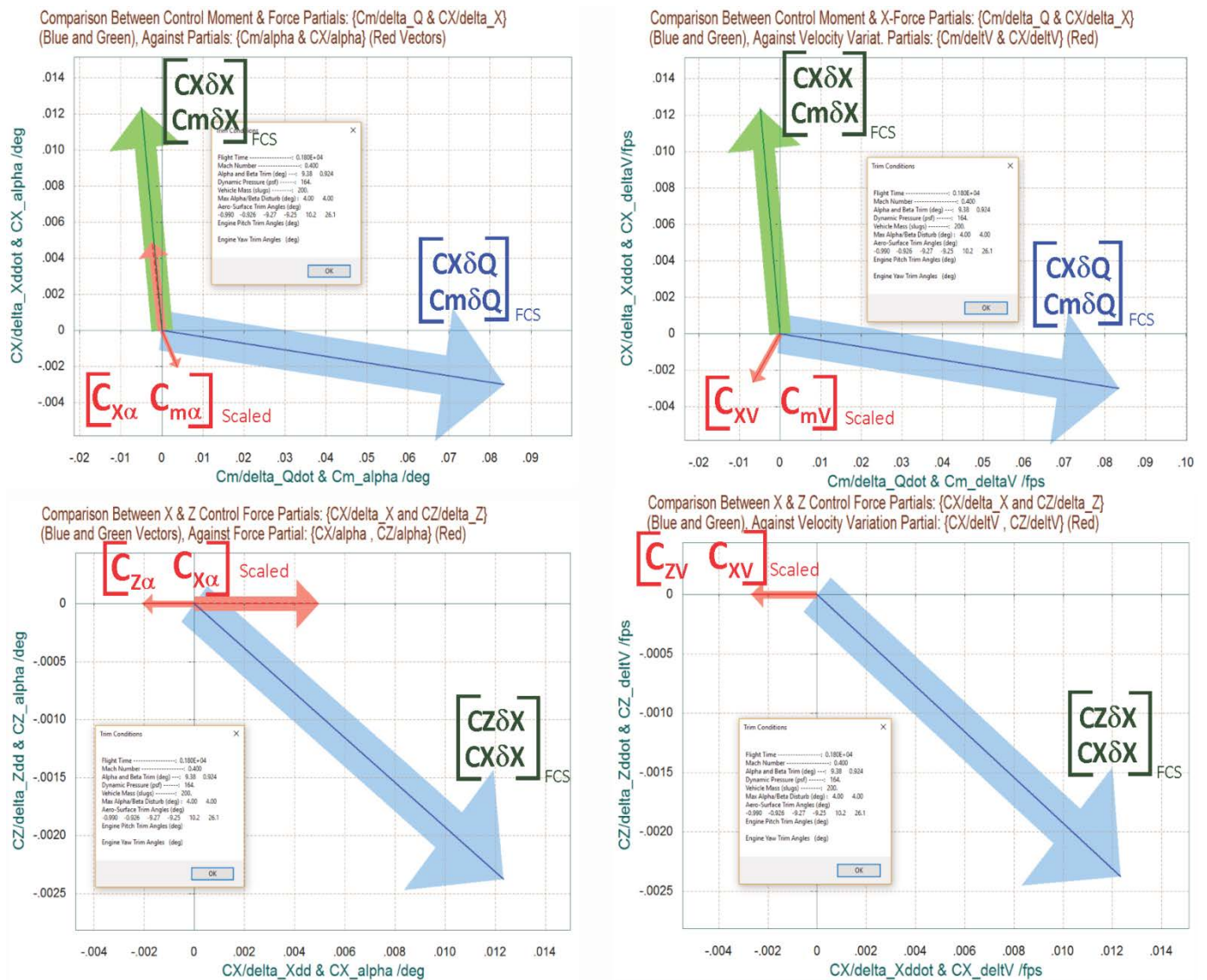


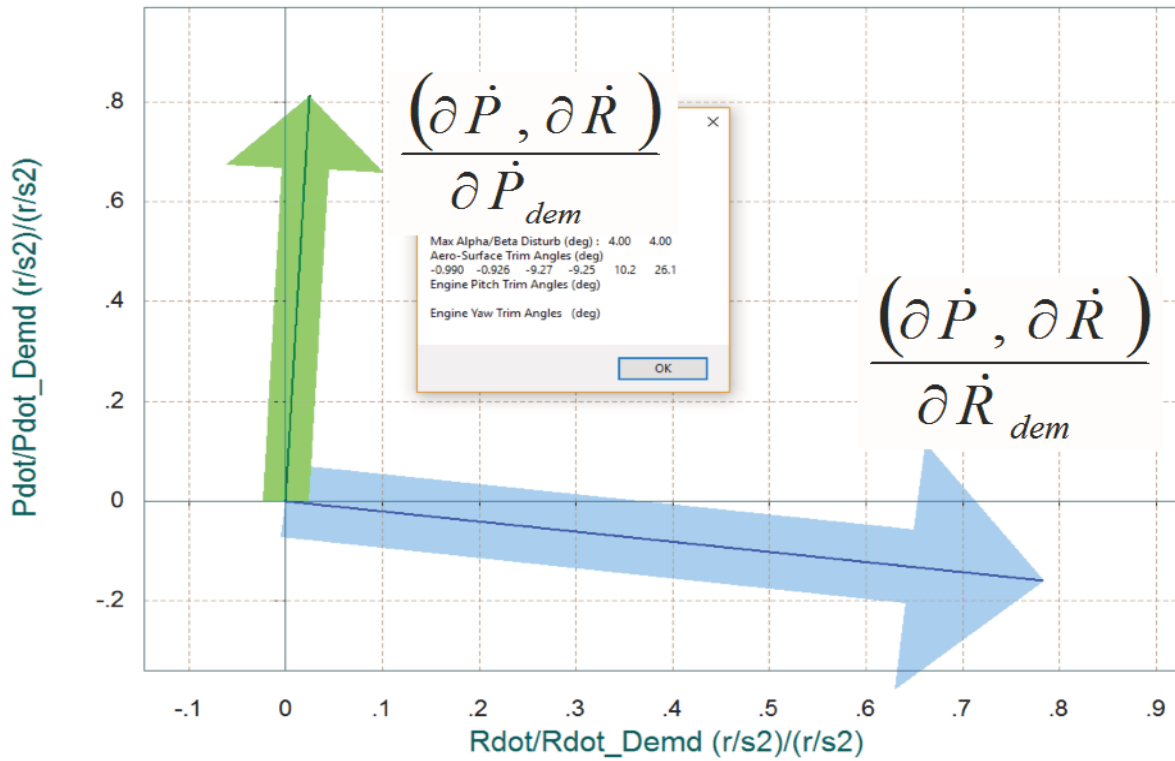
Figure 3.4.4 Moment and Force Partial in the Longitudinal Directions

The diagrams in Figure 3.4.4 are vector partials in the longitudinal directions and they show the variation in pitch moment, axial, and normal forces per pitch acceleration demand in $(\text{rad}/\text{sec}^2)$, and also per axial acceleration demand in $(\text{feet}/\text{sec}^2)$. The control vectors are identical in both: left and right diagrams, only the red dispersion vectors are different. The blue vector in the top diagrams is the x-force and pitch moment partials per pitch demand $\{CX\delta Q_{FCS}, Cm\delta Q_{FCS}\}$ and it is mostly in the horizontal pitch direction. The green vector is the partials per axial acceleration demand $\{CX\delta X, Cm\delta X\}$ and it is mainly in the vertical axial force direction. The control partials are almost orthogonal and they do not couple much into each other's direction. The red vectors on the left side are the scaled partials $\{Cm\alpha, CX\alpha, and CZ\alpha\}$. They are two because they are calculated at the two extreme $\pm\beta_{\max}$ positions. $Cm\alpha$ is negative because the vehicle is stable in this flight condition. The control vector magnitudes and directions are greater than the red alpha partials, which is an indication, that pitch control and axial controllability via the speed-brake are sufficient.

Figure 3.4.5 shows the "*Accelerations per Acceleration Demand*" vector diagrams. They are calculated by selecting the fourth option in the drop-down menu that comes up when you click on "*Select Vector Diagrams*" from the horizontal menu bar. The top figure shows the partials of accelerations per acceleration demands in roll and yaw. The green vector is $\{\dot{P}/\delta\dot{P}_{FCS}, \dot{R}/\delta\dot{P}_{FCS}\}$, and the blue vector is $\{\dot{P}/\delta\dot{R}_{FCS}, \dot{R}/\delta\dot{R}_{FCS}\}$. The axis units are in $(\text{rad}/\text{sec}^2)$ per $(\text{rad}/\text{sec}^2)$. They are almost orthogonal to each other and not far from being unit vectors, which is good.

The bottom diagram in Figure 3.4.5 shows the longitudinal partials of accelerations per acceleration demands in pitch and axial directions. The blue vector is $\{\dot{Q}/\delta\dot{Q}_{FCS}, \ddot{X}/\delta\dot{Q}_{FCS}\}$, and the green vector is $\{\dot{Q}/\delta\ddot{X}_{FCS}, \ddot{X}/\delta\ddot{X}_{FCS}\}$. It shows that both vector partials are not far from unit vectors pointing mainly in the demanded directions. This is an indication of good longitudinal controllability.

Partials of Roll and Yaw Accelerations per Roll and Yaw Control Accelerat Demands (Rdot, Pdot)/Pdot_Dem (green), (Rdot, Pdot)/Rdot_Dem (blue), (rad/sec²)/(rad/sec²)



Partials of Pitch and Axial Accelerations per Pitch and X Control Accelerat Demands (Qdot, X_dd)/Qdot_Dem (blue), (Qdot, X_dd)/Xdd_Demand (green), (r/s²)/(r/s²), (g/g)

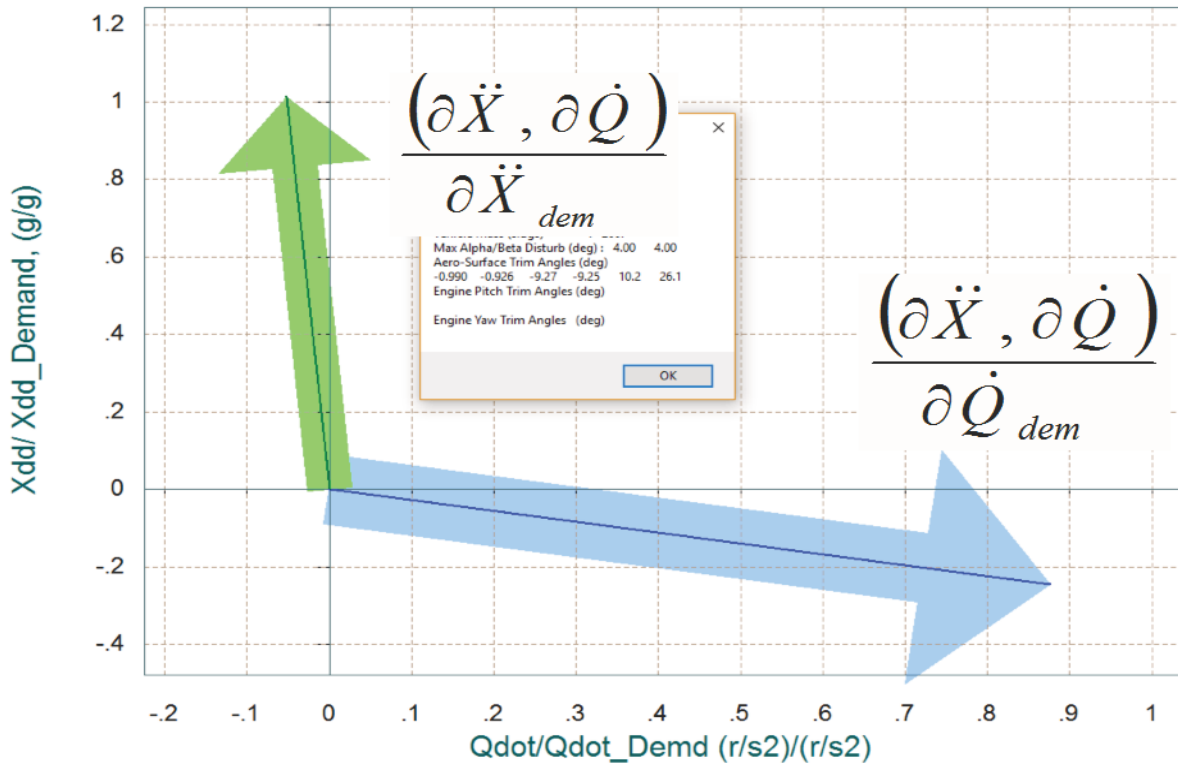
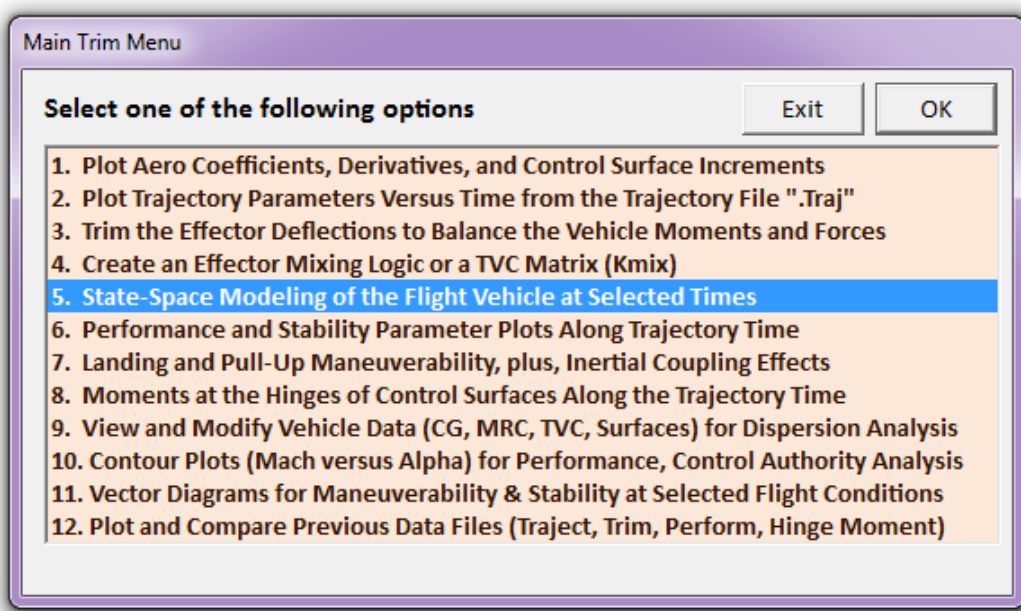


