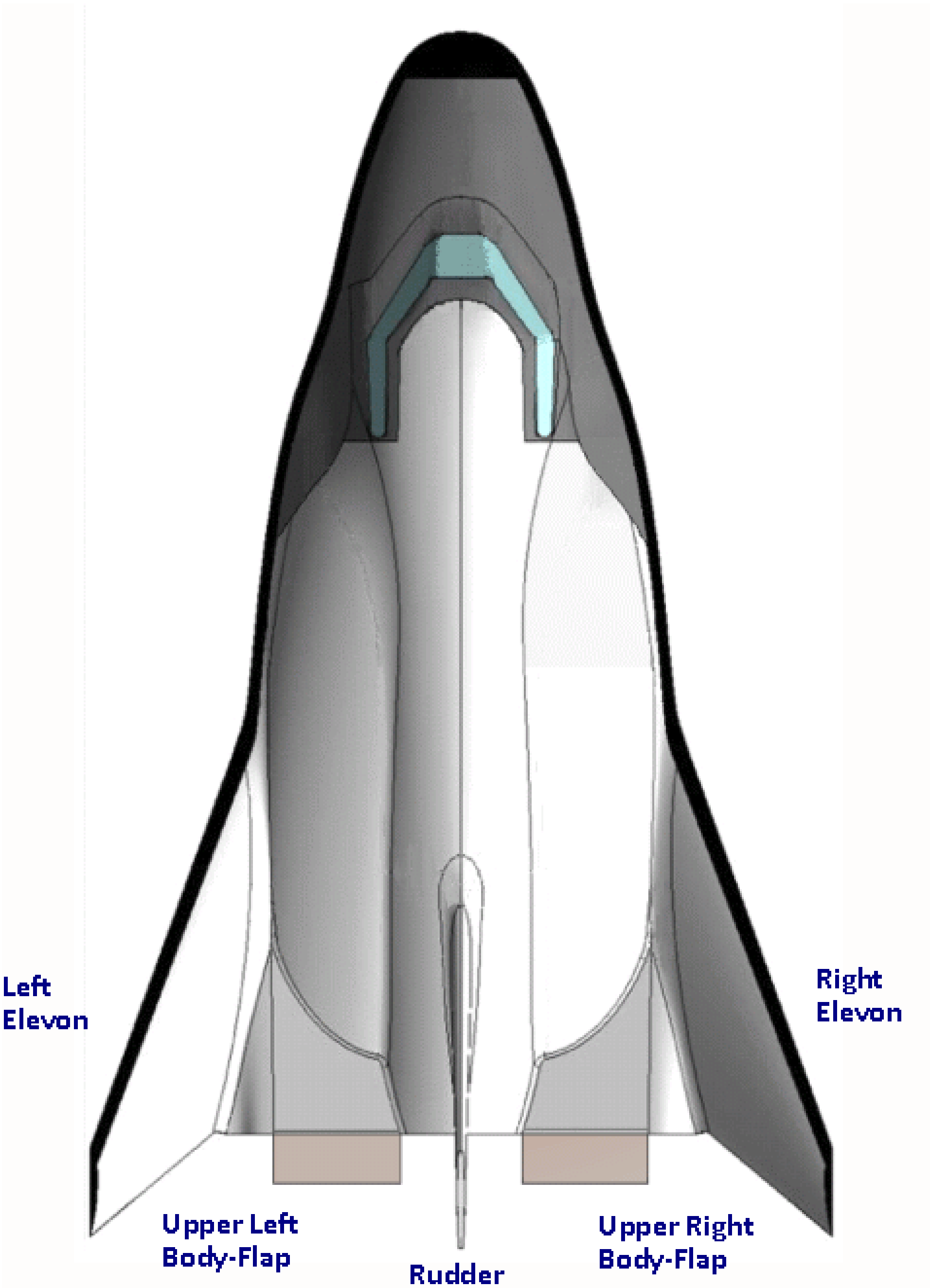
Lifting-Body Space-Plane

In this example we will study a Lifting-Body aircraft that is used as a transportation vehicle from space. It is capable of returning from space by gliding and landing autonomously by using its aero-surfaces. It is also capable of taking-off vertically like a rocket by means of two TVC engines, reaching at high altitudes and landing unpowered and autonomously.

We will use the Flixan program to analyze this vehicle during both, ascent and descent phases. We will finally show how to use Matlab/ Simulink to create a 6-dof non-linear reentry simulation from de-orbit to landing. Information and details are included which are often left out in textbooks, technical papers and presentations.


Left Elevon
Upper Left
Body-Flap
Left TVC
Engine
Lower Left
Body-Flap


Left
Elevon
Right
Elevon
Upper Left
Body-Flap
Rudder
Upper Right
Body-Flap

The purpose of this example is to demonstrate the entire flight control design of a typical reentry vehicle from de-orbit to landing, beginning with a preliminary performance and controllability analysis, control law synthesis at selected Mach points, and performing linear dynamic analysis and simulation. It teaches the student how to create dynamic models for flight control design and linear analysis, how to design simple control laws in MATLAB®, and how to generate dynamic models for analyzing robustness to uncertain parameters. The analysis concludes by creating a 6-DOF non-linear simulation of the reentry vehicle, from de-orbit to landing, using MATLAB/ Simulink®. The second part of this example demonstrates the ascent phase when the two main rockets are firing.

Figure 1 shows the vehicle effectors from the rear consisting of seven aero-surfaces, that is: two elevons, a rudder, and four body-flaps (two upper and two lower). The vectors indicate the directions of positive aero-surface rotations. It also has two TVC engines of 18,000 (lb) thrust each, which are also capable of varying thrusts. Having multiple aerosurfaces provides the capability to trim and to control this vehicle entirely by the aerosurfaces during reentry without a need for RCS. However, RCS is also available, but it is only used for maneuvering and controlling attitude at low dynamic pressures and also as a back-up system during descent. The primary function of the elevons and rudder is to provide roll, pitch, and yaw control. The four body-flaps are mainly for trimming and for speed-brake control. However, they are also used to provide some flight control assistance to the elevons.

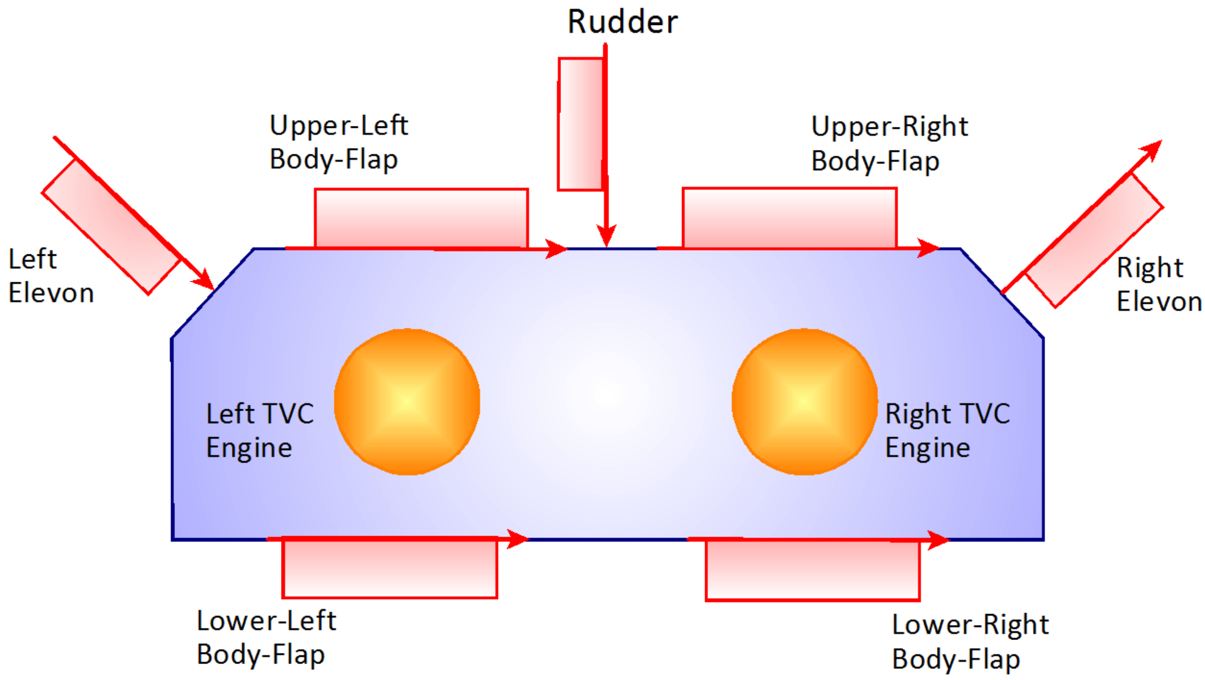


Figure 1 Control Effectors are shown from the back of the Vehicle, consisting of: Seven Aero-Surfaces and Two Throttling TVC Engines

1.0 Reentry Analysis

The reentry trajectory begins when the dynamic pressure is sufficient for the vehicle to trim and to be controlled using the seven aerosurfaces alone without any assistance from the RCS jets. The descent trajectory is separated into four phases having different control requirements and different control modes of operation. The analysis is, therefore, separated into four sections that describe and analyze in detail the four control modes, which are as follows:

1. The hypersonic phase where the Mach number varies between 28 and 20, and the flight path angle γ is at a very shallow dive of -1° to avoid overheating due to aerodynamic friction. The angle of attack is controlled at 30° that provides better heat protection due to shielding. In the lateral directions the control system is able to perform roll maneuvers and to control the heading direction by rolling about the velocity vector V_0 which reduces sideslip and hence, lateral loading.

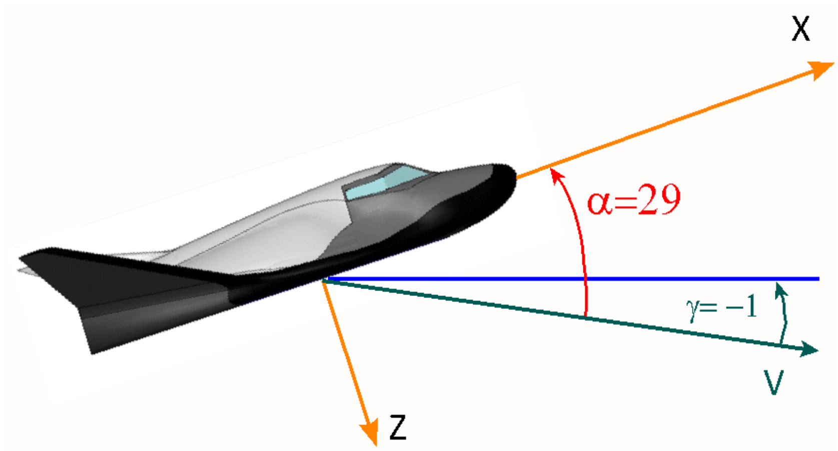
2. The normal acceleration Nz-control: during this phase the vehicle is tracking an almost steady Nz acceleration command from guidance and it gradually transitions to flight-path angle γ-control mode.

3. The flight-path angle γ-control: during this phase the flight control system tracks a flight-path angle γ_{cmd} which is commanded by the closed-loop guidance. It also performs a heading alignment maneuver prior to approach and landing to align its direction with the runway.

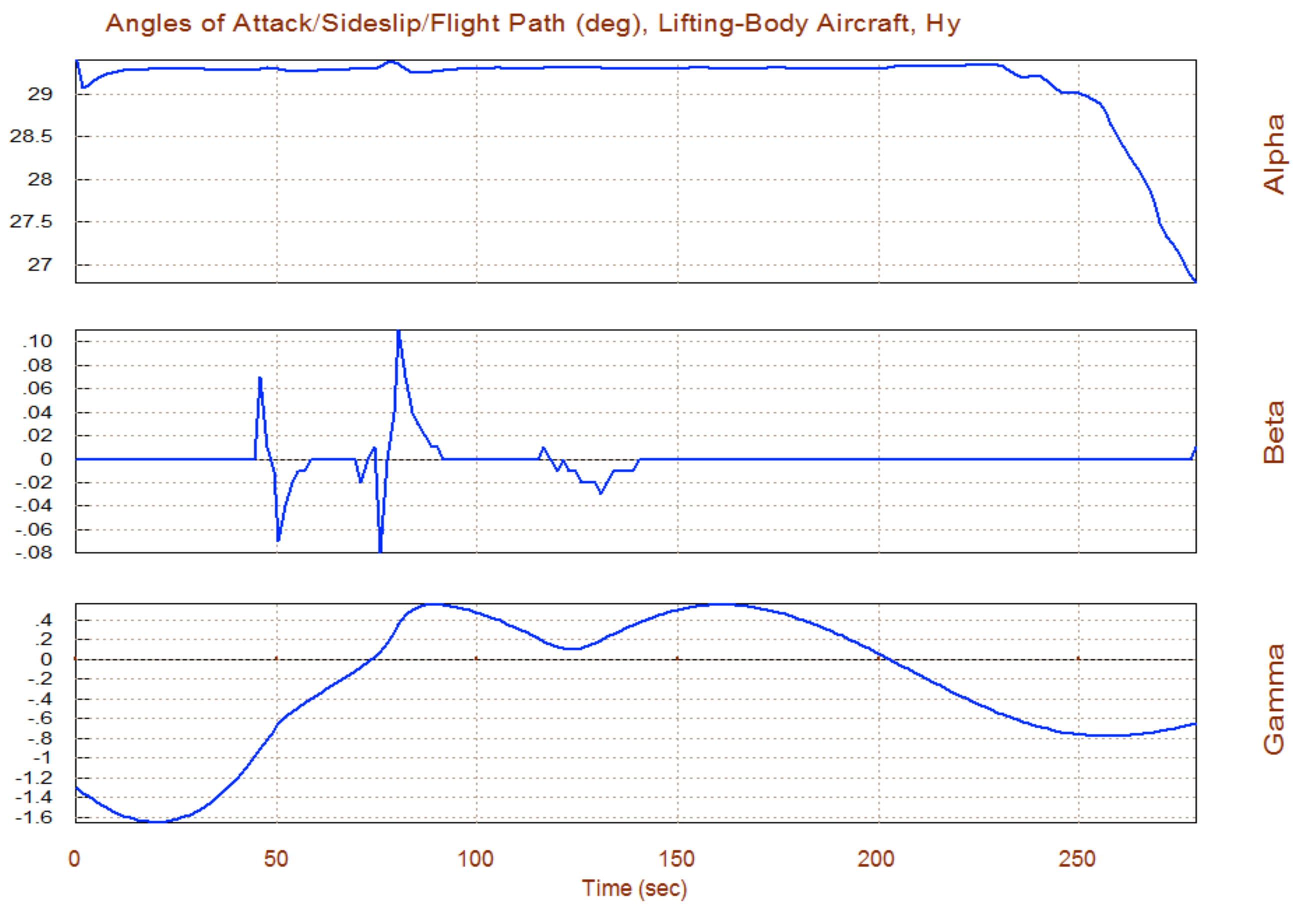
4. The approach and landing phase, where the longitudinal guidance attempts to control altitude and speed. The speed-brake is partially deployed during this phase and velocity is controlled by modulating drag. In lateral, the heading guidance controls the flight direction against cross-winds by controlling the roll angle.

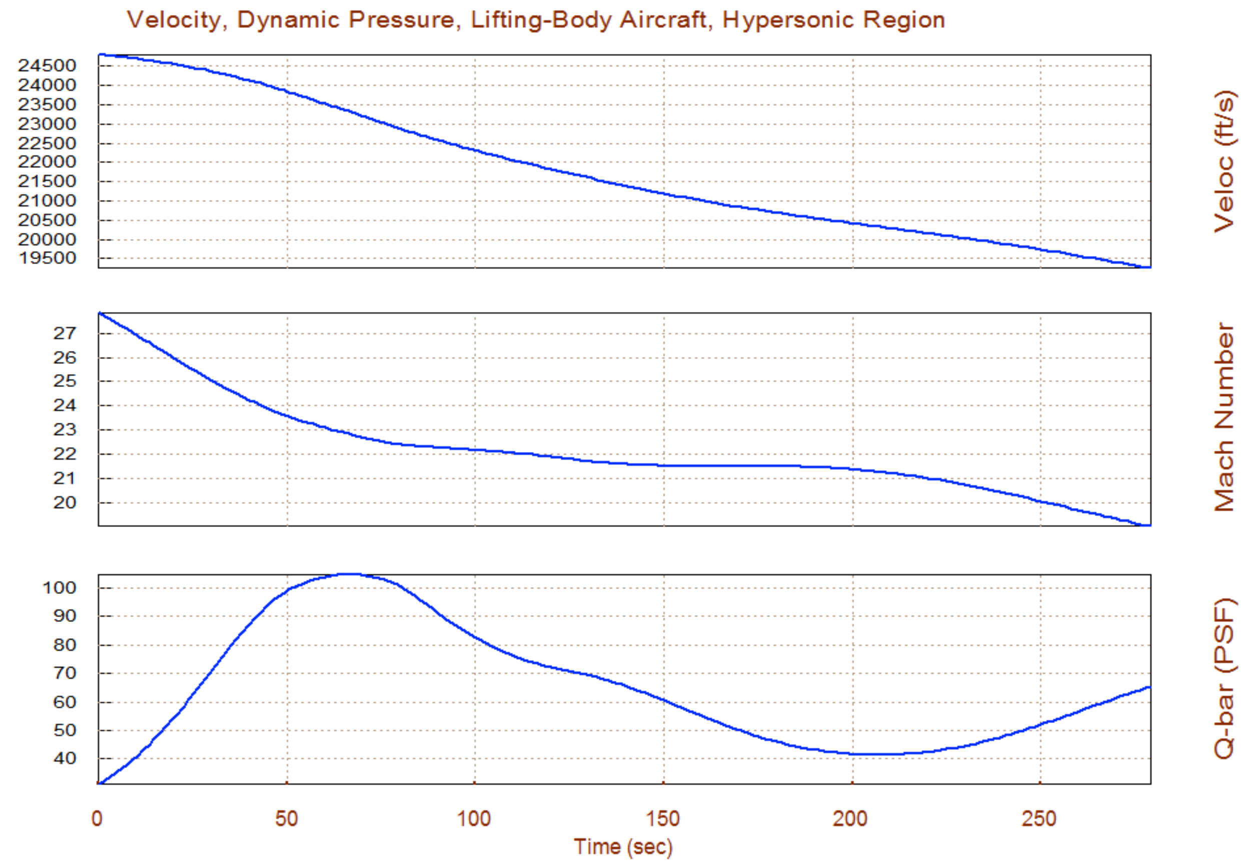
We begin the trim and controllability analysis with a preliminary reentry trajectory from a point-mass simulation. The trajectory is also separated into four segments that correspond to the four control phases described and it is analyzed in separate folders. We will examine each phase separately by trimming the effectors and analyzing static performance along the trajectory segment. We will use contour plots and vector diagrams to analyze performance and maneuverability. We will use Flixan to generate dynamic models at selected flight conditions along the trajectory, perform flight control designs, and analyze stability and robustness to uncertainties at the selected trajectory points. Separate control analysis and detail description will be presented for each control mode, including simulations. We will finally verify the control design by creating a 6-DOF non-linear simulation for the entire reentry flight from de-orbit to landing in Simulink using the control laws derived from the analysis.

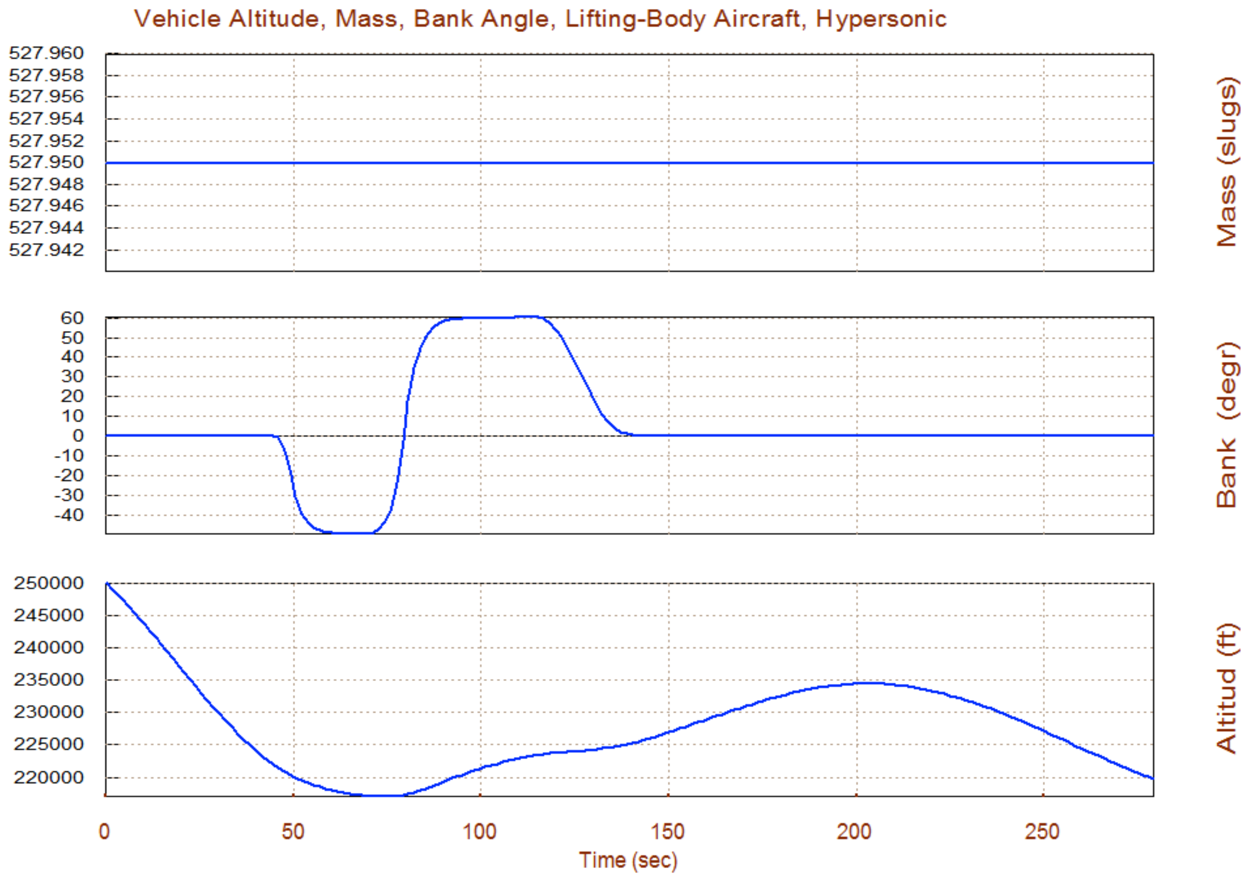
1.1 Early Reentry Phase Using Alpha Control



After de-orbiting and during the early phase of reentry (first 300 sec) the vehicle uses the RCS jets to maintain a 29.5° constant angle of attack which optimizes aero heating. Atmospheric reentry begins at an altitude of 250,000 (feet) and at Mach 28. The vehicle maintains a mostly negative shallow flight-path angle γ of approximately -1° and it rolls about the velocity vector V_0 to avoid from bouncing back off into space. As the dynamic pressure increases the aerosurfaces are used to trim and to control the angle of attack at 29.5°. The flight control system uses estimated α to control the angle of attack which is gradually reduced, and the control system eventually switches to normal acceleration Nz-control. The following figures show some of the trajectory parameters in the hypersonic region between Mach: 28 to 19.




Velocity, Dynamic Pressure, Lifting-Body Aircraft, Hypersonic Region
24500
24000
23500
23000
22500
22000
21500
21000
20500
20000
19500
Veloc (ft/s)
27
26
25
24
23
22
21
20
Mach Number
100
90
80
70
60
50
40
Q-bar (PSF)
0
50
100
150
200
250
Time (sec)


Vehicle Altitude, Mass, Bank Angle, Lifting-Body Aircraft, Hypersonic
527.960
527.958
527.956
527.954
527.952
527.950
527.948
527.946
527.944
527.942
Mass (slugs)
60
50
40
30
20
10
0
-10
-20
-30
-40
Bank (degr)
250000
245000
240000
235000
230000
225000
220000
Altitud (ft)
0
50
100
150
200
250
Time (sec)

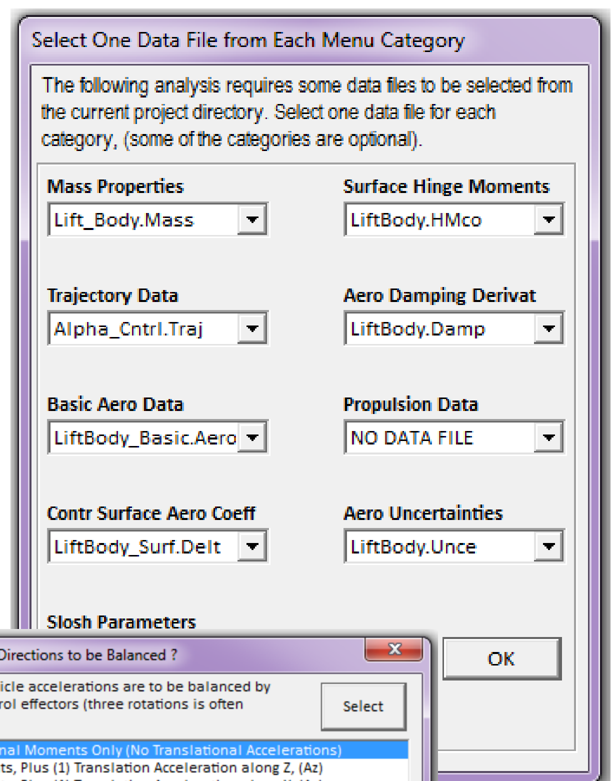
Data Files

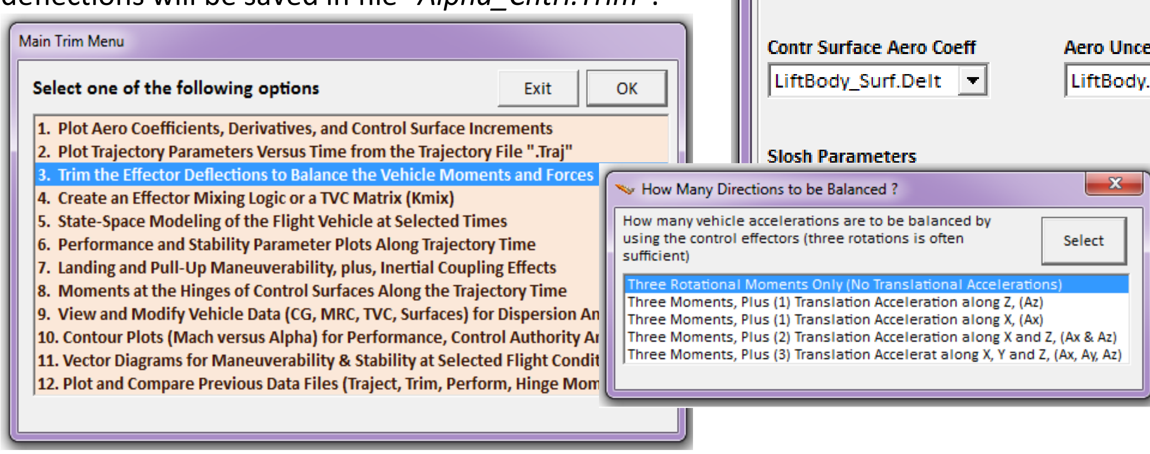
The data files for the alpha-controlled hypersonic section are in folder "*C:\Flixan\Trim\Examples\Lifting-Body Aircraft\Reentry from Space\Trim_Anal\Alpha_Control*". The alpha-controlled section of the trajectory is in file "*Alpha_Cntrl.Traj*". The mass properties for different fuel weights are in file "*Lift_Body.Mass*". The basic aero coefficients are in file "*LiftBody_Basic.Aero*". The surface increment coefficients for the 7 aero-surfaces are in file "*LiftBody_Surf.Delt*". Notice that the aero-surface bias angles in that file are already preset at the expected hypersonic trim angles. The hinge-moment coefficients are in file "*LiftBody.HMco*", the damping derivatives in file "*LiftBody.Damp*", and the aero-uncertainties in file "*LiftBody.Unce*". The surface mixing matrix "KmixM27" has already been calculated and saved in file "Kmix.Qdr".

Trimming

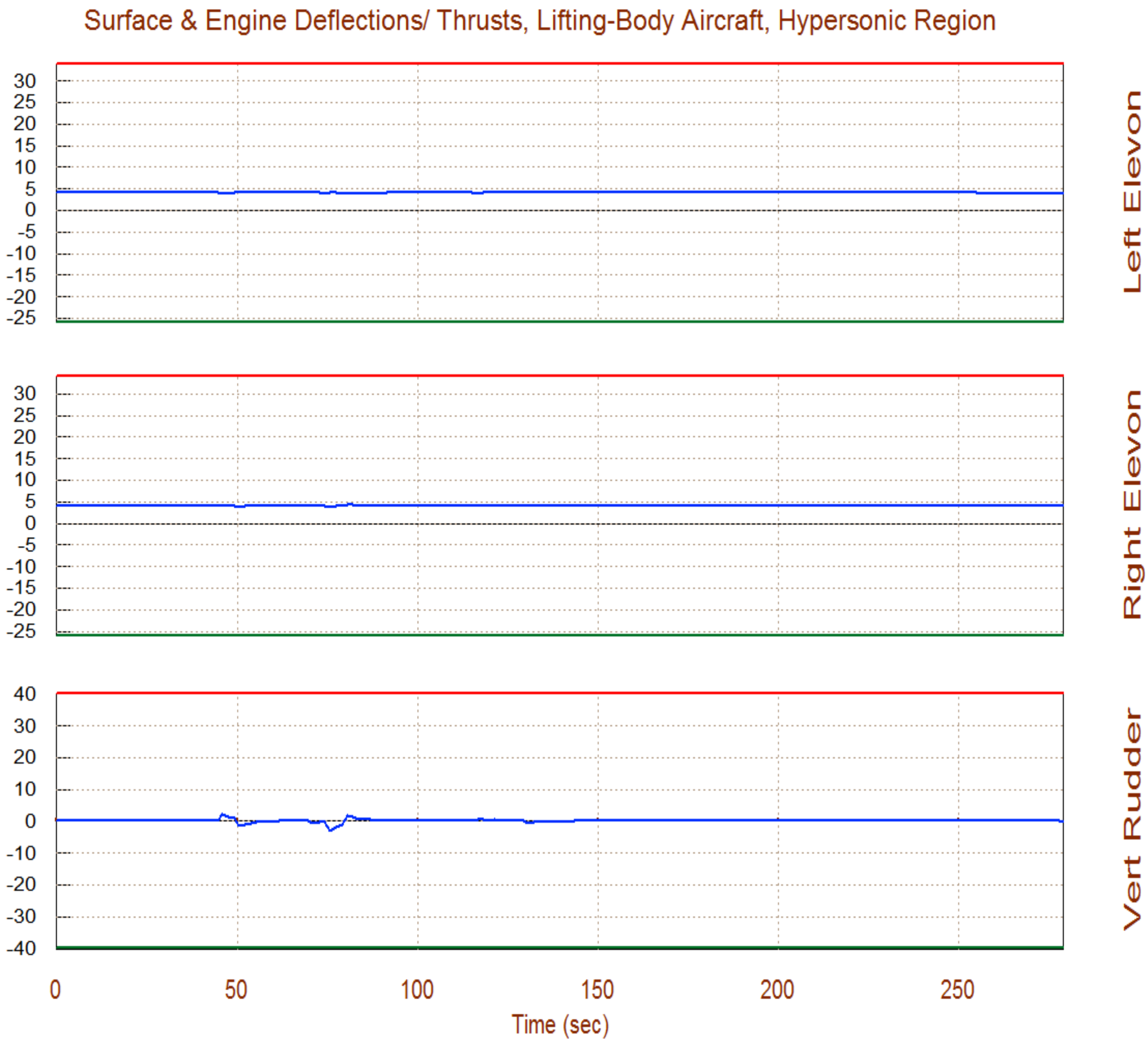
Before analyzing the vehicle performance we must use the Trim program to trim the positions of the aerosurfaces in order to balance the vehicle moments along this hypersonic trajectory. Only the moments are trimmed in this phase because the speed-brake is not active and no translational trimming is necessary. In actual flight or simulations, the pre-calculated effector trim positions are commanded open-loop (scheduled) as a function of the flight condition or time. The deflection commands produced by the flight control system are superimposed on the pre-scheduled commands, as we shall see in the 6-dof non-linear simulation.

After selecting the appropriate files in folder "*C:\Flixan\ Trim\ Examples\ Lifting-Body Aircraft\ Reentry from Space\ Trim_Anal\ Alpha_Control*", from the Trim main menu, 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 program will calculate a combination of aerosurface deflections to balance the moments based on the control authority of the aerosurfaces. At the completion of the trim, the aerosurface deflections will be saved in file "*Alpha_Cntrl.Trim*".

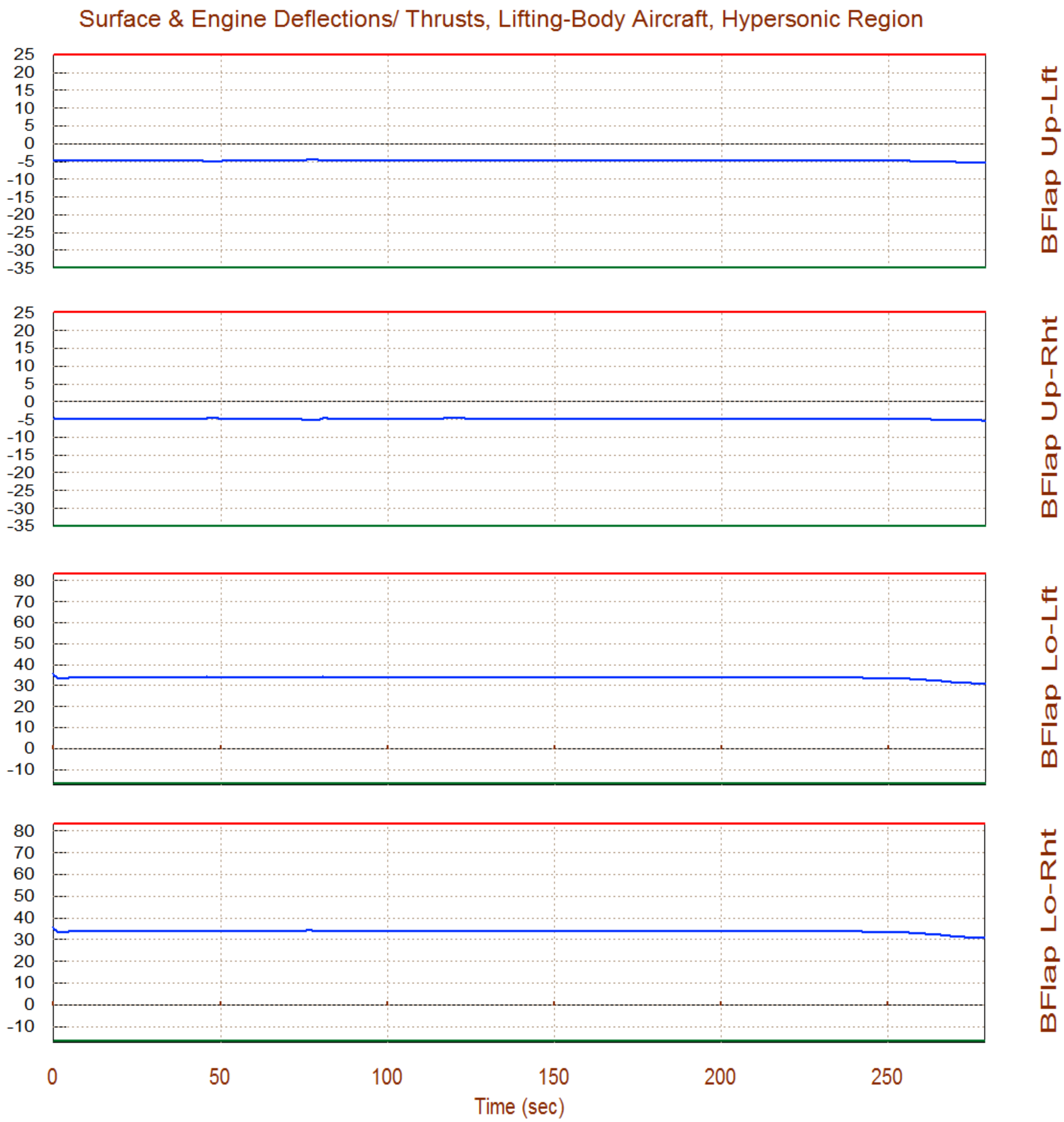




The following figures show the trim deflections for the seven aero-surfaces as a function of trajectory time during this high alpha hypersonic region.



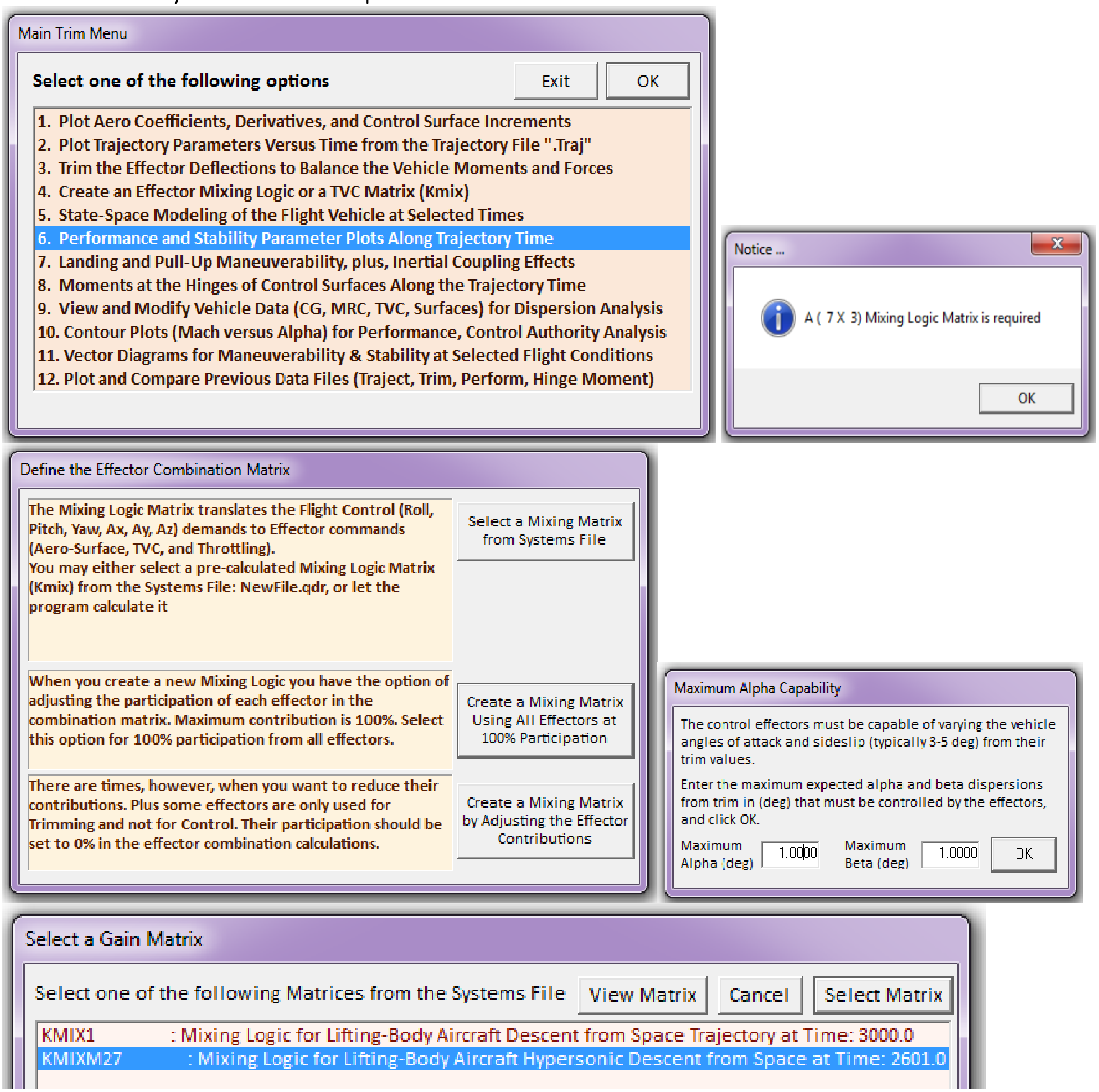
Notice that the two elevons trim at 4.5°, the two upper body-flaps trim at -5°, and the lower-left and lower-right body-flaps they both trim at 33° in this high alpha hypersonic condition. They do come down to smaller values, however, later when the angle of attack is reduced.