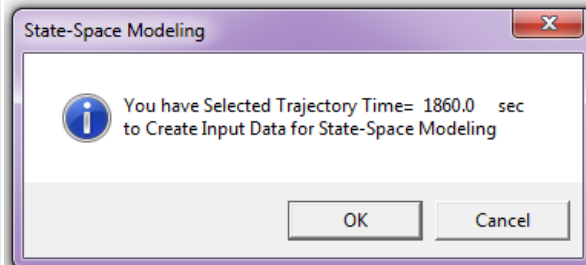
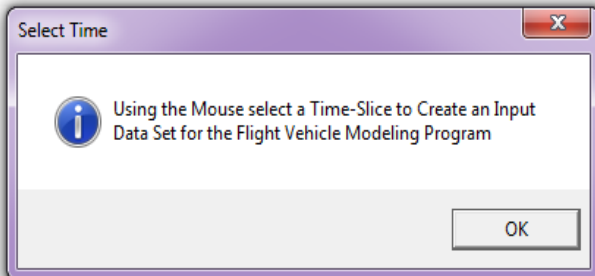
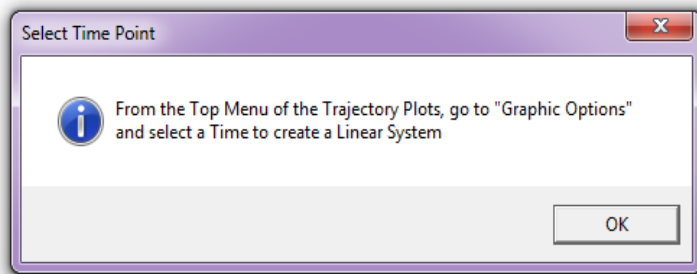
Figure 3.4.5 Accelerations per Acceleration Demand in the 4 Control Directions

3.5 Creating a Dynamic Model near Landing

We will now use the Flixan and Trim programs to create dynamic models of our reentry vehicle at $t=1860$ (sec), which is near landing and in the next section we will create an aerosurface mixing matrix, design a flight control system, and perform stability analysis and simulation. The vehicle at this point uses all 6 aerosurfaces and no RCS jets. The dynamic model has 6 control surface inputs and a wind-gust velocity disturbance input. The gust direction relative to the vehicle is defined in file T1860.inp. The flight control system in this flight condition controls not only the three rotations but speed and the rate of descent. Although the descent rate and speed are controlled independently by guidance commands, the commands, however, in absence of thrust are coordinated by guidance to provide a proper descent rate and alpha and to avoid stalling. The coordination between the 6 aerosurfaces is taken care by the mixing logic matrix which was calculated by Flixan (although a modified version was used instead). The matrix converts the 5 flight control system demands (roll, pitch, yaw, plus axial and normal accelerations) to commands for the 6 control surfaces.

So let us resume the analysis using the Trim program. Select the same files as before, and make "T1860.inp" to be the Flixan input data file. It will include the vehicle data, plus other Flixan related model building data. Re-trim the aerosurfaces, if they are not already trimmed, to make sure that you are using a current trim file. Do not select a trim initialization file and trim along the 3 moments plus axial and normal (A_x and A_z) accelerations. From the Trim main menu select option (5) to create a state-space dynamic model. A dialog reminds the user how to select a flight time for the dynamic model, click "OK". From one of the trajectory plots go the top menu bar, and choose "Graphic Options", and then from the vertical pop-up menu click on "Select Time to Create State-Space System". Then using the mouse click at time $t=1860$ sec, along the x axis, and confirm that you have selected the correct time by clicking "OK". Otherwise, click "Cancel" and try again.





Flight Vehicle Parameters

Vehicle System Title
 Re-Entry Vehicle with 6 Aero-Surfaces/ T= 1860 sec

Number of Vehicle Effectors
 Gimbaling Engines or Jets. Include Tail-Wags-Dog? 0 WITH TWD / WITHOUT TWD
 Rotating Control Surfaces. Include Tail-Wags-Dog? 6 WITH TWD / WITHOUT TWD
 Reaction Wheels? 0
 Single Gimbal CMGs? 0
 Momentum Control Devices: Include a 3-axes Stabilized Double Gimbal CMG System? Yes / No

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

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

Number of Modes
 Structure Bending 0
 Fuel Sloshing 0

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 6 Control Surfaces Control Surface No: 2 Right Flap

Surface Definition: Next Surface

Surface Rotation Angles
 Surface Trim Position (deg) -1.610600
 Largest Positive Deflection from Trim (deg) 40.00000
 Largest Negative Deflection from Trim (deg) -40.00000

Surface Location (ft) and Hinge Orientation Angles (deg)
 Xcs -18.70000
 Ycs 2.640000
 Zcs 2.073000
 Phi_cs -2.000000
 Lambda_cs 5.000000

Control Surface Mass Properties
 Control Surface Mass in (Slugs) 1.000000
 Moment of Inertia about Hinge (slug-ft^2) 0.2980000
 Moment Arm (feet), Surface CG to Hinge 0.3000000
 Control Surface Chord (feet) 1.207000
 Control Surface Reference Area (ft^2) 5.553000

Aero Force Derivatives
 Ca_delta -0.4581000E-04 Ca_delta_dot 0.000000
 Cy_delta 0.1995000E-02 Cy_delta_dot 0.000000
 Cz_delta -0.7075000E-02 Cz_delta_dot 0.000000
 Control Force Derivatives due to Surface Deflection (1/deg) and Control Force Derivatives due to Surface Rate (1/deg/sec)

Aero Moment Derivatives
 Cl_delta -0.1595000E-02 Cl_delta_dot 0.000000
 Cm_delta -0.2385000E-02 Cm_delta_dot 0.000000
 Cn_delta -0.6850000E-03 Cn_delta_dot 0.000000
 Control Moment Derivatives due to Surface Deflection (1/deg) and Control Moment Derivatives due to Surface Rate (1/deg/sec)

Hinge Moment Derivatives
 Chm_Alpha -0.6500000E-02 Hinge Moment Derivatives with respect to Changes in: Alpha, Beta, Surf Deflection (1/deg) and changes in Mach Number
 Chm_Beta 0.000000
 Chm_Delta -0.5260000E-02
 Chm_Mach 0.000000

The program is now ready to create a dynamic model at the selected time. The above dialog shows the flight vehicle parameters prepared by Trim that were extracted from the data files. The user can modify some of the data or titles in this dialog before saving it. Click on "*Update Data*" after any modifications. Do not run it yet because there is more work to be done and more data to be included in T1860.inp. Click on "*Save in File*" and the vehicle data will be saved in file "*T1860.inp*", under the title "*Re-Entry Vehicle with 6 Aero-Surfaces, Landing Phase, T= 1860 sec*". The file "*T1860.inp*" will later be processed by Flixan to generate the systems for control design and analysis using Matlab/ Simulink. In addition to the vehicle data this input file contains also system interconnection and modification data related to this analysis that will be processed by Flixan. The systems and matrices generated by Flixan will be saved in file "*T1860.Qdr*".

Processing the Input Data File

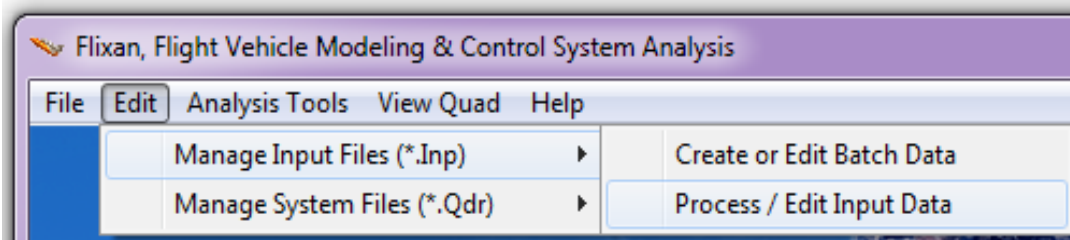
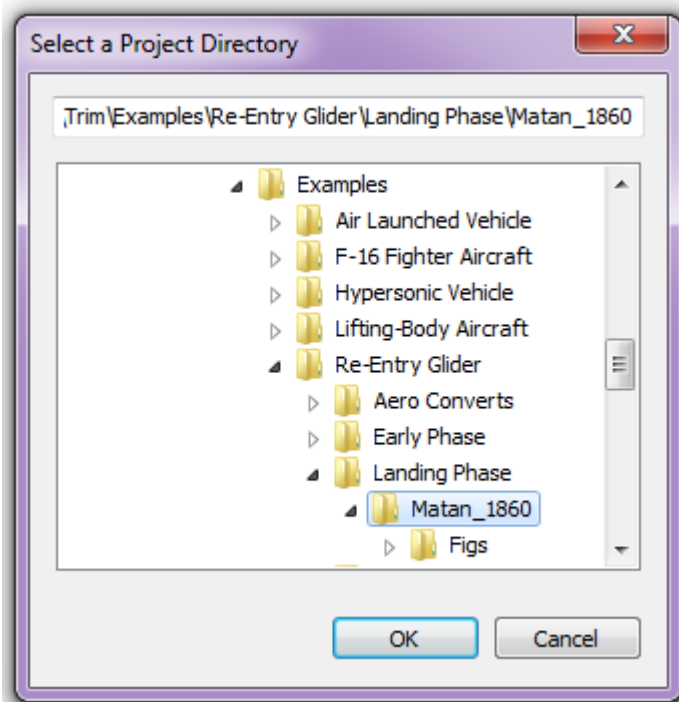
Let us now take a look and see what is inside the already existing file "*T1860.inp*" before processing it in Flixan. This file contains several sets of data and each set corresponds to and is processed by a Flixan utility. Flixan will create systems and matrices that will be used for control analysis in the next section using Matlab.

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 analyzing the Re-Entry Vehicle during Approach and Landing, at t=1860 sec*".
2. Below the batch there is a flight vehicle data set that generates a vehicle model for the flight condition that was selected above. Its title is "*Re-Entry Vehicle with 6 Aero-Surfaces, Landing Phase, T= 1860 sec*". Its output rates are body rates and it will be used in simulations.
3. The next set is also flight vehicle data that generates a vehicle model for the same flight condition as above. Its output rates, however, are stability rates (with respect to the velocity vector) and it also includes the turn-coordination terms with the vehicle dynamics. Its title is "*Re-Entry Vehicle Landing Phase (Stability Axis)*" and it will be used for control design.
4. The next set of data generates the (6x5) mixing logic matrix that converts the FCS acceleration demands (roll, pitch, yaw, Ax, Az) to surface deflection commands. The data-set title is "*Mixing Logic for Re-Entry Vehicle Landing Phase*" and the matrix name is Kmix_T1860. This matrix, however, was not used in the analysis but a different one "KSmix" was used instead.
5. The next set has a title "*Re-Entry Vehicle with (dV), Landing Phase (Simulation Model)*". It is very similar to the original vehicle model created in step-2 with a small modification. It includes one additional output in its outputs vector, the change in velocity (δV). This output is extracted from the state vector (state #10) and it will be used in the flight control feedback. This model will be used in the Matlab simulation.
6. The next two sets are system modification sets which create the design plants for the LQR algorithm that is implemented in Matlab. Their titles are "*Re-Entry Vehicle Landing Phase Pitch Design Model*" and "*Re-Entry Vehicle Landing Phase Lateral Design Model*". They basically

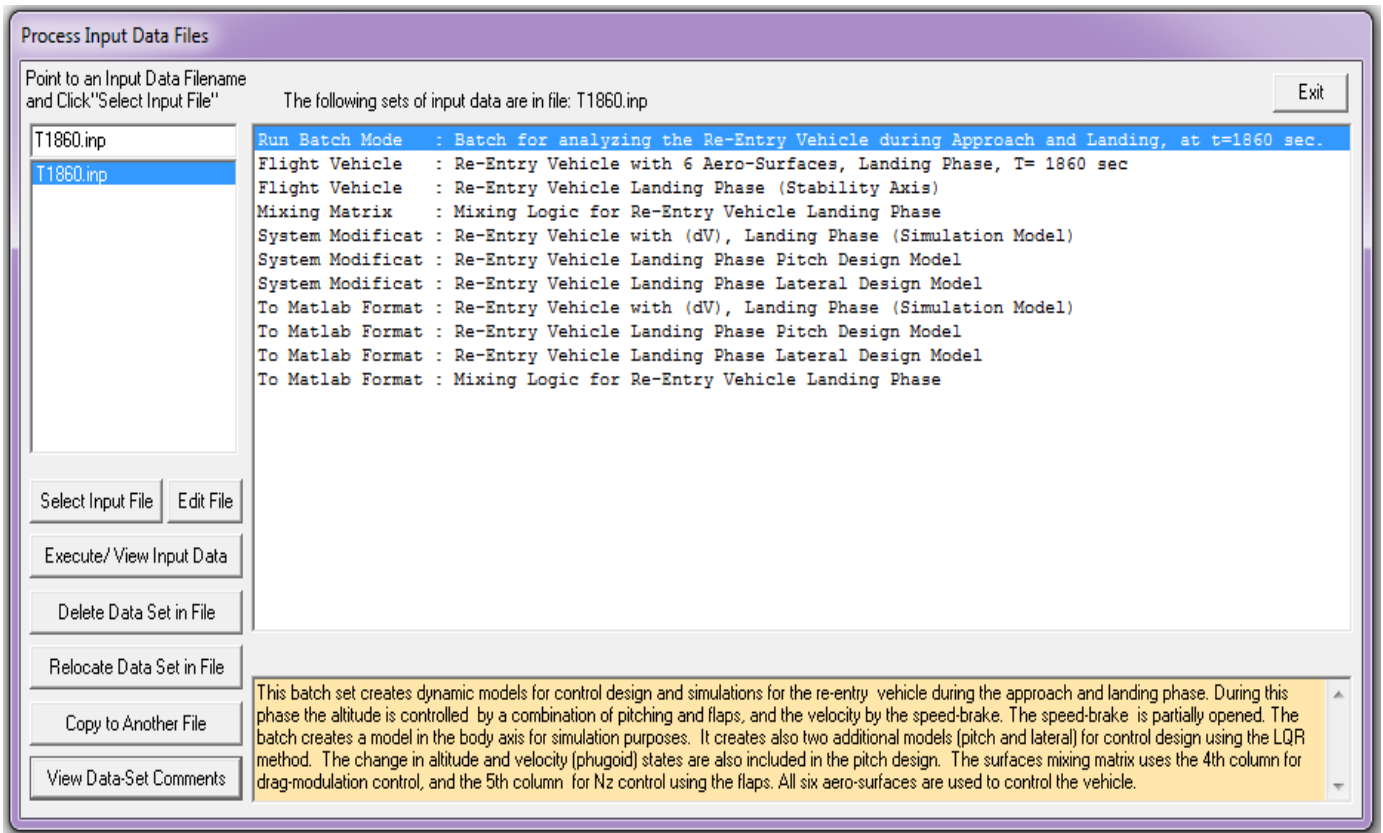
separate the stability axis model created in step-3 in two separate subsystems for longitudinal and lateral control design.

7. The last four data-sets in the input data file convert the mixing matrix and the systems created to Matlab function format so they can be loaded into Matlab for further analysis. The simulation model is saved in file "*vehicle_sim.m*". The pitch and lateral design plants are saved in "*pitch_des.m*" and "*later_des.m*", and the mixing matrix is saved as "*Kmix_T1860.mat*".

Now let us process this input file using Flixan. Start the Flixan program and select the project folder "*C:\Flixan\Trim\Examples\Re-Entry Glider\Landing Phase\Matan_1860*". This is the folder where we will analyze the T1860 flight condition. 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 "T1860.Inp". Select it and click on "Select Input File". The menu on the right side shows the data-sets which are included in "T1860.Inp". They can be processed individually, but select the batch set on the top to process them all together, and click on "Execute/View". Flixan will process the input file and create the systems in file "T1860.Qdr". It will also create the Matlab system files. The procedure described can be used to create models and analyze other flight condition along the trajectory.



3.6 Control Design and Analysis

The control analysis is performed using Matlab in the subdirectory "C:\Flixan\Trim\Examples\Re-Entry Glider\Landing Phase\Matan_1860". The following Matlab script file "init.m" is used to load the models and matrices generated in the previous section and to design simple state-feedback flight control laws for the longitudinal and the lateral directions using the LQR method. The longitudinal and lateral design plants are loaded from files: "pitch_des.m" and "later_des.m", and also the surface mixing matrix "KSmix.mat". The design plants are augmented to include the corresponding columns of matrix KSmix. This is done in Simulink files "Ldes4x.Mdl" and "Pdes6x.Mdl", see Figure (3.6.1), and the 5 control demands are separated to lateral and longitudinal. The roll and yaw demands which correspond to KSmix columns (1 and 3) are included in the lateral design plant "Ldes4x.Mdl". The pitch, Nz, and axial acceleration demands which correspond to KSmix columns (2, 5, and 4) go to the longitudinal design plant "Pdes5x.Mdl". Notice that both pitch and Nz control demands are used for altitude control. It provides a little better performance than using only pitch for altitude control. The lateral state-vector consists of (ps, rs, β , ϕ s). The longitudinal state-vector includes both, the short-period and the phugoid modes and its state-vector consists of (θ , q, α , δh , δv). All variables are variations from their nominal variables, which are: $\theta_0=-16^\circ$, $\alpha_0=6^\circ$, $h_0=5600$ (ft), $v_0=465$ (ft/sec).

```

% LQR Design & Param Initialization file init.m
d2r=pi/180; r2d=180/pi;
[Aps, Bps, Cps, Dps] = pitch_des;           % Load Pitch aero-surf Design Model
[Als, Bls, Cls, Dls] = later_des;          % Load Lateral aero-surf Design Model
[As, Bs, Cs, Ds] = vehicle_sim;           % Simulation Model 6-dof
load KSmix.mat -ascii; Kmix=KSmix;         % Load Surfaces Mix Logic (6 x 5)

alfa0=6.0; V0=465.37; Thet0=-16.0; ge=32.174; % Additional Vehicle Parameters
calfa=cos(alfa0*d2r); salfa=sin(alfa0*d2r); % for Body to Stability Transform

% Lateral LQR Design Using States: (ps, rs, beta, phi-stab)
% Convert Lateral State Vector from Body to Stability Axes, Outputs=States
[A14,B14,C14,D14]= linmod('Ldes4x');       % 5-state model {p,r,beta,pint}
A15= C14*A14*inv(C14); B15= C14*B14;     % Stability axis System
C15= C14*inv(C14); D15= D14;
R=[1,1]*1; R=diag(R);                     % LQR Weights R=[1,1]*2
Q=[10 2 1.5 20]; Q=diag(Q);               % LQR Weights Q=[10 2 0.5 20]
[Kpr,s,e]=lqr(A15,B15,Q,R);                % Perform LQR design on Jets
save Kpr_T1860.mat Kpr -ascii              % Lateral State-Feedback Gain

% Pitch LQR Design Using the 6 Aero-Surfaces, States: {theta,q,alfa,dH,dV}
[Ap4,Bp4,Cp4,Dp4]= linmod('Pdes6x');     % Include Kmix in design model
R=[3,1,1]; R=diag(R);                     % LQR Control Weights (Pitch,Nz,Ax)
Q=[0.0001 0.1 0.01 14 4]; Q=diag(Q);     % LQR State Weights {theta,q,alfa,dH,dV}
[Kq,s,e]=lqr(Ap4,Bp4,Q,R);                % Perform LQR design on Surf
save Kq_T1860.mat Kq -ascii               % Longitudinal State-Feedback Gain

```

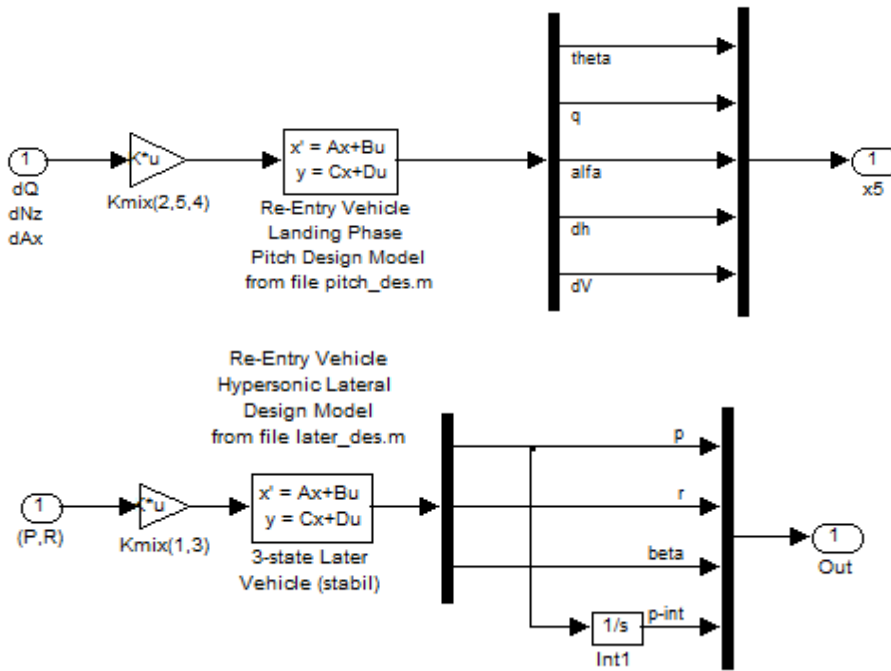


Figure 3.6.1 The Pitch and Lateral Control Design Plants Include the corresponding columns of Kmix. The inputs are acceleration demands; Pitch, Normal, and Axial accelerations in the Longitudinal Model, Roll and Yaw accelerations in the Lateral Model.

The LQR control gains are first evaluated using simple closed-loop simulation models. If the time responses are too fast or too slow or if they use up too much or too little control we adjust the weights and try again until the responses are perfect. The pitch simulation model is in file "Sim_Pitch_Simple.Mdl", shown in figure (3.6.2).

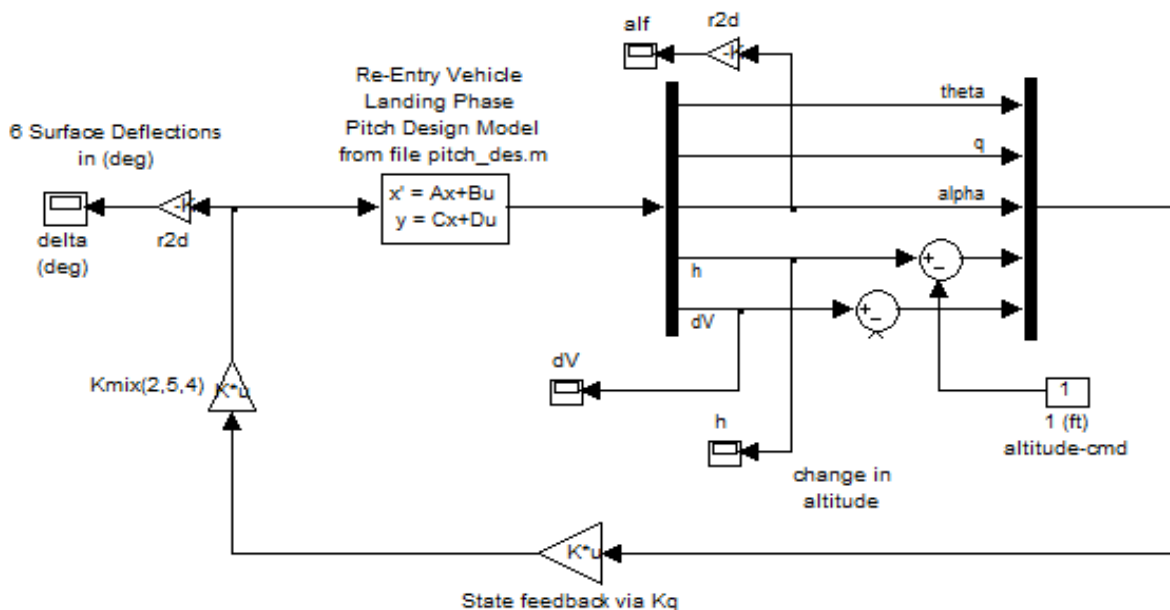


Figure 3.6.2 Simple Longitudinal Simulation Model "Sim_Pitch_Simple.Mdl" for Evaluation of the LQR Design

The state-feedback matrix K_q and columns (2, 5, and 4) of the surface combination matrix K_{mix} (corresponding to Pitch, N_z , and Axial acceleration demands) are included in the feedback loop. The output of K_{mix} are surface deflections in (rad) and they are converted to (deg) below.