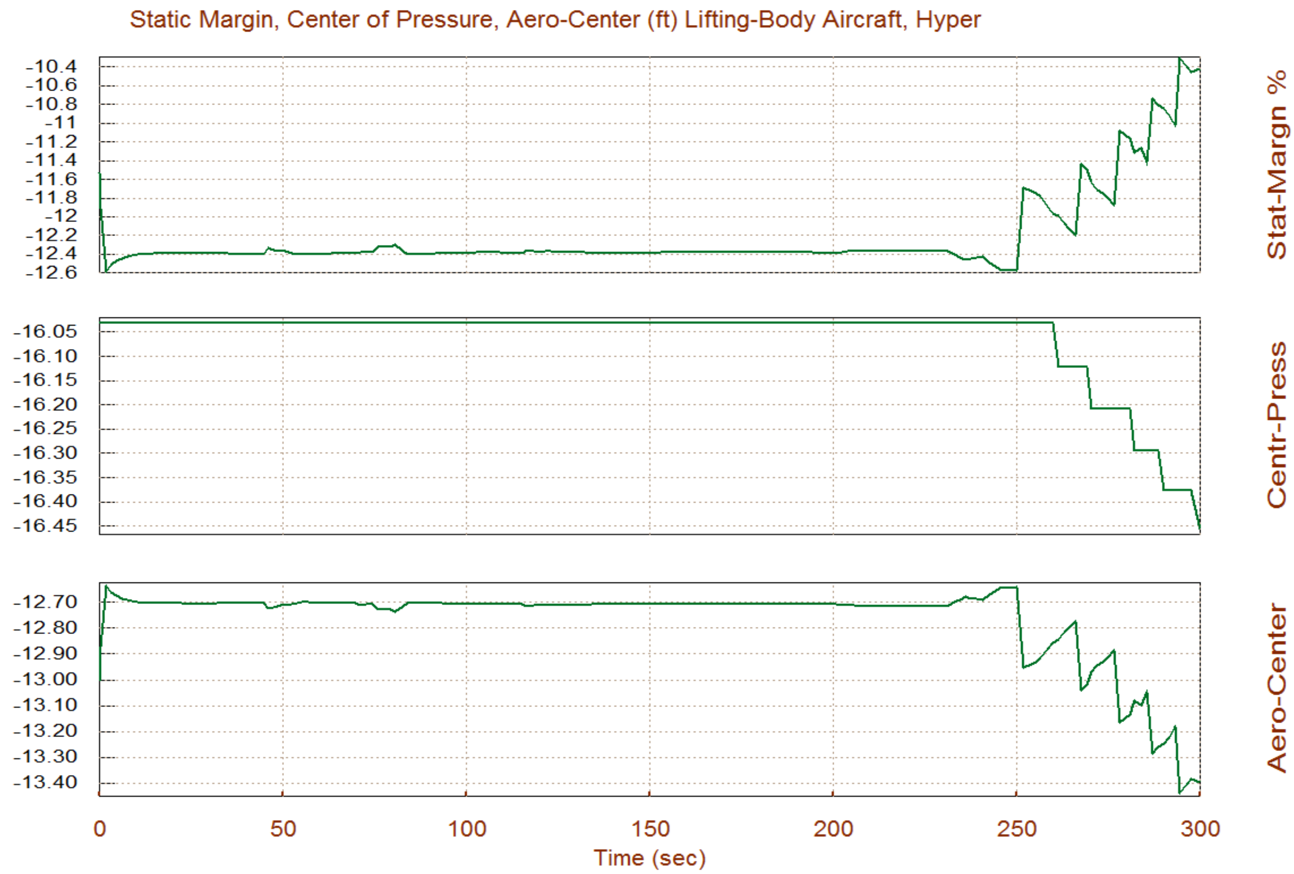


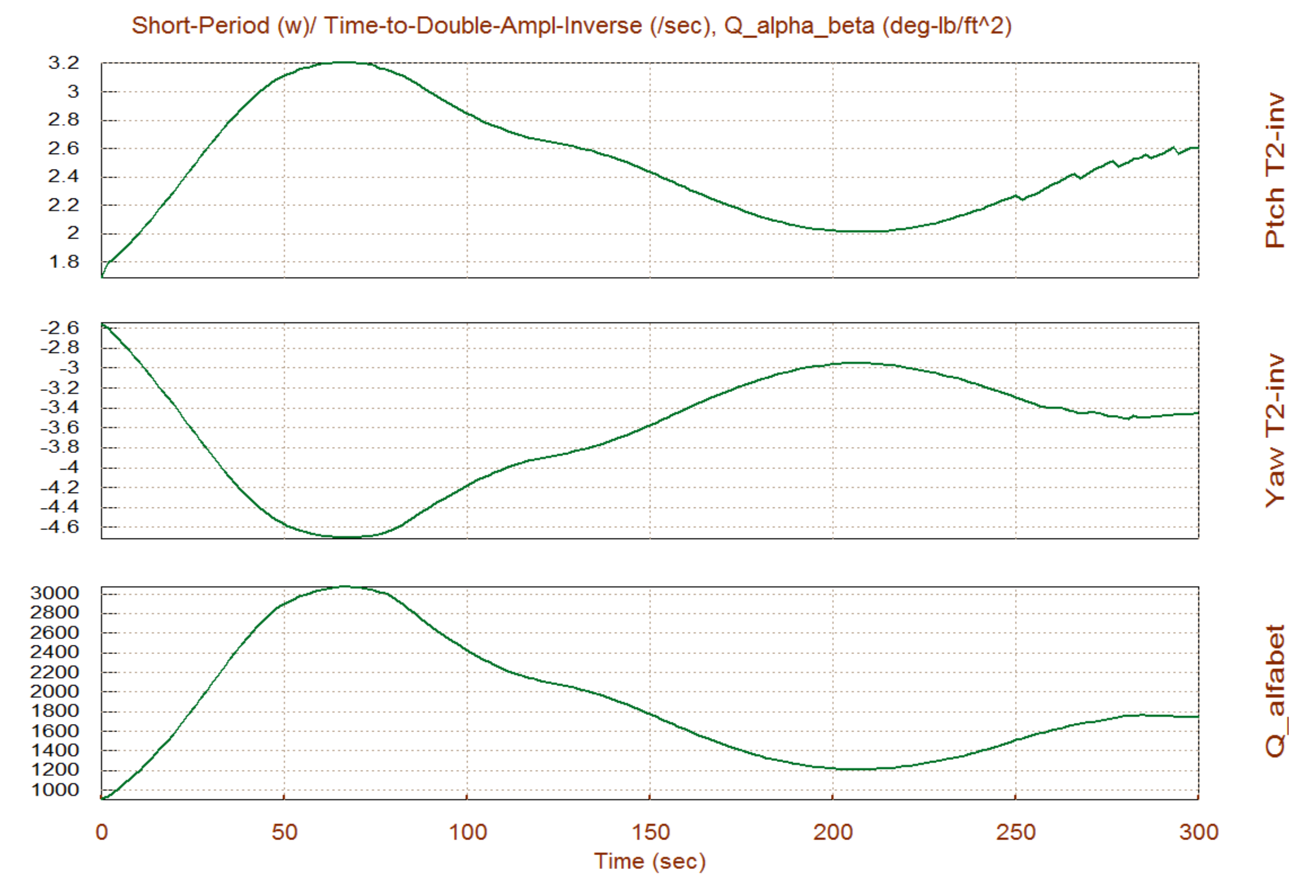
Performance Parameters along the Trajectory

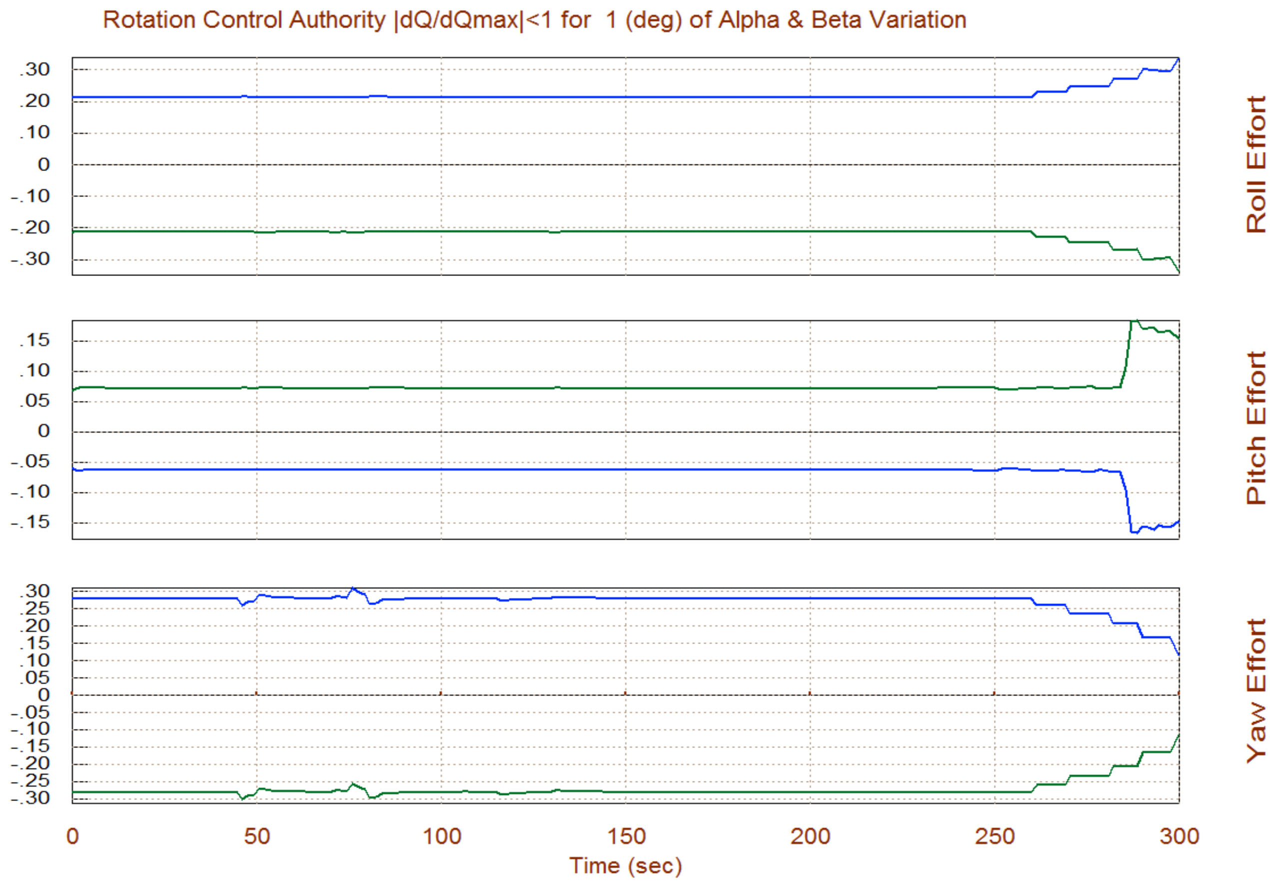
Having obtained the trim positions of the aerosurfaces, our next objective is to check the static performance and stability parameters that were described in Section 3, along the trajectory. Before examining the vehicle performance, however, the analyst must select a mixing logic matrix that defines how the seven aerosurfaces are combined together to control the 3 rotational axes. The mixing logic matrix Kmix defines the effectors allocation in roll, pitch, and yaw, and the control effectiveness strongly depends on this matrix.

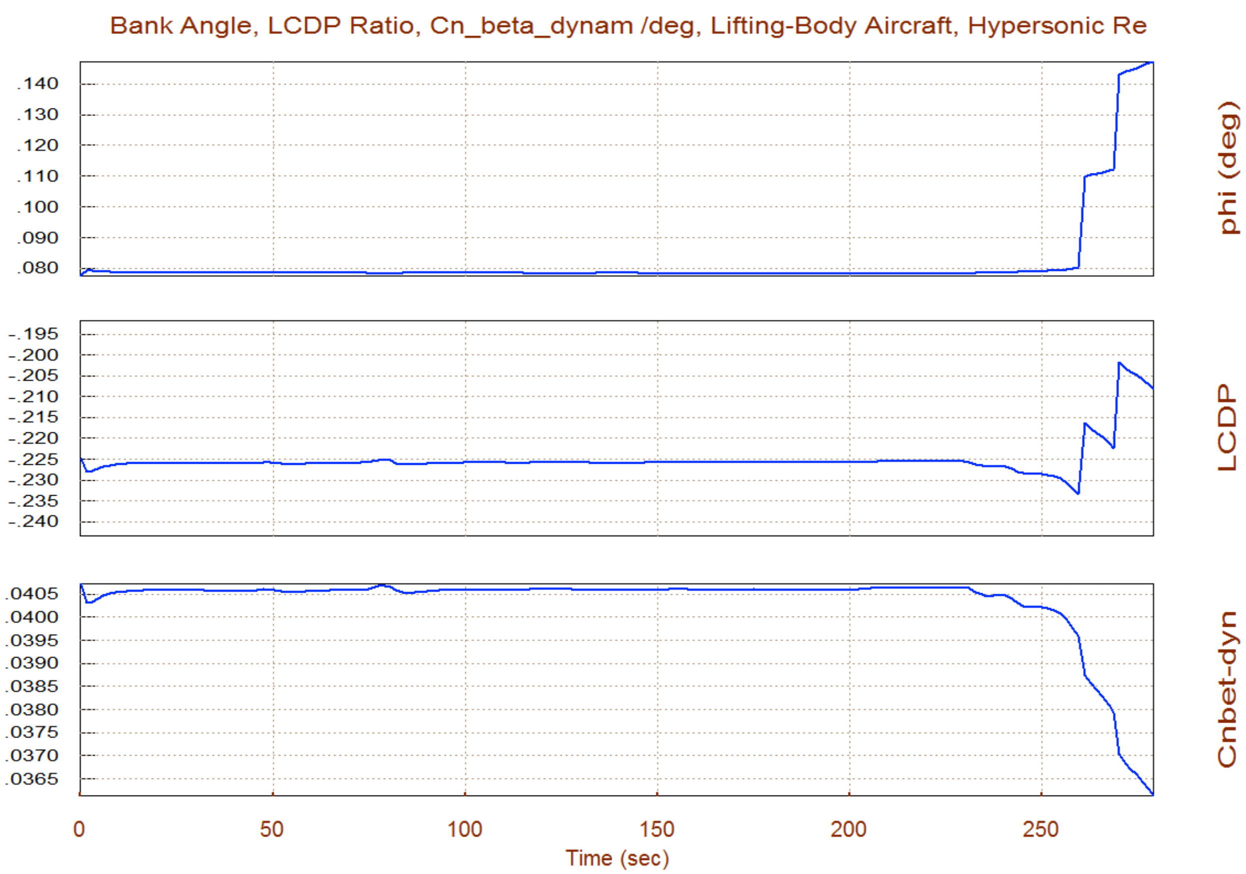
In actual flight or simulations the mixing logic matrix is scheduled as a function of Mach and α, similar to the control gains. In this example, however, we shall use a constant matrix KmixM27 from file "Kmix.Qdr" along the entire trajectory segment. We must also define the maximum expected magnitude of the α_{max} and β_{max} dispersion angles. In this early phase they are small and are both set to ±1°. This $\pm\alpha_{max}$ dispersion may also be interpreted as maneuverability requirement in terms of being able to achieve a certain acceleration demand from guidance. The vehicle should have the control authority to attain this requirement.

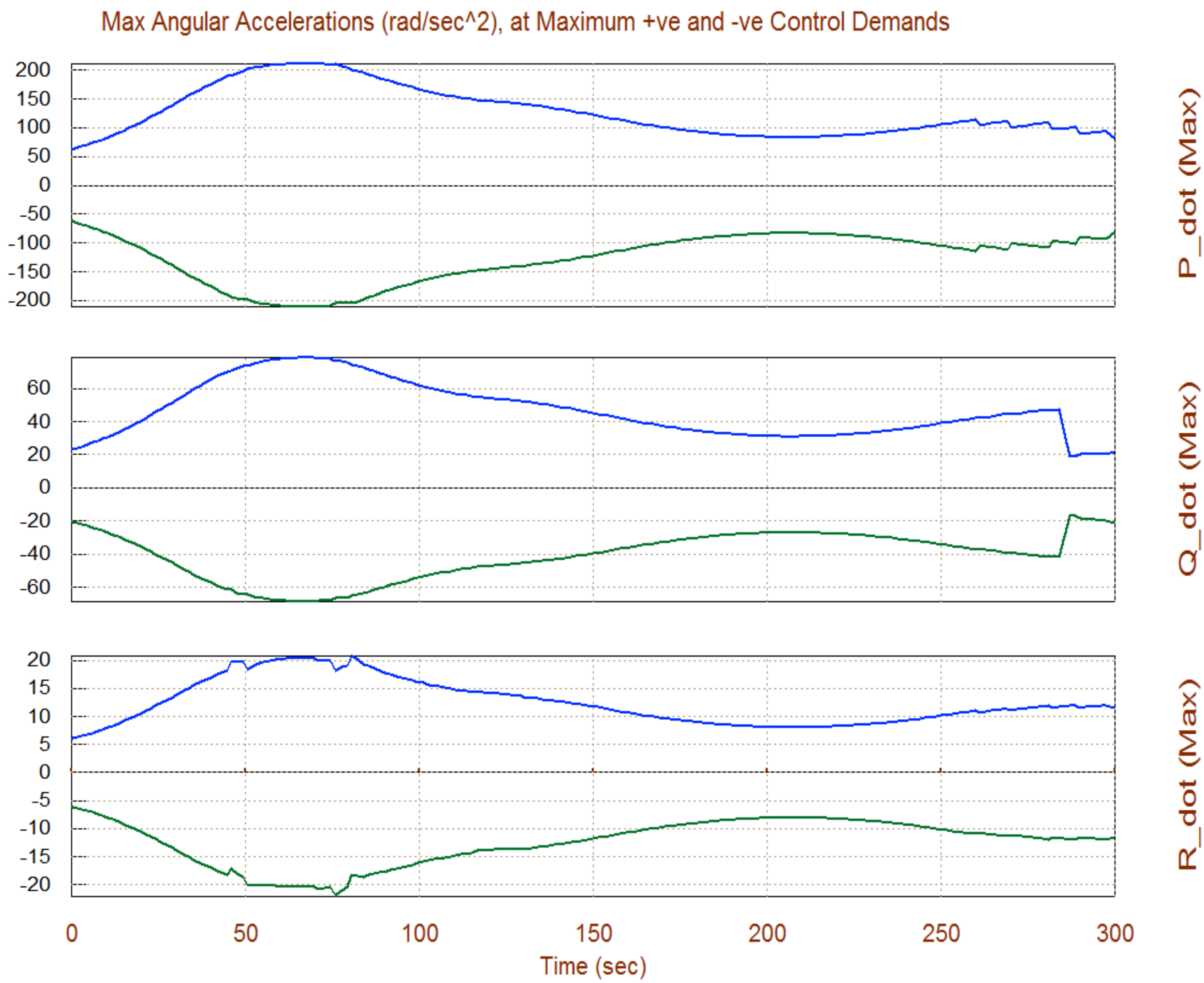



Static Margin, Center of Pressure, Aero-Center (ft) Lifting-Body Aircraft, Hyper
Stat-Margn %
Centr-Press
Aero-Center
Time (sec)


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)


Rotation Control Authority |dQ/dQmax|<1 for 1 (deg) of Alpha & Beta Variation
Roll Effort
Pitch Effort
Yaw Effort
Time (sec)

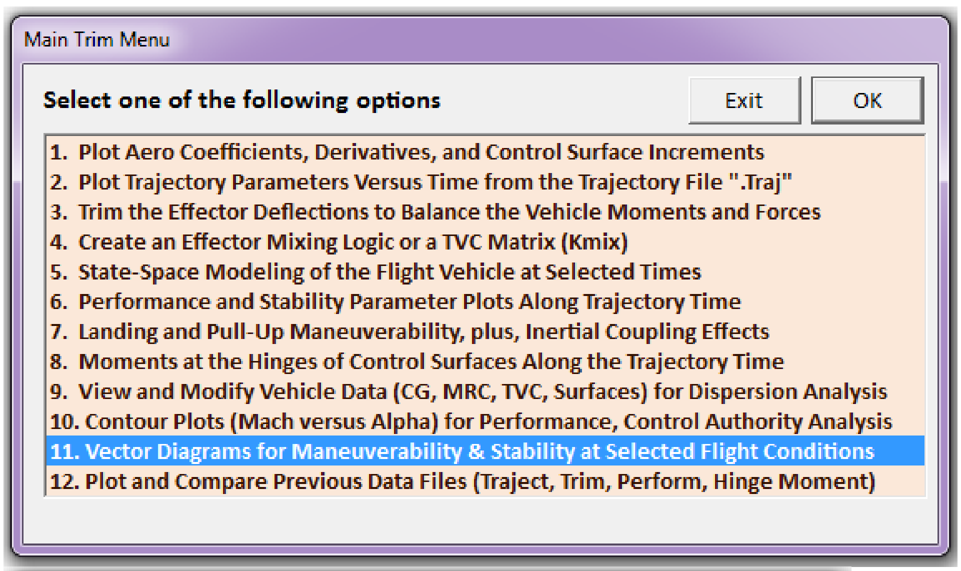

Bank Angle, LCDP Ratio, Cn_beta_dynam /deg, Lifting-Body Aircraft, Hypersonic Re
phi (deg)
LCDP
Cnbet-dyn
Time (sec)

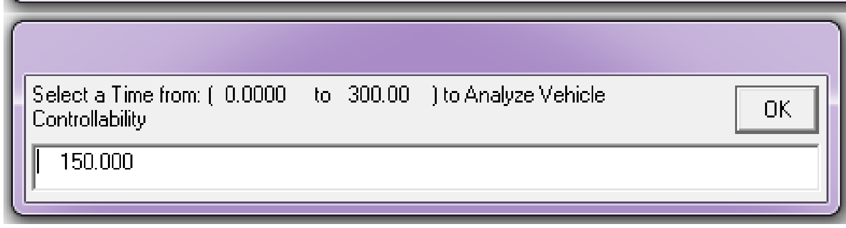


The above performance analysis results show that in the longitudinal direction the vehicle is unstable with a peak time-to-double-amplitude 0.31 sec. In the lateral direction it is statically stable with a Dutch-roll resonances peaking to 4.6 (rad/sec). The peak (Q-alpha, Q-beta) loading, with ±1° dispersion in α_{max} and β_{max} angles, is 3000 (psf-deg) which is acceptable. The control effort against α_{max} and β_{max} dispersions is less than 0.5 in all three axes which allows sufficient control authority for other functions. The Cnβ-dynamic is positive which means that the vehicle is directionally stable, but the LCDP ratio is negative and small in magnitude. It means that without RCS the roll control will be reversed and slow, which may be acceptable since the roll maneuvers are slow during this phase. The bank angle parameter (ϕ) is meaningless here and we ignore it because it is only applicable for near landing. The maximum acceleration plots show the acceleration capability of the aerosurfaces. They provide sufficient acceleration for control in positive and negative directions from trim. It should typically be greater than 1.5 (deg/sec^2). The acceleration capability increases with dynamic pressure.

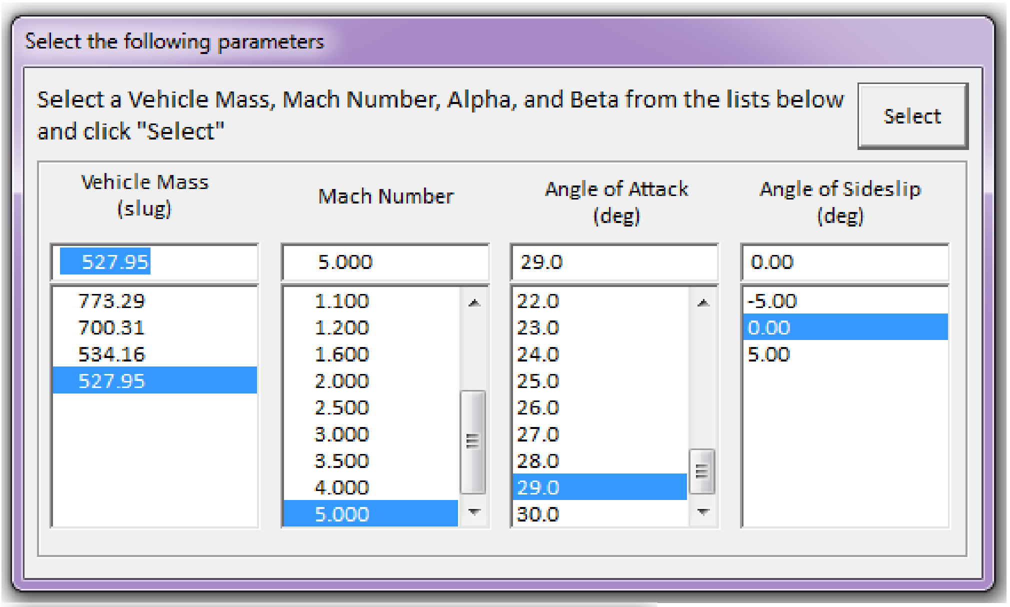
Controllability Analysis by Using Vector Diagrams

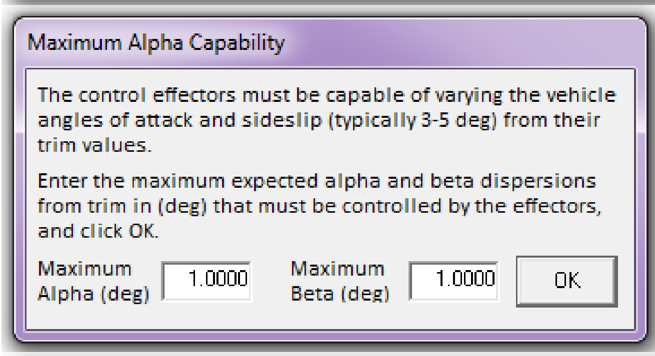
Vector diagrams are 2-dimensional diagrams for analyzing the vehicle controllability in two directions at a fixed flight condition. We visually compare the control moment capability of the aero-surfaces, in roll and yaw in this case, against the aero-moments, in the same two directions, generated by the wind-shear disturbance that is defined in terms of $\pm\beta_{max}$. The vehicle must have the control authority to counteract the disturbance moments. It is not just a magnitude comparison but it also allows us to examine the directions of the controls against the direction of the disturbance. It helps to evaluate the orthogonality of the control system, compare the accelerations magnitudes from the controls against those generated from specified aerodynamic angles, and to determine if the controls are more powerful and their directions are capable to counteract the disturbance moments in the roll and yaw directions in this case. From the Trim menu select option (11), and select an arbitrary flight condition to analyze in the middle of the alpha-control trajectory, corresponding to t=150 sec, at Mach 27.

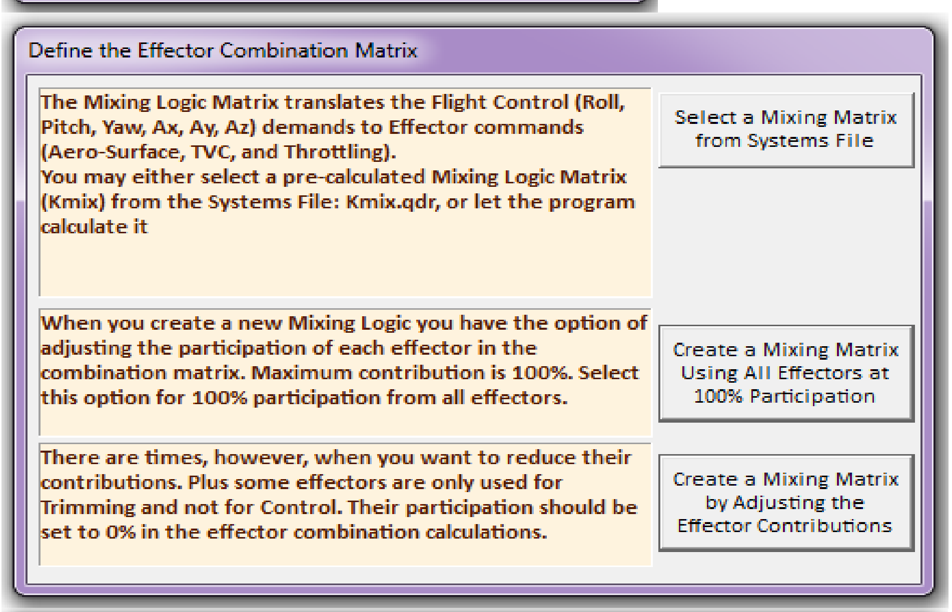


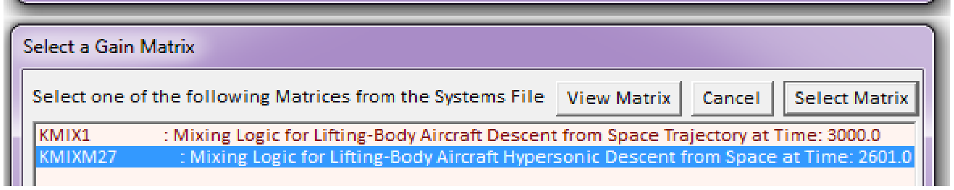


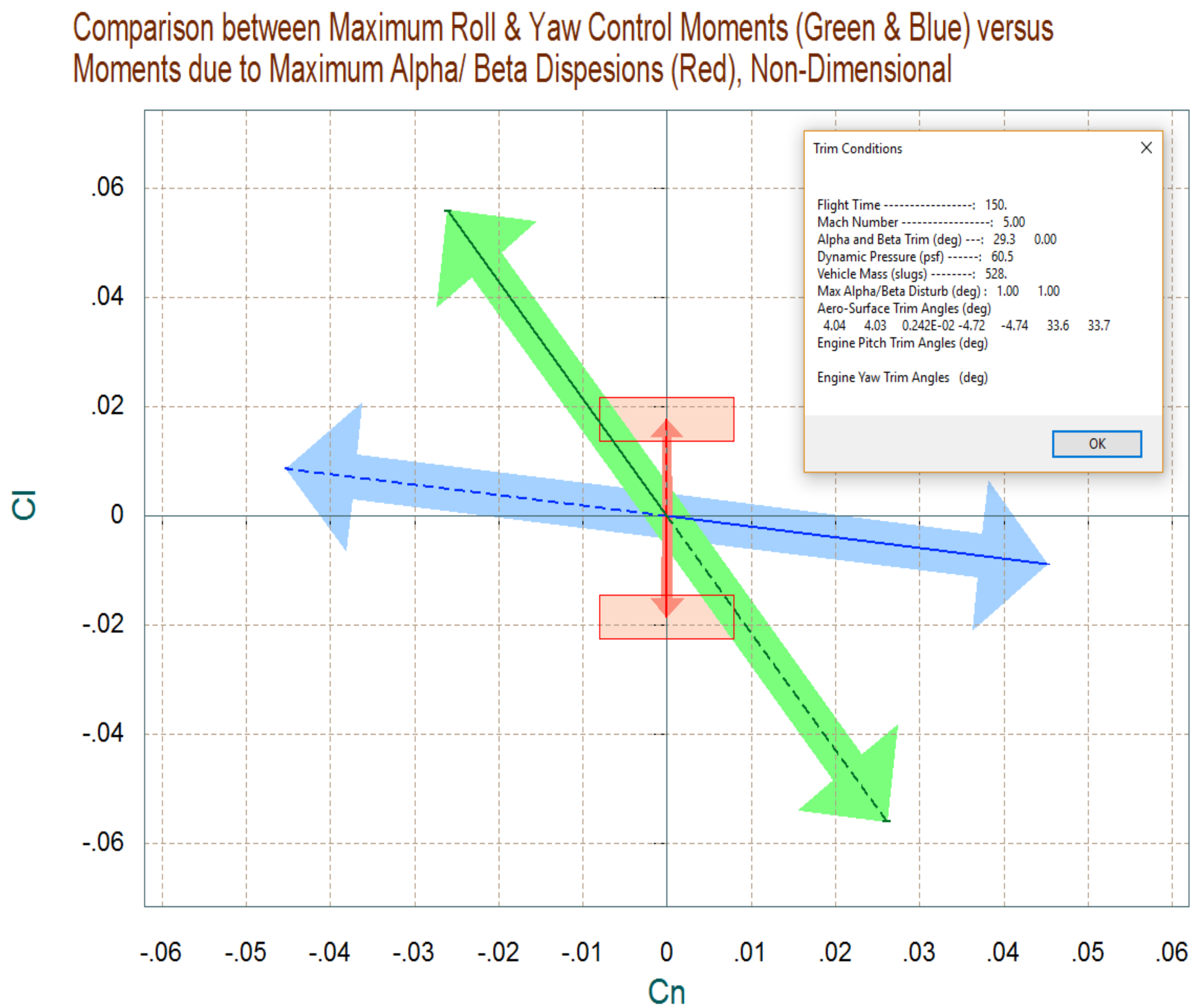
The following dialog consists of menus for selecting the vehicle mass, Mach number, alpha, and beta. The default values correspond to the selected flight time. You may keep the default parameters or change them into something different. In this case we select the default values and click "*Select*". The disturbances are caused by wind-shear that is defined by the maximum alpha and beta produced. In the following dialog enter the maximum disturbance angles (α_{max} and β_{max}) and then select the (7x3) control surface combination matrix "KmixM27" which is already saved in file Kmix.Qdr, as shown.


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)
527.95
5.000
29.0
0.00
773.29
700.31
534.16
527.95
1.100
1.200
1.600
2.000
2.500
3.000
3.500
4.000
5.000
22.0
23.0
24.0
25.0
26.0
27.0
28.0
29.0
30.0
-5.00
0.00
5.00

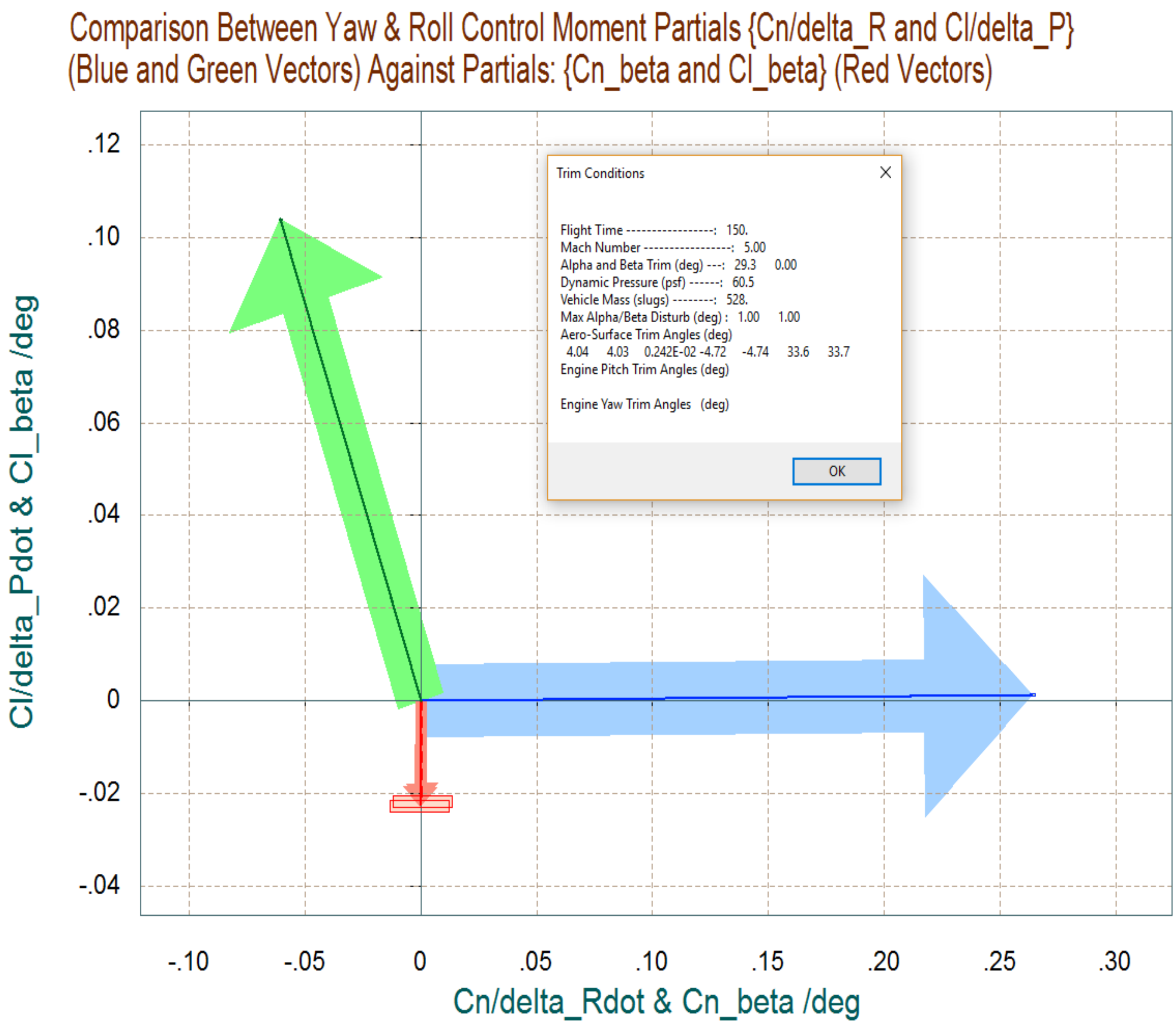

Maximum Alpha Capability
The control effectors must be capable of varying the vehicle angles of attack and sideslip (typically 3-5 deg) from their trim values.
Enter the maximum expected alpha and beta dispersions from trim in (deg) that must be controlled by the effectors, and click OK.
Maximum Alpha (deg)
1.0000
Maximum Beta (deg)
1.0000
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 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

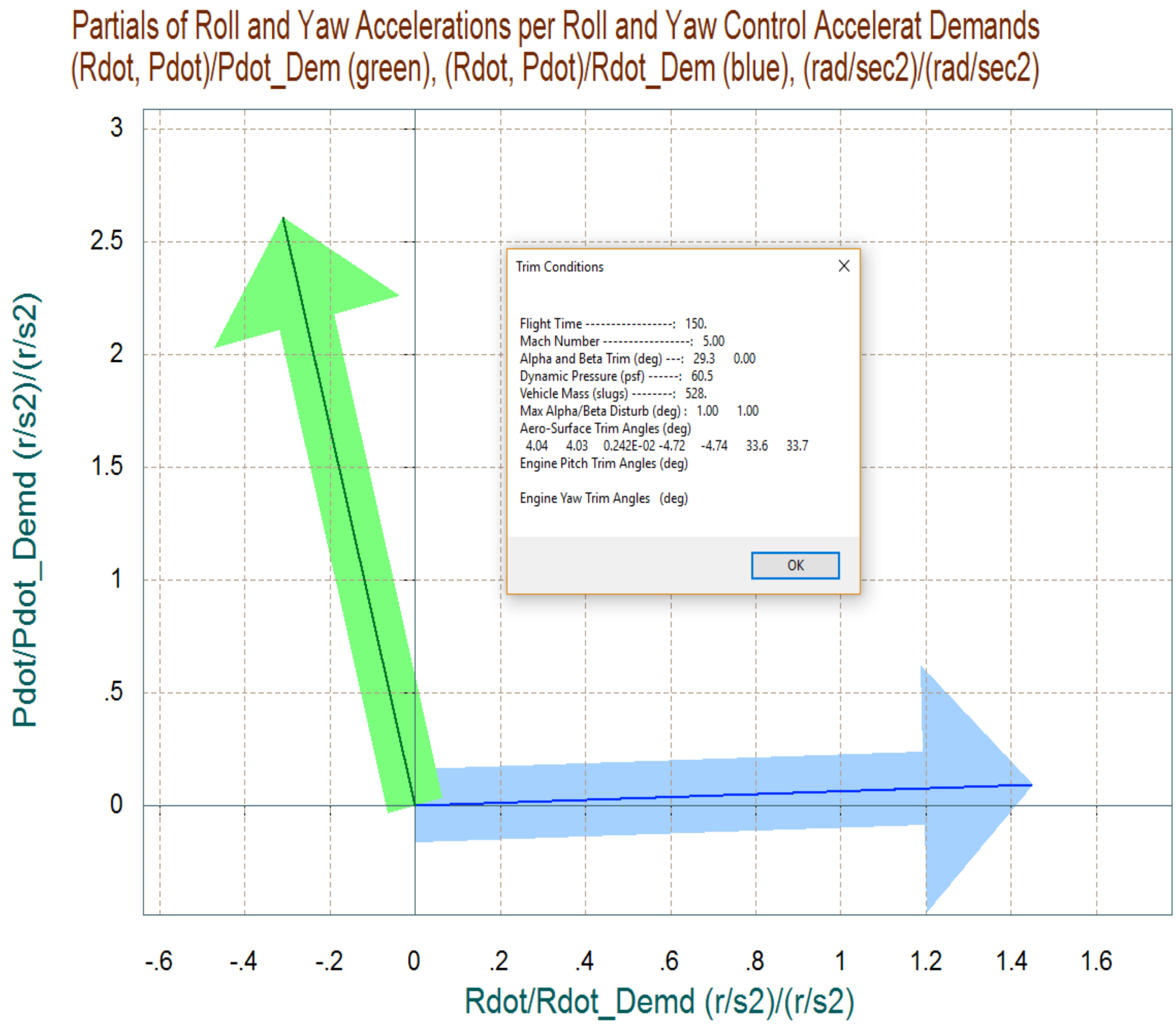

Select a Gain Matrix
Select one of the following Matrices from the Systems File
View Matrix
Cancel
Select Matrix
KMIX1 : Mixing Logic for Lifting-Body Aircraft Descent from Space Trajectory at Time: 3000.0
KMIXM27 : Mixing Logic for Lifting-Body Aircraft Hypersonic Descent from Space at Time: 2601.0



The above vector diagram shows the roll and yaw moments (non-dimensional) produced when the roll and yaw FCS demands are maximized (before saturating the aerosurfaces). The solid blue vector corresponds to max positive yaw FCS demand ($\delta R_{+FCSMax}$), and the dashed blue vector in the opposite direction corresponds to max negative yaw demand ($\delta R_{-FCSMax}$). Similarly, the green vectors correspond to the maximum roll FCS demands ($\delta P_{\pm FCSMax}$). The two red vectors represent the disturbance moments generated by the variations in the angles of attack $\pm\alpha_{max}$ and sideslip $\pm\beta_{max}$ from their trim positions. The disturbance due to β variations is mainly in roll, positive β_{max} generates a negative rolling moment because the vehicle has significant amount of dihedral effect. The red rectangles centered at the tips of the arrows show the expected uncertainty in Cl and in Cn in this flight condition. The aero-uncertainties are obtained from the uncertainties file "*LiftBody.Unce*".