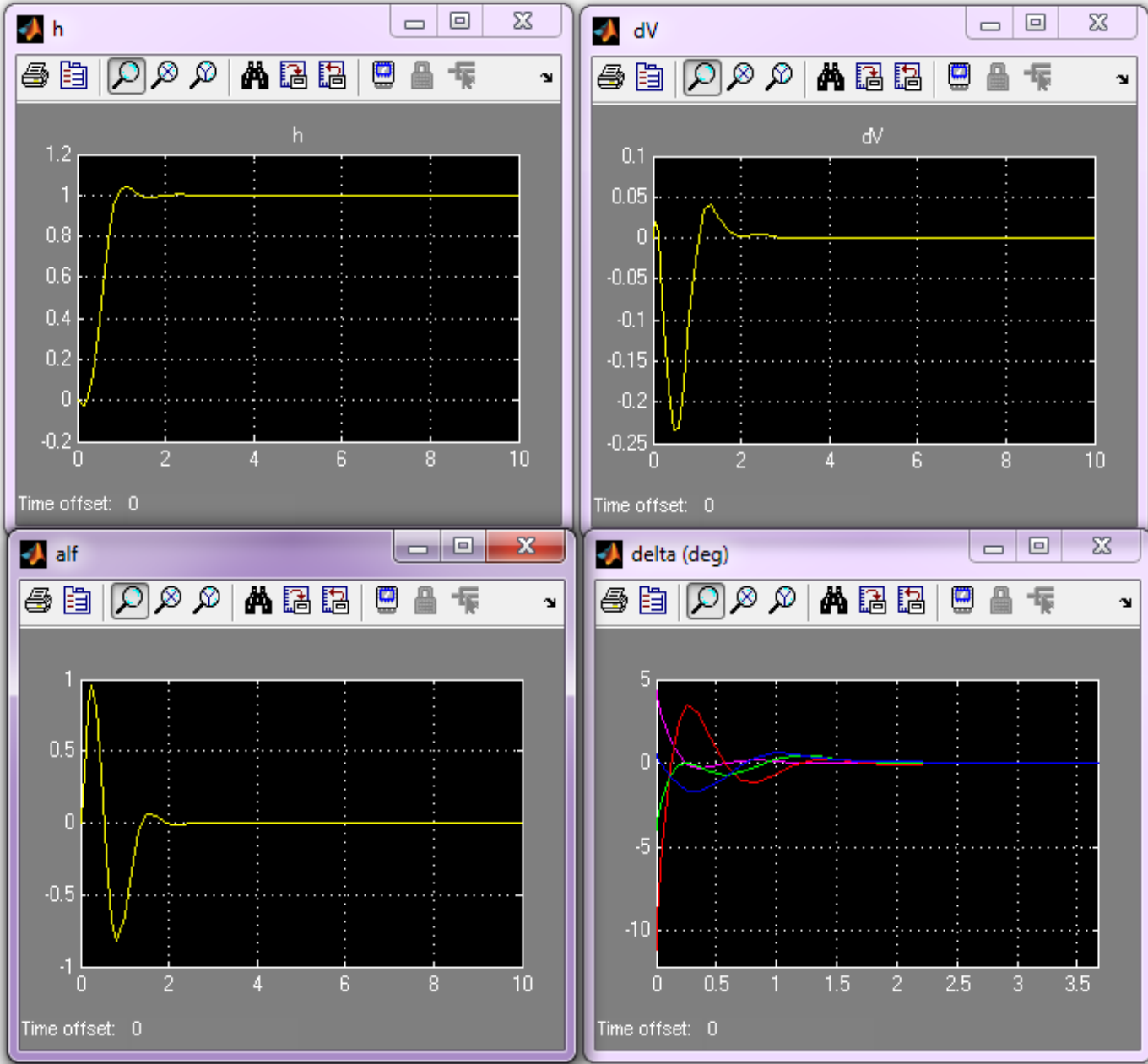


Figure 3.6.2(a) Longitudinal Model Response to a Change in Altitude Command of 1 (ft)

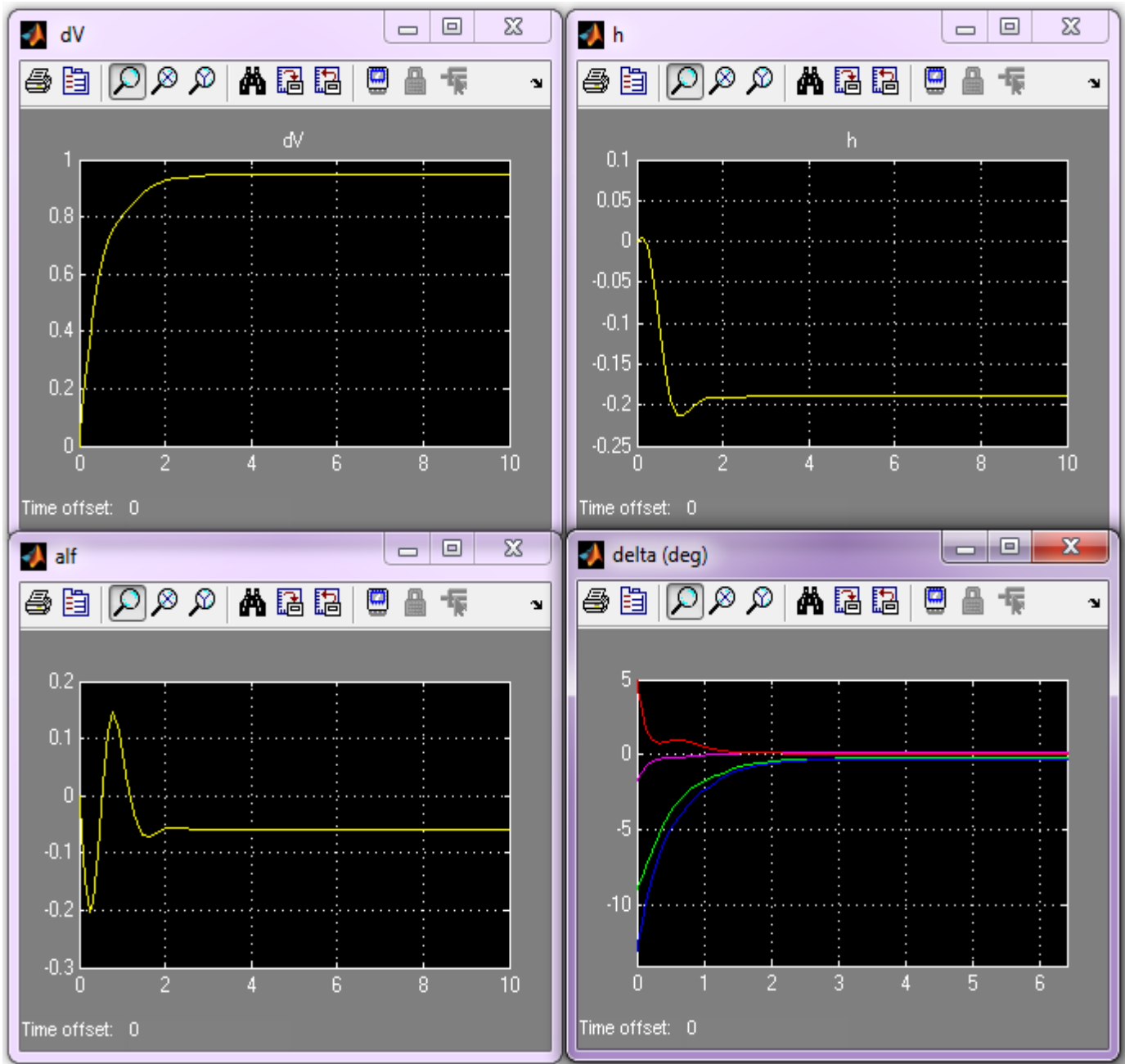


Figure 3.6.2(b) Longitudinal Model Response to a Change in Velocity Command of 1 (ft/sec)

The lateral simulation model is in file "Sim_Lateral_Simple.Mdl". It is shown in figure (3.6.3) responding to a 10 (deg) roll command about V0. The state-feedback matrix Kpr and columns (1 and 3) of the surface combination matrix Kmix (corresponding to roll and yaw demands) are included in the feedback loop. The output of Kmix are surface deflections in (rad) and they are converted to (deg) below.

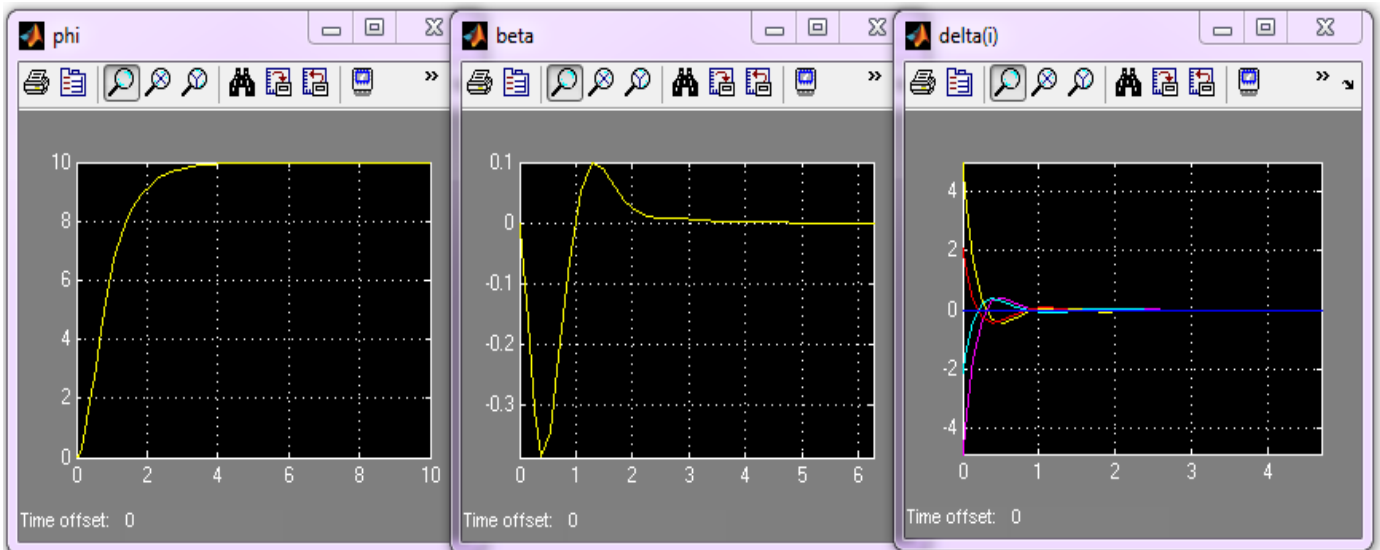
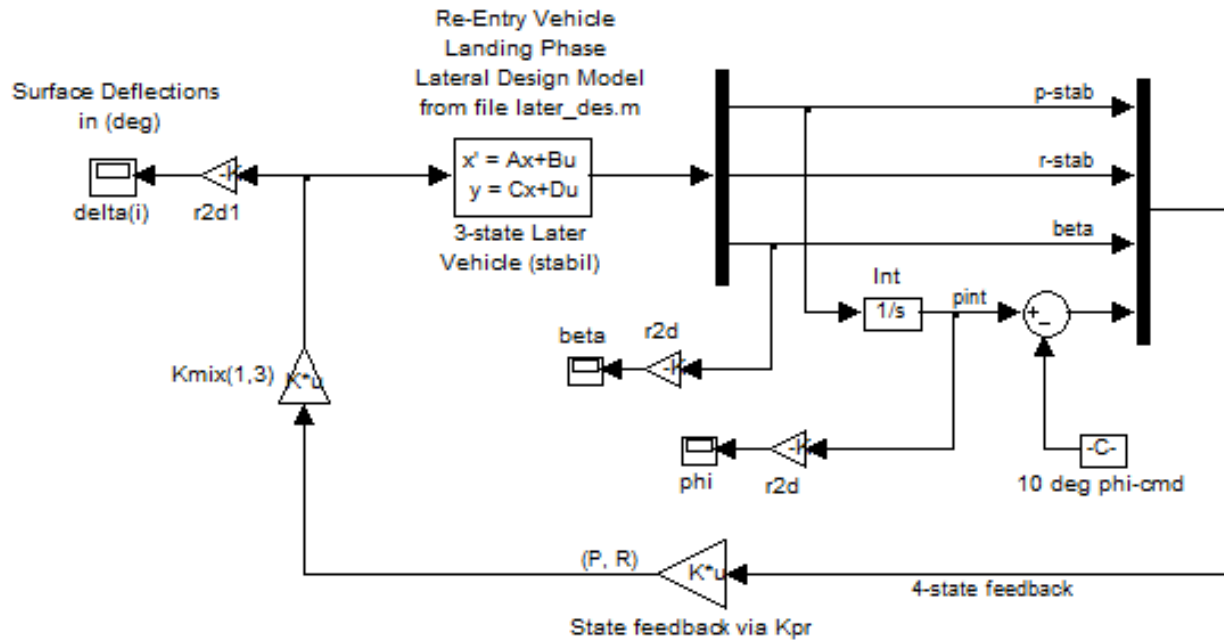


Figure 3.6.3 Simple Lateral Simulation Model "Sim_Lateral_Simple.Mdl" for Evaluation of LQR Design

3.7 Auto-Landing Control System and Simulation

The simulation model is in file "*Landing_Sim.mdl*" and it is shown in Figure (3.7.1). The vehicle dynamic model is the green block that was loaded from file "*vehicle_sim.m*". The vehicle subsystem receives the 5 control demands consisting of: two lateral FCS demands (δP_{FCS} , δR_{FCS}) that come from the heading control system (upper red loop), and three longitudinal FCS demands (δQ_{FCS} , δZ_{FCS} , δX_{FCS}) that come from the altitude/ speed control system (lower blue loop). The two flight control subsystems are shown in Figures (3.6.3 and 3.6.4).

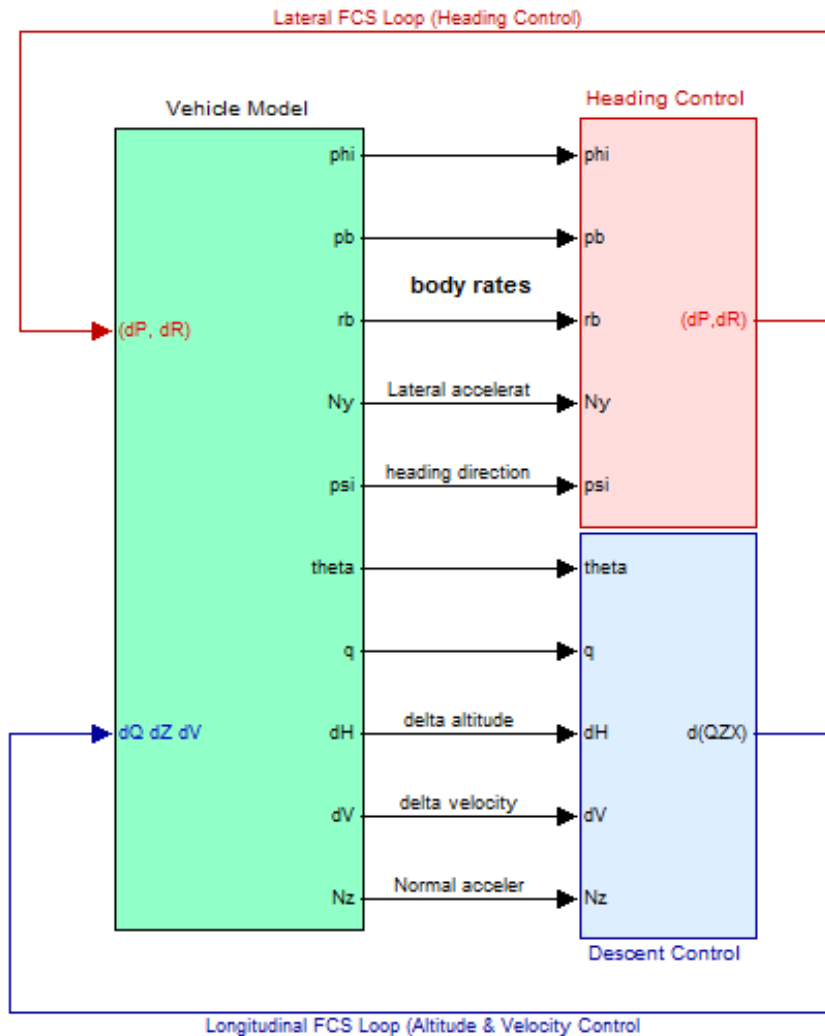


Figure 3.7.1 Simulink Model "*Landing_Sim.mdl*" used for Auto-Landing Simulations

Flight Vehicle Dynamics Re-Entry Vehicle Near Landing, Simulation Model

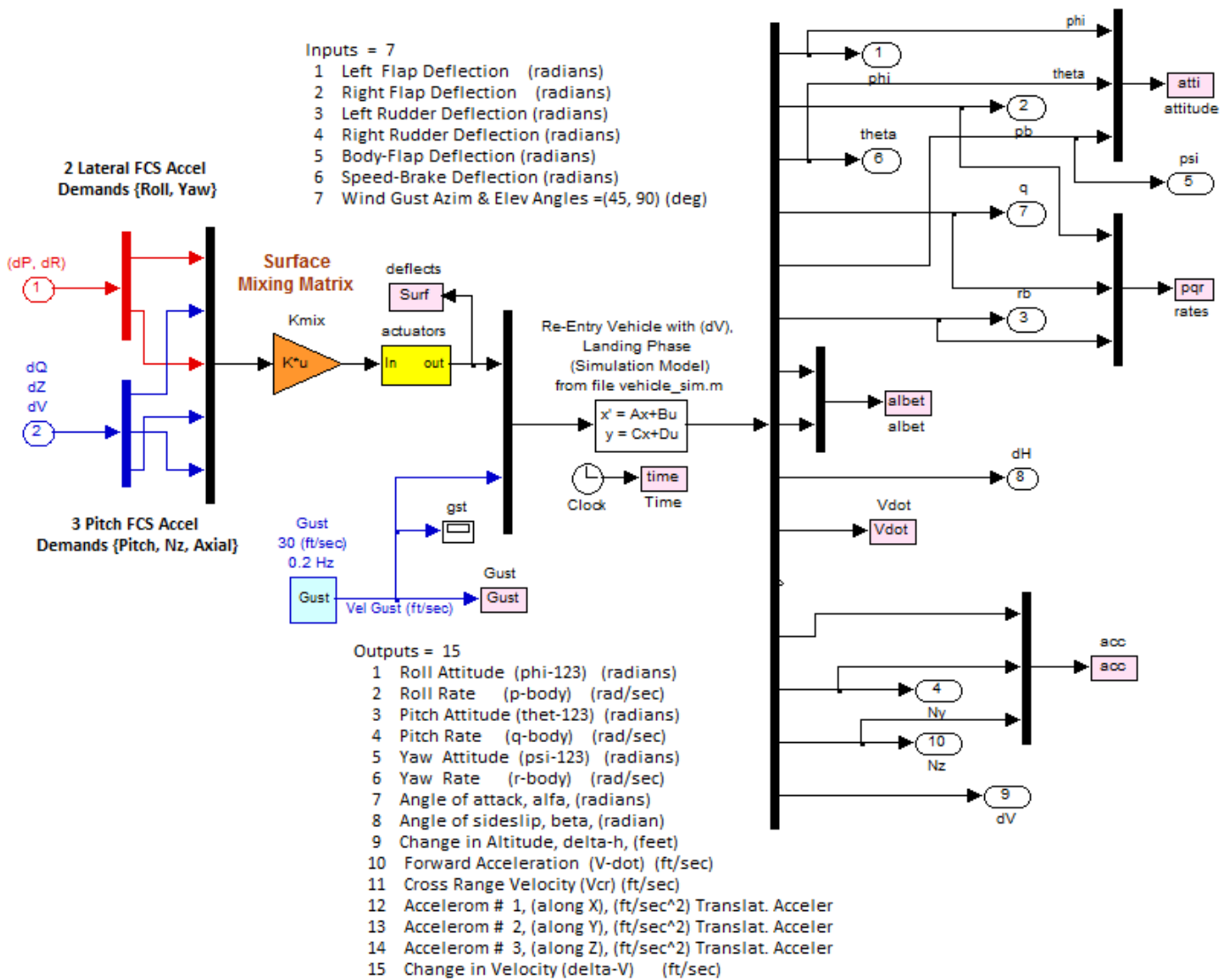


Figure 3.7.2 Re-Entry Vehicle Dynamic Model

The vehicle dynamics block is shown in detail in figure (3.7.2). The state-space system's title is "Re-Entry Vehicle with (dV), Landing Phase (Simulation Model)" that was created in file "vehicle_sim.m". On the left side it receives the lateral (red) and longitudinal (blue) flight control demands which are converted to surface deflection commands by the surface mixing matrix KSmix. The deflection commands are filtered by a set of first order actuators and become surface deflections that drive the first 6 inputs of the vehicle model. Input number 7 is a wind-gust velocity disturbance input. The direction of the disturbance is defined in the vehicle data. This input is excited by a noise generator that creates random gusts with amplitudes varying ± 10 (ft/sec). The system's outputs are listed above, and some of the outputs are used for flight control feedback. The output data are saved for plotting using file "pl.m".

Control System Architecture

During the final approach and before landing the vehicle aligns its direction with the runway and controls its rate of descent and speed. The lateral control system is shown in figure (3.7.3). It receives a heading direction command (ψ_{cmd}) from guidance and aligns its heading with the runway. The heading error becomes a roll command that temporarily rolls the vehicle to change its heading direction.

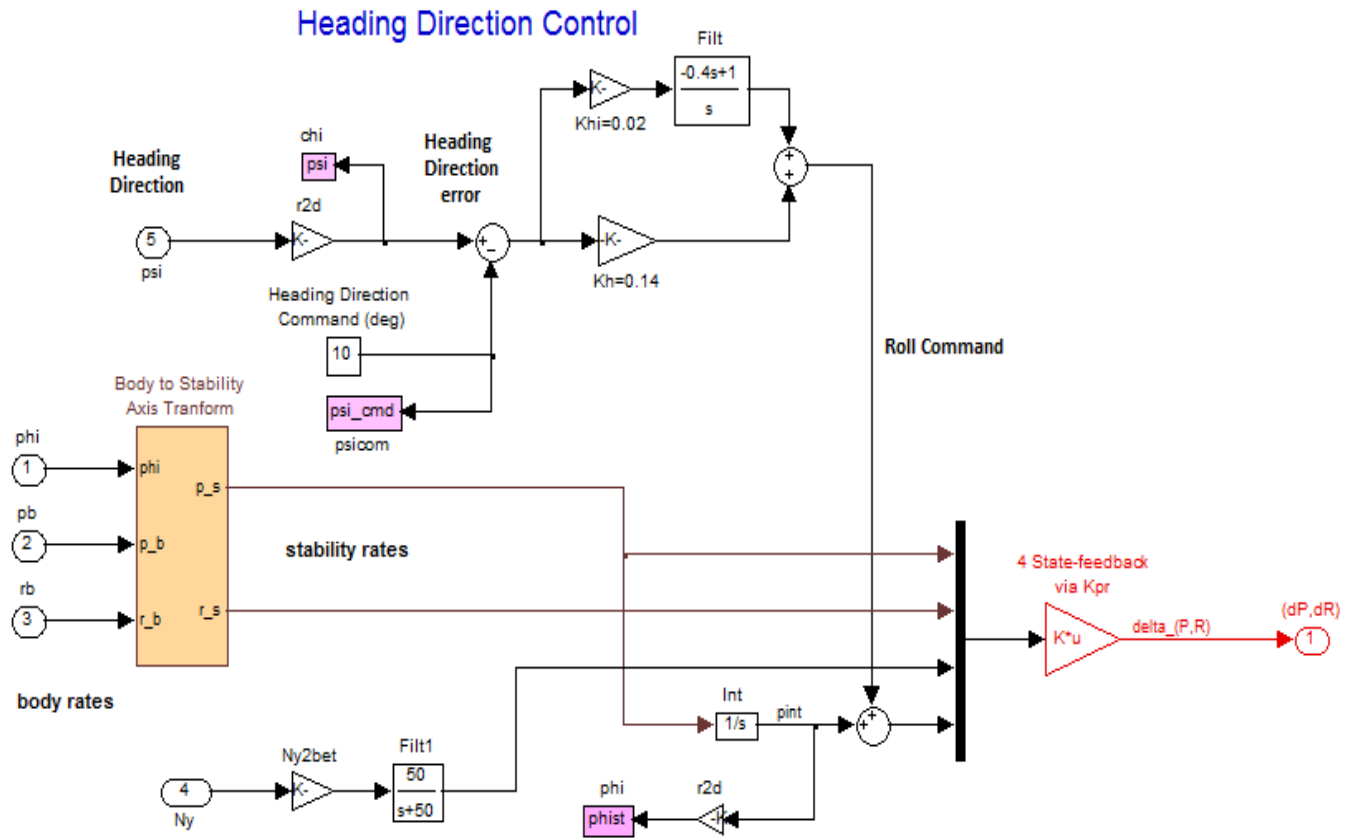


Figure 3.7.3 Heading Direction Control System

The state-feedback control gain (K_{pr}) was calculated by the LQR method. However, instead of beta in the state vector the lateral accelerometer measurement (N_y) is used. The scaled N_y is a good approximation for beta in this case.

Descent Control System

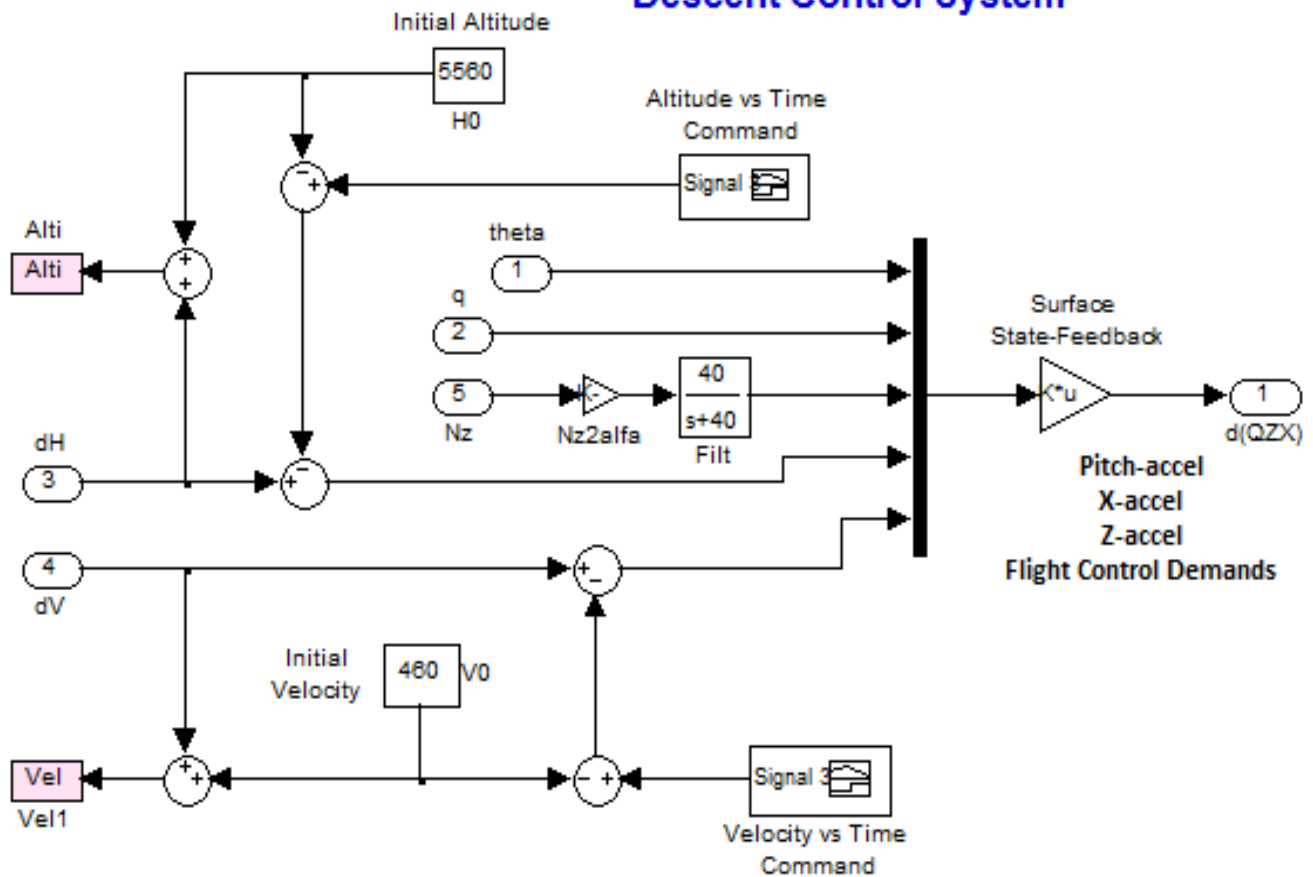
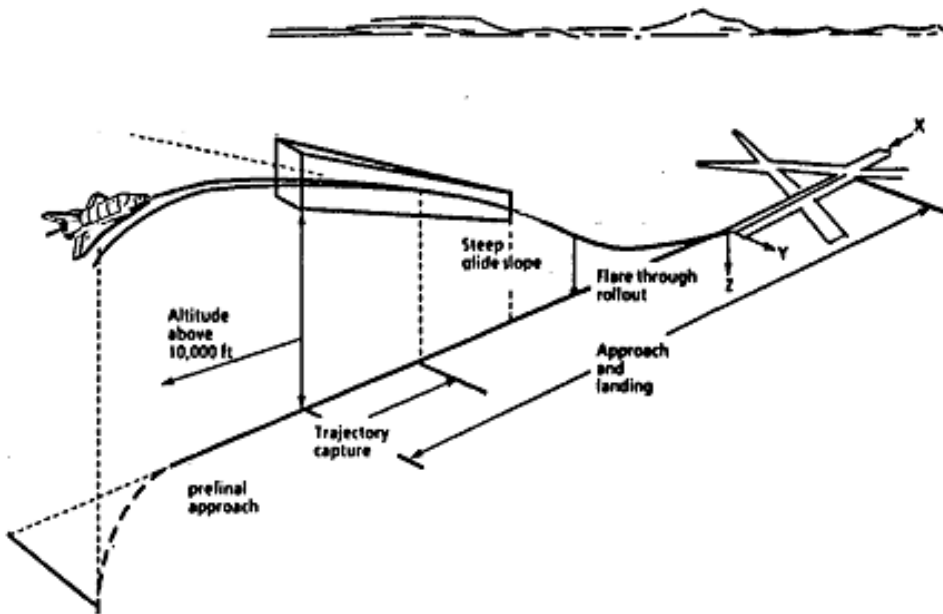