The vector partials in the above figure show the moment partials variation in roll and yaw per roll and yaw acceleration demands in (rad/sec^2). The blue vector pointing towards the right is the moment partials per yaw control demand {$Cn\delta R_{FCS}$, $Cl\delta R_{FCS}$} which is entirely in the yaw direction. The green vector pointing upwards is the moment partials per roll control demand {$Cn\delta P_{FCS}$, $Cl\delta P_{FCS}$} which is mostly in the roll direction but it also couples into yaw. The red vectors at the bottom are the scaled {$Cn\beta$, $Cl\beta$} partials. Notice that $Cl\beta$ is negative due to the dihedral and it is much bigger in magnitude than $Cn\beta$. The red rectangle centered at the tip of the {$Cn\beta$, $Cl\beta$} vector is due to the uncertainties in the two partials from file "*LiftBody.Unce*".



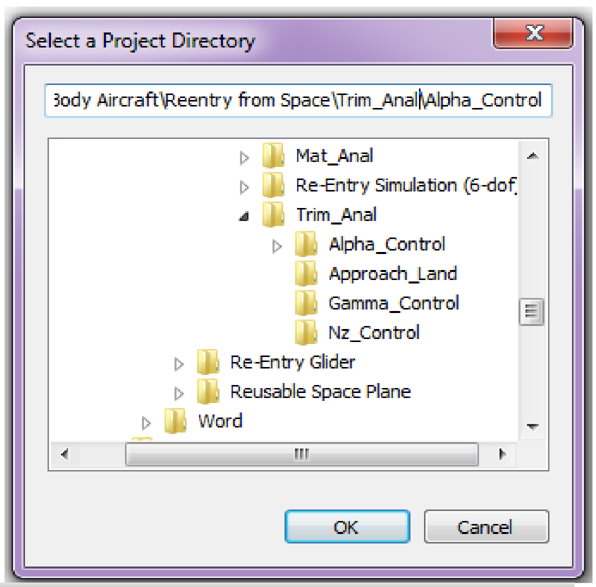
The vector diagram in this figure shows the partials of the accelerations per acceleration demands in roll and yaw. The green vector pointing upwards shows the roll/yaw acceleration per roll acceleration demand {$\dot{P}/\delta P_{FCS}$, $\dot{R}/\delta P_{FCS}$}, and the horizontal blue vector is the roll/yaw accelerations per yaw demand {$\dot{P}/\delta R_{FCS}$, $\dot{R}/\delta R_{FCS}$}. The axes units are in (rad/sec^2) per (rad/sec^2). Ideally, the mixing logic matrix attempts to make them unit vectors pointing in their corresponding direction along the +vertical and +horizontal axes. This would achieve perfect open-loop control. This ideal situation, however, is rarely achievable open-loop, plus it would be unreliable. It is not even necessary to diagonalize the plant because the control feedback compensates for imperfections. They are, however, close to being orthogonal and they are pointing in the proper directions and this is sufficient for flight control design

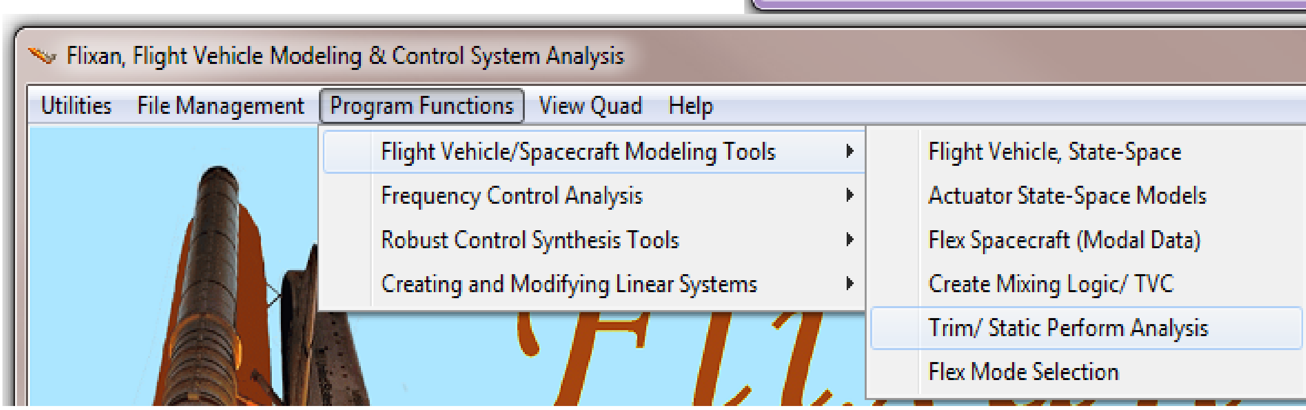
Dynamic Modeling, Control Design, and Stability Analysis

We will now create a dynamic model of the reentry vehicle at a fixed flight condition in the hypersonic region. We will demonstrate how to design pitch and lateral control laws in MATLAB®, analyze control system stability in the frequency domain, and simulate its performance when tracking alpha and phi commands. The same process is repeated for modeling, designing, and analyzing other flight conditions in the same region of the trajectory. The control laws are eventually be used in a 6-dof simulation and interpolated between design points. Notice that the control system linear analysis and design is performed in separate folders at selected Mach numbers, under "*C:\Flixan\Trim\Examples\Lifting-Body Aircraft\ Reentry from Space\Mat_Anal*", where each selected flight condition is examined, designed, and analyzed separately. The control laws will later be used in the 6-dof simulation and interpolated between the design points.

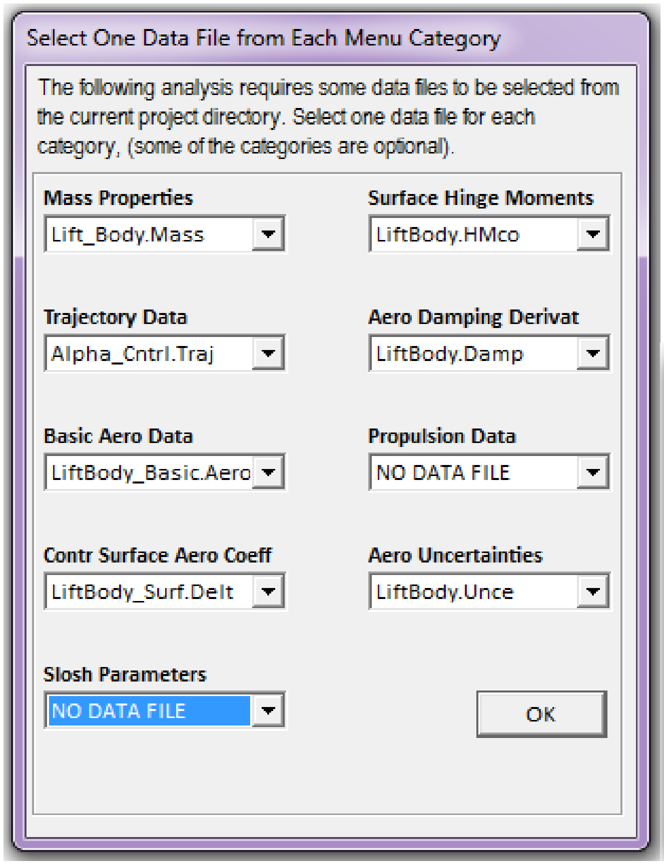
Vehicle Model Preparation

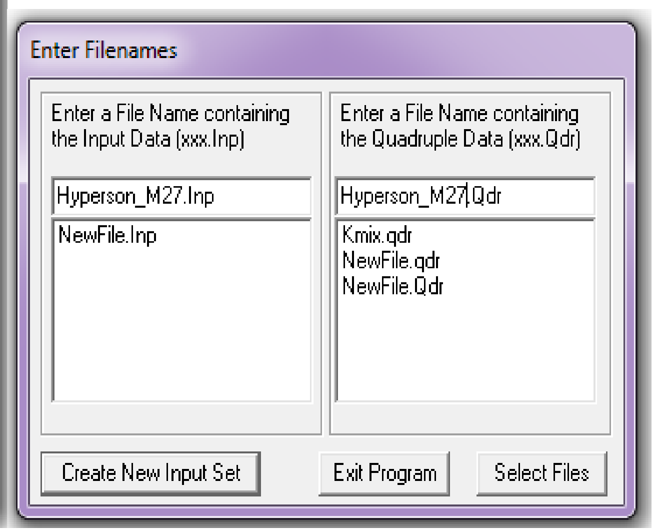
Let us first create a dynamic model for our reentry vehicle at t=12 (sec), which corresponds to Mach 27. Start the Flixan program and select folder: "*C:\Flixan\ Trim\Examples\Lifting-Body Aircraft\ Reentry from Space\Trim_Anal\Alpha_Control*". From the Flixan menu bar go to "*Program Functions*" and select the "*Trim/ Static Performance Analysis*" program, as shown below.



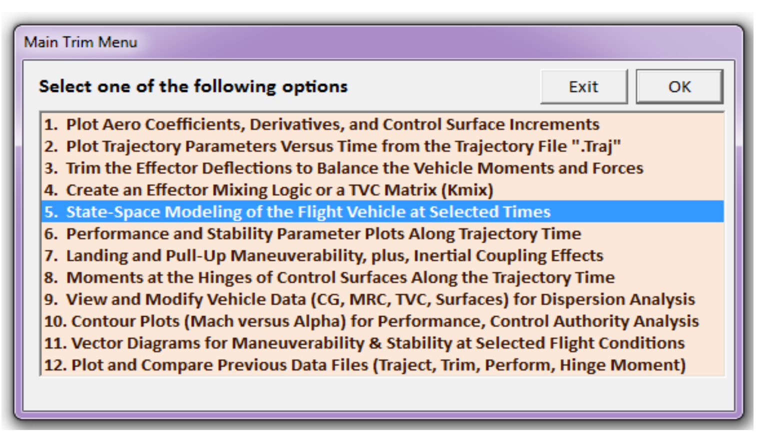


From the Trim filenames selection menu below, select the following files. Use the next dialog to create a new input filename "*Hyperson_M27.Inp*" that will receive the vehicle input data plus other Flixan related model building data.

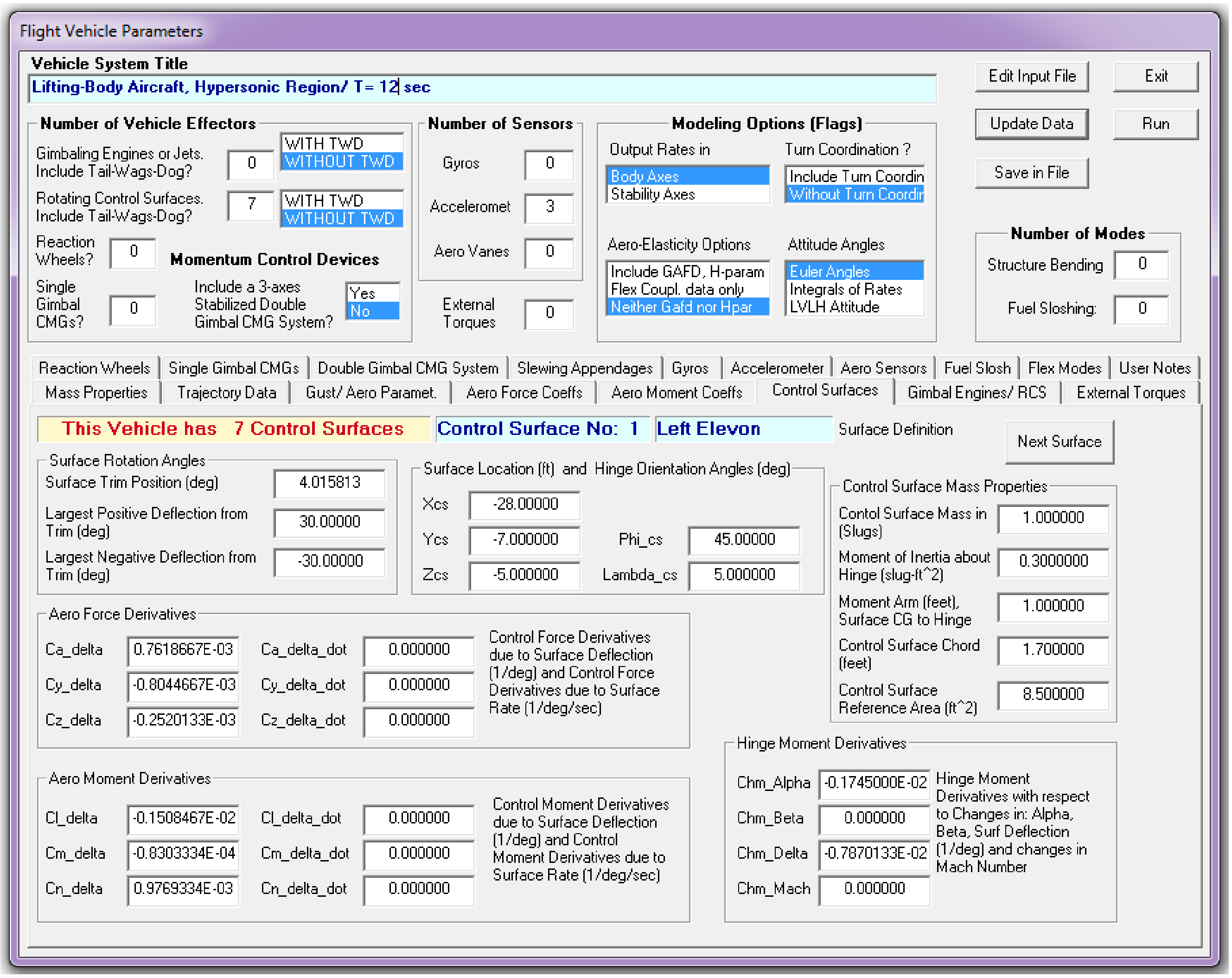




From the Trim main menu select option (5) to create a state-space dynamic model. A dialog reminds the user how to select a flight time for the dynamic model, click "OK". From one of the trajectory plots go the top menu bar, and choose "*Graphic Options*", and then from the vertical pop-up menu click on "*Select Time to Create State-Space System*". Then with the mouse click at time t=12 sec, along the x axis, and confirm that you have selected the correct time by clicking "OK". Otherwise, click "Cancel" and try again.



The following dialog shows the flight vehicle parameters prepared by Trim for the selected flight condition. They are extracted from the vehicle data files. The user can modify some of the data or titles using this dialog before saving it. Click on the "*Update Data*" button after every modification. Do not run it yet because there is more work to be done and more data to be included in file "*Hyperson_M27.Inp*". Instead, click on "*Save in File*" and the vehicle data will be saved in file "*Hyperson_M27.Inp*", under the title "*Lifting-Body Aircraft Hypersonic Descent from Space /T= 12 sec (Simul Model)*". The file "*Hyperson_M27.Inp*" will eventually be processed by Flixan to generate the vehicle systems for control design and analysis using Matlab/ Simulink. However, in addition to the vehicle data this (already prepared) input file contains also system interconnection and modification data which are related to this analysis and will be processed by Flixan. The systems and matrices generated by Flixan will be saved in file "*Hyperson_M27.Qdr*".

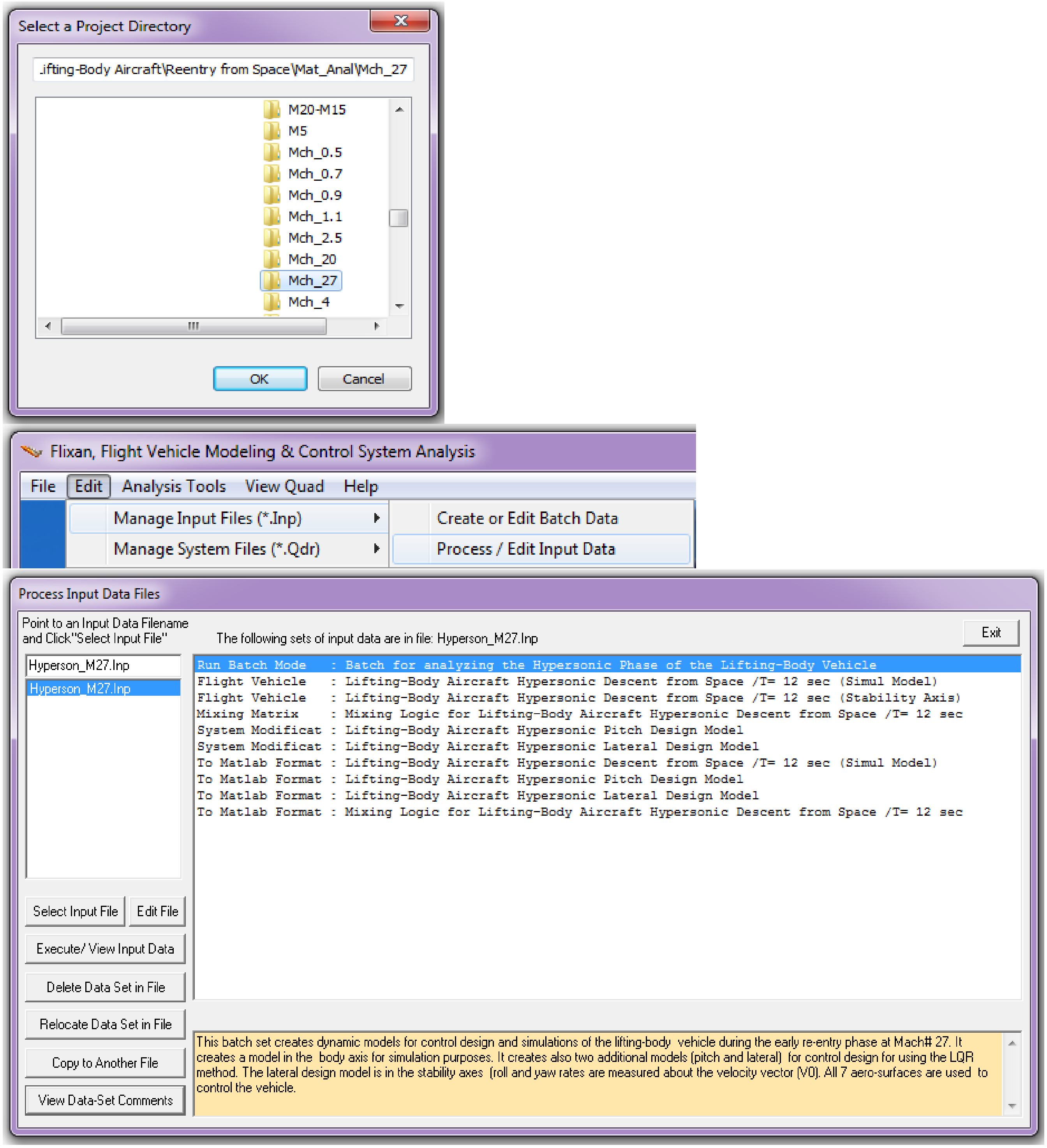


Let us now take a look inside file "*Hyperson_M27.inp*" that has already been prepared in the example folder and see what it contains. The preparation details are omitted here because they are beyond the scope of this example. The file contains several sets of data and each set corresponds to and it is processed by a Flixan utility. The Flixan program will create systems and matrices that will be used for control analysis using Matlab in the next section.

1. At the top of the file there is a batch set for processing the remaining data-sets in batch mode. This is faster because it processes them all together, instead of each one interactively. Its title is "*Batch for analyzing the Hypersonic Phase of the Lifting-Body Vehicle*".
2. Below the batch there is a flight vehicle data set that generates the vehicle simulation model at t=12 sec that corresponds to Mach # 27. Its title is "*Lifting-Body Aircraft Hypersonic Descent from Space /T= 12 sec (Simul Model)*". Its output vector is in the body axis.
3. The next set generates the same vehicle model but instead the rates are in the stability axes instead of body. The turn-coordination flag is also turned-on. It means that the roll and yaw rates are about the velocity vector and they include also the turn-coordination terms which assume that the turn-coordination logic is included in the vehicle model. Its title is "*Lifting-Body Aircraft Hypersonic Descent from Space /T= 12 sec (Stability Axis)*".
4. The next set generates a mixing logic matrix "KmixM27a" that converts the (roll, pitch, and yaw) flight control demands to 7 aero-surface deflection commands. Its title is "*Mixing Logic for Lifting-Body Aircraft Hypersonic Descent from Space /T= 12 sec*". Notice that the 4 body-flaps are de-emphasized in the mixing-logic matrix calculation because their maximum deflections from nominal in the vehicle input data are reduced to 10° instead of 30°. This places higher demands on the elevons and rudder.
5. The next two sets calculate pitch and lateral state-space design plants for the LQR design method. The LQR algorithm uses these models to calculate state-feedback gains. The state-feedback gains in combination with the mixing matrix convert the vehicle state variables to deflection commands for the seven aero-surfaces.
6. The last 4 data-sets in the input data file convert the systems created to Matlab function (*.m) format so they can be loaded into Matlab for further analysis. The simulation model is saved in file "*vehicle_sim.m*". The design plants are saved in files "*Pitch_des.m*" and "*Later_des.m*", and the mixing-logic matrix is saved in file "*KmixM27a.Mat*". The mixing-logic matrix is modified by the analyst to "*KmixM27.Mat*" in order to further enhance roll controllability (the magnitude of the LCDP ratio was too small otherwise).

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 "*Hyperson_M27*.Inp". This file has been moved to folder "*C:\Flixan\Trim\Examples\Lifting-Body Aircraft\Reentry from Space\Mat_Anal\ Mch_27*", 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 "*Hyperson_M27.Inp*" form 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 titled "*Batch for analyzing the Hypersonic Phase of the Lifting-Body Vehicle*", and click on "*Execute/ View Input Data*". Flixan will process the input file and save the systems and matrices in file "*Hyperson_M27*.Qdr". It will also create the matrices and system functions for Matlab analysis.



LQR Control Design

Two separate dynamic models are created for control design and linear analysis. The output rates in the first model are defined in stability axes (roll rate is about the velocity vector), and it is used for control design. The output rates in the second dynamic model are body rates, and it is used for linear analysis and simulations. A mixing logic matrix "KmixM27" is also created to convert the (roll, pitch, and yaw) flight control demands to 7 aero-surface deflection commands. The participation of the 4 body-flaps is de-emphasized in the calculation of KmixM27 because we would prefer the elevons and rudder to be more active in flight control having greater control authority and bandwidth. The pitch and lateral design models are combined with the mixing logic and the LQR method is used to calculate state-feedback gains. The file "init.m", below, loads the simulation and design systems and the surface mixing matrix into MATLAB® and performs the pitch and lateral LQR designs.

```
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
[Ave, Bve, Cve, Dve] = vehicle_sim;              % Simulation Model 6-dof
load KmixM27.mat -ascii; Kmix=KmixM27;           % Load Surfaces Mix Logic (7 x 3)

alfa0=29.274; V0=24675.1; Thet0=27.69; 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
[A14,B14,C14,D14]= linmod('Ldes5x');             % 5-state model {ps,rs,bet,pint,betint}
A15= C14*A14*inv(C14);   B15= C14*B14;           % Stability axis System
C15= C14*inv(C14);       D15= D14;

% Lateral LQR Design Using Only the RCS Jets     % States: {ps,rs,bet,psint,betint}
R=[1,1]*5; R=diag(R);                            % Cntrl LQR Weights R=[1,1]*5
Q=[1 0.4 0.5 0.2 0.005]*3; Q=diag(Q);            % State LQR Weights Q=[1 0.4 0.5 0.2 0.005]
[Kpr,s,e]=lqr(A15,B15,Q,R)                       % Lateral LQR design
save Kpr_M27_0.mat Kpr -ascii

% Pitch LQR Design Using the 7 Aero-Surfaces     % States: {gami,gama,q,alfa,alfint}
[Ap4,Bp4,Cp4,Dp4]= linmod('Pdes4xb');            % 4-state des model {gami,gama,q,alfa,alfint}
R=4; Q=[0.001 0.1 20.0 100]; Q=diag(Q);          % LQR Weights {gama,q,alfa,alf_int}
[Kq,s,e]=lqr(Ap4,Bp4,Q,R)                        % Perform LQR design on Surf
save Kq_M27_0.mat Kq -ascii
```

Pitch Design

The pitch design model "*Lifting-Body Aircraft Hypersonic Pitch Design Model*" from file "*pitch_des.m*" consisting of states: {θ, q, and α}. It is augmented (using Simulink file Pdes4x.Mdl) to include also α-integral in the state-vector. The phugoid states (δh and δV) are not included in this model. The pitch controller is a (1x4) state-feedback gain matrix Kq_M27_0.mat of states: (θ, q, α, α-integral). It regulates the angle of attack, which is initially at 30° and gradually it is reduced to smaller values, as required to control heating.

The following Simulink model "*Sim_Pitch_Simple.Mdl*" is used for evaluating the pitch LQR design. It includes the state-feedback matrix Kq and the mixing-logic matrix KmixM27. It shows the system's response to 1° change command in alpha. The control deflections are mainly in the two elevons but the four body-flaps are also participating by smaller amounts. This is adjusted by the Q and R matrices in the LQR algorithm.

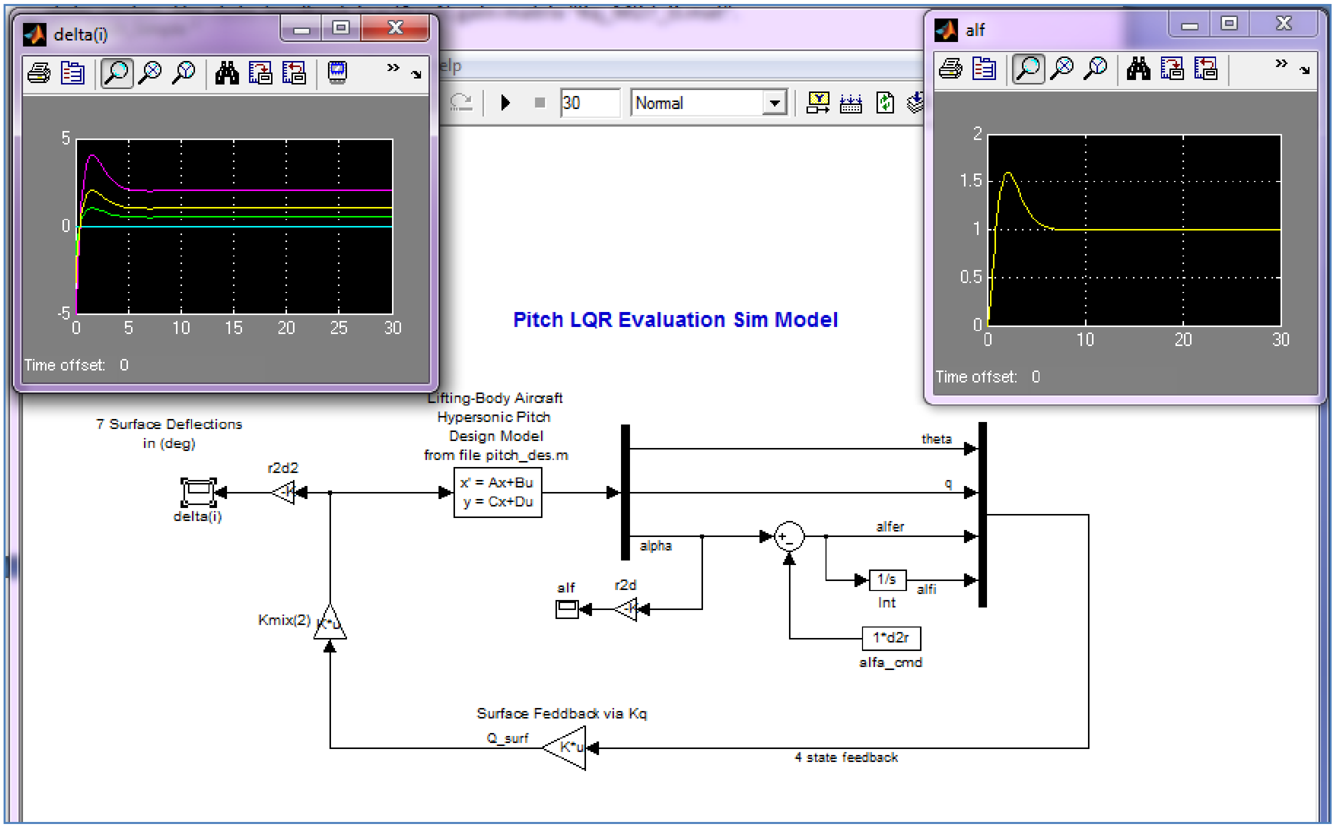


Figure 2 Pitch Simulation Model "Sim_Pitch_Simple.mdl" for evaluating the Pitch LQR Design

Lateral Design

The lateral design uses the system "*Lifting-Body Aircraft Hypersonic Lateral Design Model*" from file "*later_des.m*" consisting of states: {p_s, r_s, and β}. The rates are defined about the velocity vector. It is augmented (using Simulink file Ldes5x.Mdl) to include also p_s-integral and β-integral in the state-vector. The stability axis model is preferred over the body axis model in the lateral LQR design because the vehicle is commanded to roll about the velocity vector. Rotating about V_0 minimizes the beta transients and the lateral loads during turns. The lateral LQR state-feedback controller is a (2x5) gain matrix of: (p_s, r_s, β, p_s-integral, β-integral) states, and performs roll maneuvers by rolling the vehicle about the velocity vector V_0.

The lateral dynamic model used in the LQR design also includes the turn-coordination terms. It assumes that turn-coordination is included in the vehicle model. The state-feedback matrix generated by the LQR algorithm using Matlab is a (2 x 5) gain matrix "Kpr_M27_0.mat".

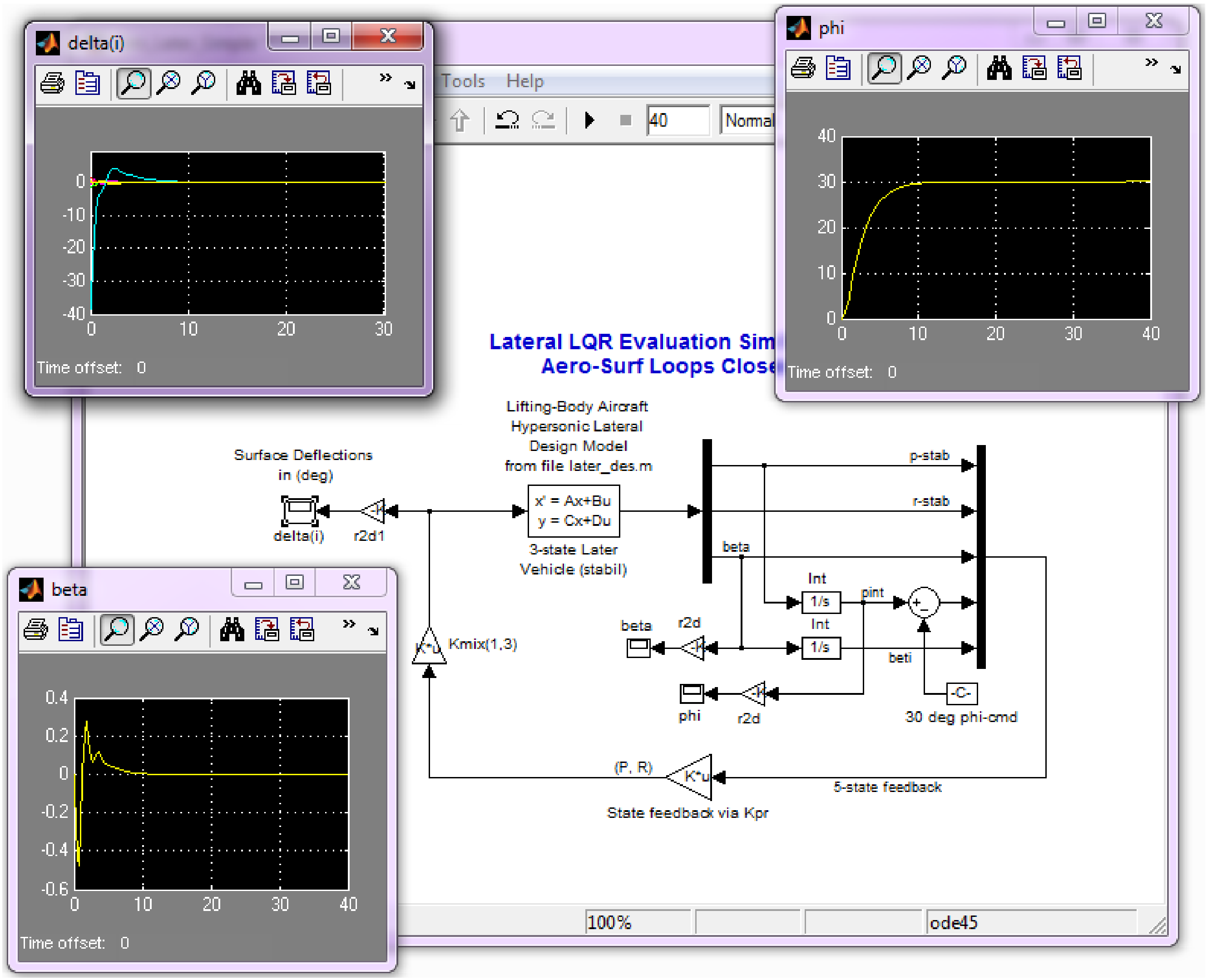
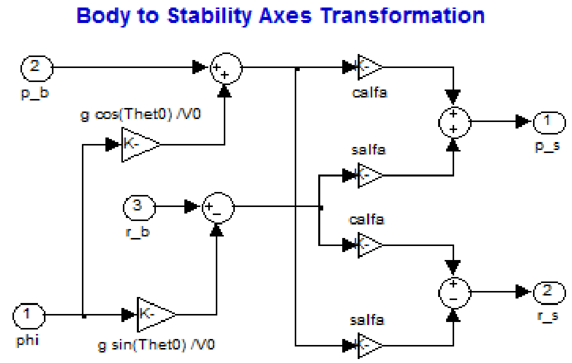


Figure 1.3 Lateral Simulation Model "Sim_Later_Simple.mdl" for evaluating the Lateral LQR Design

The Simulink model "*Sim_Later_Simple.Mdl*", shown in Figure (1.3), is used for evaluating the lateral LQR design. It includes the state-feedback matrix Kpr and the mixing-logic matrix KmixM27. It shows the system's response to 30° roll command about the velocity vector. The surface deflections are mainly in rudder and differential elevons. The disturbance in beta is very small as expected which minimizes the lateral load.

Linear Simulation Model



The design for the Mach 27 case is tested using the linear simulation model shown in Figure 1.4. It analyzes the coupled system's response to commands and to wind disturbances. The Matlab simulation model is in file "*Simul_6dof.mdl*". The output rates in this model are body rates since the rate-gyro measurements are in body axes. The controller, however, was design based on the stability axis model and it expects to see roll and yaw rates about the velocity vector V_0. A body to stability axis transformation block is, therefore, included in the simulation to convert the (p & r) body rates to stability rates (p_{stab} & r_{stab}) because the LQR controller expects roll and yaw rates relative to the velocity vector V_0. The linearized turn-coordination terms are also included in this block. During a roll maneuver the surface deflections are mainly in rudder and differential elevons and the transient in beta is small which minimizes the lateral load, as expected.

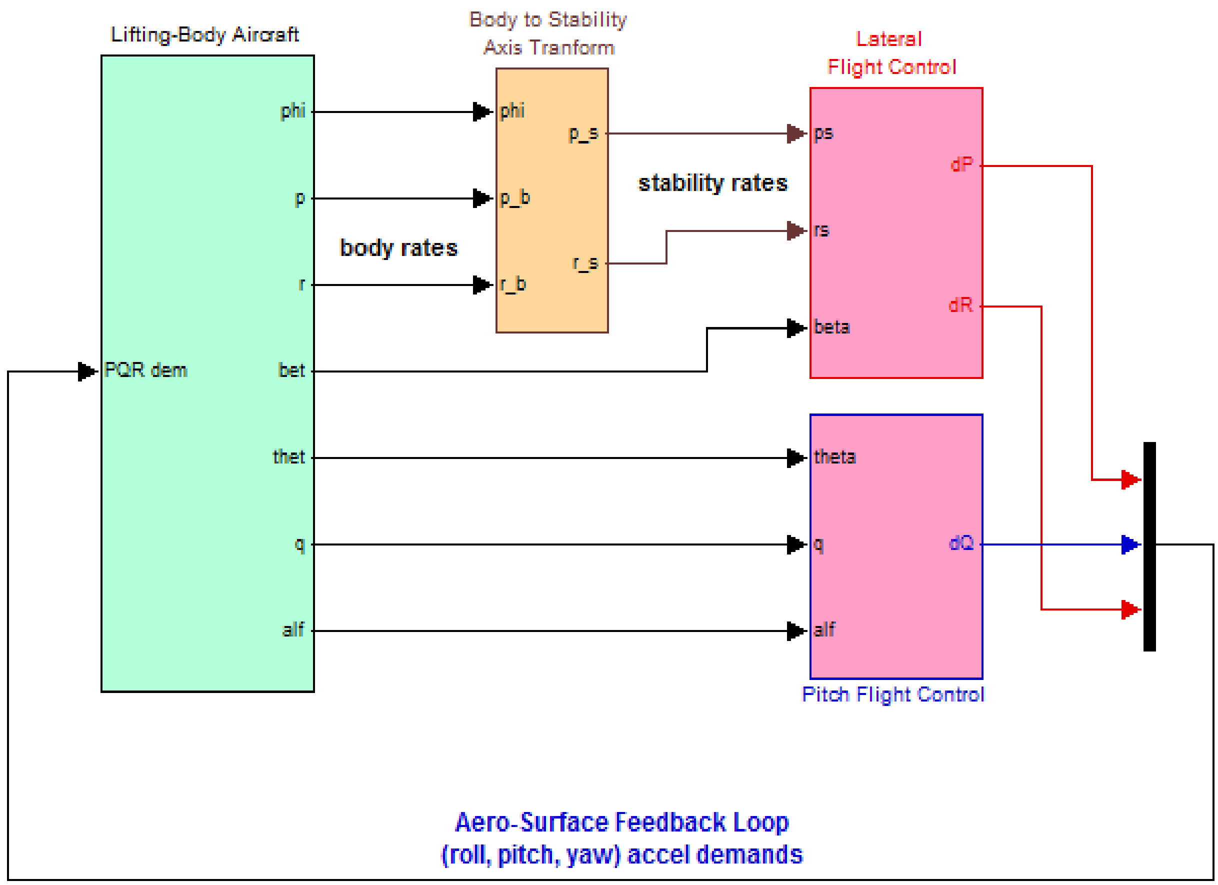


Figure 1.4a Simulation Model in File "Simul_6dof.Mdl"

Figure (1.4b) shows the vehicle dynamics (green) block expanded. It uses the body-axis vehicle model "*Lifting-Body Aircraft Hypersonic Descent from Space /T= 12 sec (Simul Model)*" that was generated by Flixan and it is loaded into Matlab from file "*vehicle_sim.m*". The inputs to this block are: roll, pitch, and yaw acceleration demands from flight control which are converted into surface deflections by the surface mixing logic Kmix. Low-pass filters are also used to model the actuator dynamics. 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 "Hyperson_M27.Inp", and it excites both pitch and yaw, perpendicular to the X-body and at 45° between +Y and +Z axes (typical).

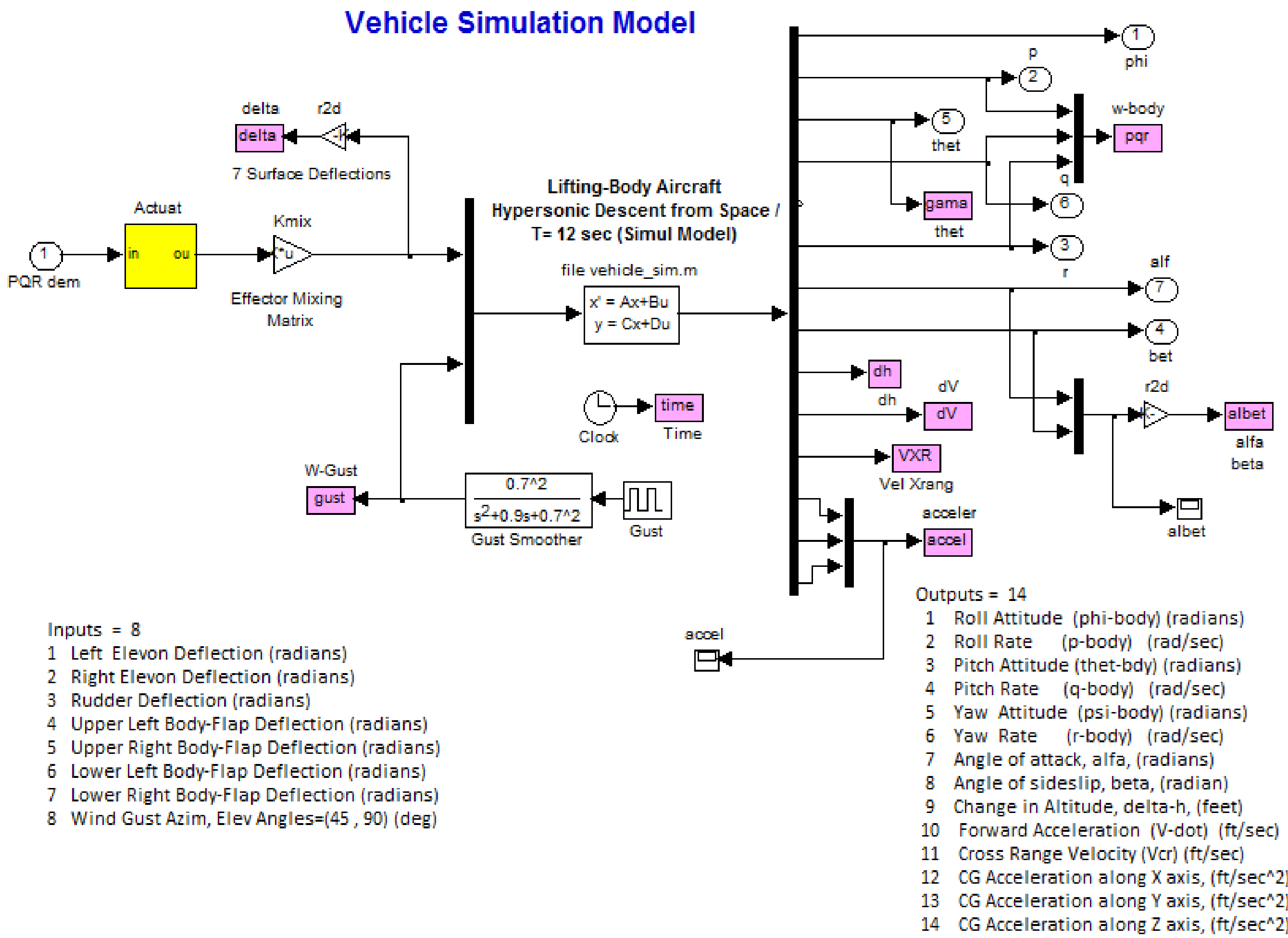
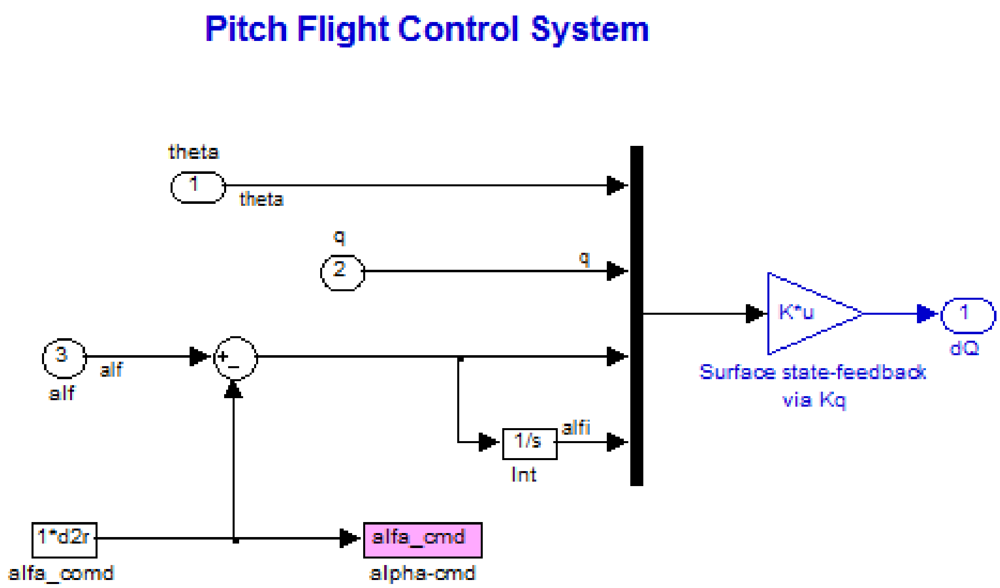


Figure 1.4b Vehicle Dynamics Block including the aero-surface Mixing Logic, Gust disturbance and Actuators

The pitch and lateral control laws are state-feedback gains as already described. The pitch controller consists of a (1x4), (θ, q, α, α-integral) state-feedback gain Kq. It regulates the angle of attack which is initially at 30 (deg) and gradually it is reduced to smaller values, as required to control heating. The lateral controller is a (2x5), (p_s, r_s, β, p_s-integr, β-integr) state-feedback gain Kpr. It is used to perform roll maneuvers by rolling the vehicle about the velocity vector (V_0).



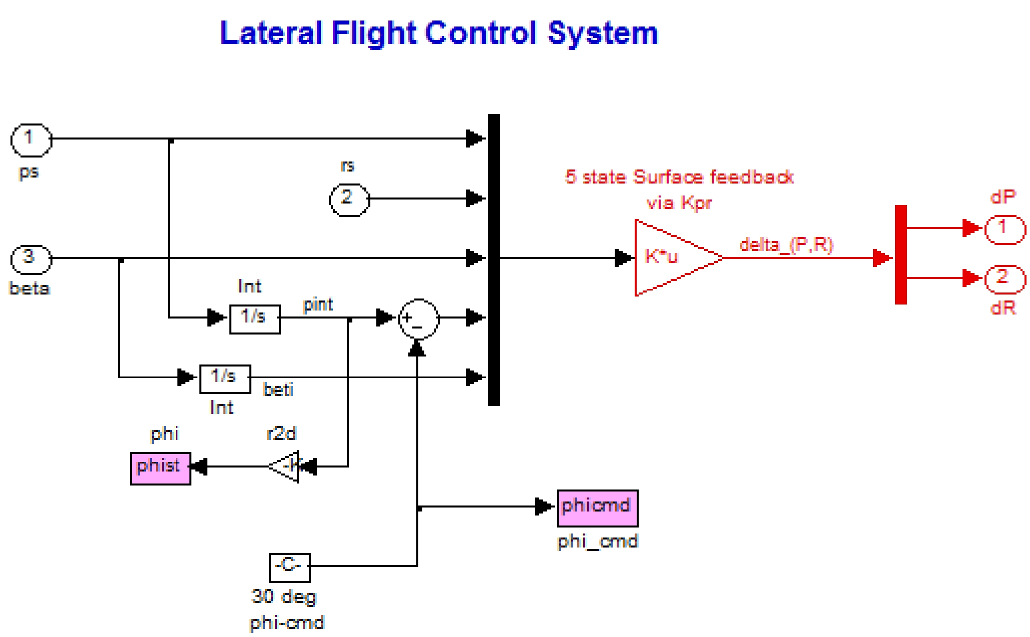
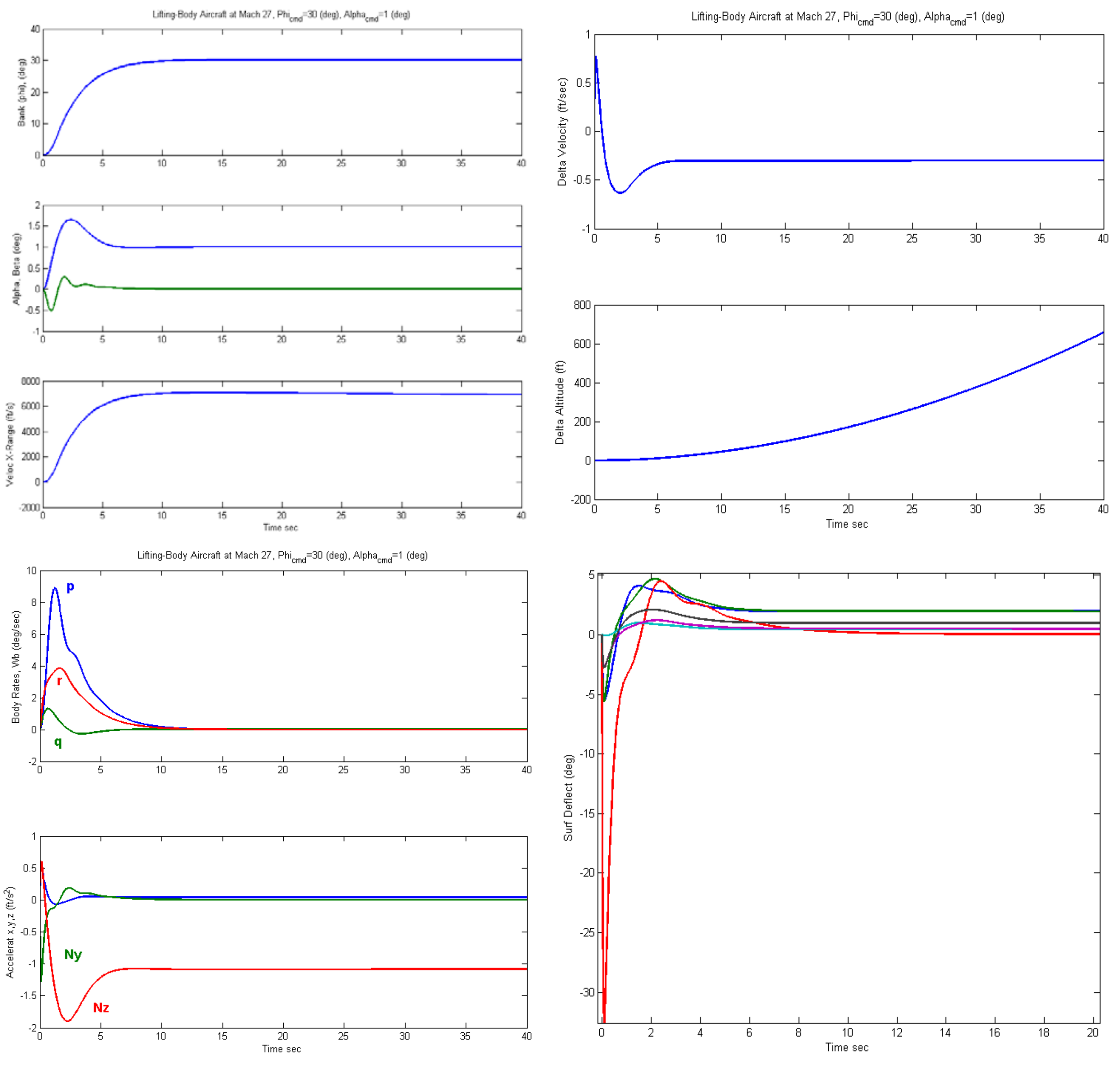


Figure 1.5 Pitch and Lateral state-feedback Control Laws derived by the LQR method

Simulation Results

The following plots were obtained from the simulation model above by simultaneously applying commands in both alpha and phi for the Mach# 27 case. That is, α_{cmd}=1°, and ϕ_{cmd}=30°. Both alpha and phi respond as expected to the step commands. The vehicle rolls 30° about the velocity vector creating a very small sideslip transient in β.



Stability Analysis

Figure 1.5 shows the Simulink model "Stab_Anal.mdl" used for analyzing the stability margins in the frequency domain. This model is similar to the simulation "Simul_6dof.Mdl" but it is configured for open-loop analysis. One loop is opened at a time and the other two loops are closed (in the case shown below the pitch loop is opened). The Matlab file "Frequ.m" uses this model to calculate the frequency response across the opened loop. The next two figures show the Nichols plots in the pitch and roll directions and the red lines show the phase and gain margins for the Mach # 27 case.

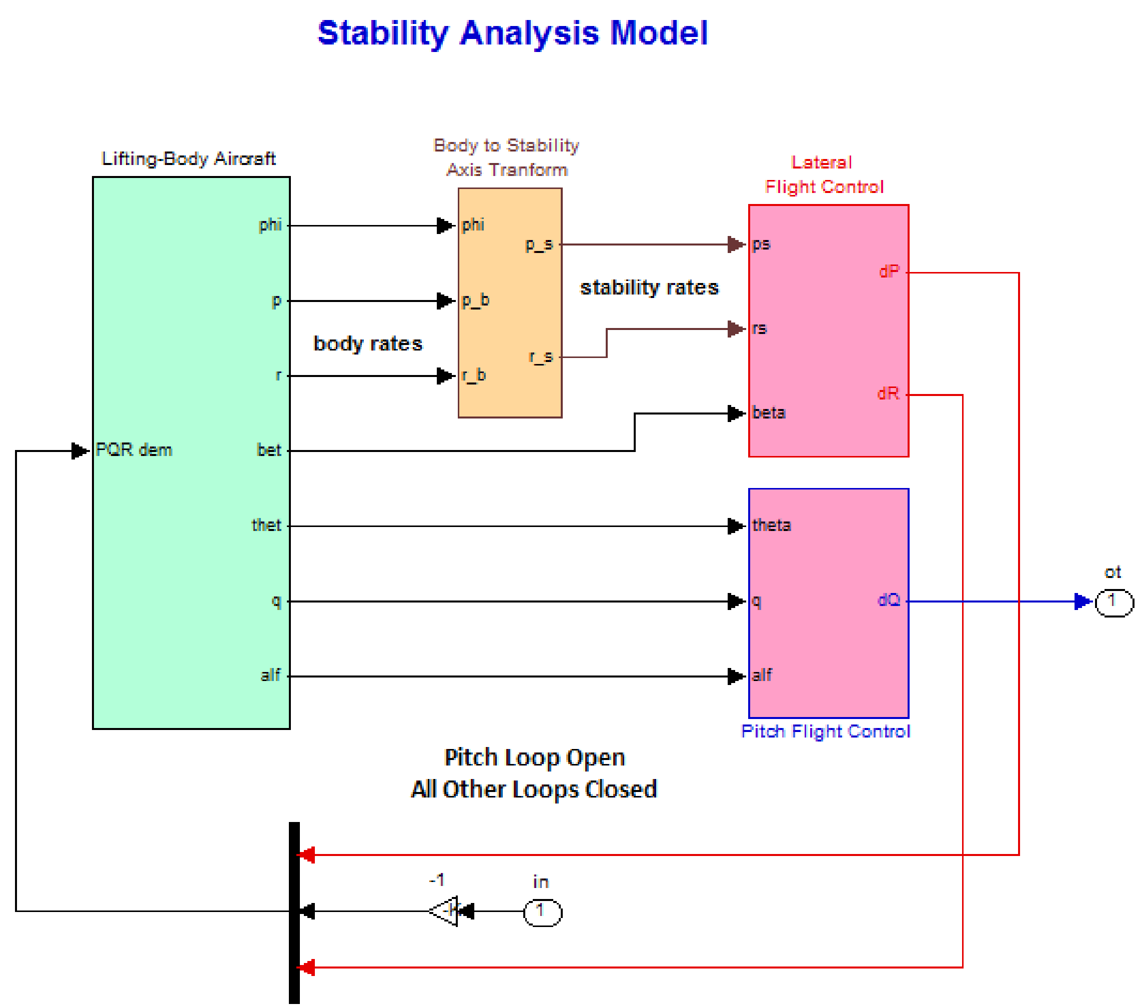
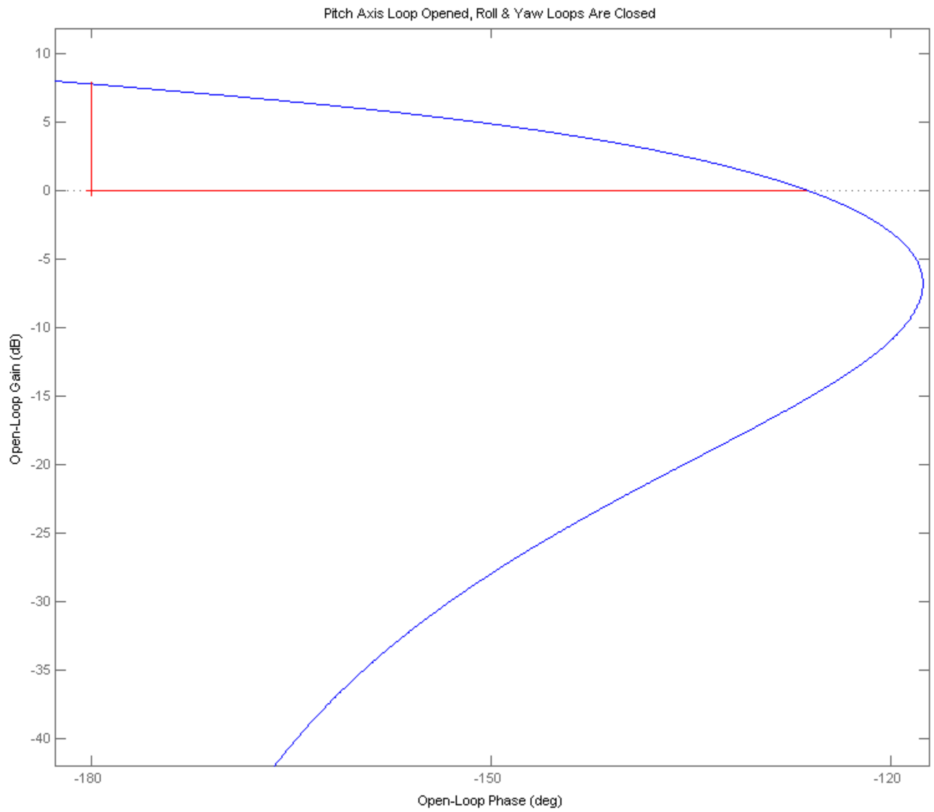
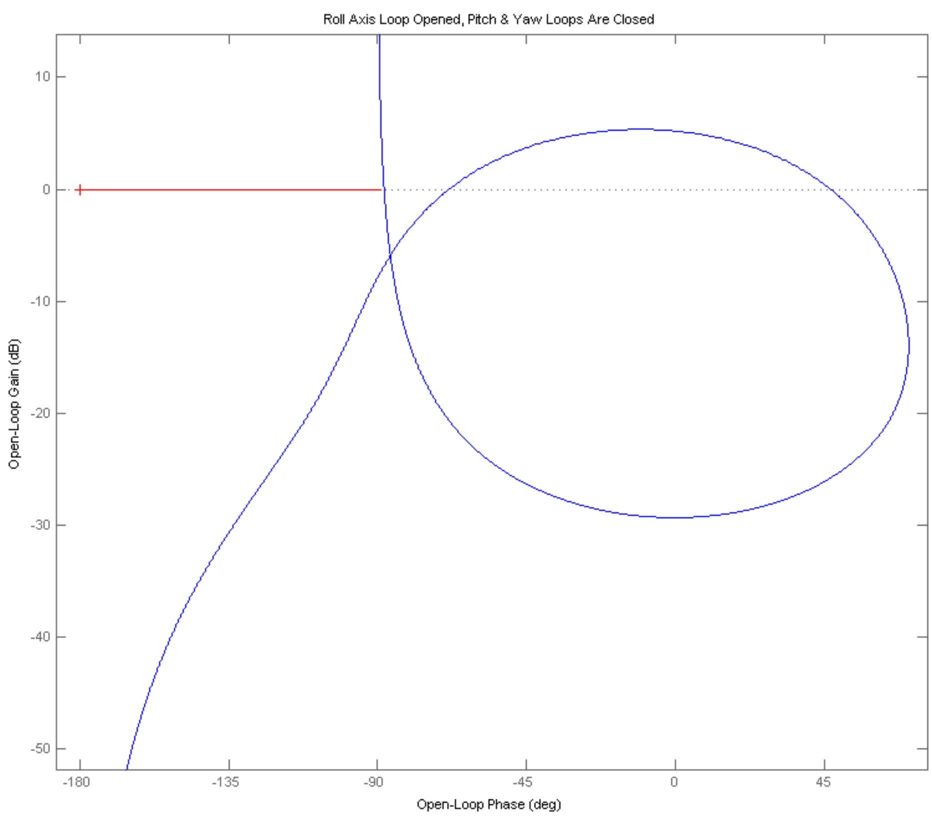


Figure 1.5 Stability Analysis Model "Stab_Anal.mdl" used for frequency response analysis

Stability Margins in the Pitch Loop



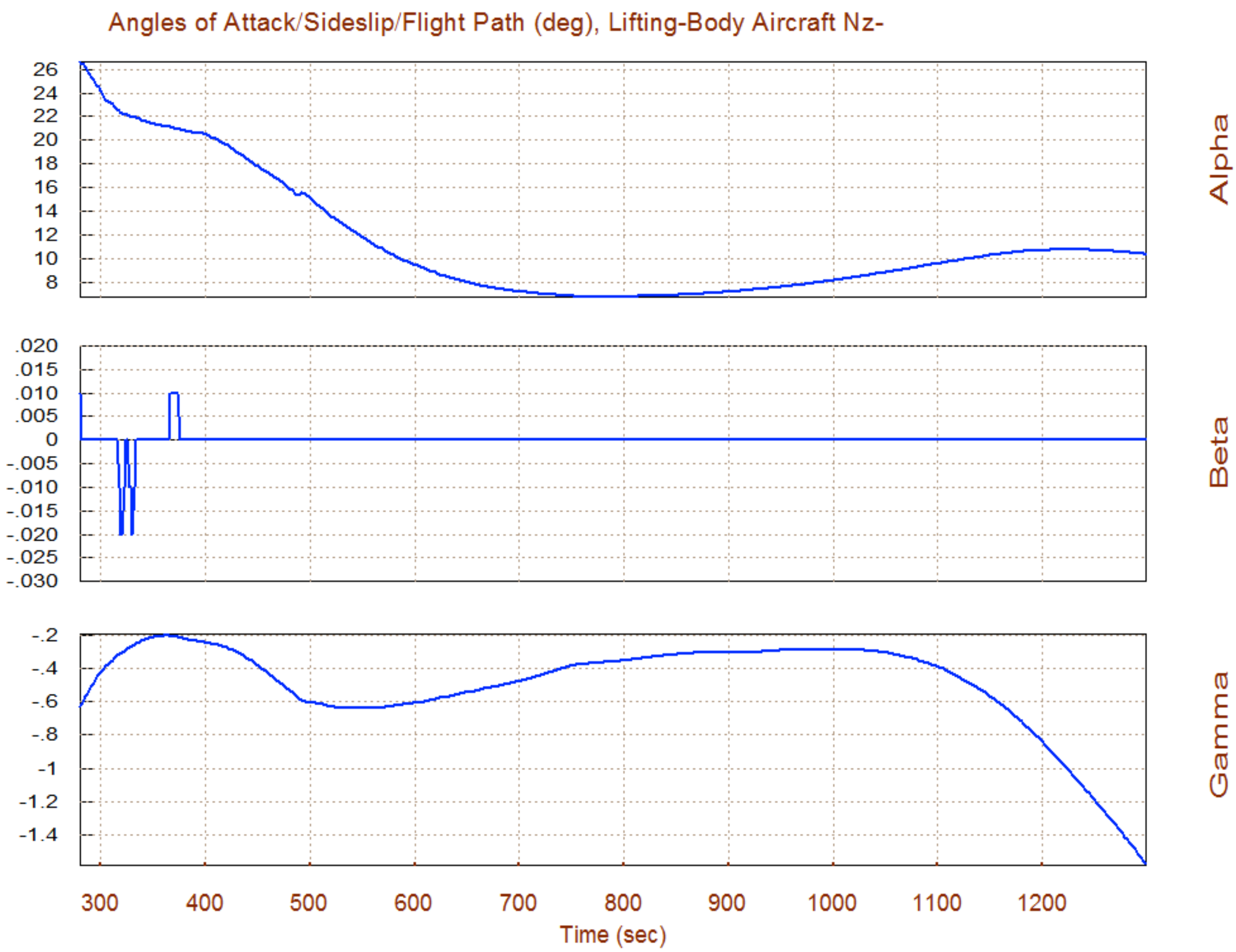
Stability Margins in the Roll Loop

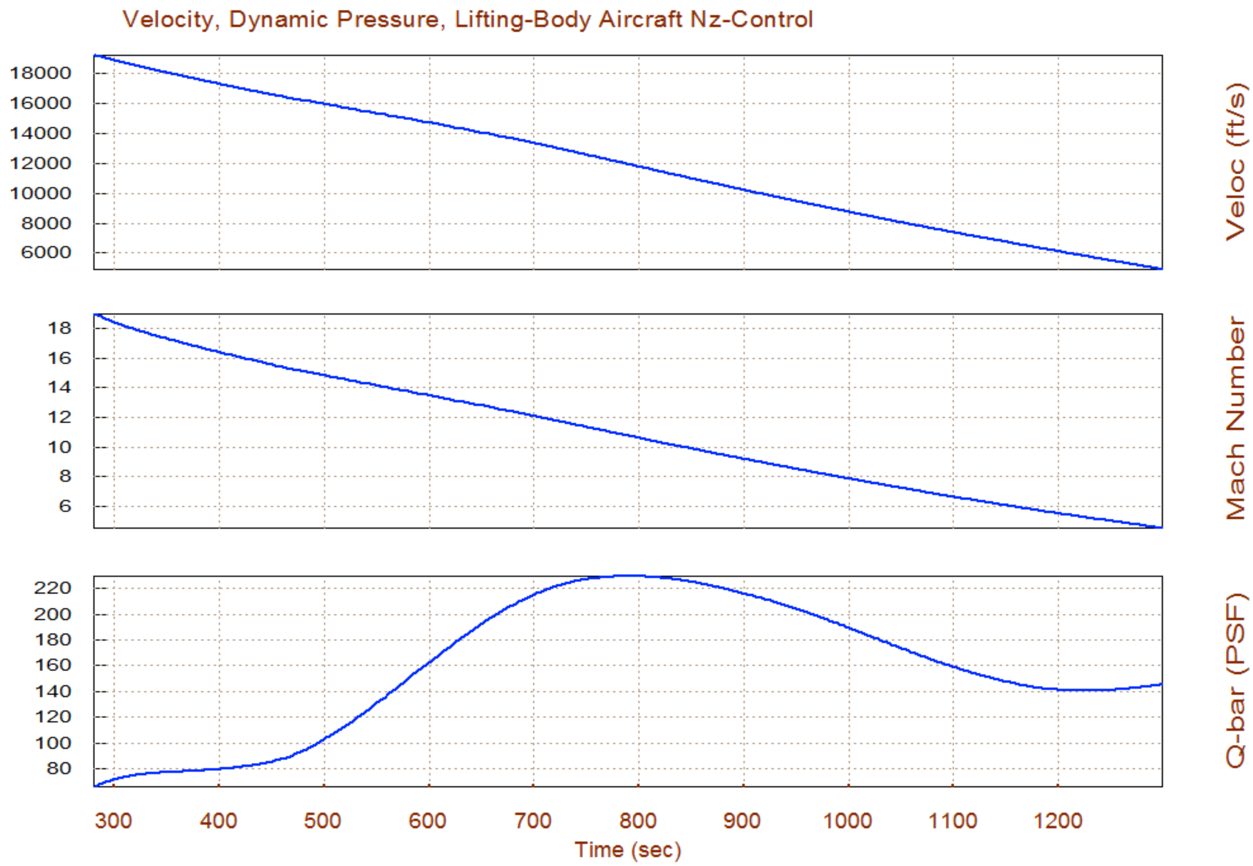


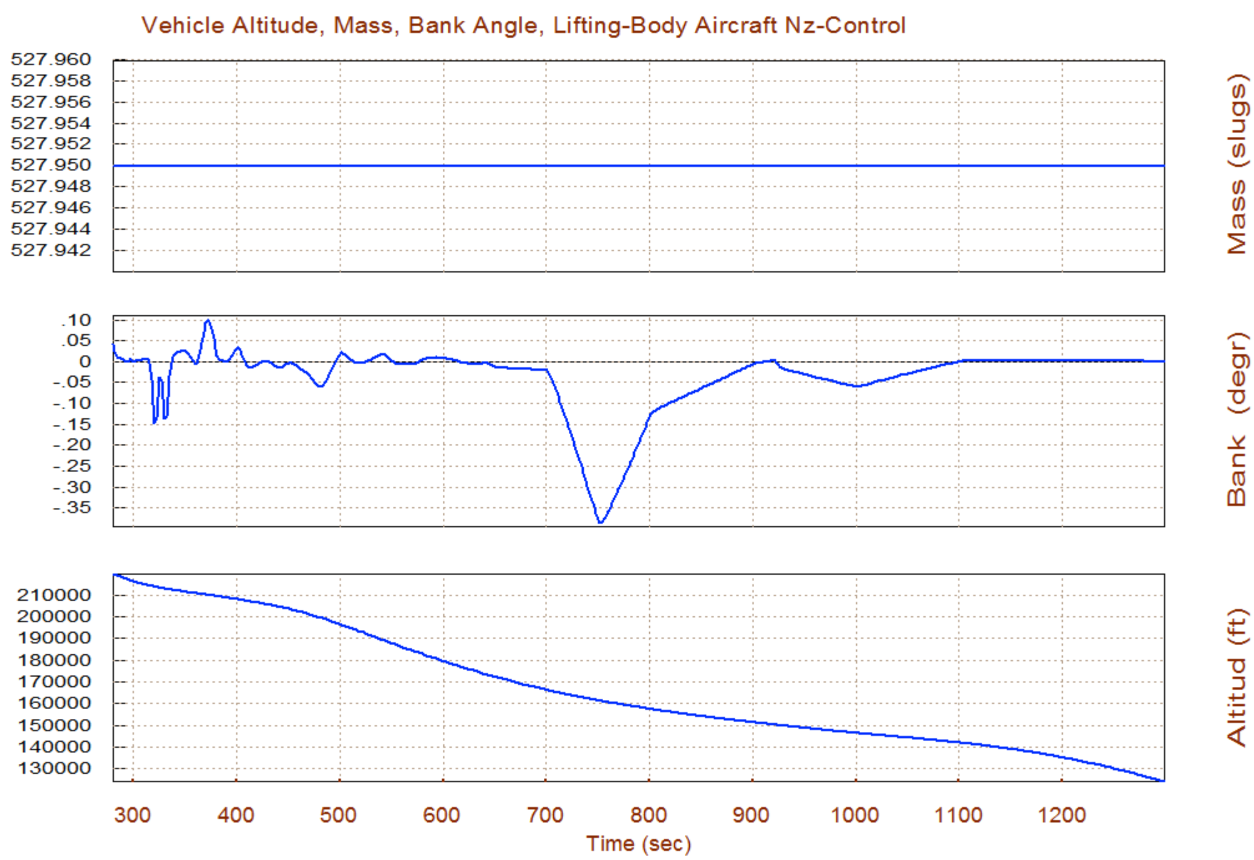
1.2 Normal Acceleration Control Mode

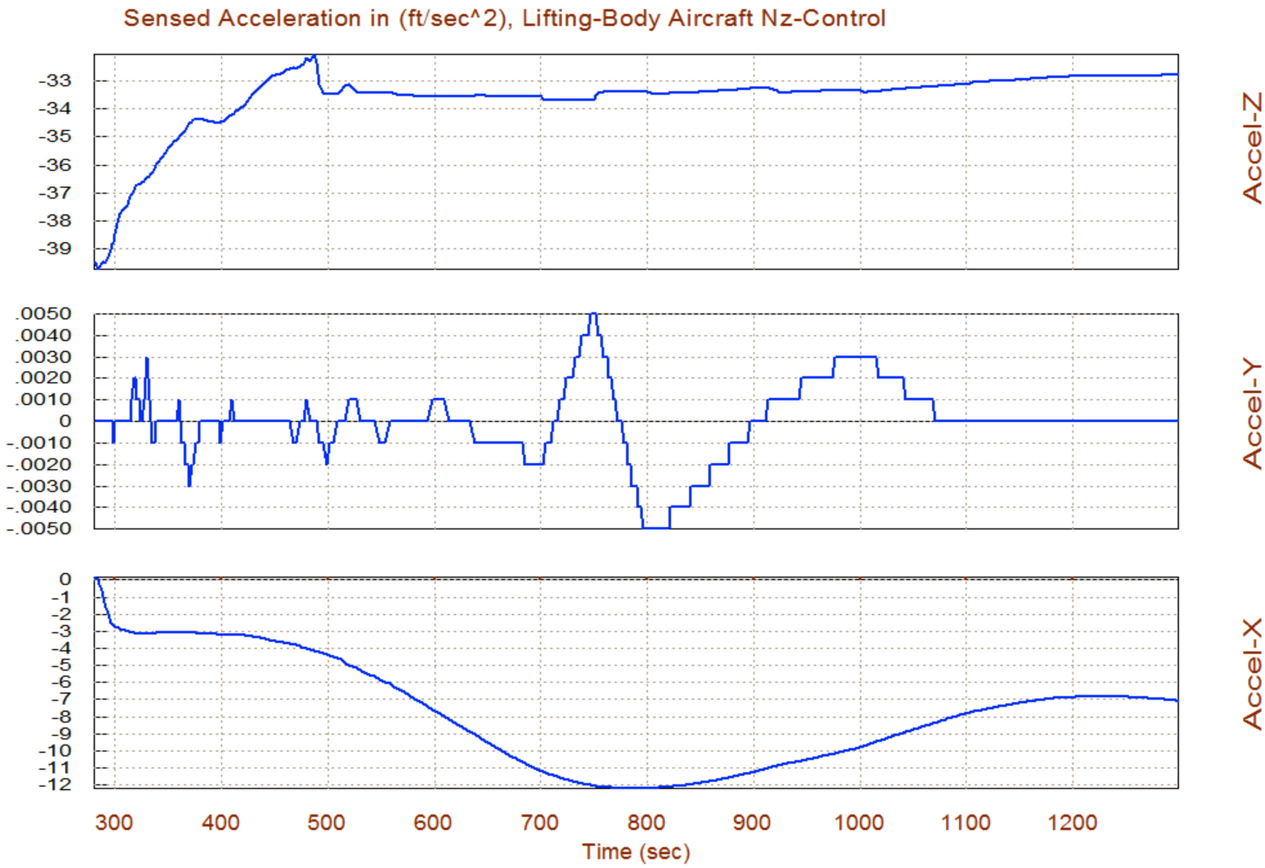
As the α-command is beginning to come down from 29.5°, at t=270 sec the flight control system is transitioning from the alpha-control mode to the Nz-control mode by using feedback from the normal accelerometer. Initially it attempts to maintain a steady Nz of -33.5 (feet/sec^2) and the command is gradually reduced to a smaller value. The angle of attack is also gradually reduced and the descent rate is observed in the flight-path angle γ that begins to come down steeper.

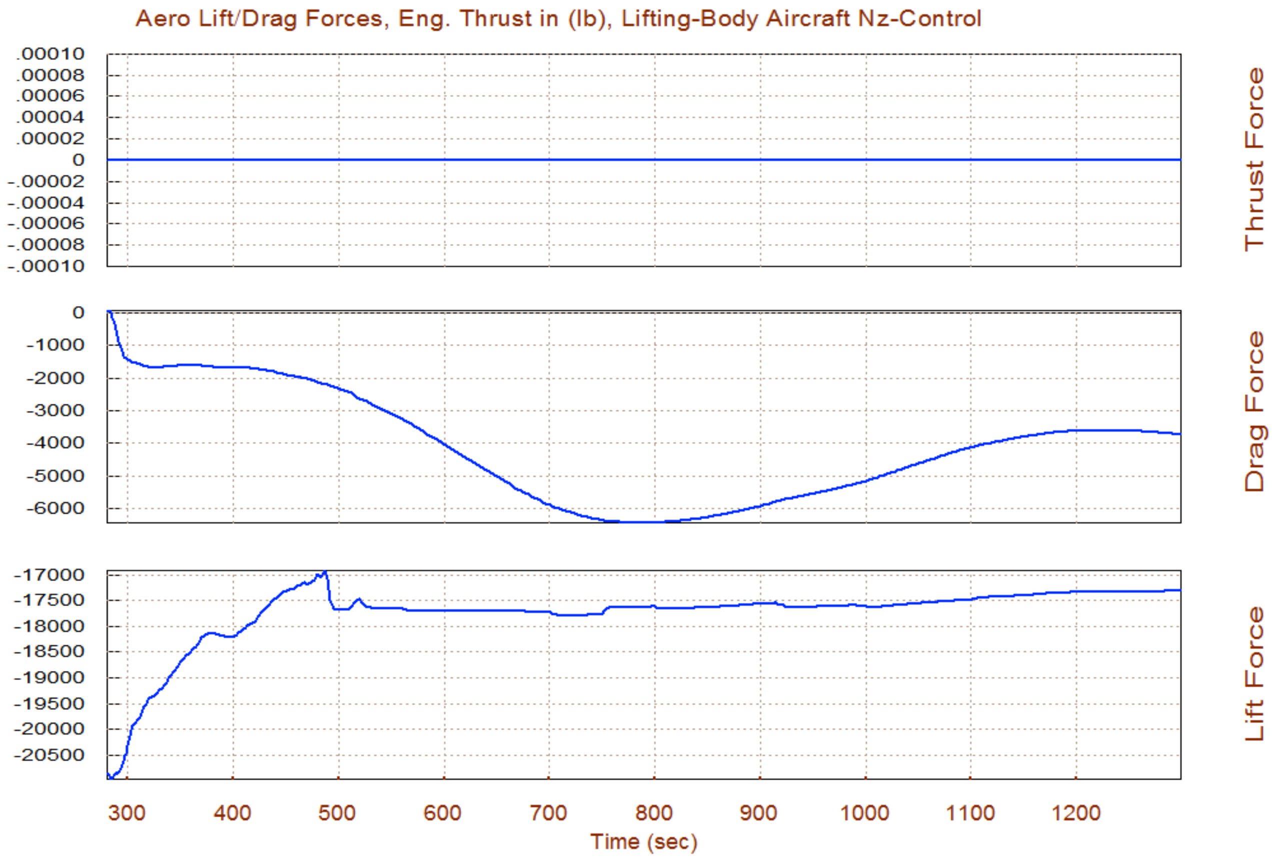
This section of the trajectory is analyzed in folder "*C:\Flixan\ Trim\Examples\Lifting-Body Aircraft\ Reentry from Space\ Trim_Anal\ Nz_Control*". The Nz-controlled section of the trajectory is in file "*Nz_Control.Traj*". The surface mixing matrix "KmixM10" has already been calculated and saved in file "Kmix.Qdr". The remaining files are the same as in the alpha-control section. The following figures show some of the trajectory parameters in the Nz-control region of the trajectory between Mach (19 to 5).