Figure 3.7.4 Longitudinal Flight Control System Controls Altitude and Speed

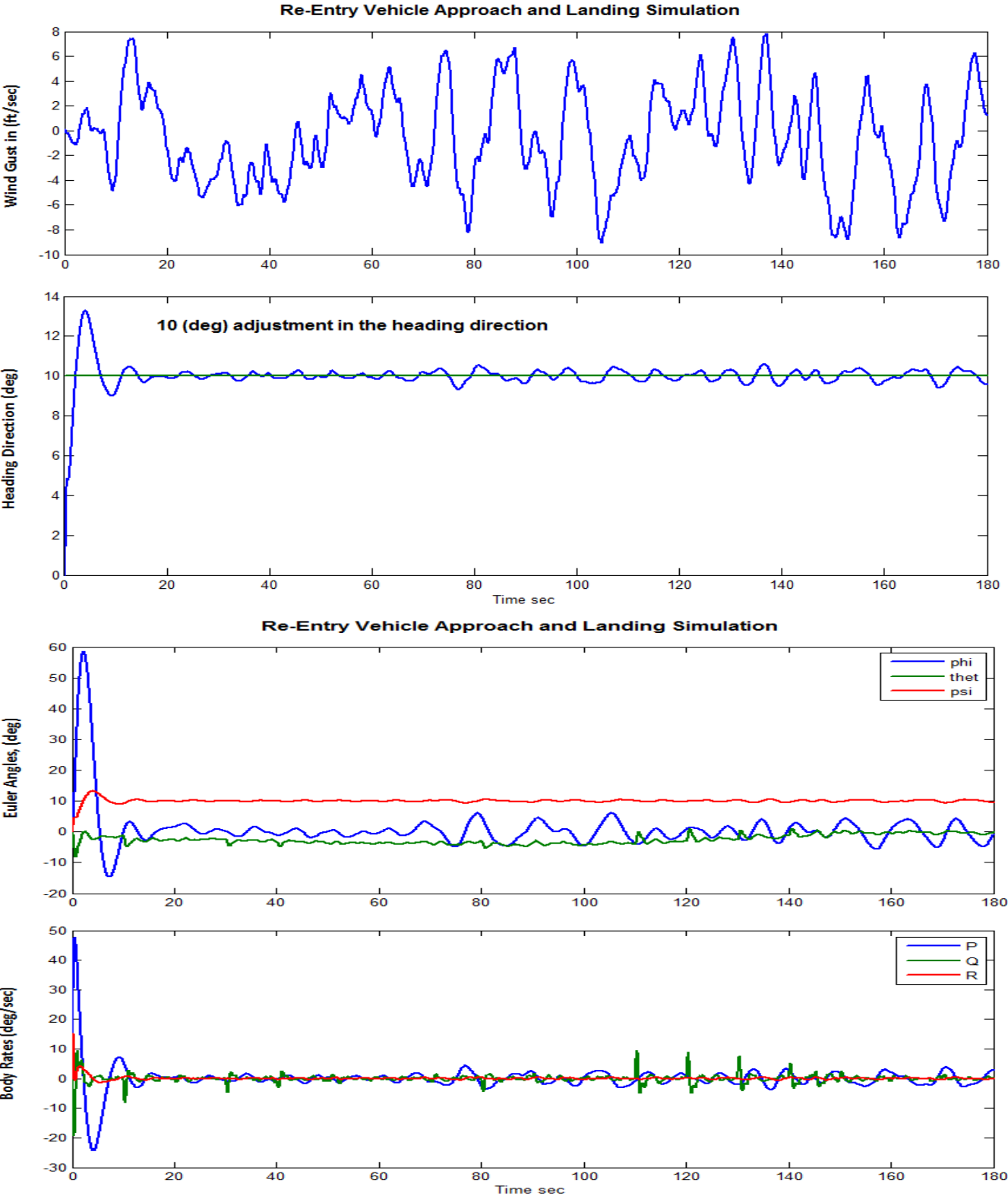
The longitudinal flight control system used in the simulation model is shown in figure (3.7.4). In the longitudinal direction the control system receives coordinated altitude and speed commands. Guidance calculates the changes in altitude (δh_{cmd}) and speed (δV_{cmd}) commands which control its rate of descent and speed. It uses the longitudinal state-feedback control gain (K_q) that was calculated by the LQR method. The inputs to the state-feedback matrix are: (θ , q , scaled N_z instead of α , altitude error δh , and speed error δV). Filtered accelerometer measurements are used instead of α and β because they are directly measured, otherwise α and β must be estimated.

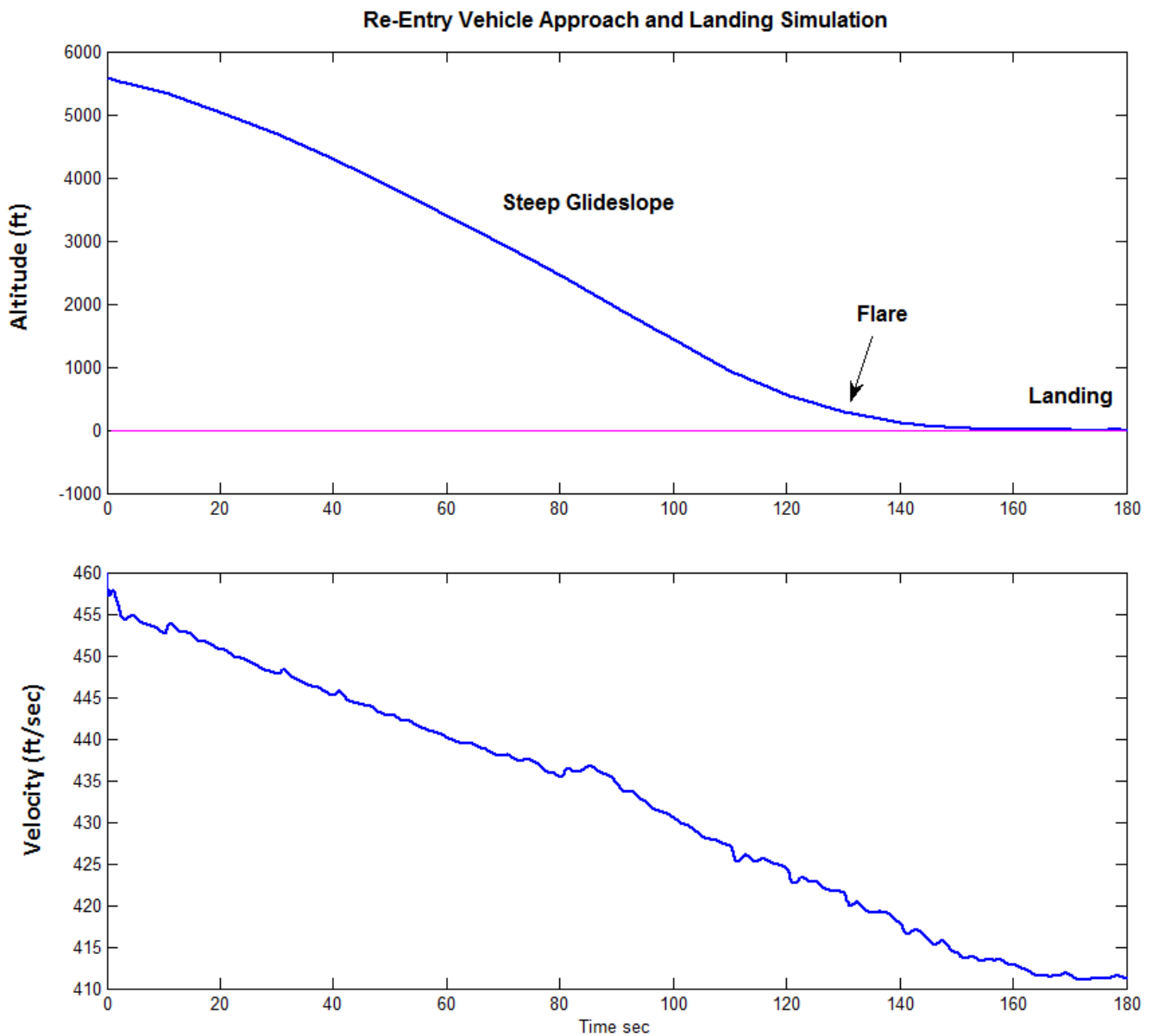
Simulation

We will now use the simulation model described in figure (3.7.1) to perform a descent and landing simulation of the re-entry vehicle starting from an altitude of 5,560 (ft), $\alpha=6^\circ$, and a speed of 460 (ft/sec), which corresponds to the linearized model at $t=1860$ (sec), all the way to landing. This linear simulation is of course an approximation because the vehicle dynamic parameters change with time. For more accurate analysis a non-linear 6-dof simulation is required to accurately model the approach and landing phase (similar to the simulations presented in the F16 or Lifting-Body aircraft examples). But even this linear simulation is very useful in evaluating the flight control performance, plus it is much easier to implement in comparison with a non-linear 6-dof simulation.



In the simulation the vehicle is initially commanded to perform a 10° change in its heading direction to align itself with the runway. The first plot shows its response to the heading command. It banks to the right for a short time and returns to horizontal when the commanded heading is achieved.