Velocity, Dynamic Pressure, Lifting-Body Aircraft Nz-Control
Veloc (ft/s)
Mach Number
Q-bar (PSF)
Time (sec)


Vehicle Altitude, Mass, Bank Angle, Lifting-Body Aircraft Nz-Control
Mass (slugs)
Bank (degr)
Altitud (ft)
Time (sec)

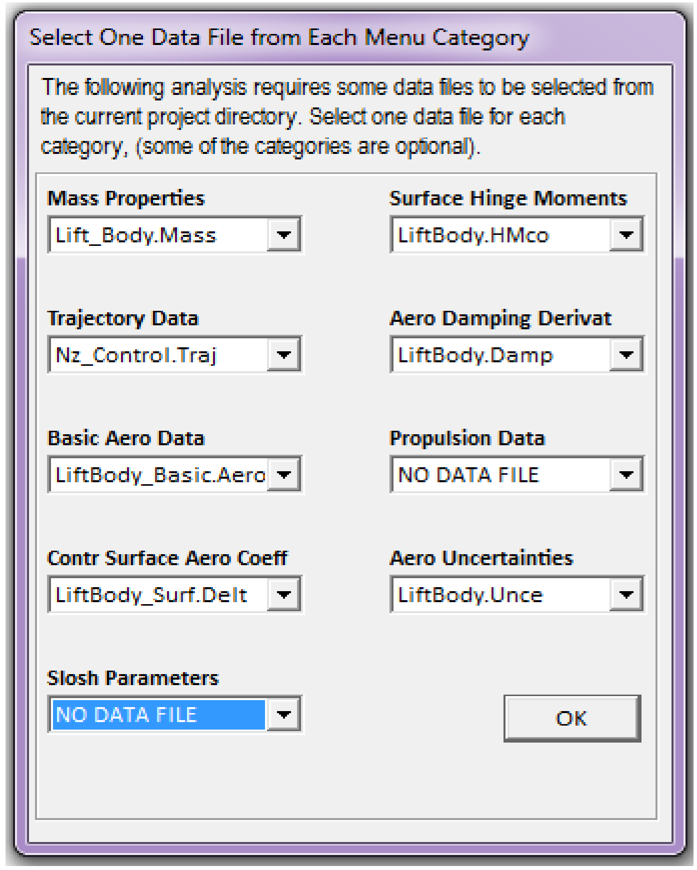

Sensed Acceleration in (ft/sec^2), Lifting-Body Aircraft Nz-Control
Accel-Z
Accel-Y
Accel-X
Time (sec)

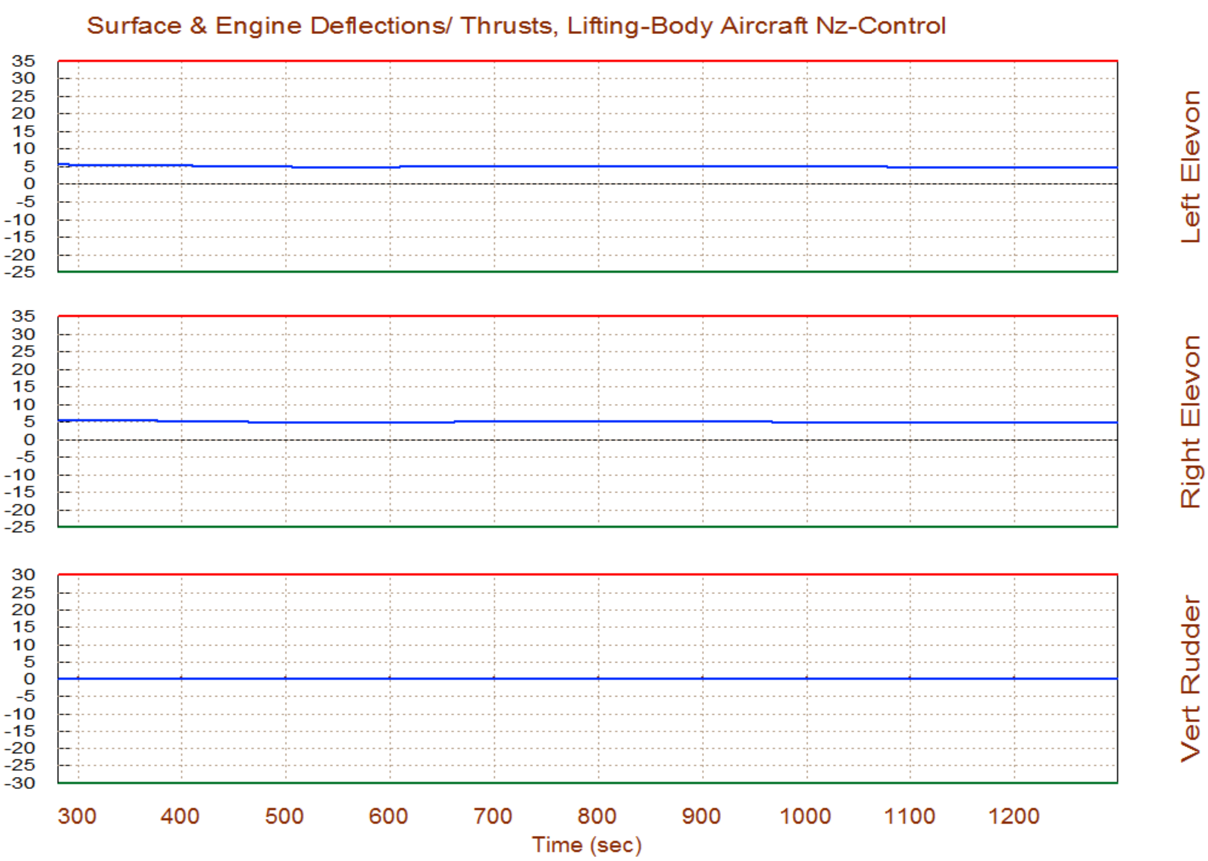

Aero Lift/Drag Forces, Eng. Thrust in (lb), Lifting-Body Aircraft Nz-Control
Thrust Force
Drag Force
Lift Force
Time (sec)

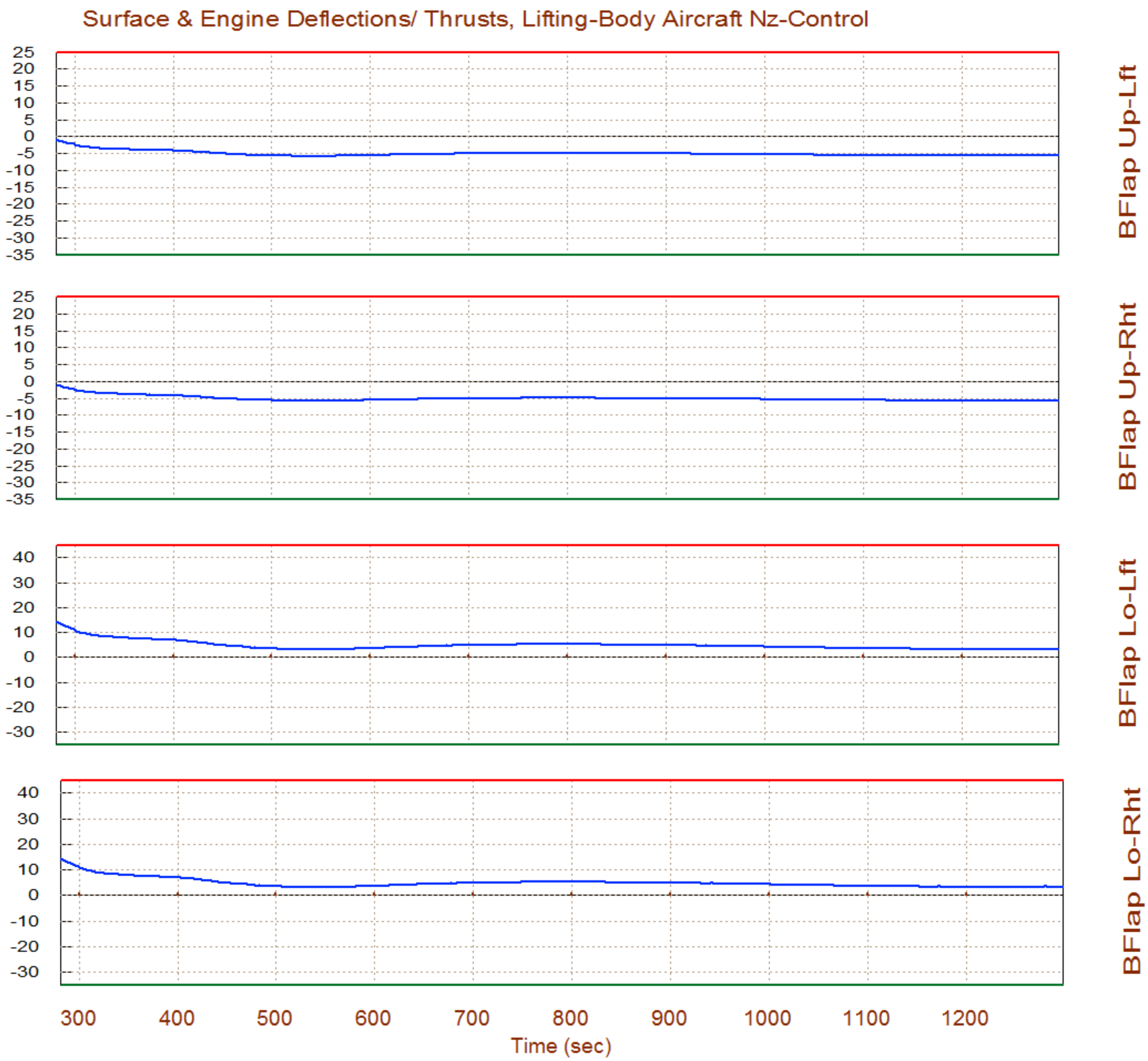
Aerosurface Trimming

We will now trim the aerosurfaces along this Nz-control section of the trajectory to determine the new aerosurface trim positions that balance the vehicle moments, similar to the α-control region. Only the moments are trimmed, no translational trimming is necessary in this phase.

Start Flixan and select the appropriate files in folder "*C:\Flixan\ Trim\ Examples\ Lifting-Body Aircraft\ Reentry from Space\ Trim_Anal\ Nz_Control*". From the Trim main menu 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 program will determine a combination of surface deflections that balance the moments based on the individual surface capabilities. The trim aerosurface deflections are then saved in file "*Nz_Control.Trim*".



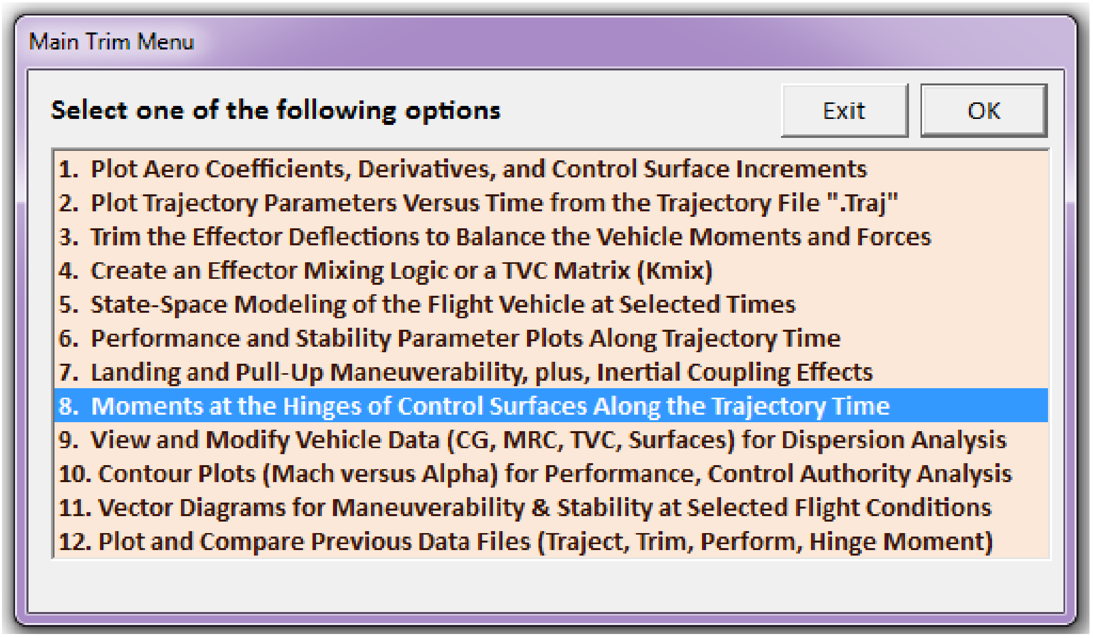


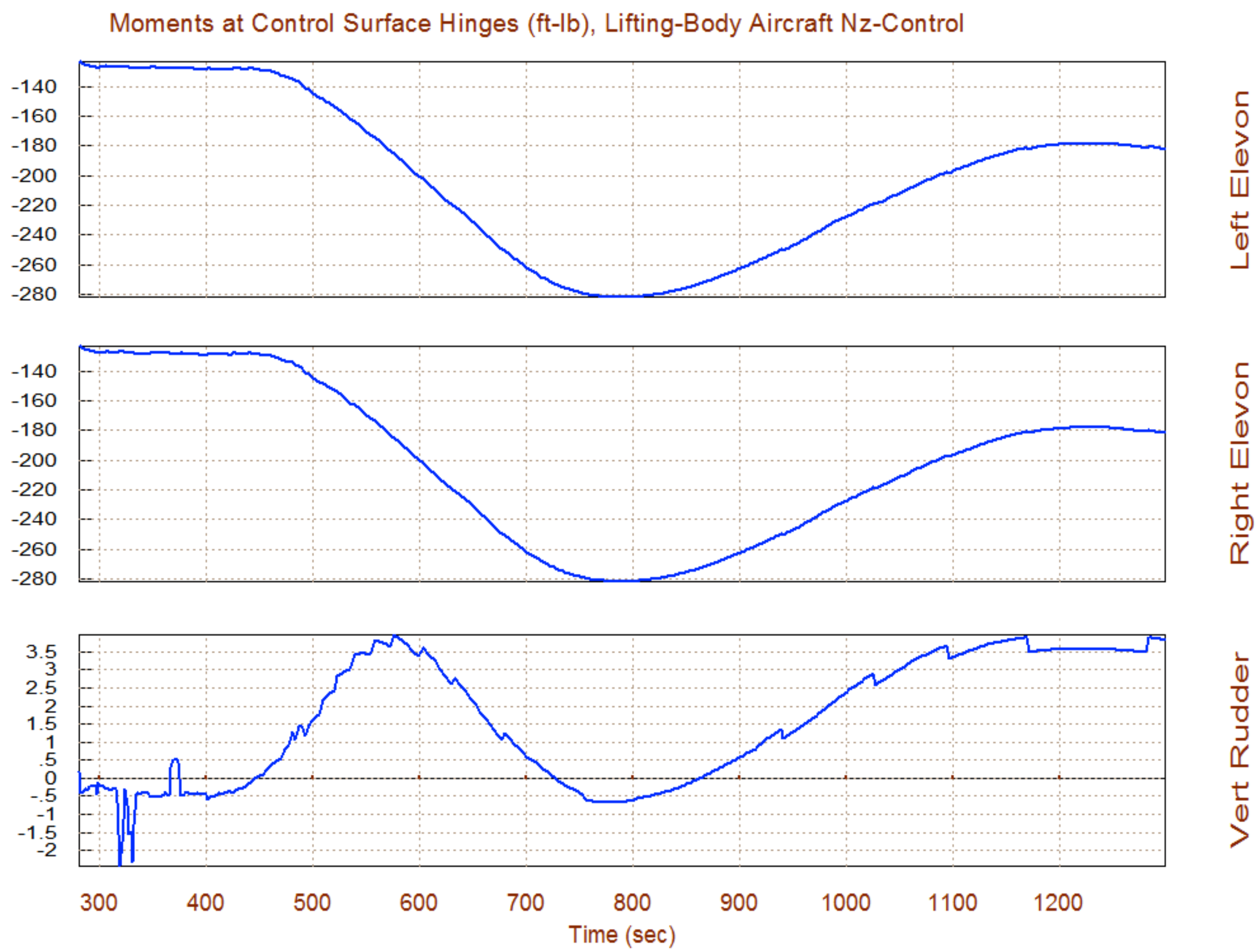


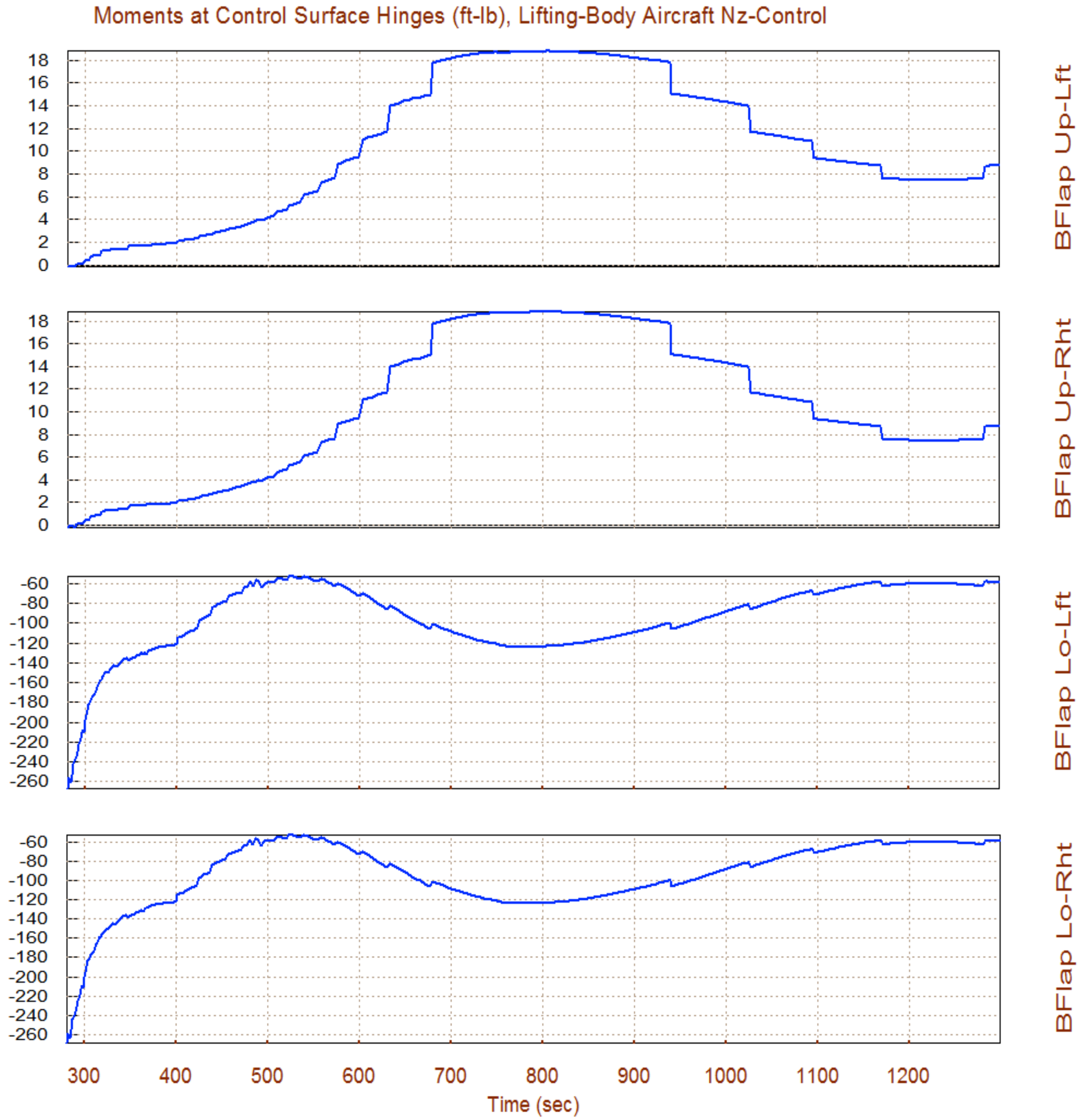
Notice that the trim angles of the lower left and lower right body-flaps have come down to smaller angles in comparison with the previous alpha control region. They now trim at approximately 5° instead of 33° earlier. This is because the angle of attack also came down from 30°. The Elevon trim angles did not change much.

Hinge Moments along the Trajectory

The hinge moments Option-8 from the Trim main menu calculates and plots the moments at the hinges of the 7 aerosurfaces along the trajectory as a function of time. It uses the hinge-moment coefficients data from file "*LiftBody.HMco*" to calculate the moments as described in equation 3.50. The hinge moments are saved in file "*Nz_Control.HiMo*", as a function of the trajectory time.


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)

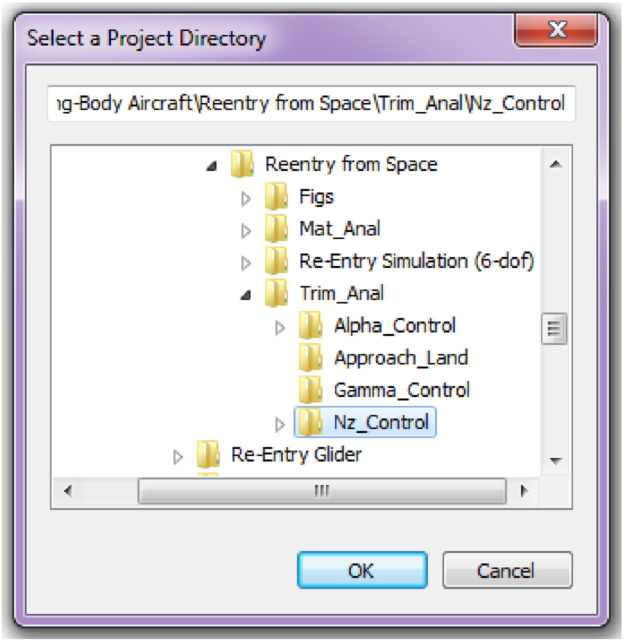

Moments at Control Surface Hinges (ft-lb), Lifting-Body Aircraft Nz-Control
Left Elevon
Right Elevon
Vert Rudder
-140
-160
-180
-200
-220
-240
-260
-280
3.5
3
2.5
2
1.5
1
.5
0
-.5
-1
-1.5
-2
300
400
500
600
700
800
900
1000
1100
1200
Time (sec)

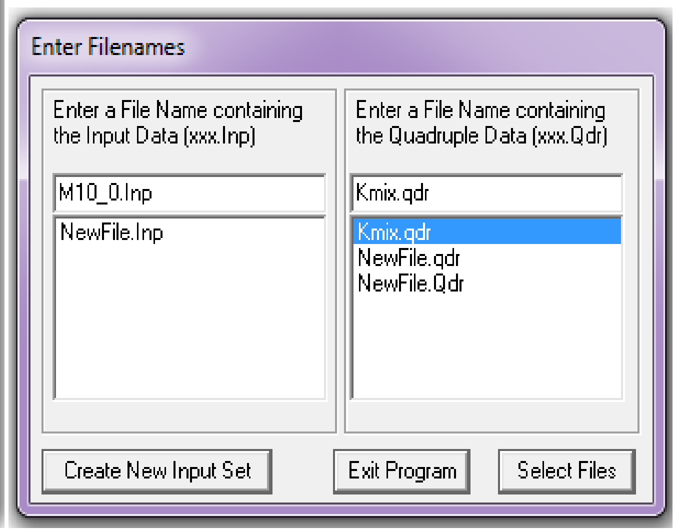


This option is useful for sizing the actuator torques. It is, however, available only when a hinge-moments coefficients file (.HMco) is available in the project directory.

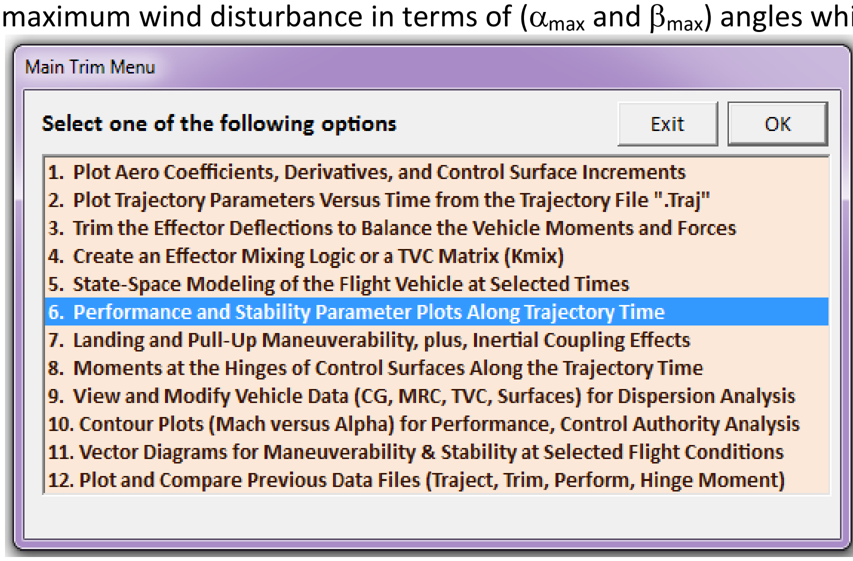
Performance Parameters along the Nz-Control Phase of Trajectory

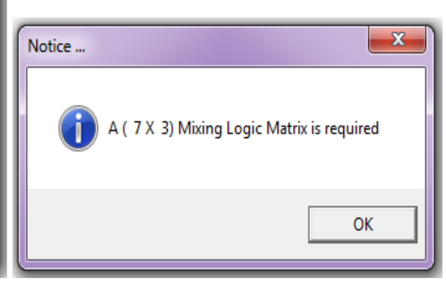
We are now in able to calculate the static performance parameters along the Nz-control phase of the trajectory. It is important to select the systems file "Kmix.Qdr" before beginning the performance analysis because it includes the new mixing matrix KmixM10 that will combine the seven aerosurfaces together. A new input filename "Nz_M10_0.Inp" is also created that will include the input data for the dynamic model.

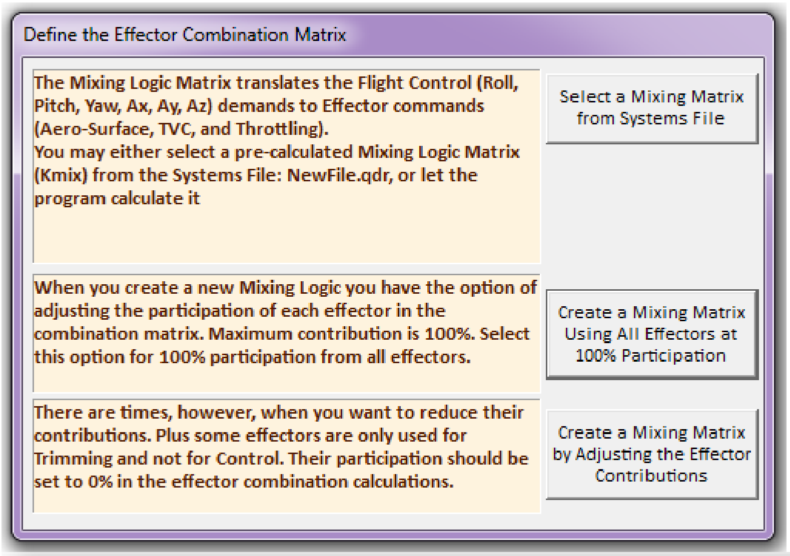


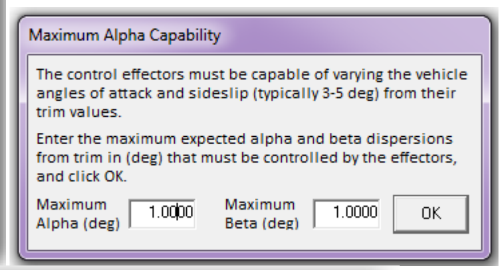


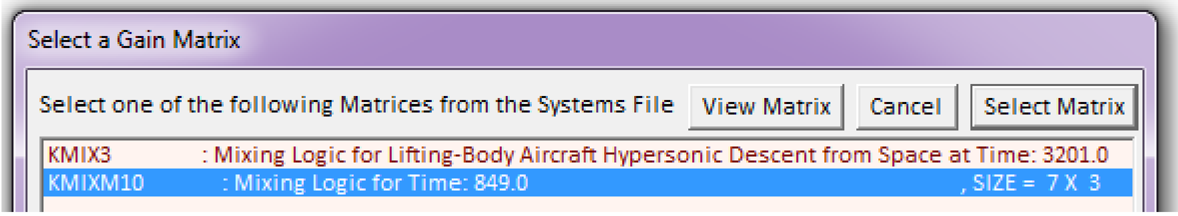
Use the Trim main menu to select option-6 and generate the static performance and stability parameters along the Nz-controlled section of the trajectory. These parameters are described in Section 3. However, before analyzing the vehicle performance, the program needs to know how the 7 aerosurfaces are combining together to control the 3 rotational axes. The mixing logic matrix defines the effector allocation along roll, pitch, and yaw, and the control effectiveness strongly depends on this matrix. We will select the matrix KmixM10 from file "Kmix.Qdr". We must also define the maximum wind disturbance in terms of (α_{max} and β_{max}) angles which are both set to 1° in this case.

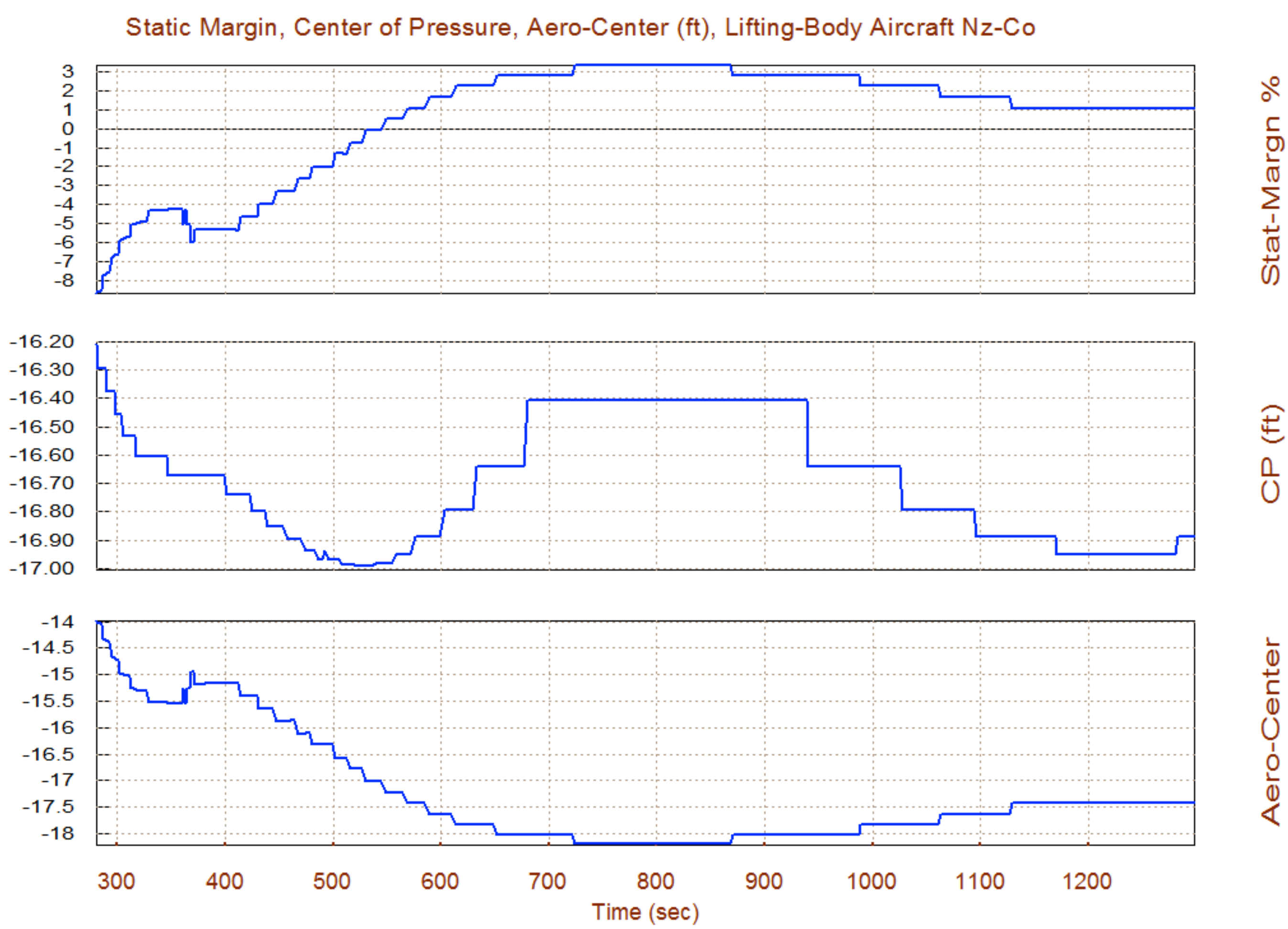


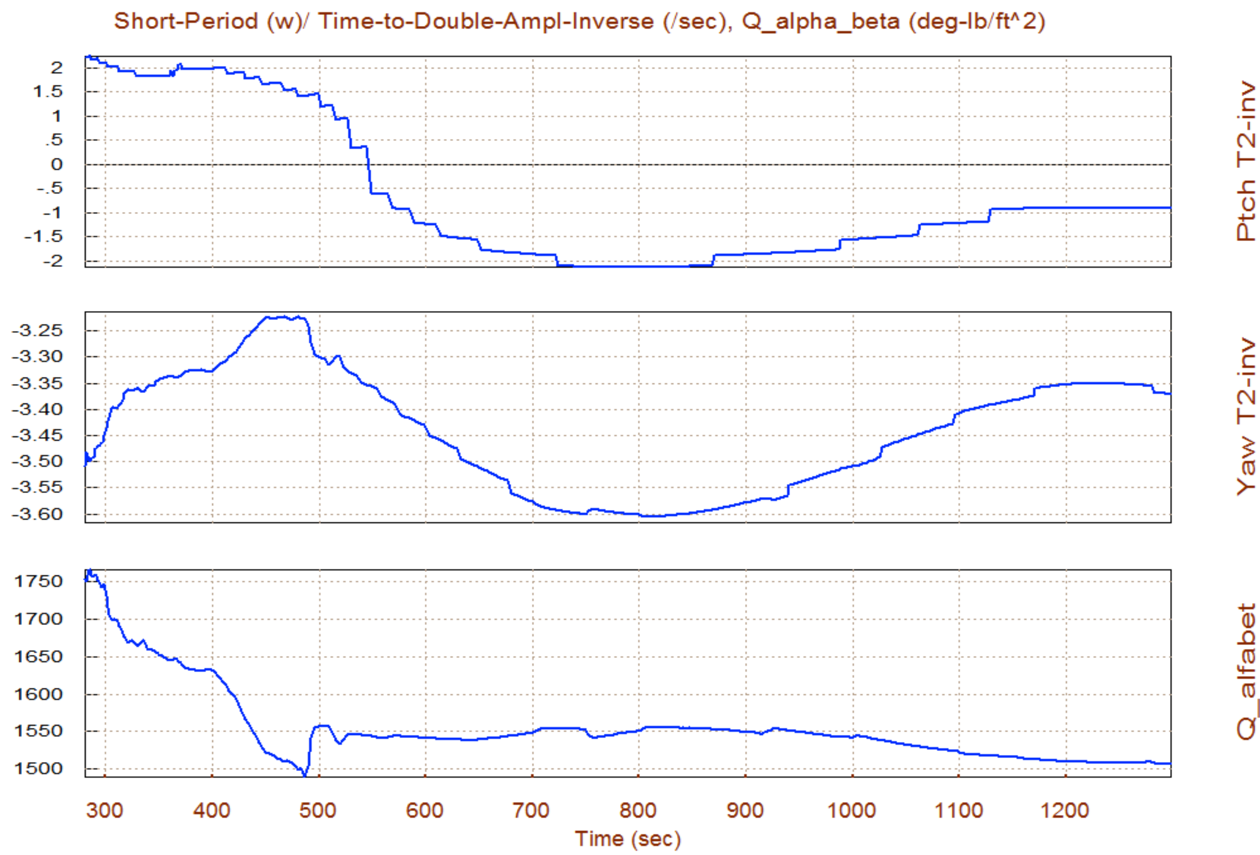


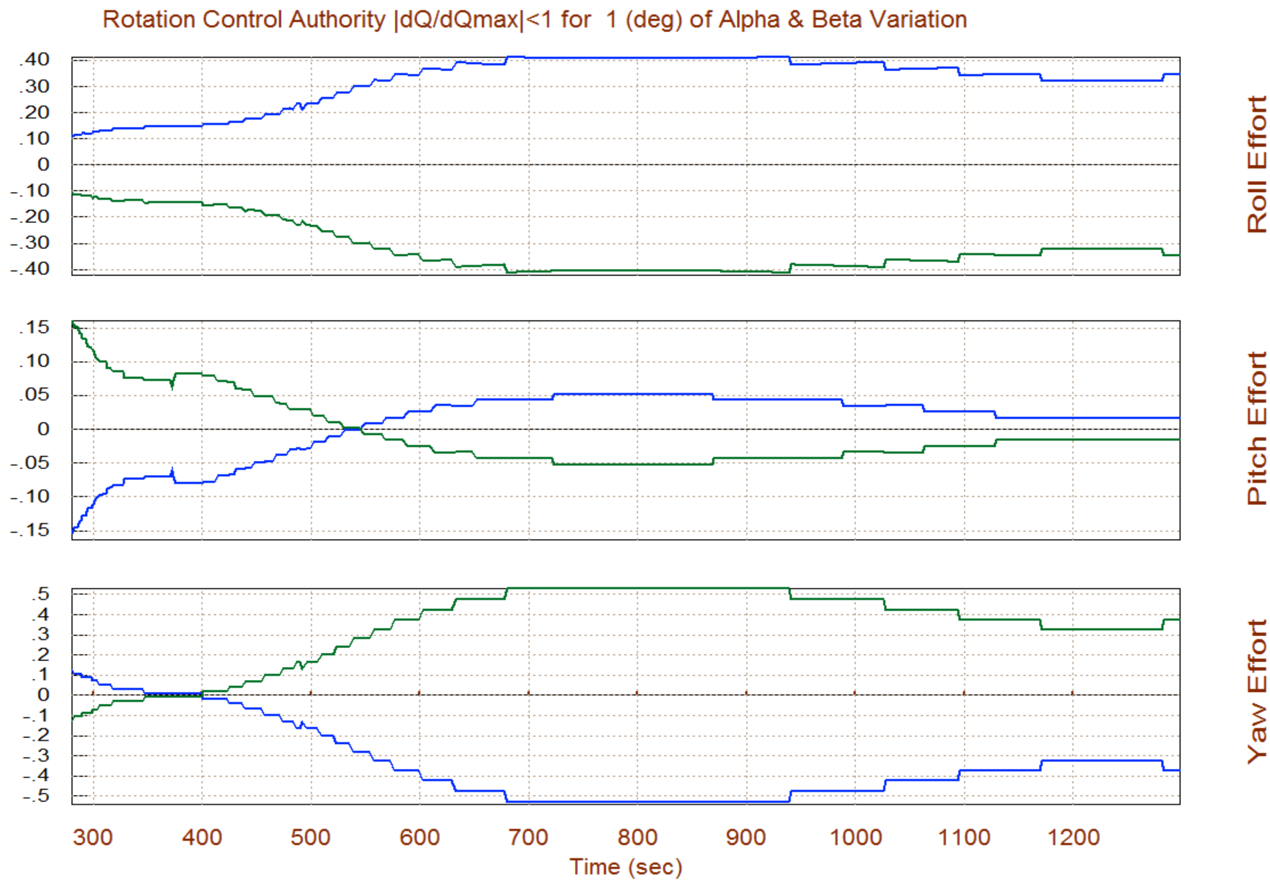

Define the Effector Combination Matrix
The Mixing Logic Matrix translates the Flight Control (Roll, Pitch, Yaw, Ax, Ay, Az) demands to Effector commands (Aero-Surface, TVC, and Throttling).
You may either select a pre-calculated Mixing Logic Matrix (Kmix) from the Systems File: NewFile.qdr, or let the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

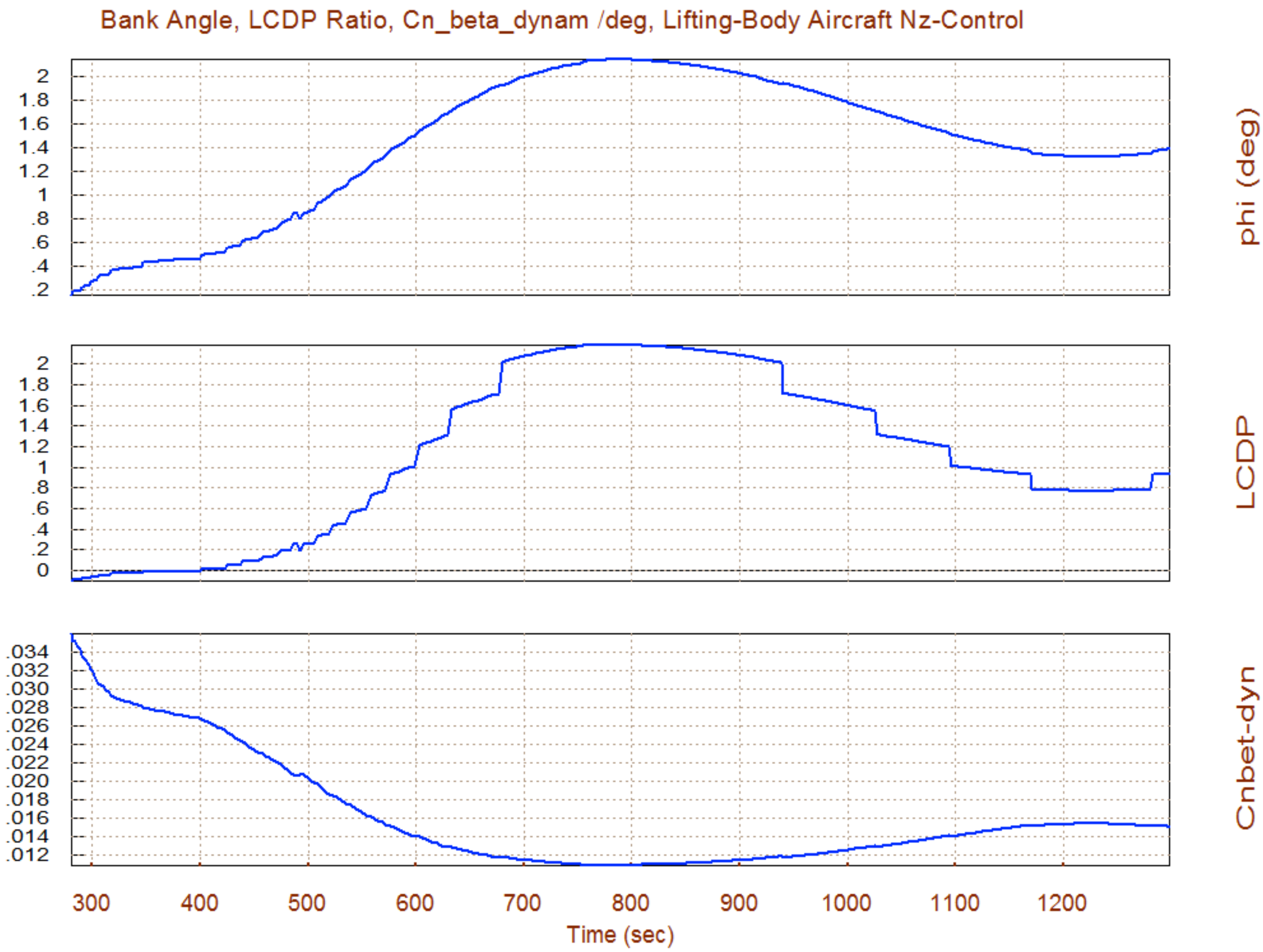

Maximum Alpha Capability
The control effectors must be capable of varying the vehicle angles of attack and sideslip (typically 3-5 deg) from their trim values.
Enter the maximum expected alpha and beta dispersions from trim in (deg) that must be controlled by the effectors, and click OK.
Maximum Alpha (deg)
1.0000
Maximum Beta (deg)
1.0000
OK


Select a Gain Matrix
Select one of the following Matrices from the Systems File
View Matrix
Cancel
Select Matrix
KMIX3 : Mixing Logic for Lifting-Body Aircraft Hypersonic Descent from Space at Time: 3201.0
KMIXM10 : Mixing Logic for Time: 849.0 , SIZE = 7 X 3


Static Margin, Center of Pressure, Aero-Center (ft), Lifting-Body Aircraft Nz-Co
Stat-Margn %
CP (ft)
Aero-Center
Time (sec)
300
400
500
600
700
800
900
1000
1100
1200


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)

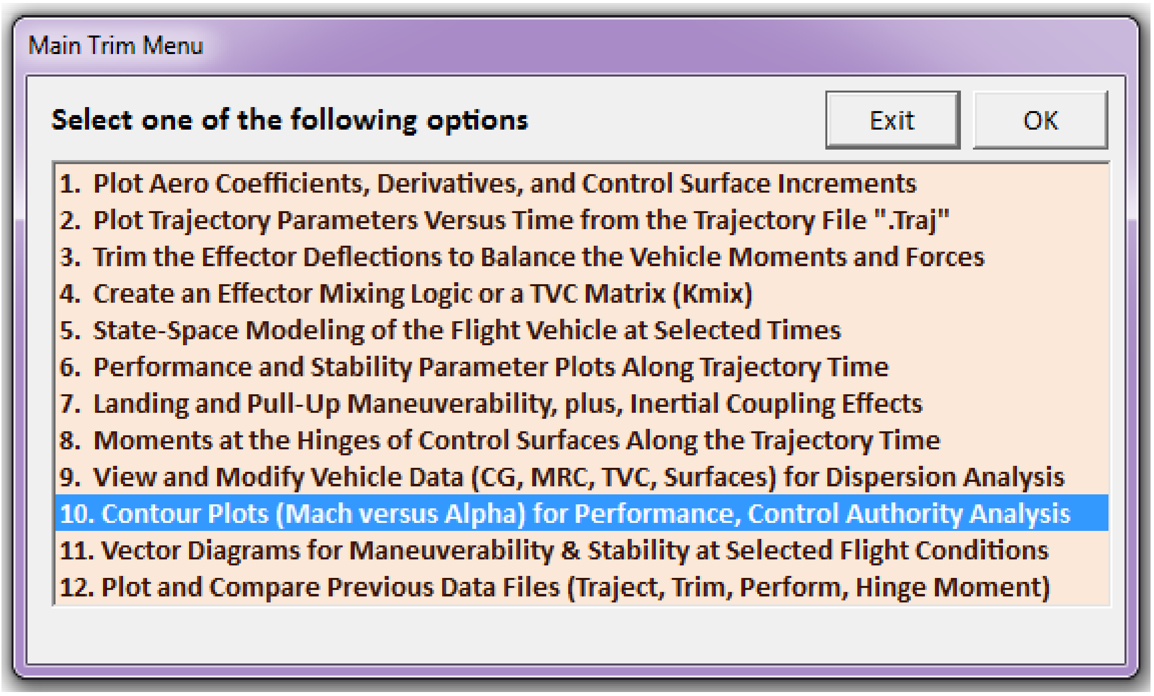

Rotation Control Authority |dQ/dQmax|<1 for 1 (deg) of Alpha & Beta Variation
Roll Effort
Pitch Effort
Yaw Effort
Time (sec)



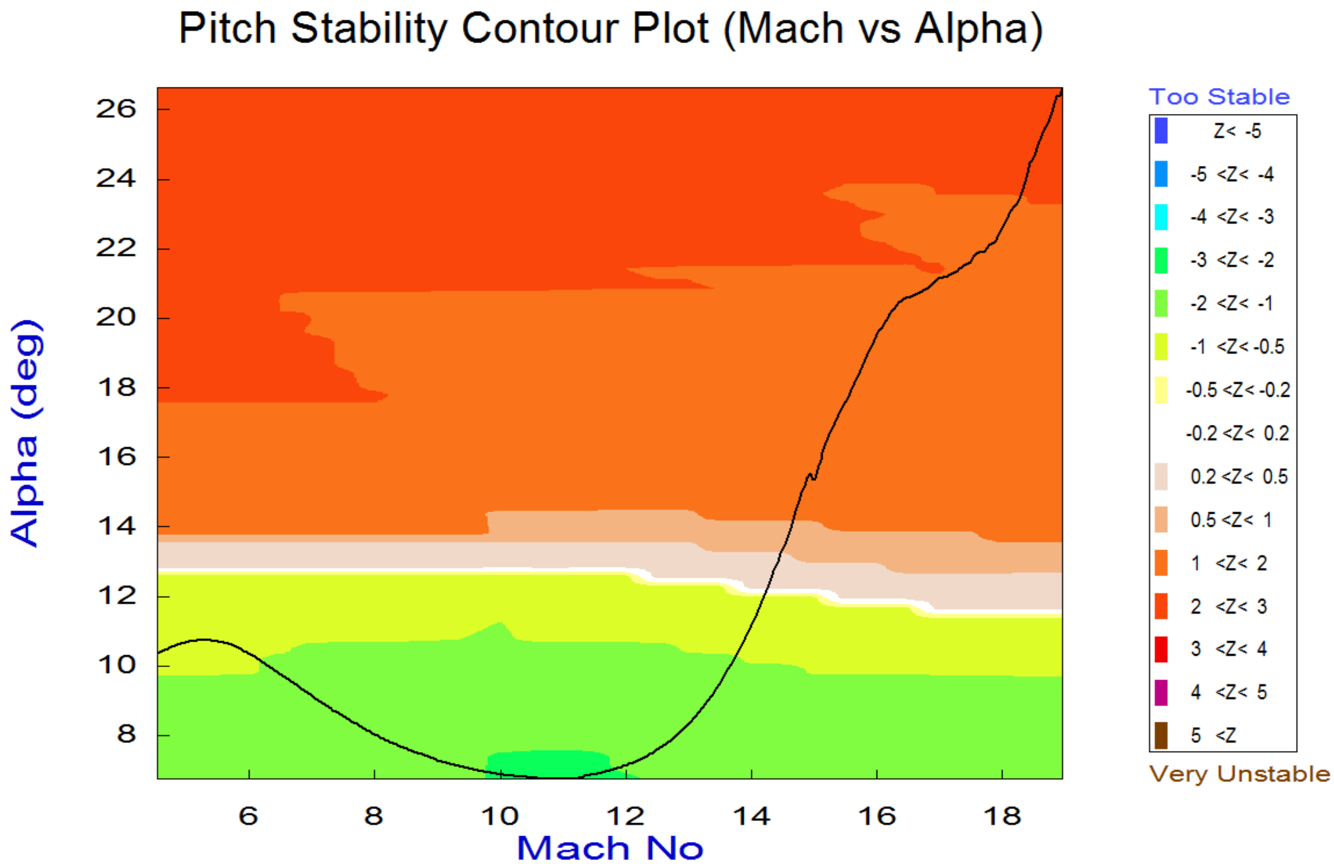
The performance results show that in the longitudinal direction the vehicle initially is statically unstable with a peak time-to-double-amplitude 0.5 sec, but as the angle of attack is reduced it becomes statically stable, after t=550 sec, with a short-period resonance of 2 (rad/sec) or 3% static margin. In the lateral direction it is statically stable with the Dutch-roll resonances peaking to 3.6 (rad/sec). The peak (Q-alpha, Q-beta) loading due to the (α_{max} and β_{max}) dispersions is 1700 (psf-deg), which is lower than before. Remember, that this is due to the 1° of (α_{max} and β_{max}) peak excursions. The magnitude of the control effort required to overcome the $\pm\alpha_{max}$ and $\pm\beta_{max}$ dispersions does not exceed 0.5 in all three axes. It is symmetric in both directions from trim. This allows sufficient control authority for other functions. The Cnβ-dynamic is positive which means that the vehicle is directionally stable. The LCDP ratio is now becoming positive after 400 sec and its magnitude increases to 2. This improves the roll controllability and it does not require roll-reversal. The bank angle parameter ϕ is the bank angle due to a β_{max}= 1°. It is useful only near landing.

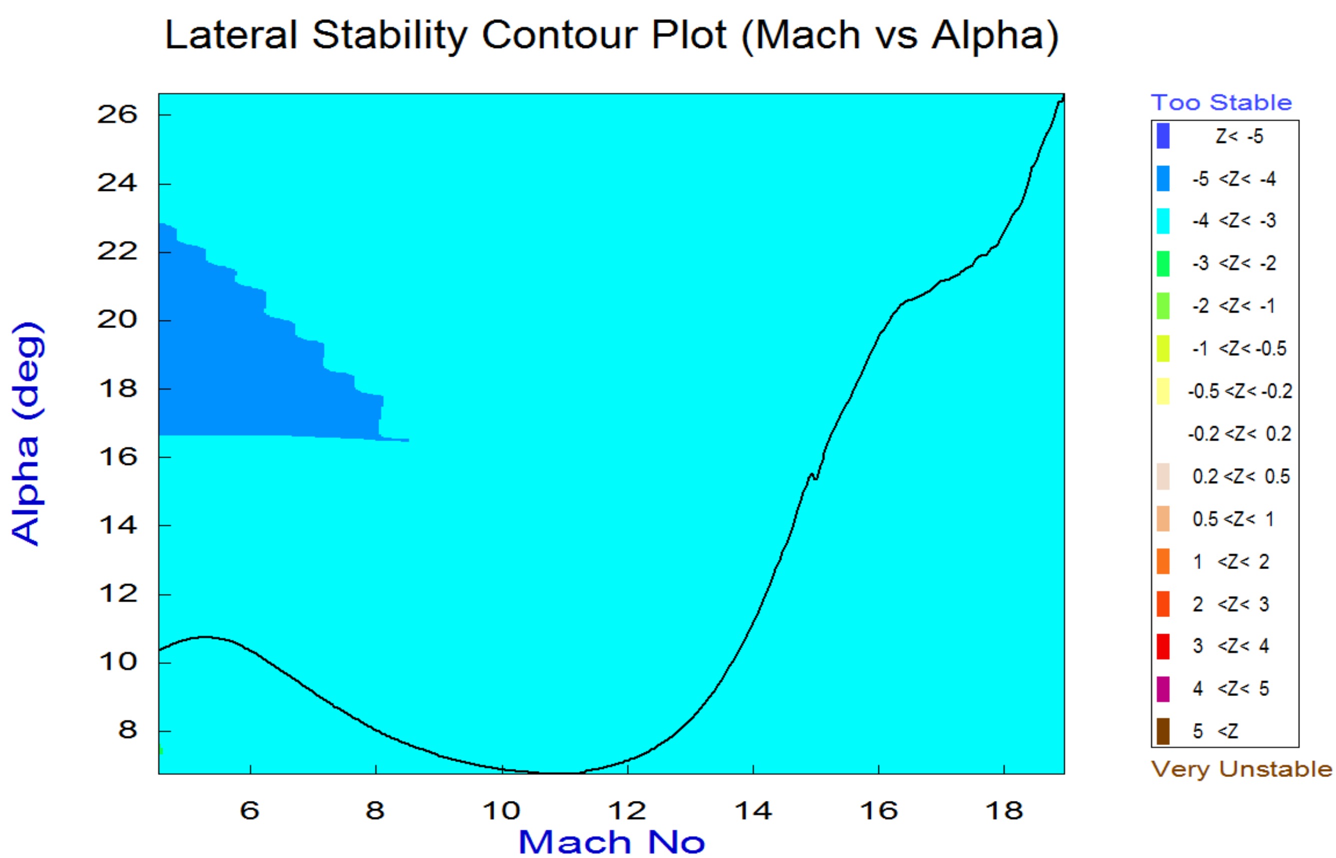
Contour Plots Analysis

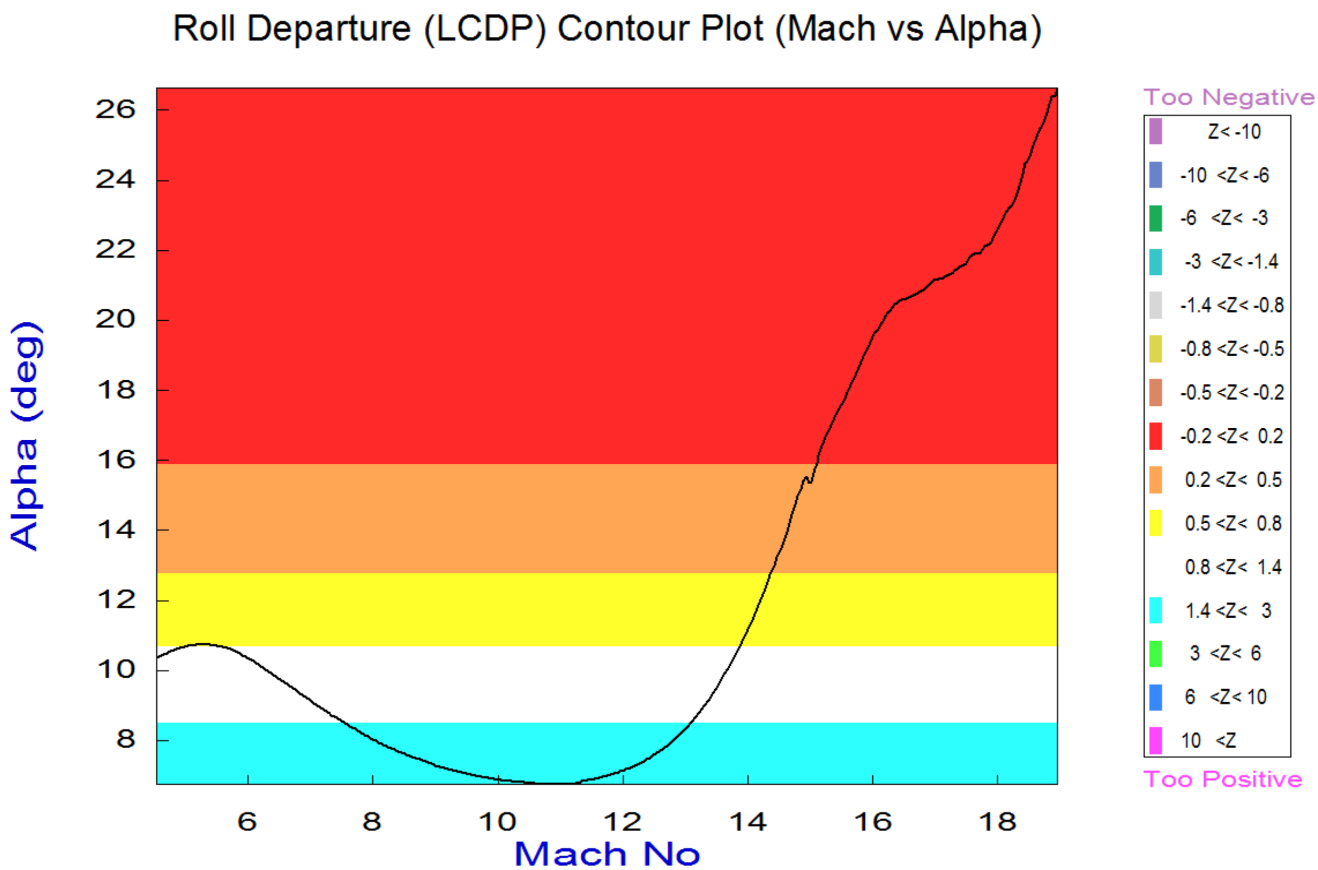
Contour plots allow us to assess vehicle performance over the entire Mach versus Alpha range. The contour plots are selected from the 10th option in the Trim main menu, as shown. Performance parameters are function of the effector mixing matrix. We must, therefore, select again the matrix KmixM10 from file "Kmix.Qdr".

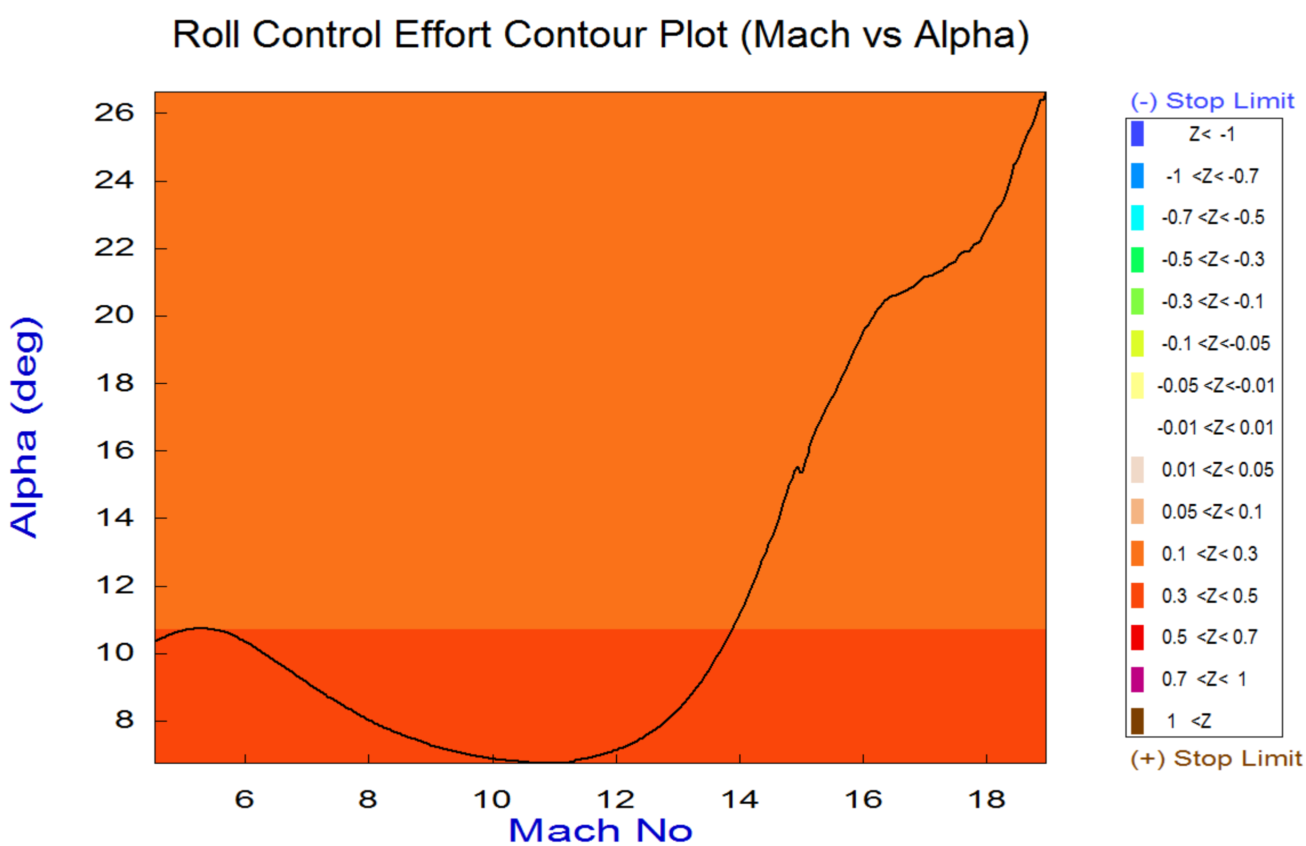


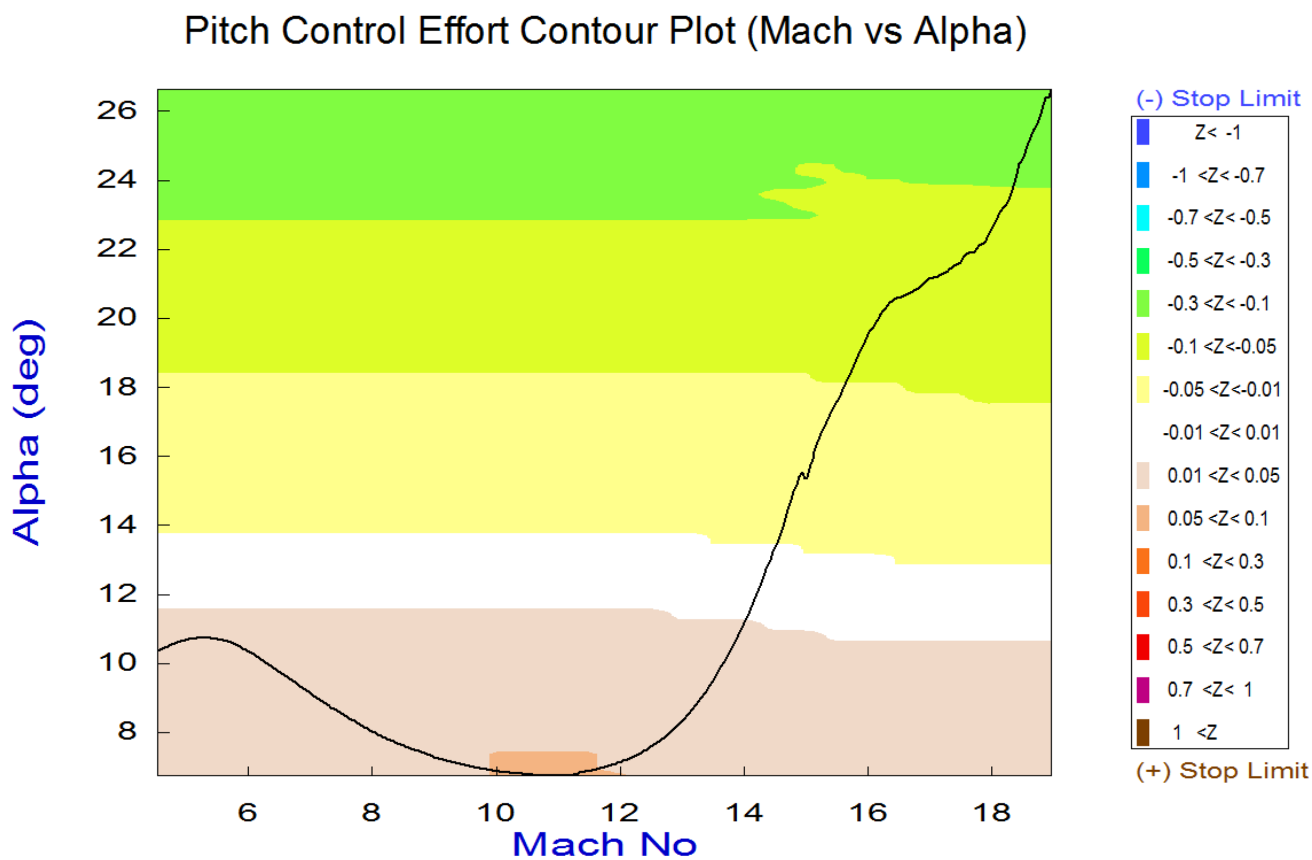
The following figures show contour plots for some of the critical performance parameters. The first two plots show the pitch and lateral stability parameter (T2-inverse) in the entire Mach versus alpha range. The Nz-control trajectory is shown by the dark line beginning in the upper right-hand corner and ending in the lower left-hand side. In the pitch axis the vehicle is unstable at angles of attack greater than 13° because T2-inverse>0. The rate of instability, however, is manageable. Neutral stability in pitch occurs at approximately α=12.5° as seen by the thin almost horizontal white band. In the lateral direction the vehicle is statically stable across the entire region and the stability parameter is almost constant. The LCDP ratio which is a measure of dynamic roll controllability is good for angles of attack below 14°. The contour plots were calculated using a constant mixing-logic matrix and it seems that a different mixing logic should be used at high angles of attack. In actual flight or simulations the mixing-logic is not constant but it is also scheduled similar to the control gains as a function of Mach and alpha. The pitch and yaw control authority against 1° of α_{max} and β_{max} aero disturbances is very good. The roll control authority for β_{max}= 1° disturbances is marginally acceptable for angles of attack below 11°.

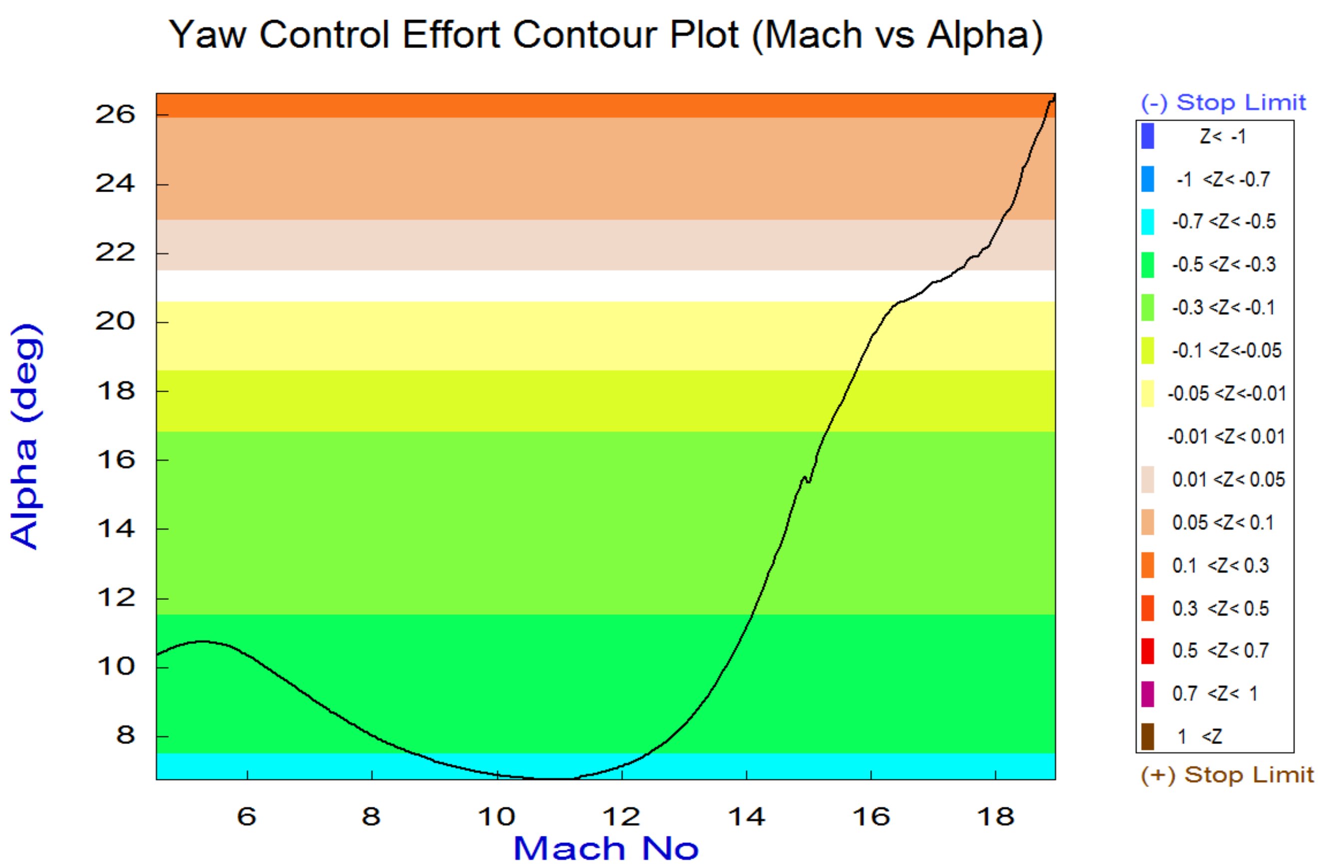

Pitch Stability Contour Plot (Mach vs Alpha)
Alpha (deg)
26
24
22
20
18
16
14
12
10
8
6
8
10
12
14
16
18
Mach No
Too Stable
Z< -5
-5 <Z< -4
-4 <Z< -3
-3 <Z< -2
-2 <Z< -1
-1 <Z< -0.5
-0.5 <Z< -0.2
-0.2 <Z< 0.2
0.2 <Z< 0.5
0.5 <Z< 1
1 <Z< 2
2 <Z< 3
3 <Z< 4
4 <Z< 5
5 <Z
Very Unstable


Lateral Stability Contour Plot (Mach vs Alpha)
Alpha (deg)
26
24
22
20
18
16
14
12
10
8
6
8
10
12
14
16
18
Mach No
Too Stable
Z< -5
-5 <Z< -4
-4 <Z< -3
-3 <Z< -2
-2 <Z< -1
-1 <Z< -0.5
-0.5 <Z< -0.2
-0.2 <Z< 0.2
0.2 <Z< 0.5
0.5 <Z< 1
1 <Z< 2
2 <Z< 3
3 <Z< 4
4 <Z< 5
5 <Z
Very Unstable


Roll Departure (LCDP) Contour Plot (Mach vs Alpha)
Alpha (deg)
26
24
22
20
18
16
14
12
10
8
6
8
10
12
14
16
18
Mach No
Too Negative
Z< -10
-10 <Z< -6
-6 <Z< -3
-3 <Z< -1.4
-1.4 <Z< -0.8
-0.8 <Z< -0.5
-0.5 <Z< -0.2
-0.2 <Z< 0.2
0.2 <Z< 0.5
0.5 <Z< 0.8
0.8 <Z< 1.4
1.4 <Z< 3
3 <Z< 6
6 <Z< 10
10 <Z
Too Positive

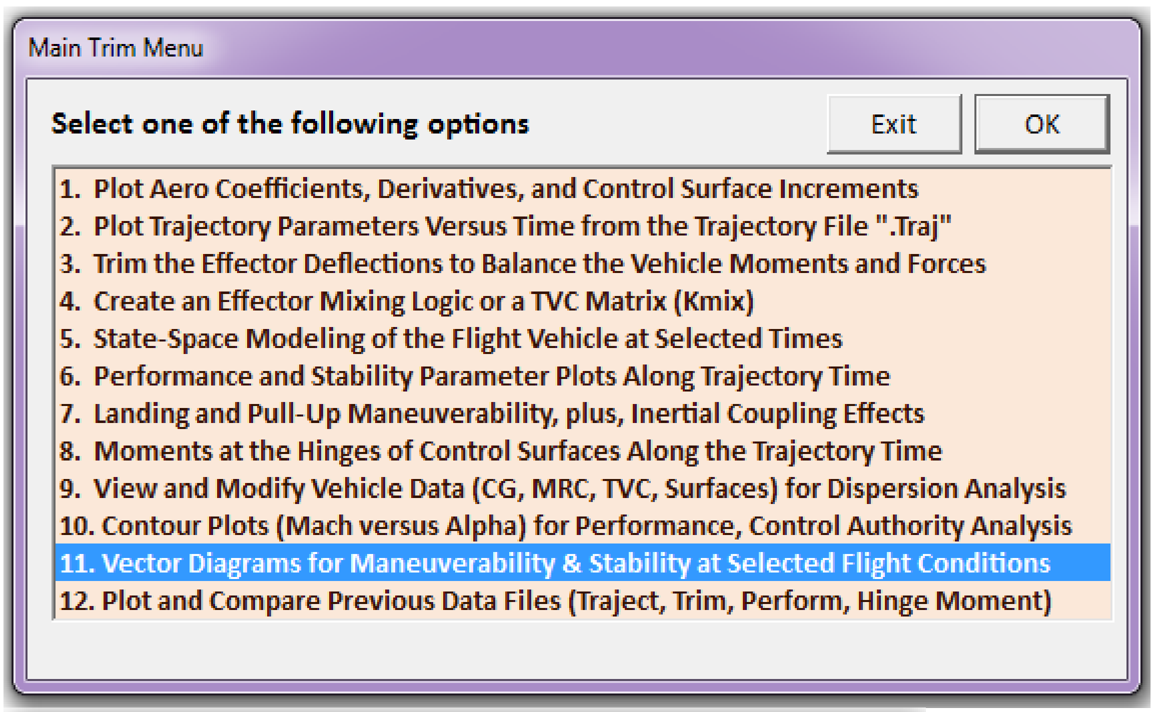

Roll Control Effort Contour Plot (Mach vs Alpha)
Alpha (deg)
26
24
22
20
18
16
14
12
10
8
6
8
10
12
14
16
18
Mach No
(-) Stop Limit
Z< -1
-1 <Z< -0.7
-0.7 <Z< -0.5
-0.5 <Z< -0.3
-0.3 <Z< -0.1
-0.1 <Z<-0.05
-0.05 <Z<-0.01
-0.01 <Z< 0.01
0.01 <Z< 0.05
0.05 <Z< 0.1
0.1 <Z< 0.3
0.3 <Z< 0.5
0.5 <Z< 0.7
0.7 <Z< 1
1 <Z
(+) Stop Limit

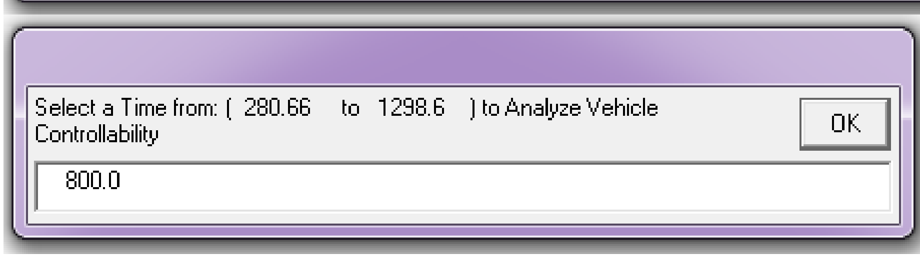

Pitch Control Effort Contour Plot (Mach vs Alpha)
Alpha (deg)
26
24
22
20
18
16
14
12
10
8
6
8
10
12
14
16
18
Mach No
(-) Stop Limit
Z< -1
-1 <Z< -0.7
-0.7 <Z< -0.5
-0.5 <Z< -0.3
-0.3 <Z< -0.1
-0.1 <Z<-0.05
-0.05 <Z<-0.01
-0.01 <Z< 0.01
0.01 <Z< 0.05
0.05 <Z< 0.1
0.1 <Z< 0.3
0.3 <Z< 0.5
0.5 <Z< 0.7
0.7 <Z< 1
1 <Z
(+) Stop Limit


Yaw Control Effort Contour Plot (Mach vs Alpha)
Alpha (deg)
26
24
22
20
18
16
14
12
10
8
6
8
10
12
14
16
18
Mach No
(-) Stop Limit
Z< -1
-1 <Z< -0.7
-0.7 <Z< -0.5
-0.5 <Z< -0.3
-0.3 <Z< -0.1
-0.1 <Z<-0.05
-0.05 <Z<-0.01
-0.01 <Z< 0.01
0.01 <Z< 0.05
0.05 <Z< 0.1
0.1 <Z< 0.3
0.3 <Z< 0.5
0.5 <Z< 0.7
0.7 <Z< 1
1 <Z
(+) Stop Limit

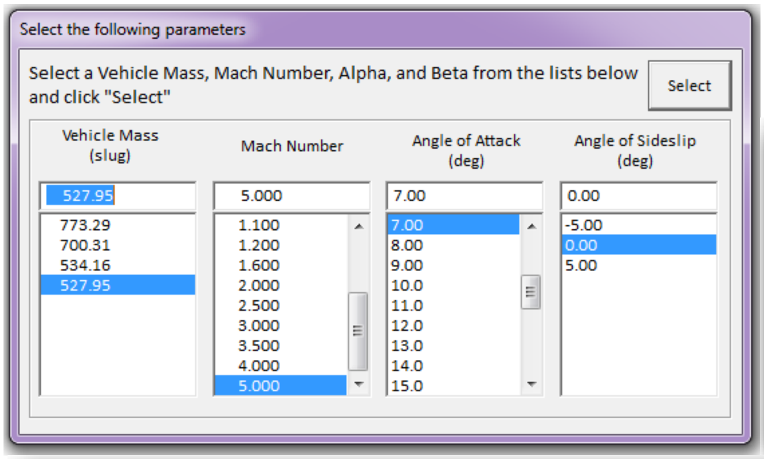
Controllability Analysis by Using Vector Diagrams

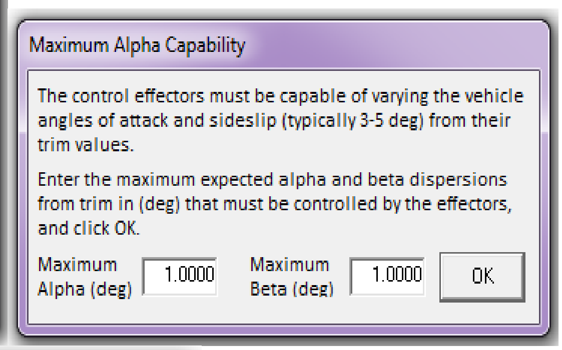
Vector diagrams are 2-dimensional diagrams used for analyzing the vehicle controllability at a specified flight condition. We compare the control authority of the aerosurfaces in two directions against the effect of wind-shear disturbance on the vehicle due to beta in the same two directions and determine if the vehicle has the capability to counteract the disturbance moments. Vector diagrams also analyze the orthogonality of the control system; compare the acceleration magnitudes of the controls against dispersions, and determine if the effectors are powerful enough and capable of counteracting the disturbance moments along the control directions. From the Trim menu select option-11, and then an arbitrary flight condition at t=800 sec, which is in the middle of the Nz-controlled trajectory, corresponding to Mach 10. The following vector diagram analysis corresponds to the selected flight condition. The aero disturbances are defined by the maximum α_{max} and β_{max} dispersions from trim which are set to ±1°. A 7x3 control surface combination matrix "KmixM10" was designed for this Mach 10 flight condition.

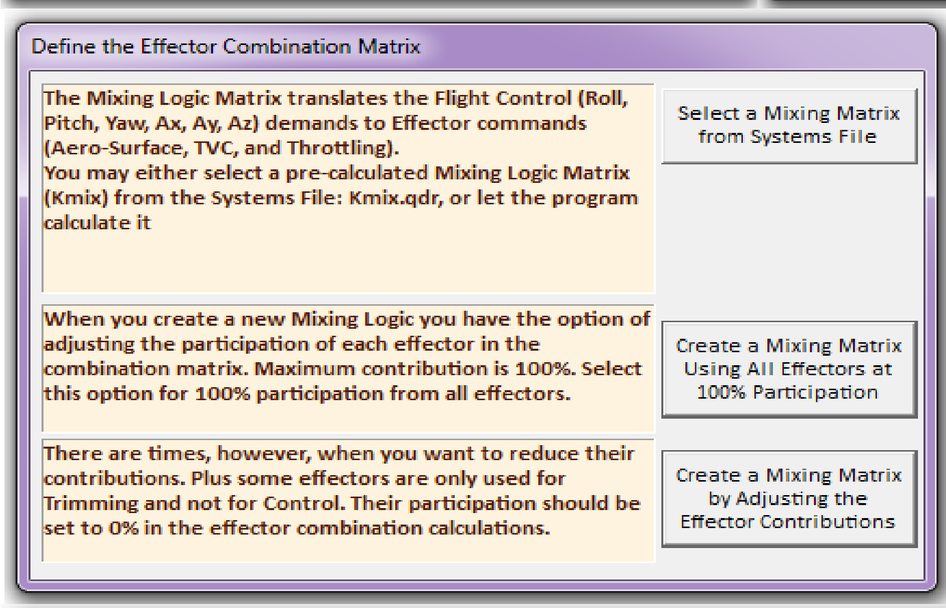


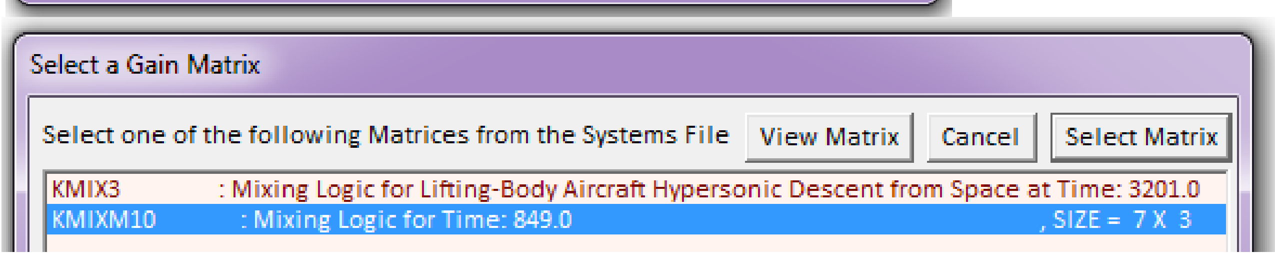


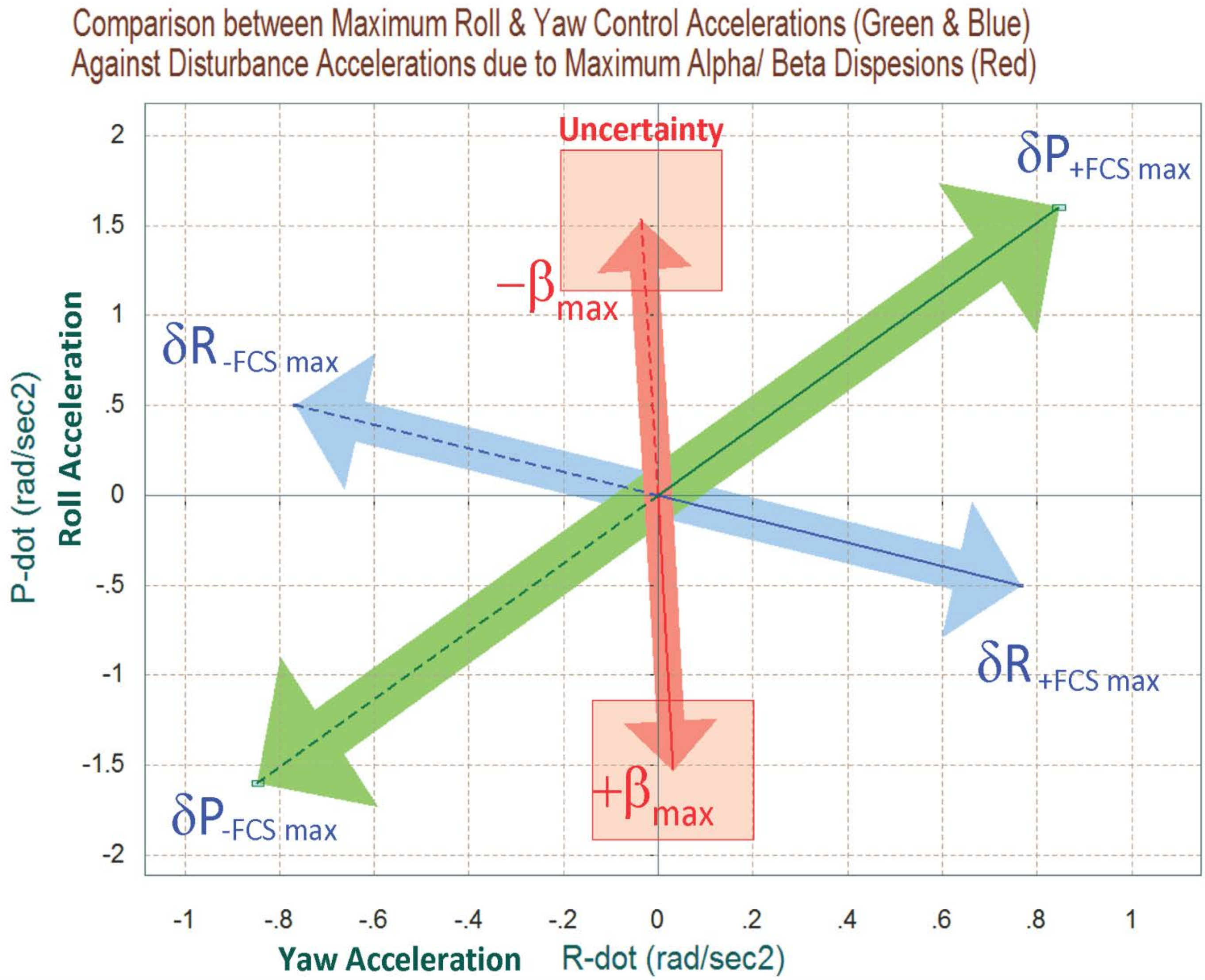
The following dialog consists of menus used for selecting the vehicle mass, Mach number, alpha, and beta. The default values that correspond to the selected flight time were selected by clicking on "*Select*". The wind-shear disturbances are defined by the maximum alpha and beta produced. In the following dialog enter the maximum disturbance angles (α_{max} and β_{max})=1°, and then select the (7x3) control surface combination matrix "KmixM10" from file Kmix.Qdr, as shown.