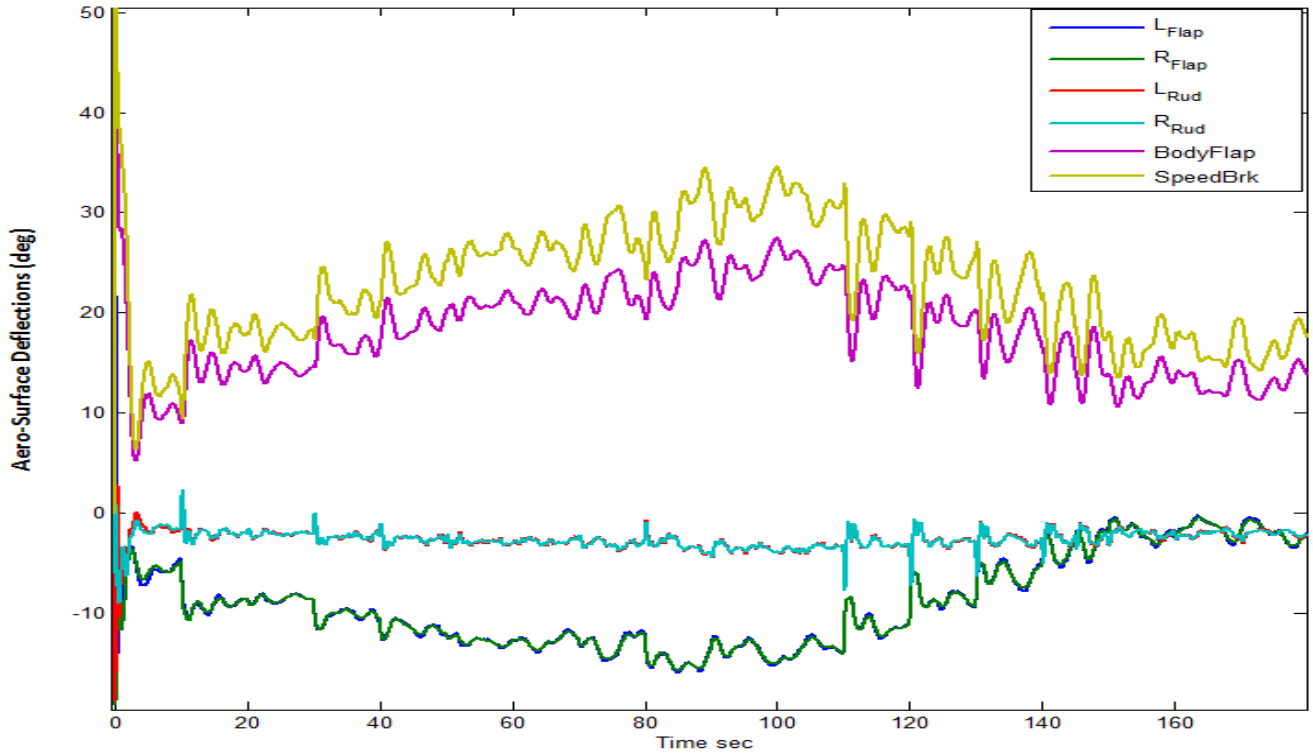




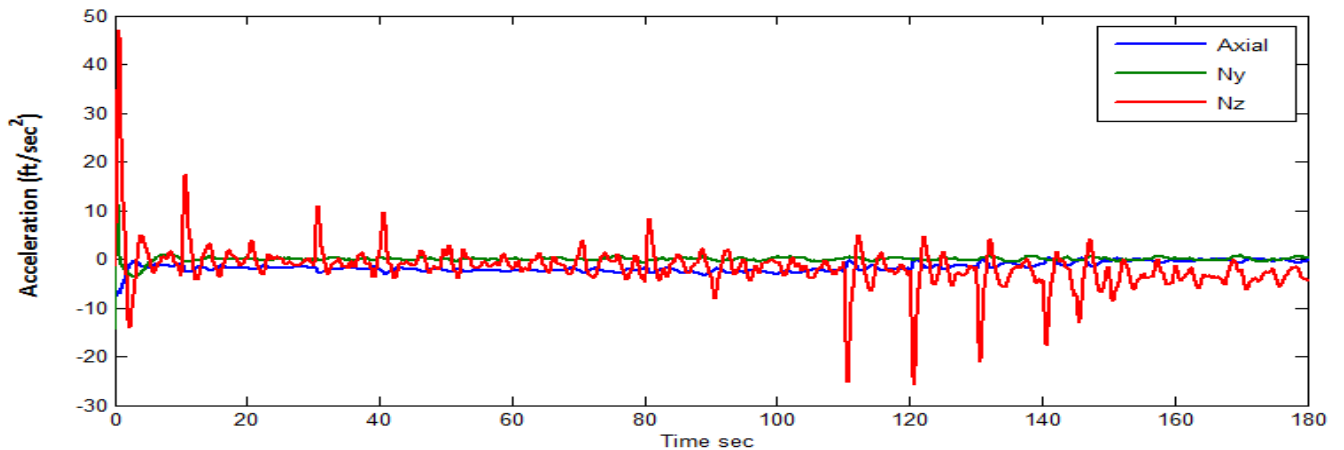
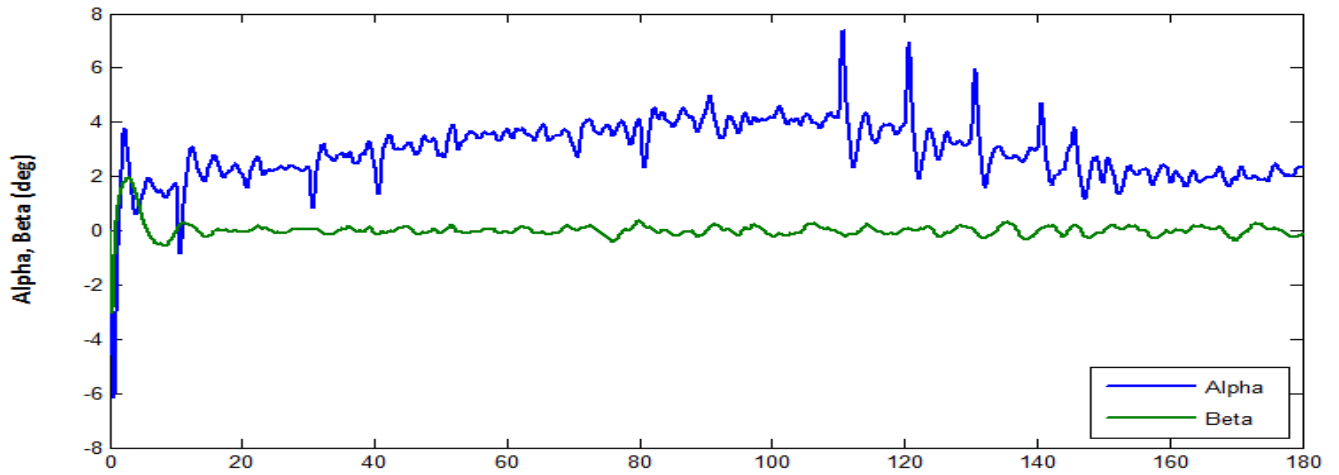
In the longitudinal axis the control system receives from guidance coordinated altitude and speed commands versus time. The above plot shows the altitude versus time response of the vehicle. The altitude follows the altitude descent command through a steep gamma glide-slope the flare (nose up) and landing (where $\gamma=0$). The effects of the noisy wind-gusts have a effect in the velocity versus time plot.

The next plot shows the deflections of the control surfaces. Note that these deflections are not measured from zero, but they are increments relative to their trim values. That is, the trim deflections at t=1860 sec, which are shown in the input data file "T1860.Inp". Notice how the speed-brake and body-flap deflections increase prior to the flare to dissipate the extra energy and to control the angle of attack as needed in order to slow down the rate of descent.

Re-Entry Vehicle Approach and Landing Simulation



Re-Entry Vehicle Approach and Landing Simulation



Stability Analysis

The next important analysis to perform is to check the gain and phase margins of the LQR control design. The Simulink model used for frequency response analysis is in file "*Stab_Anal.Mdl*", shown in Figure (3.7.5). It is used from the script file "freq.m" that calculates the frequency response across the opened loop. The loop opening is adjustable. Either the heading loop, velocity loop, or the altitude loop is opened at a time, with the other two closed. The stability analysis Bode and Nichols Charts are shown in Figure (3.7.6).

```
% Stability Analysis Script
d2r=pi/180; r2d=180/pi;
init
label='Velocity Control Loop Opened, all other loops are closed'
[Ao,Bo,Co,Do]=linmod('Stab_Anal'); % Freq analysis system
sys= SS(Ao,Bo,Co,Do);
w=logspace(-3, 3, 30000);
figure(1); Nichols(sys,w); title(label);
figure(2); Bode(sys,w); title(label);
```

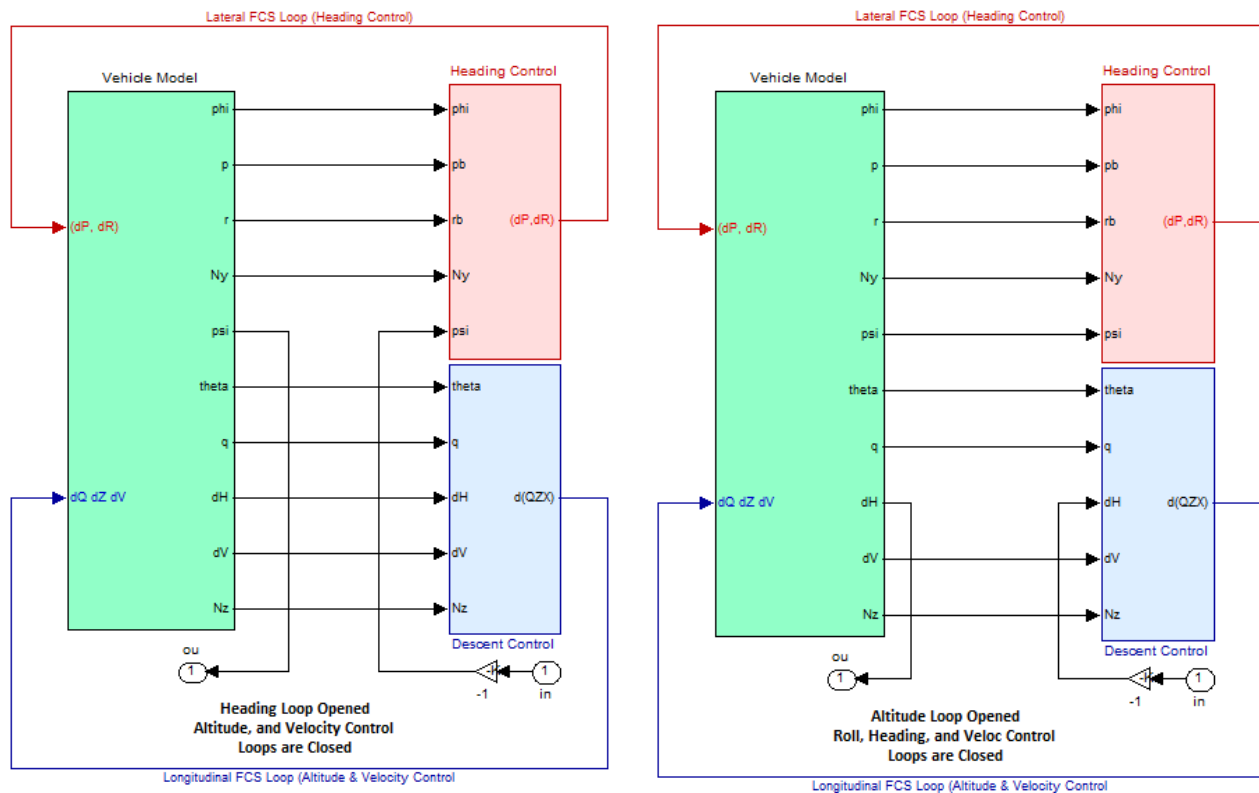
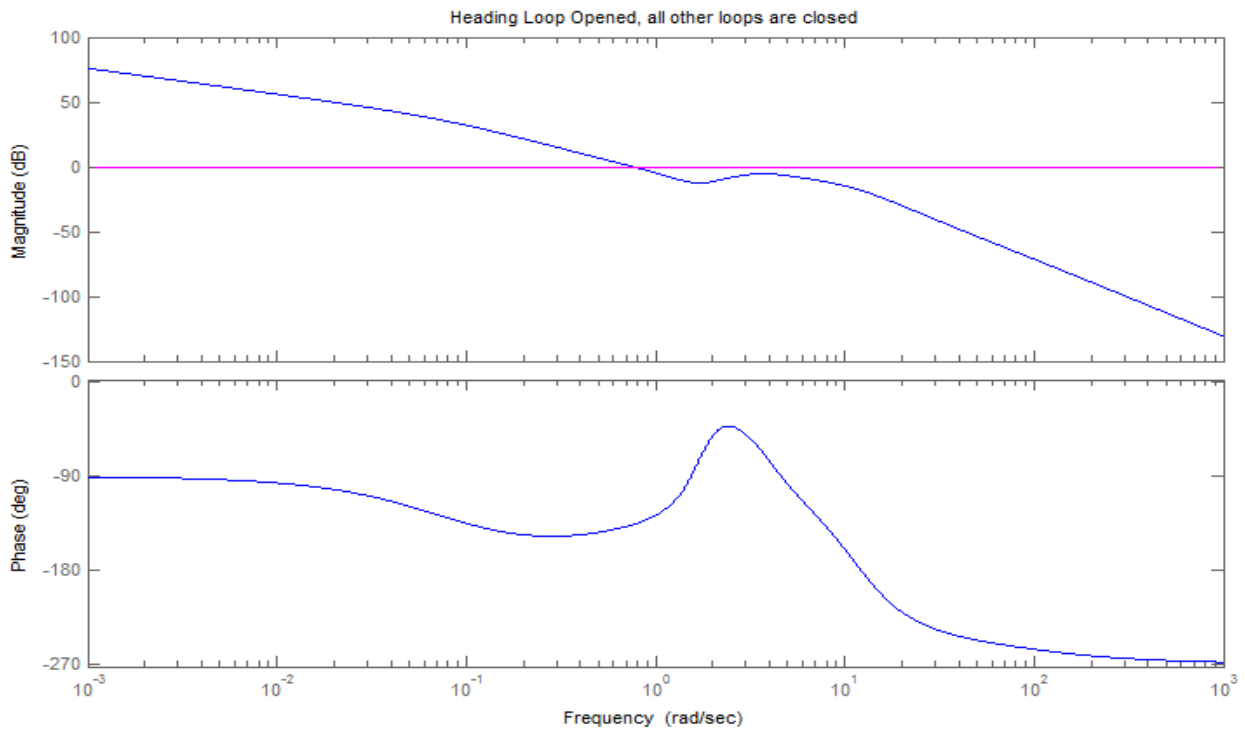
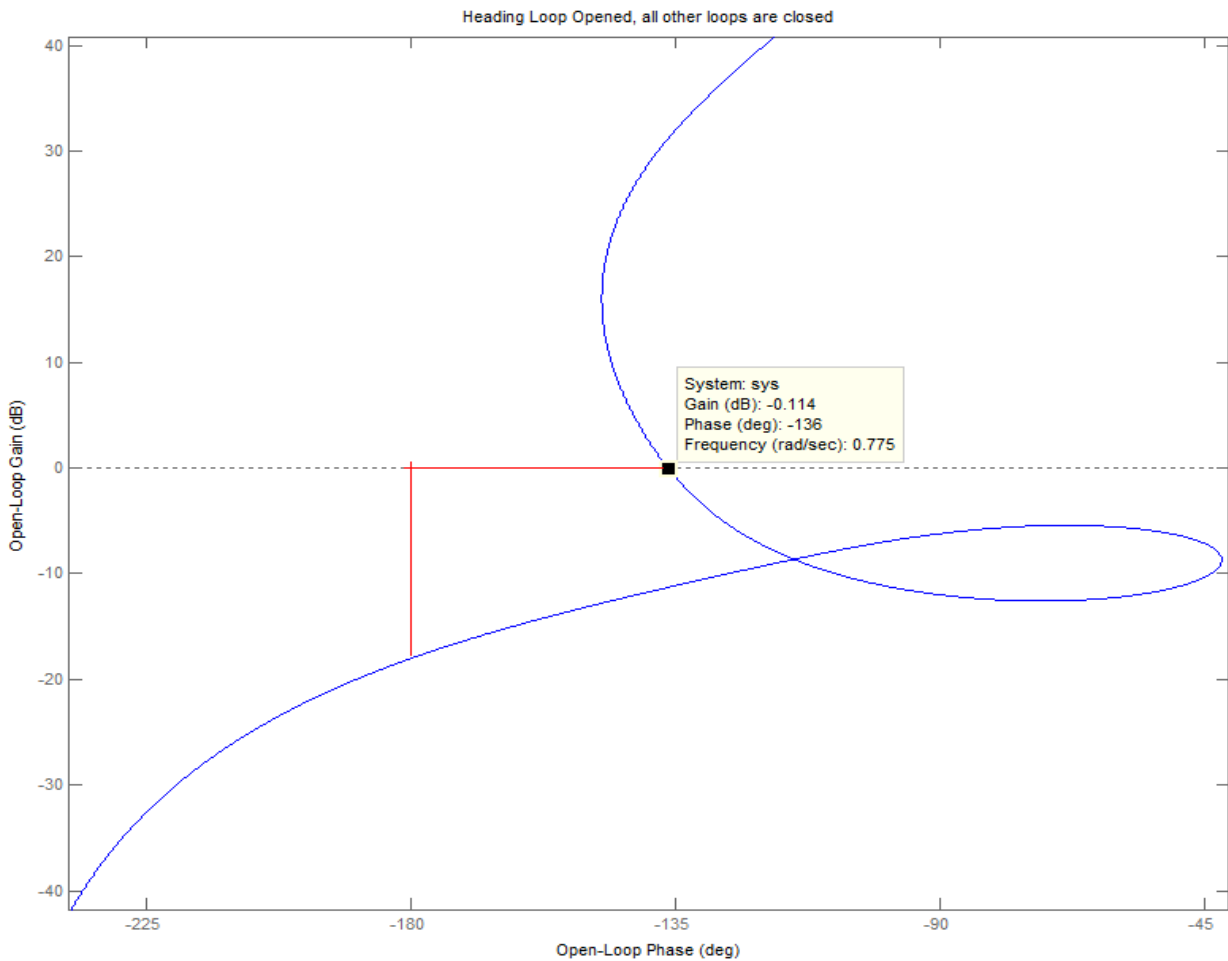
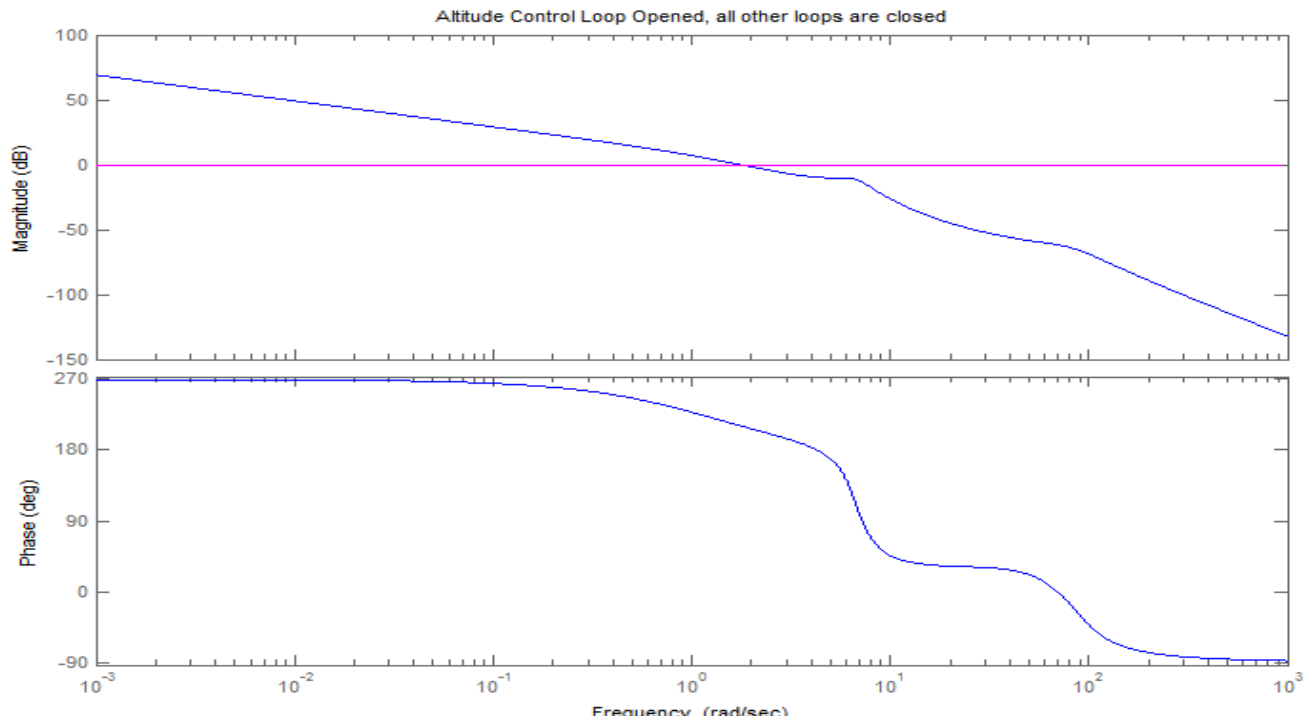