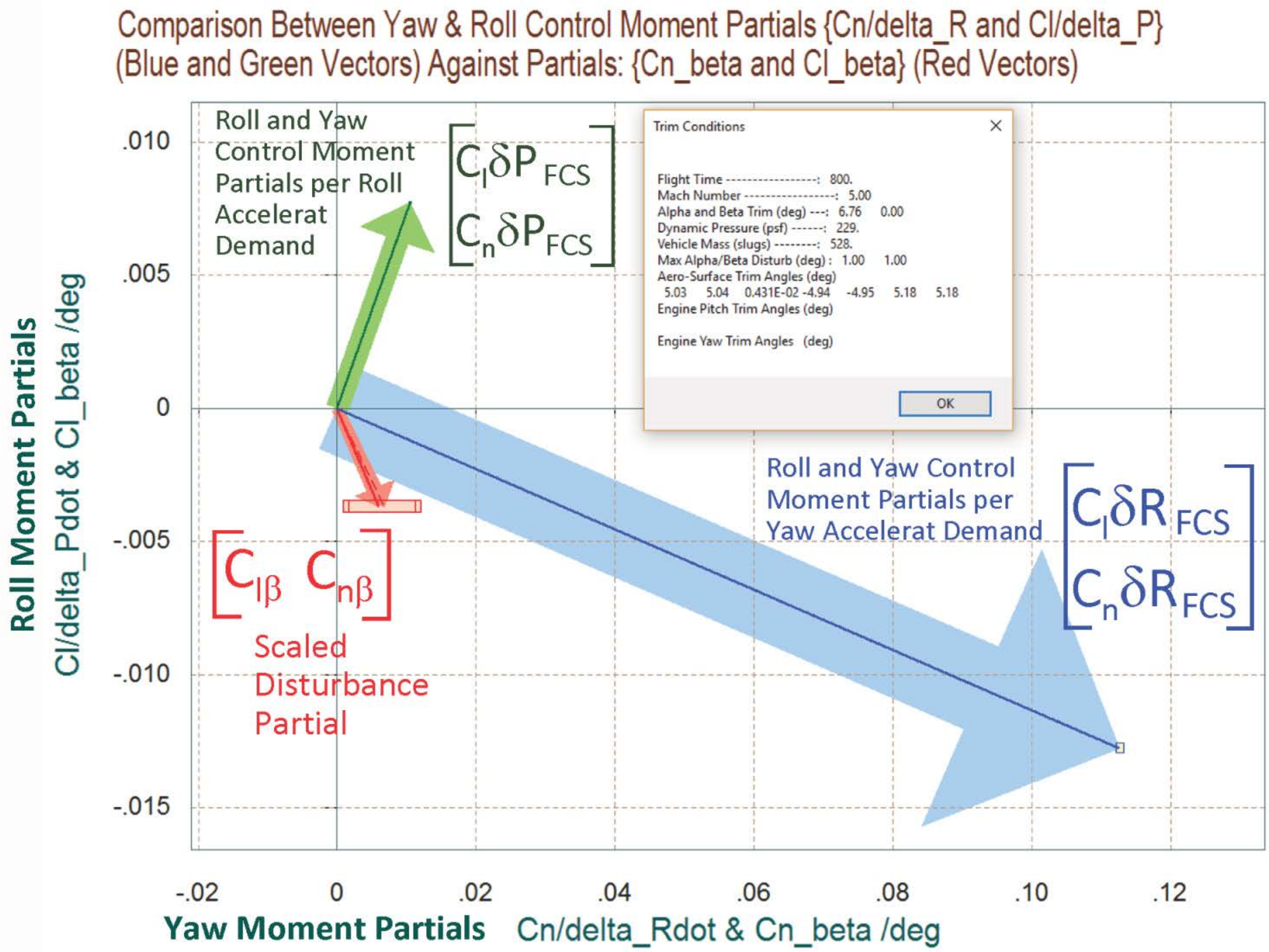






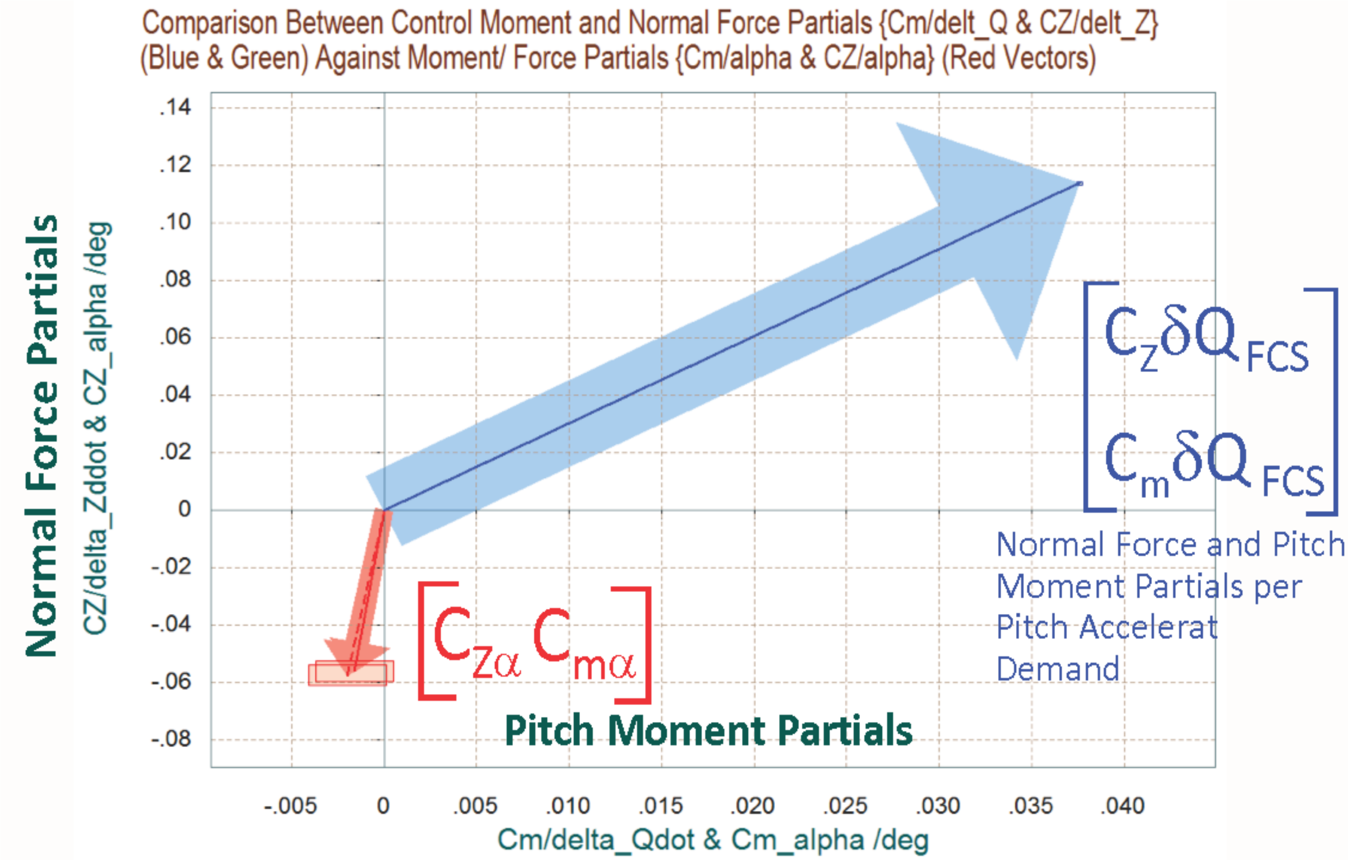


The above vector diagram shows the roll and yaw accelerations produced when the roll and yaw FCS demands are maximized, that is, before saturating at least one of the aerosurfaces. The solid blue vector is the acceleration produced by max positive yaw FCS demand $\delta R_{+FCSMax}$ and the dashed blue vector in the opposite direction is the acceleration from a max negative yaw demand $\delta R_{-FCSMax}$. Similarly, the green vectors pointing in opposite directions correspond to the ±roll FCS demands $\delta P_{\pm FCSMax}$. The solid red vector pointing downwards represents the roll and yaw accelerations produced by a positive dispersion β_{max}, and the dashed red vector in the opposite direction is the acceleration produced by $-\beta_{max}$. The disturbance due to β variations is mostly in roll caused by the dihedral of the lifting-body airframe. The red rectangles at the tips of the arrows signify the amount of uncertainty in roll and yaw accelerations. The uncertainties are calculated from file "*LiftBody.Unce*".

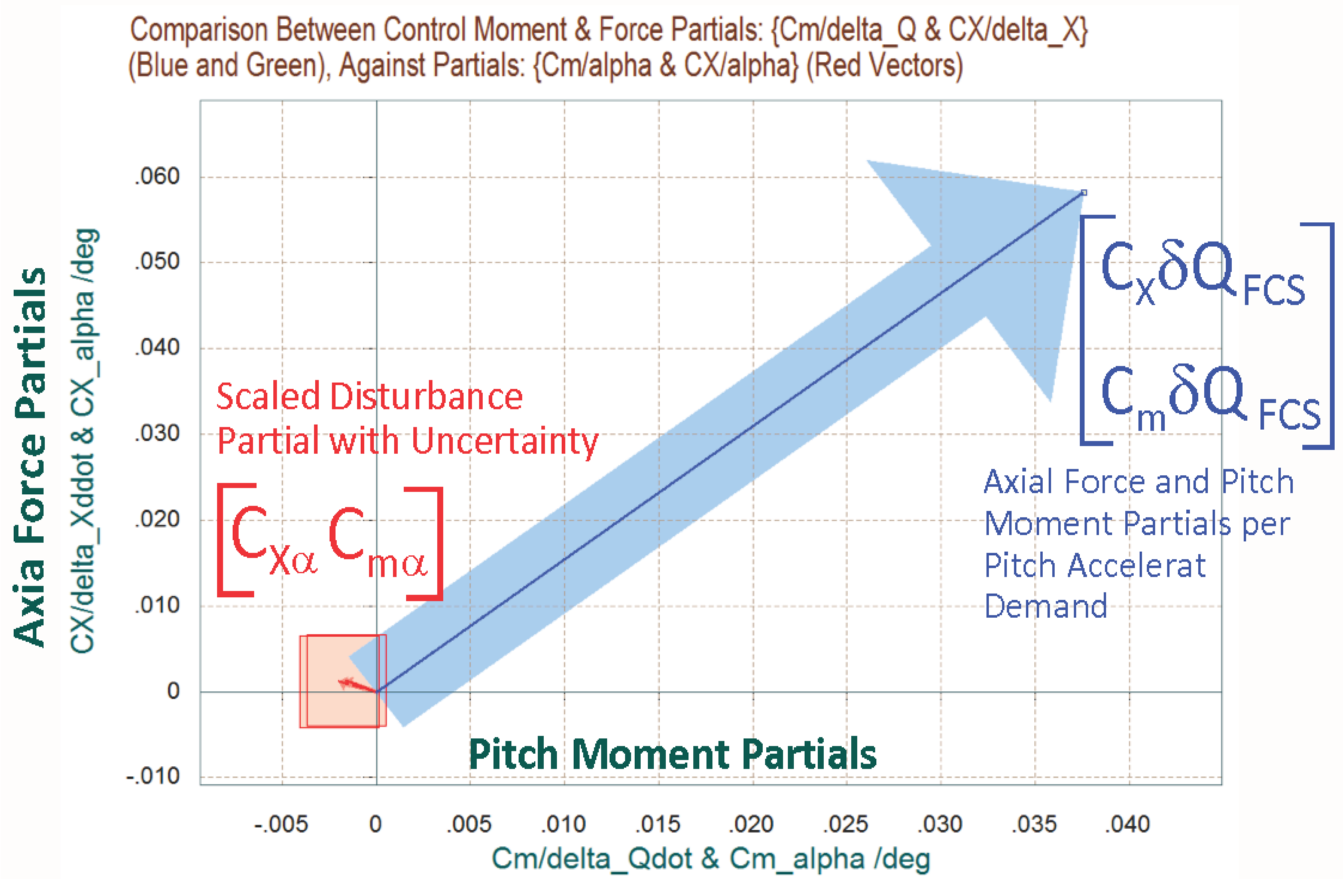


The above figure is a moment partials vector diagram showing the variation in roll and yaw moments per acceleration demands in roll and yaw in (rad/sec^2). The blue vector represents the moments per yaw demand {ClδR, CnδR} and it is pointing in the yaw direction. The green vector is per roll demand {ClδP , CnδP} and it affects both directions. The red vectors pointing downward are the scaled {Cnβ, Clβ} partials. Notice that Clβ is negative due to the dihedral and it is bigger in magnitude than Cnβ. The red rectangle centered at the tip of the {Cnβ, Clβ} vector is due to the uncertainties in the two partials obtained from file "*LiftBody.Unce*".

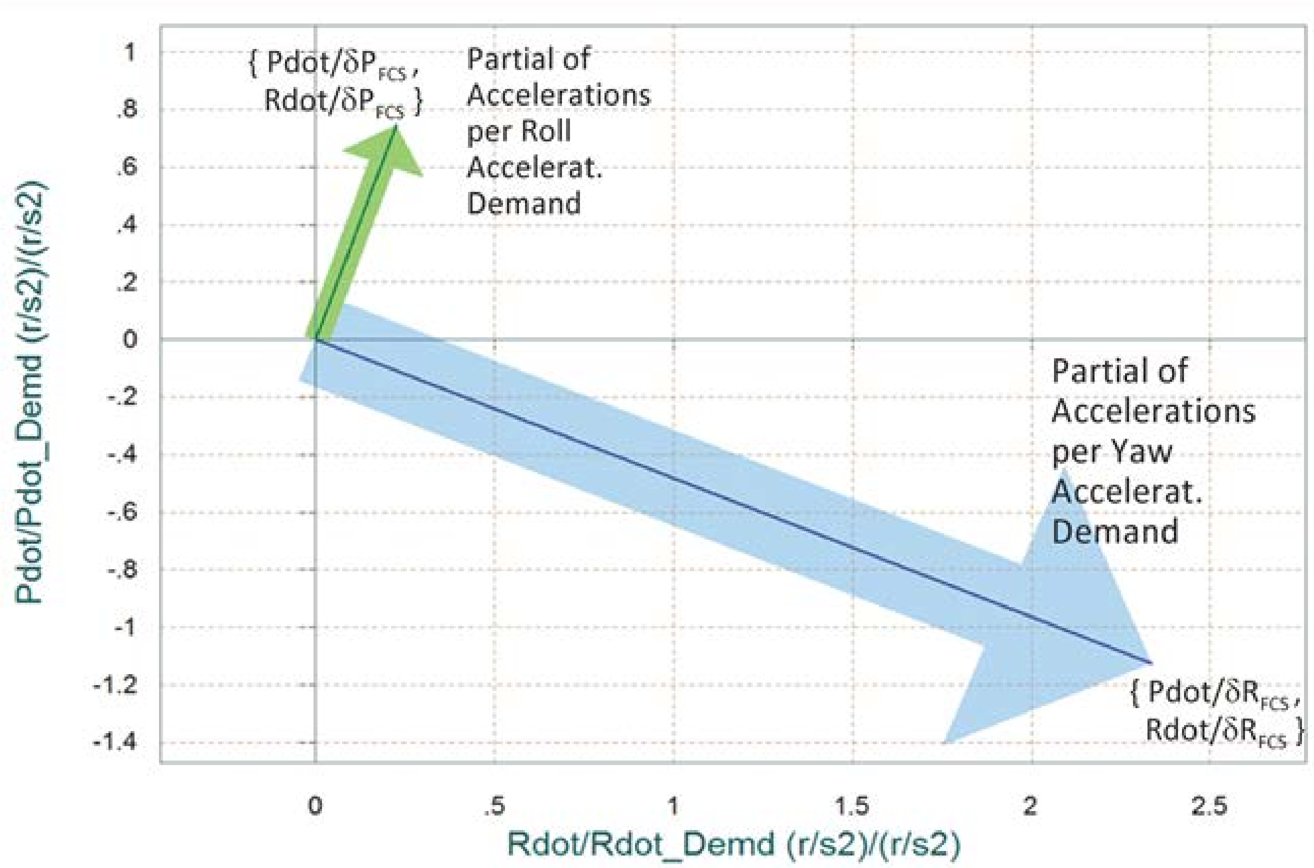
The partial diagrams in the next page can be interpreted as a 3-dimentional figure. They show the variations in the pitch moment, normal and axial forces per pitch acceleration demand {$C_X\delta Q_{FCS}$, $Cz\delta Q_{FCS}$, $Cm\delta Q_{FCS}$}. It shows that a pitch demand produces positive accelerations in all three directions: pitch, Z, and X. The red vectors are {$C_{X\alpha}$, $C_{Z\alpha}$, Cm_{α}} partials. They are two because they are calculated at the two extreme values of $\pm\beta_{max}$. Negative Cmα is indicative that the vehicle is stable at t=800 sec. The red disturbance vector partials aer scaled in order to be comparable with the blue control partials, as already described, and the control vectors are clearly more dominant in all directions.



Comparison Between Control Moment and Normal Force Partials {Cm/delt_Q & CZ/delt_Z}
(Blue & Green) Against Moment/ Force Partials {Cm/alpha & CZ/alpha} (Red Vectors)
Normal Force Partials
CZ/delta_Zddot & CZ_alpha /deg
.14
.12
.10
.08
.06
.04
.02
0
-.02
-.04
-.06
-.08
-.005
0
.005
.010
.015
.020
.025
.030
.035
.040
Cm/delta_Qdot & Cm_alpha /deg
Pitch Moment Partials
Normal Force and Pitch
Moment Partials per
Pitch Accelerat
Demand

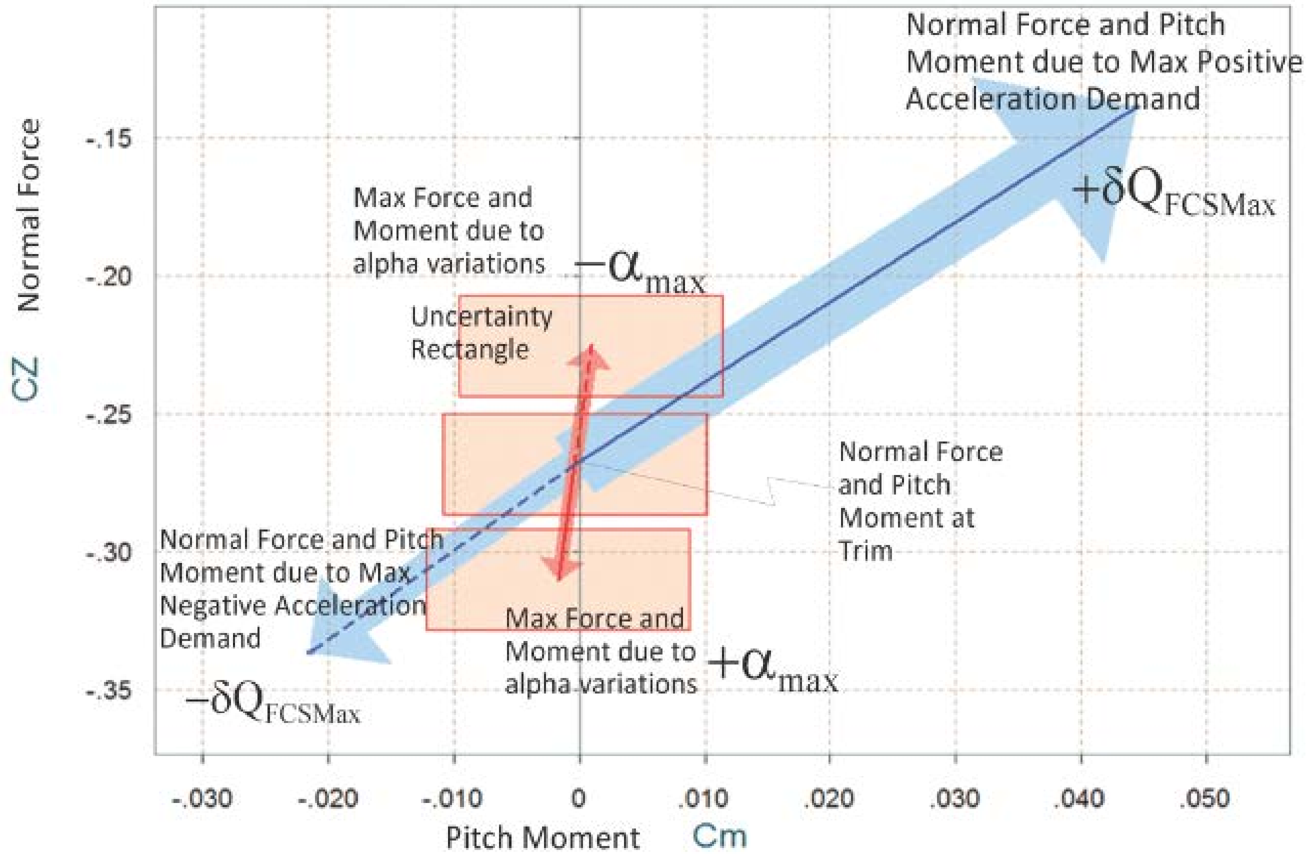


Comparison Between Control Moment & Force Partials: {Cm/delta_Q & CX/delta_X}
(Blue and Green), Against Partials: {Cm/alpha & CX/alpha} (Red Vectors)
Axia Force Partials
CX/delta_Xddot & CX_alpha /deg
.060
.050
.040
.030
.020
.010
0
-.010
-.005
0
.005
.010
.015
.020
.025
.030
.035
.040
Cm/delta_Qdot & Cm_alpha /deg
Scaled Disturbance
Partial with Uncertainty
Pitch Moment Partials
Axial Force and Pitch
Moment Partials per
Pitch Accelerat
Demand

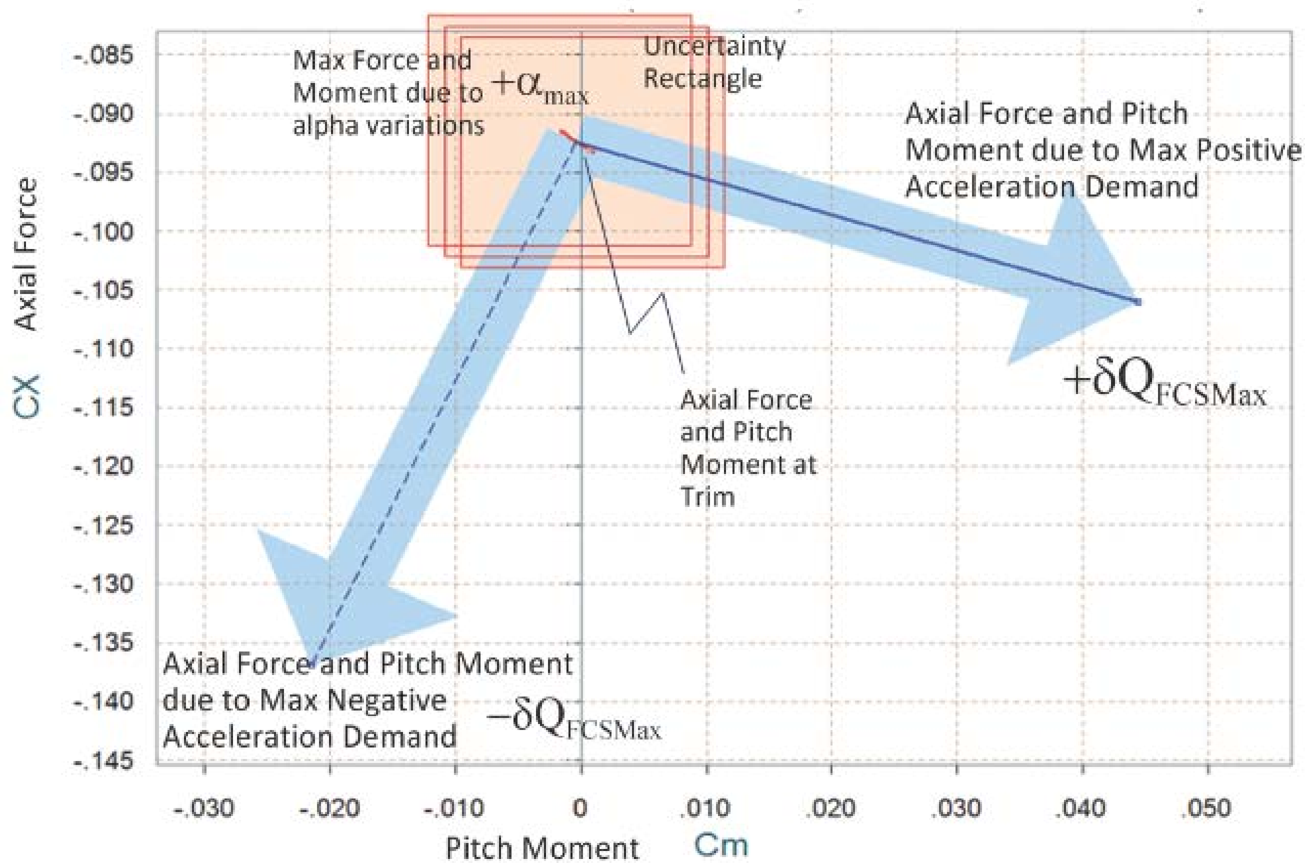


The figure above shows the partials of accelerations per acceleration demands in roll and yaw. The upward green vector pointing towards the roll direction is $\{\dot{P}/\delta P_{FCS}, \dot{R}/\delta P_{FCS}\}$, and the blue vector pointing towards yaw is $\{\dot{P}/\delta R_{FCS}, \dot{R}/\delta R_{FCS}\}$. The axis units are in (rad/sec^2)/(rad/sec^2). Ideally they should be unit vectors pointing in the demanded directions (green vector along the +vertical axis and blue vector along +horizontal), but this is not an absolute requirement because the flight control system compensates for that. They are, however, close to being orthogonal and this is sufficient for flight control design.

The next two figures show the pitch moment coefficient Cm plotted against the CZ and the CX force coefficients. The blue vectors show the maximum pitch moment and forces produced when the pitch control demand is maximized (just prior to saturation). The solid blue vector is the forces and moment produced by $\delta_{+QFCSMax}$, and the dashed blue vector is due to $\delta_{-QFCSMax}$. The red vectors are the forces and moments generated by the dispersions $\pm\alpha_{max}$ and $\pm\beta_{max}$ which are both ±1° in this case, increasing α causes the z-force to become more negative (up). The red rectangles represent the uncertainty in the moment and force coefficients. The vehicle is trimmed in pitch because Cm=0 when the control δQ_{FCS}=0. It is, however, accelerating in both -x and -z directions because C_X and C_Z are negative when δQ_{FCS}=0. Notice how either a positive or negative pitch control demand has a negative effect on C_X (drag increase). Notice also that a +pitch control demand reduces the magnitude of C_Z, reducing lift as the elevons rotate upwards to increase the pitching moment.



Normal Force and Pitch Moment due to Max Positive Acceleration Demand
$+\delta Q_{FCSMax}$
Max Force and Moment due to alpha variations
$-\alpha_{max}$
Uncertainty Rectangle
Normal Force and Pitch Moment at Trim
Normal Force and Pitch Moment due to Max Negative Acceleration Demand
Max Force and Moment due to alpha variations
$+\alpha_{max}$
$-\delta Q_{FCSMax}$
Normal Force
CZ
-.15
-.20
-.25
-.30
-.35
-.030
-.020
-.010
0
.010
.020
.030
.040
.050
Pitch Moment
Cm



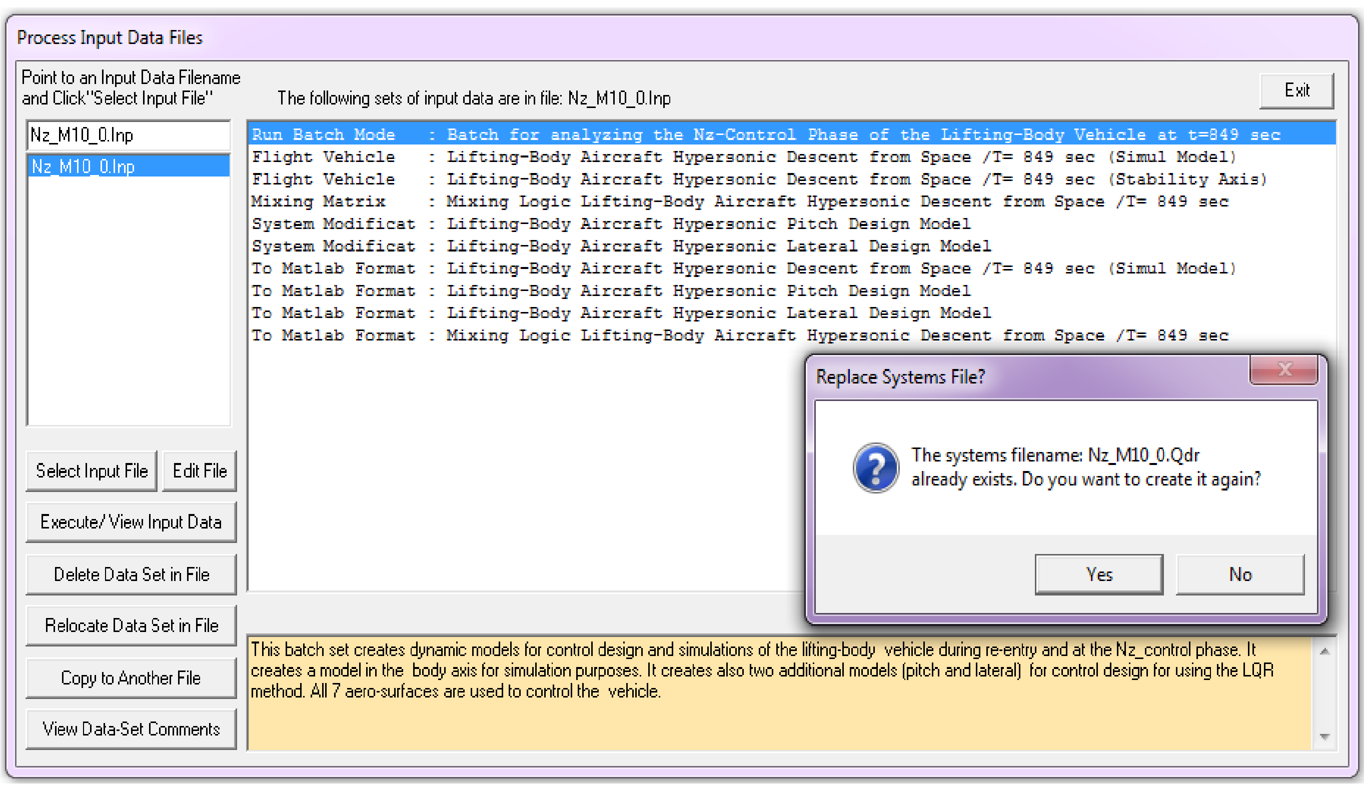
Max Force and Moment due to alpha variations
$+\alpha_{max}$
Uncertainty Rectangle
Axial Force and Pitch Moment due to Max Positive Acceleration Demand
$+\delta Q_{FCSMax}$
Axial Force and Pitch Moment at Trim
Axial Force and Pitch Moment due to Max Negative Acceleration Demand
$-\delta Q_{FCSMax}$
Axial Force
CX
-.085
-.090
-.095
-.100
-.105
-.110
-.115
-.120
-.125
-.130
-.135
-.140
-.145
-.030
-.020
-.010
0
.010
.020
.030
.040
.050
Pitch Moment
Cm

Modeling, Control Design, and Stability Analysis

We will now create a dynamic model at a fixed flight condition, Mach 10, at t=849 (sec), in the Nz-controlled region. We will design control laws, analyze stability in the frequency domain, and simulate its performance in tracking the normal acceleration and phi commands. The process, systems and analysis are very similar to the previous Mach 27 case, so we will skip the details. The vehicle dynamic model is already generated at trajectory time t=849 (sec), which corresponds to Mach 10, and the input data file is in file "*Nz_M10_0.Inp*". The Matlab analysis is performed in folder "*C:\Flixan\Trim\Examples\Lifting-Body Aircraft\Reentry from Space\Mat_Anal\Mch_10*".

Processing the Input Data

The input data file "*Nz_M10_0.Inp*" will now be processed by Flixan as before. It creates a vehicle simulation model "*Lifting-Body Aircraft Hypersonic Descent from Space /T= 849 sec (Simul Model)*" in file "*vehicle_sim*", and the pitch and lateral stability axis design models "*Lifting-Body Aircraft Hypersonic Pitch Design Model*" and "*Lifting-Body Aircraft Hypersonic Lateral Design Model*" in files "*pitch_des.m*" and "*later_des.m*" respectively. It also generates a mixing logic matrix KmixM10a corresponding to this flight condition. A different matrix, however, will be used in the control analysis because it improves roll controllability (LCDP). To process this file, start Flixan and select the project directory containing the input data file. Then go to "*Edit*", "*Manage Input Files*" and "*Process/ Edit Input Data*". When the following dialog appears, select the input data file "*Nz_M10.Inp*" form the left menu and click on "*Select Input File*".



The menu on the right shows 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 titled "*Batch for analyzing the Nz-Control Phase of the Lifting-Body Vehicle at t=849 sec*", and click on "*Execute/ View Input Data*". Flixan will process the input file and save the systems and matrices in file "*Nz_M10*.Qdr". It will also create the matrices and system functions for Matlab analysis.

LQR Control Design

The file "init.m", which is similar to the Mach 27 case, loads the simulation and design systems and the surface mixing matrix into Matlab and performs the pitch and lateral LQR designs.

Pitch Design

The pitch Nz-control design is very similar to the α-control in the Mach 27 case. The {α & α-integral} state-feedback, however, is replaced with {Nz & Nz-integral} feedback respectively. This is not hard to do because for this particular flight condition there is an almost proportional relationship between α and Nz. The pitch design model "*Lifting-Body Aircraft Hypersonic Pitch Design Model*" from file "*pitch_des.m*" consisting of states: {θ, q, and α} is augmented (using Simulink file Pdes4xa.Mdl) to include also α-integral in the state-vector. The phugoid states (δh and δV) are not included in the design model. The state-feedback is a (1 x 4) gain matrix "Kq_M10_0.mat". It is generated using the LQR algorithm in Matlab. The Simulink model "*Sim_Pitch_Simple_a.Mdl*" is used for evaluating the preliminary LQR design. It includes the state-feedback matrix Kq and the mixing-logic matrix KmixM10. It calculates the system's response to 1° change command in alpha. The surface deflections are mainly in the two elevons, but the four body-flaps are also participating by a smaller amount. The Nz and Nz-integral feedback is implemented in the 6-dof simulation model.

Lateral Design

The lateral design is almost identical to the Mach 27 case. It uses the system "*Lifting-Body Aircraft Hypersonic Lateral Design Model*" from file "*later_des.m*" consisting of states: {p_s, r_s, and β}. The rates are about the velocity vector. It is augmented (using Simulink file Ldes5x.Mdl) to include also p_s-integral and β-integral in the state-vector. The stability axis model is preferred over the body axis model in the lateral LQR design because the vehicle is commanded to roll about the velocity vector. This minimizes the beta transients and the lateral loads during turns. The lateral dynamic model used in the LQR design also includes the turn-coordination terms. It assumes that turn-coordination is included in the vehicle model. The state-feedback matrix generated by the LQR algorithm using Matlab is a (2 x 5) gain matrix "Kpr_M10_0.mat". The Simulink model "*Sim_Later_Simple.Mdl*" is used for evaluating the lateral LQR design. It includes the state-feedback matrix Kpr and the mixing-logic matrix KmixM10.

Linear Simulation Model

The Matlab simulation model for the Mach 10 case is in file "*Simul_6dof.mdl*", shown in Figure 1.2.2. It is similar to the α-control case but instead of α-feedback it uses Nz-feedback instead. It is used for evaluating the coupled system's response to roll and Nz commands and to wind disturbances. The output rates in this model are body rates since the rate-gyro measurements are in body axes. The controller, however, was design based on the stability axis model and it expects to see roll and yaw rates about the velocity vector V_0. A body to stability axis transformation block is, therefore, included in the simulation to convert the (p & r) body rates to stability rates (p_{stab} & r_{stab}) which are required in the lateral LQR state-vector feedback. The linearized turn-coordination terms are also included in this block.