Figure 3.7.5 Simulink Model "*Stab_Anal.Mdl*" used for frequency response stability analysis. It is shown in two different configurations: (a) for heading loop stability, and (b) for altitude control loop stability analysis.

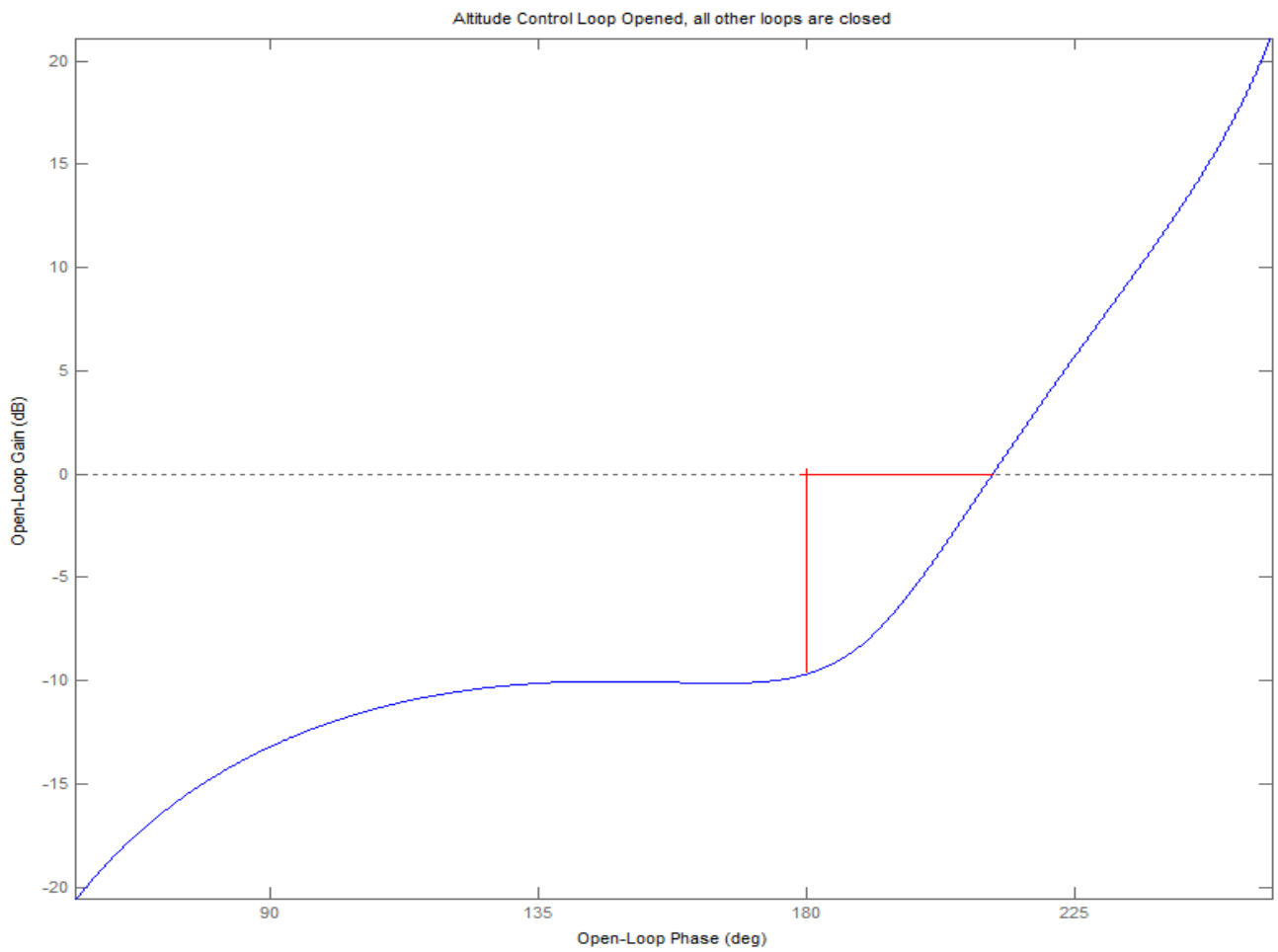


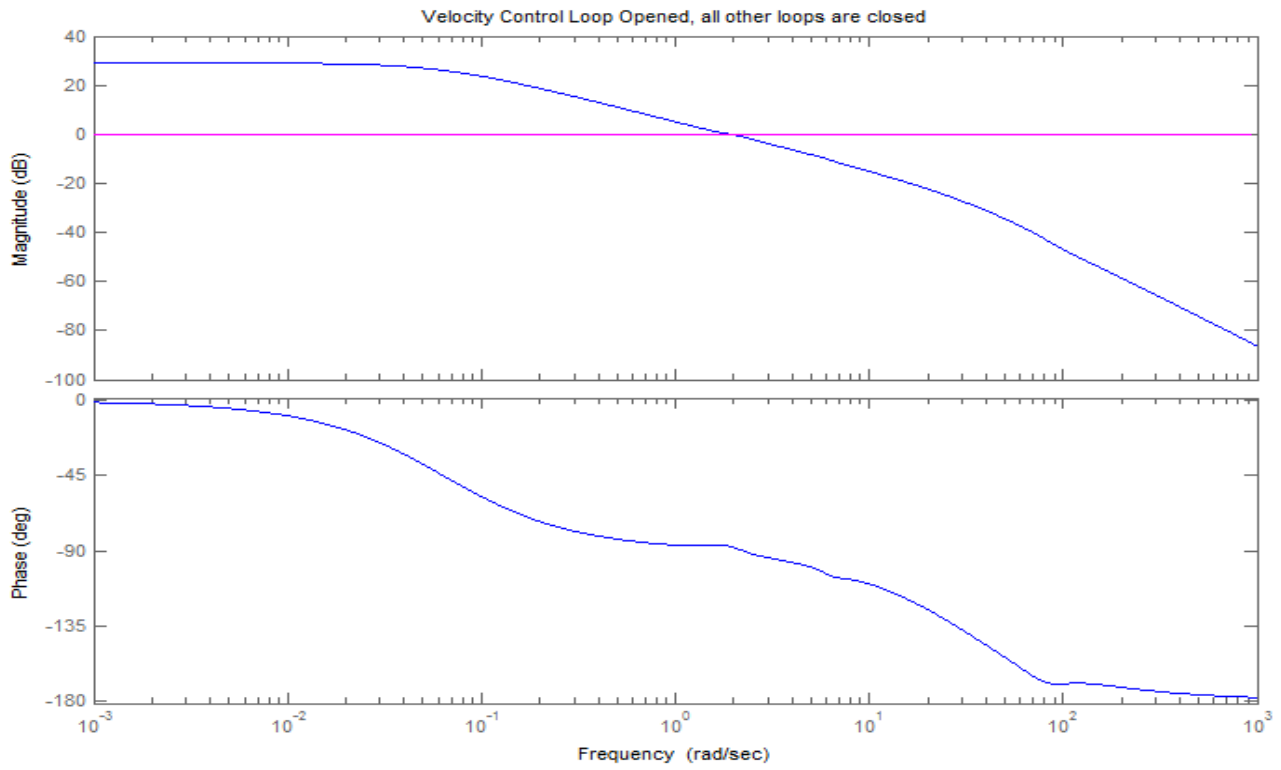
Heading Loop Stability Margins





Altitude Control Loop Stability Margins





Velocity Control Loop Stability Margins