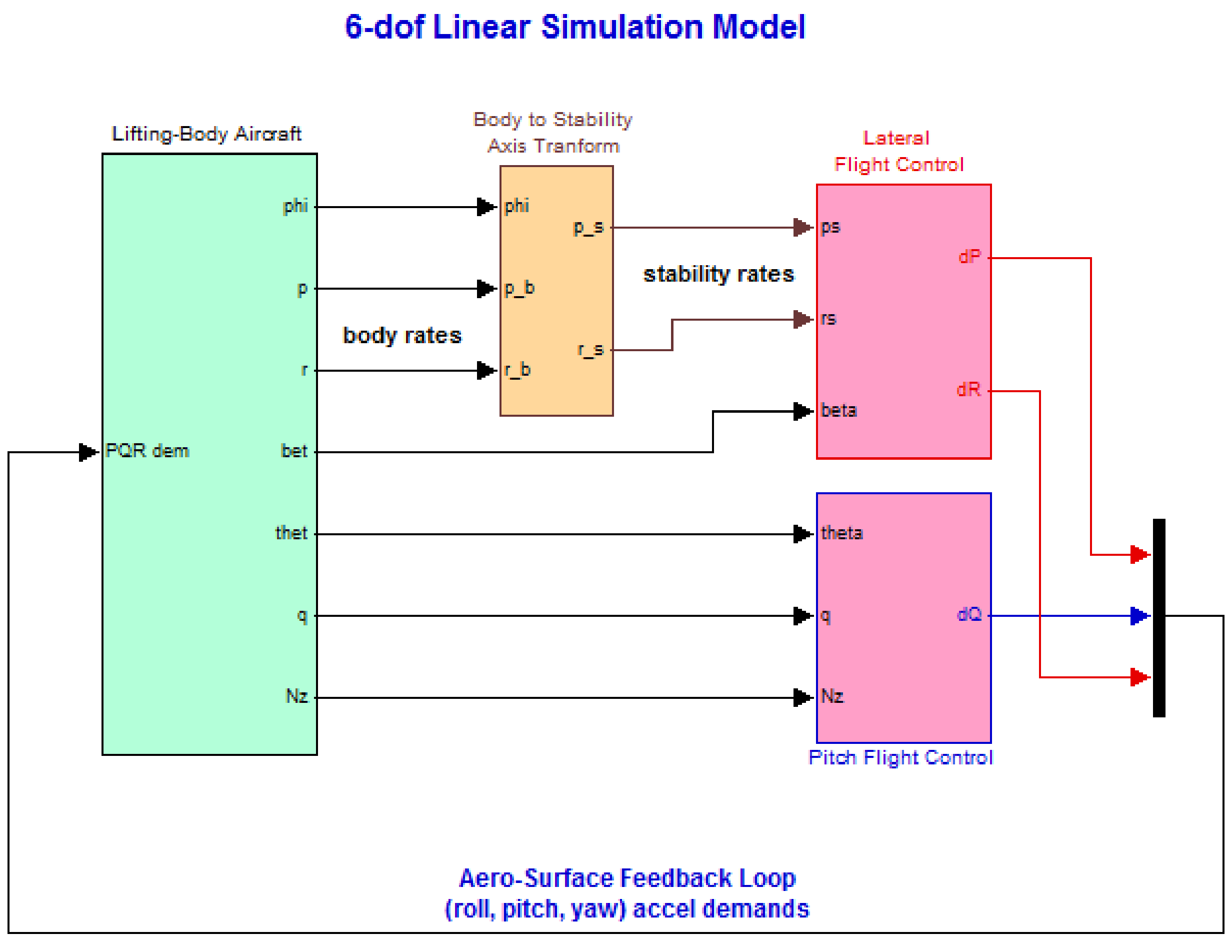


Figure 1.2.2a Simulation Model in File "Simul_6dof.Mdl"

Figure 1.2.2b shows the vehicle dynamics (green) block expanded. It uses the body-axis vehicle model "*Lifting-Body Aircraft Hypersonic Descent from Space /T= 849 sec (Simul Model)*" that was generated by Flixan and it is loaded into Matlab from file "*vehicle_sim.m*". The inputs to this block are: roll, pitch, and yaw acceleration demands from flight control which are converted into surface deflections by the surface mixing logic KmixM10. Low-pass filters are also used to model the actuator dynamics. 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 "Nz_M10.Inp", and it excites both pitch and yaw, perpendicular to the X-body and at 45° between +Y and +Z axes (typical).

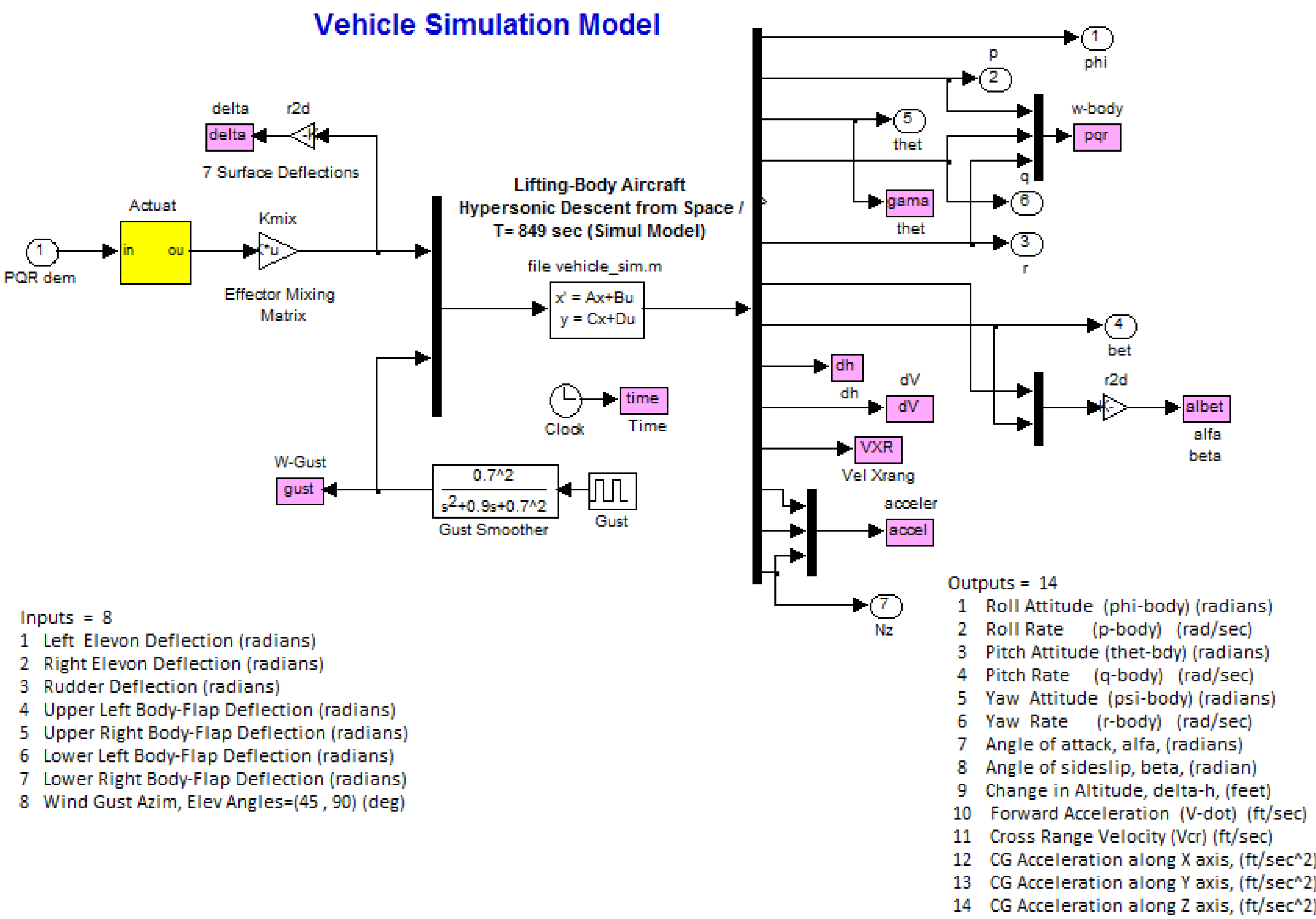


Figure 1.2.2b Vehicle Dynamics Block including the aero-surface Mixing Logic, Gust disturbance and Actuators

The pitch and lateral control laws are state-feedback gains as already described. The pitch controller consists of a (1x4), (θ, q, α, α-integral) state-feedback gain Kq. The vehicle is commanded to a certain Nz-command and the Nz-error is approximated to an α-error by a gain relationship "Nz2a". By using this simple modification the pitch control system now regulates the normal acceleration which is approximately -34 (ft/sec^2). An Nz-filter was also included. The lateral controller is a (2x5), (p_s, r_s, β, p_s-integr, β-integr) state-feedback gain Kpr. It is used to perform roll maneuvers by rolling the vehicle about the velocity vector (V_0).

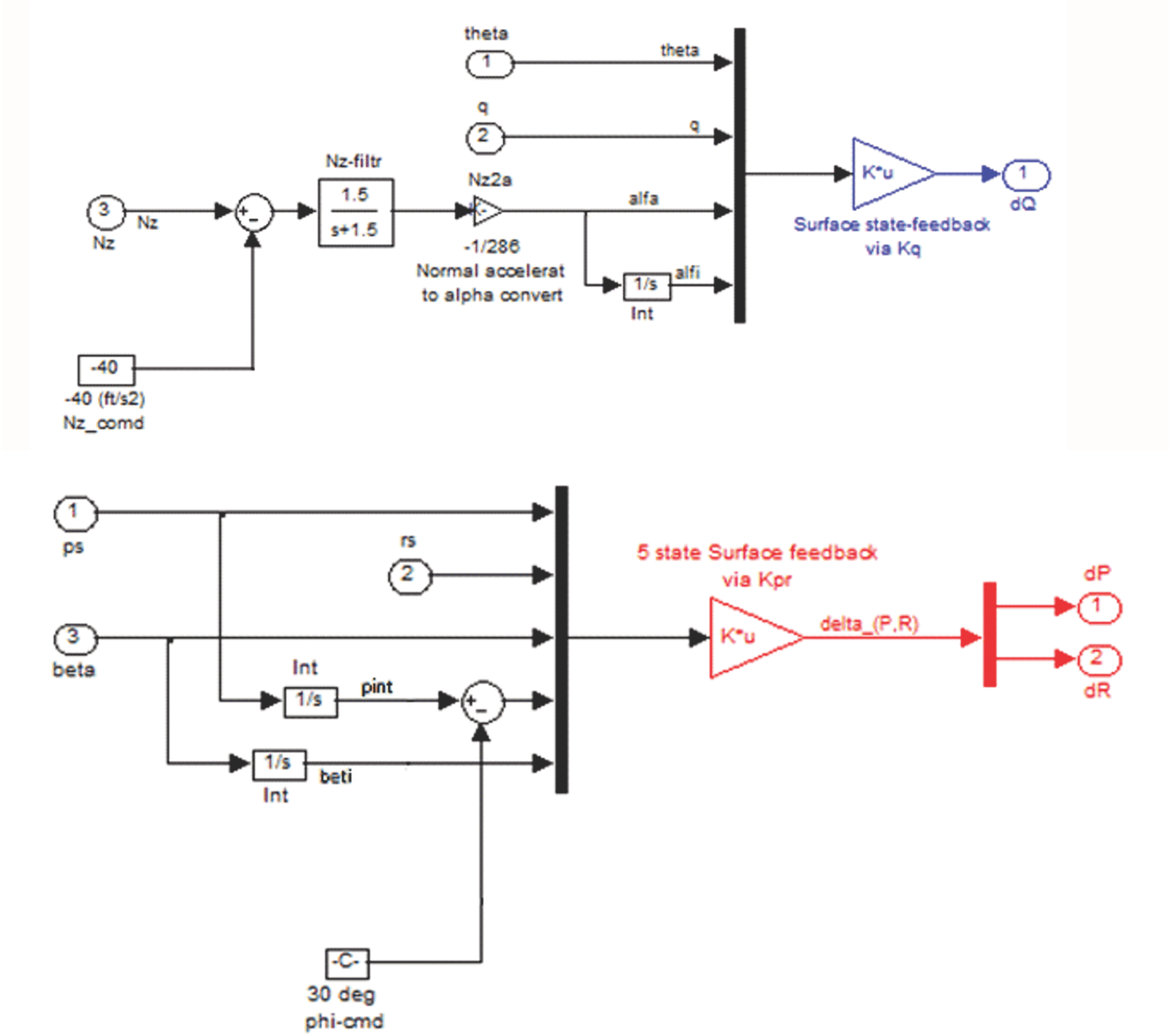


Figure 1.2.2c Pitch and Lateral State-Feedback Control Laws derived by the LQR method

Simulation Results

We will now use the linear simulation model for the Mach 10 case and command it to perform Nz and roll maneuvers together. The commands are: Nz_{cmd}=-40 (ft/sec^2), and ϕ_{cmd}=10°. Both variables respond as expected to the step commands. The vehicle rolls 10° about the velocity vector creating a very small sideslip transient in β.

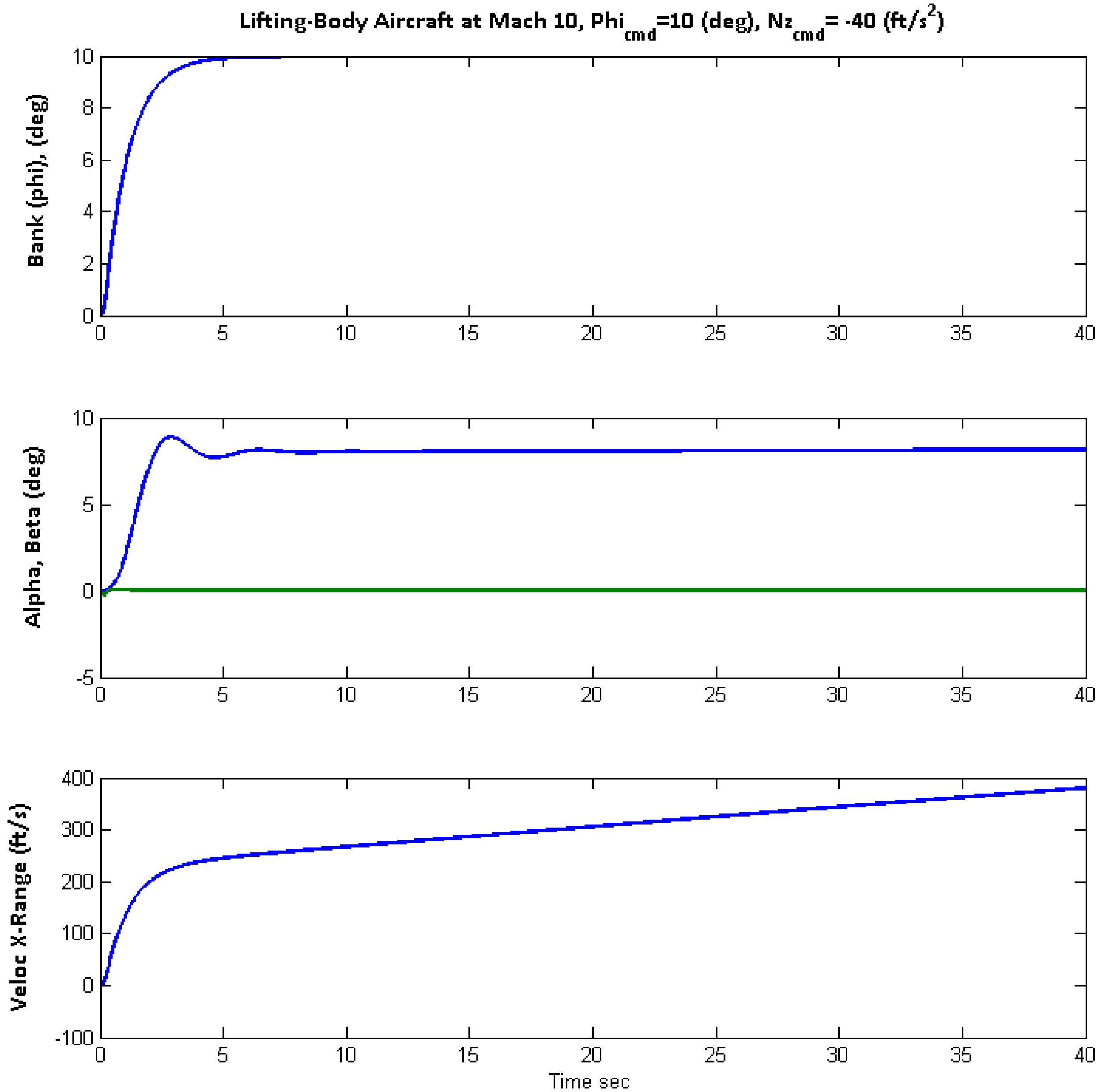
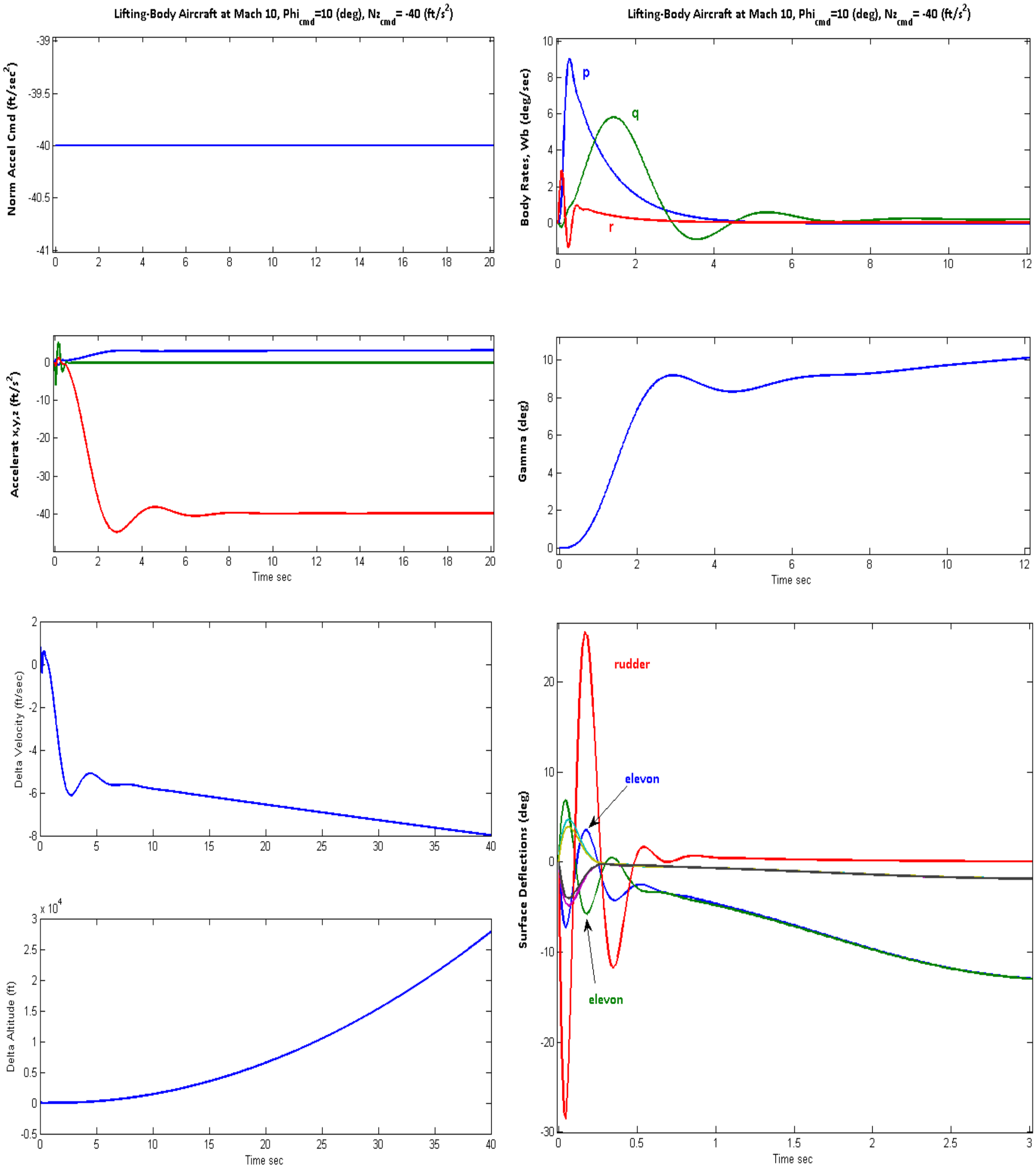


Figure 1.2.3 Vehicle response to simultaneously applied phi and Nz commands at Mach 10



Lifting-Body Aircraft at Mach 10, Phi_cmd=10 (deg), Nz_cmd= -40 (ft/s^2)
Norm Accel Cmd (ft/sec^2)
Lifting-Body Aircraft at Mach 10, Phi_cmd=10 (deg), Nz_cmd= -40 (ft/s^2)
Body Rates, Wb (deg/sec)
p
q
r
Accelerat x,y,z (ft/s^2)
Time sec
Gamma (deg)
Time sec
Delta Velocity (ft/sec)
Delta Altitude (ft)
x 10^4
Time sec
Surface Deflections (deg)
rudder
elevon
elevon
Time sec

Stability Analysis

Figure 1.2.4 shows the Simulink model "*Stab_Anal.mdl*" used for analyzing the stability margins for the Mach 10 case. This model is similar to the simulation "*Simul_6dof.Mdl*" but it is configured for open-loop analysis. One loop is opened and the other two loops are closed (in the case shown below the roll loop is opened). The Matlab file "Frequ.m" uses this model to calculate the frequency response across the opened loop. The next two figures show the Nichols plots in the pitch and roll directions and the red lines are highlighting the phase and gain margins for the Mach 10 case.

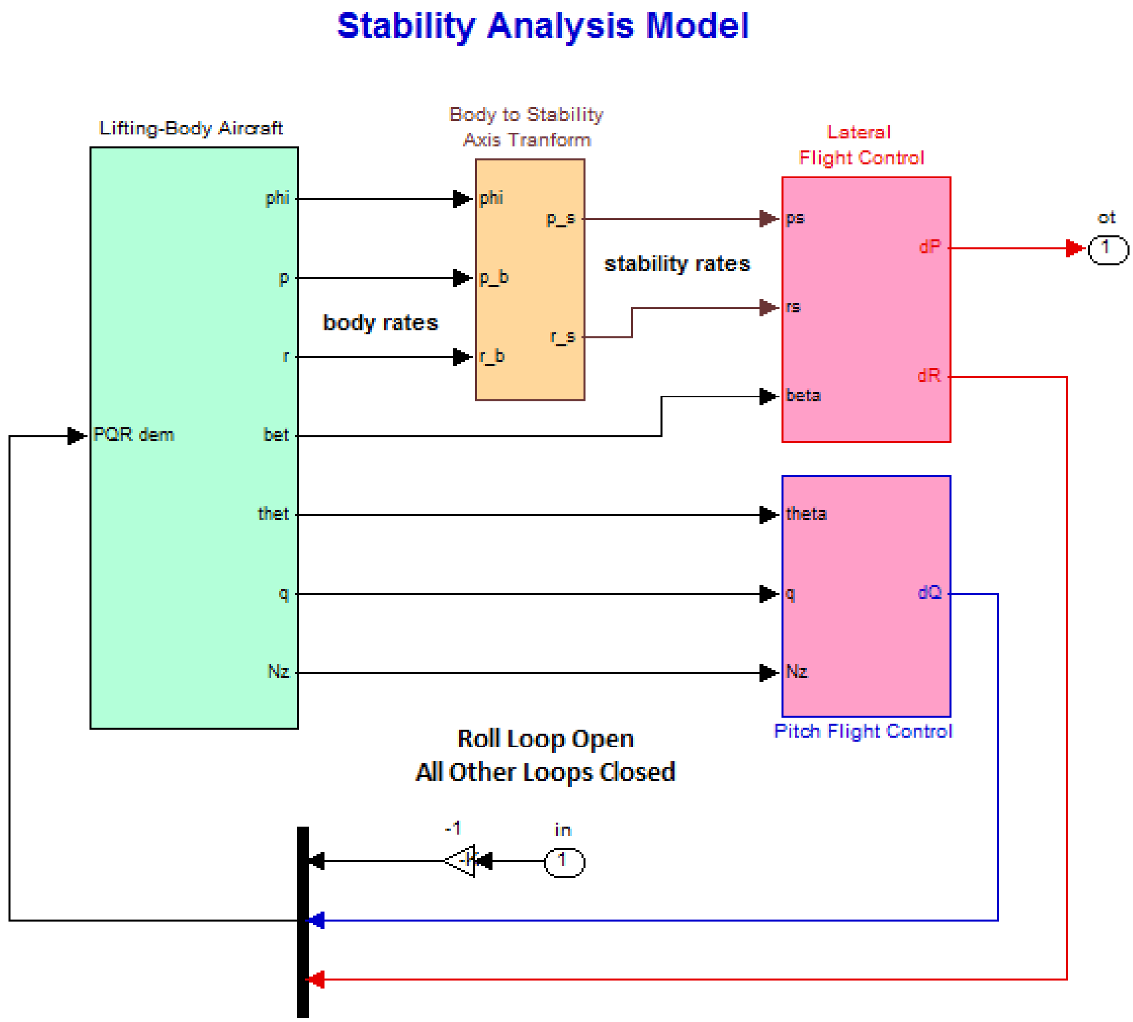
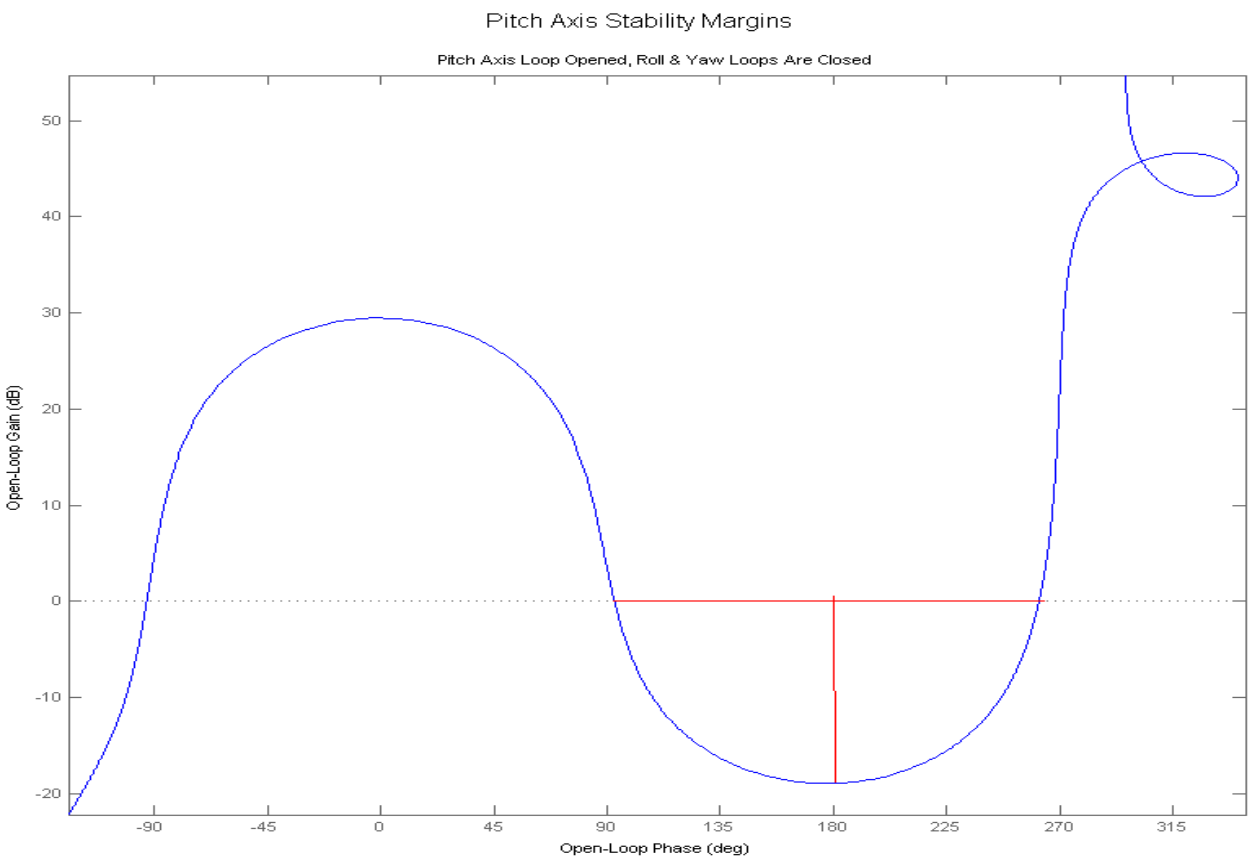
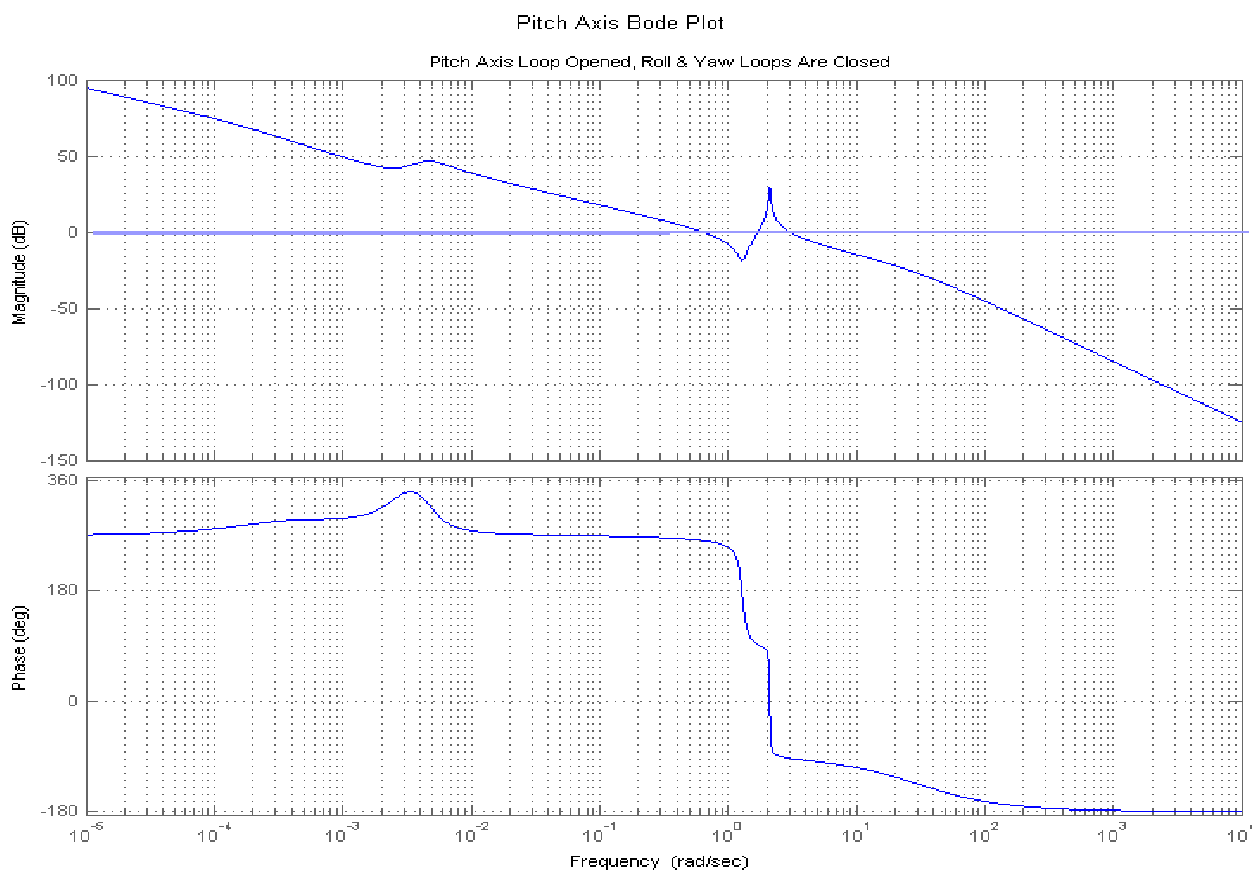
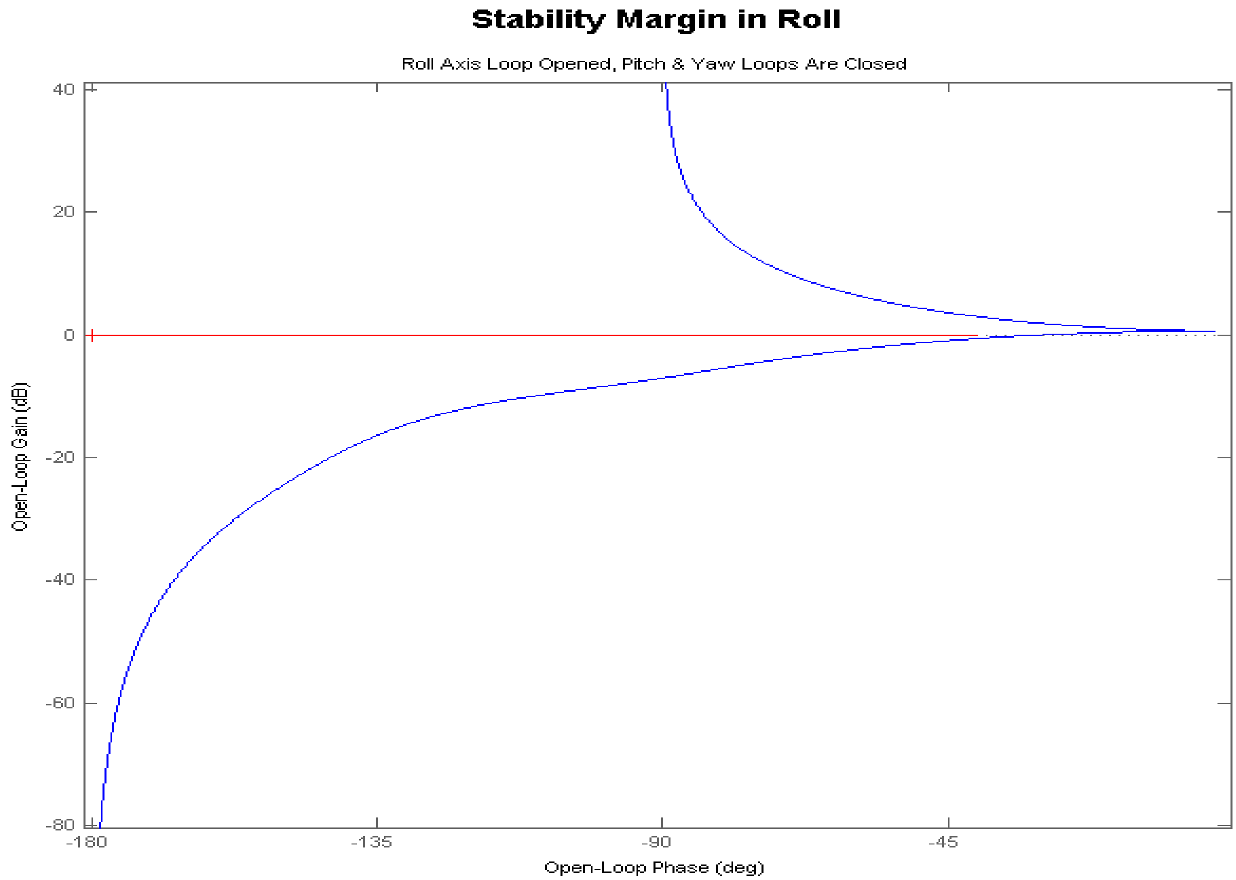
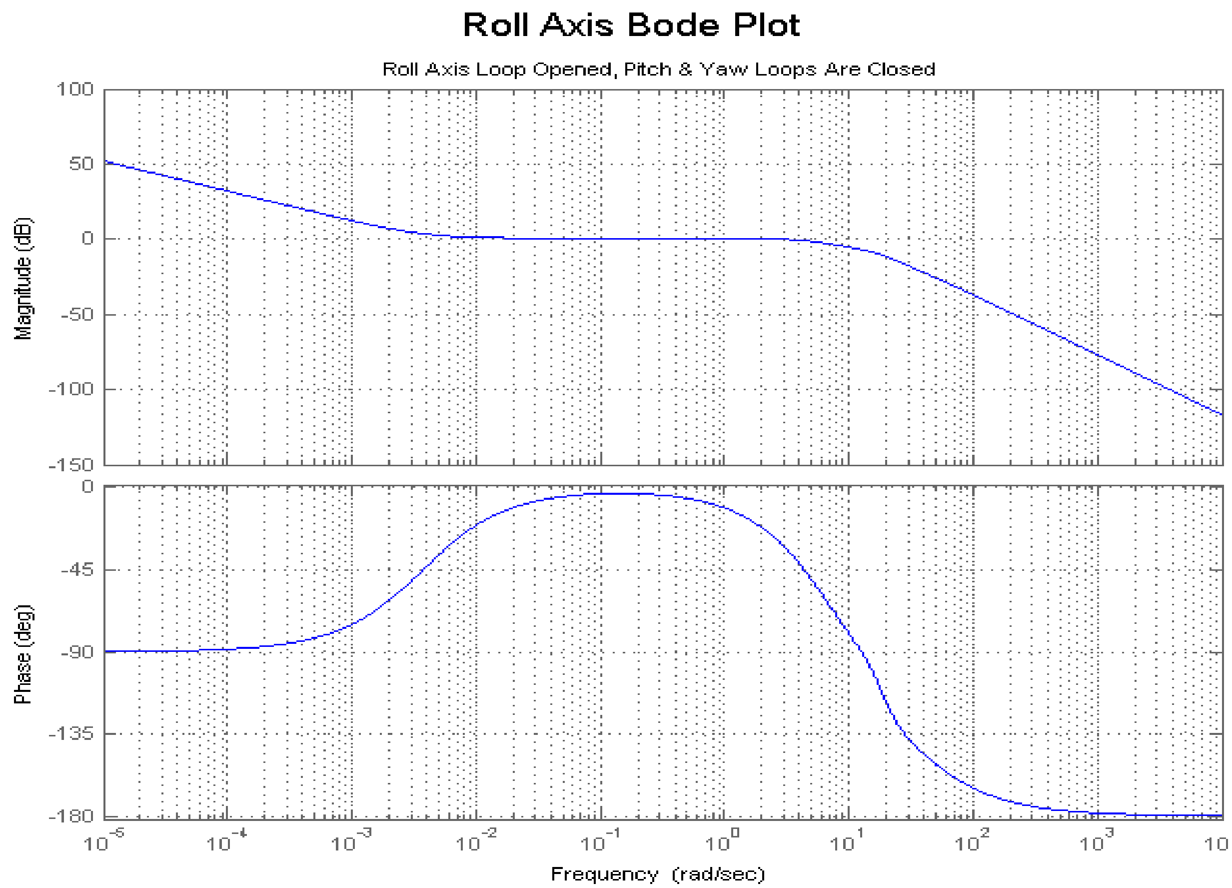


Figure 1.2.4 Stability analysis model "Stab_Anal.mdl" used for frequency response analysis


Pitch Axis Stability Margins
Pitch Axis Loop Opened, Roll & Yaw Loops Are Closed
Open-Loop Gain (dB)
50
40
30
20
10
0
-10
-20
-90
-45
0
45
90
135
180
225
270
315
Open-Loop Phase (deg)

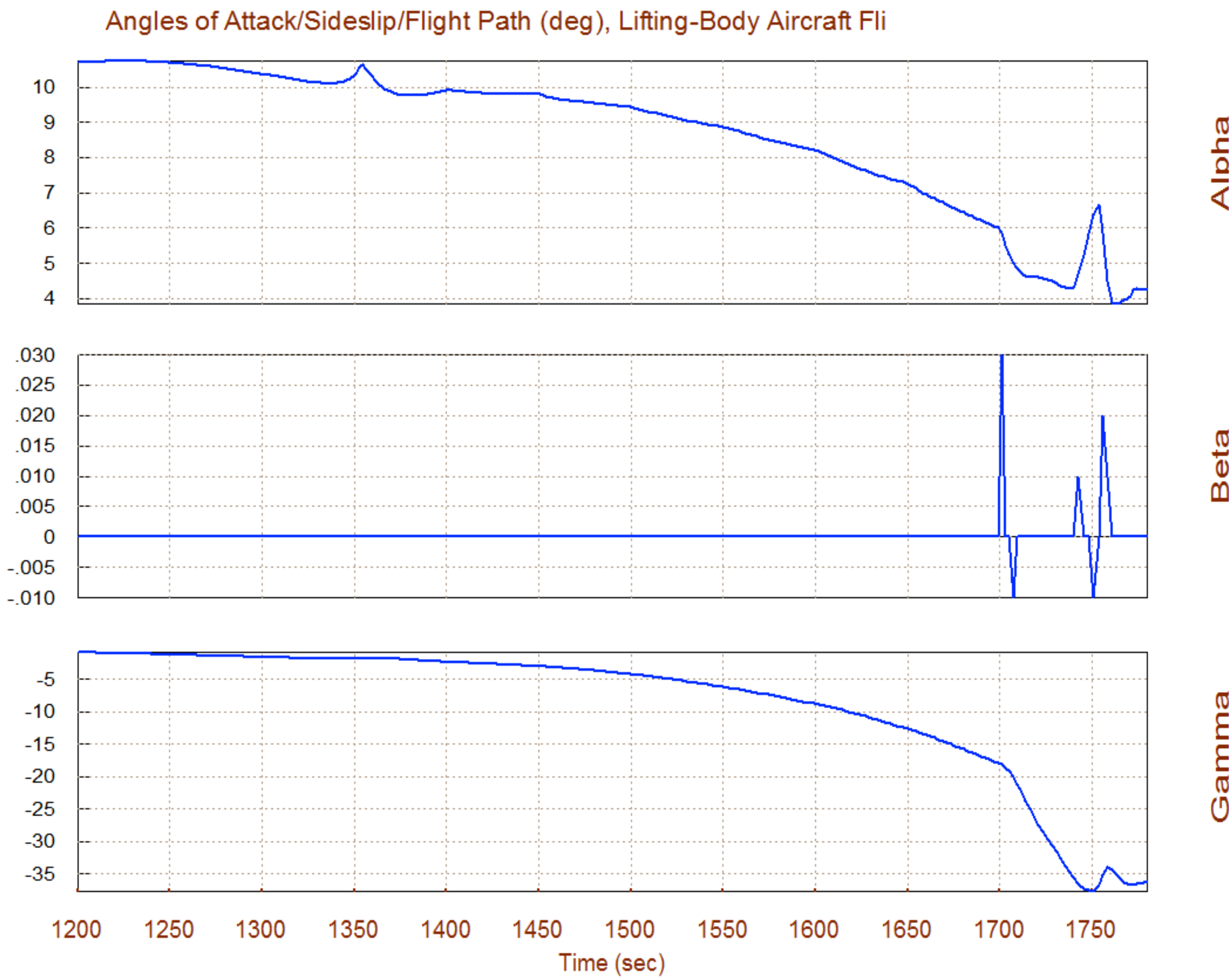

Pitch Axis Bode Plot
Pitch Axis Loop Opened, Roll & Yaw Loops Are Closed
Magnitude (dB)
100
50
0
-50
-100
-150
Phase (deg)
360
180
0
-180
Frequency (rad/sec)

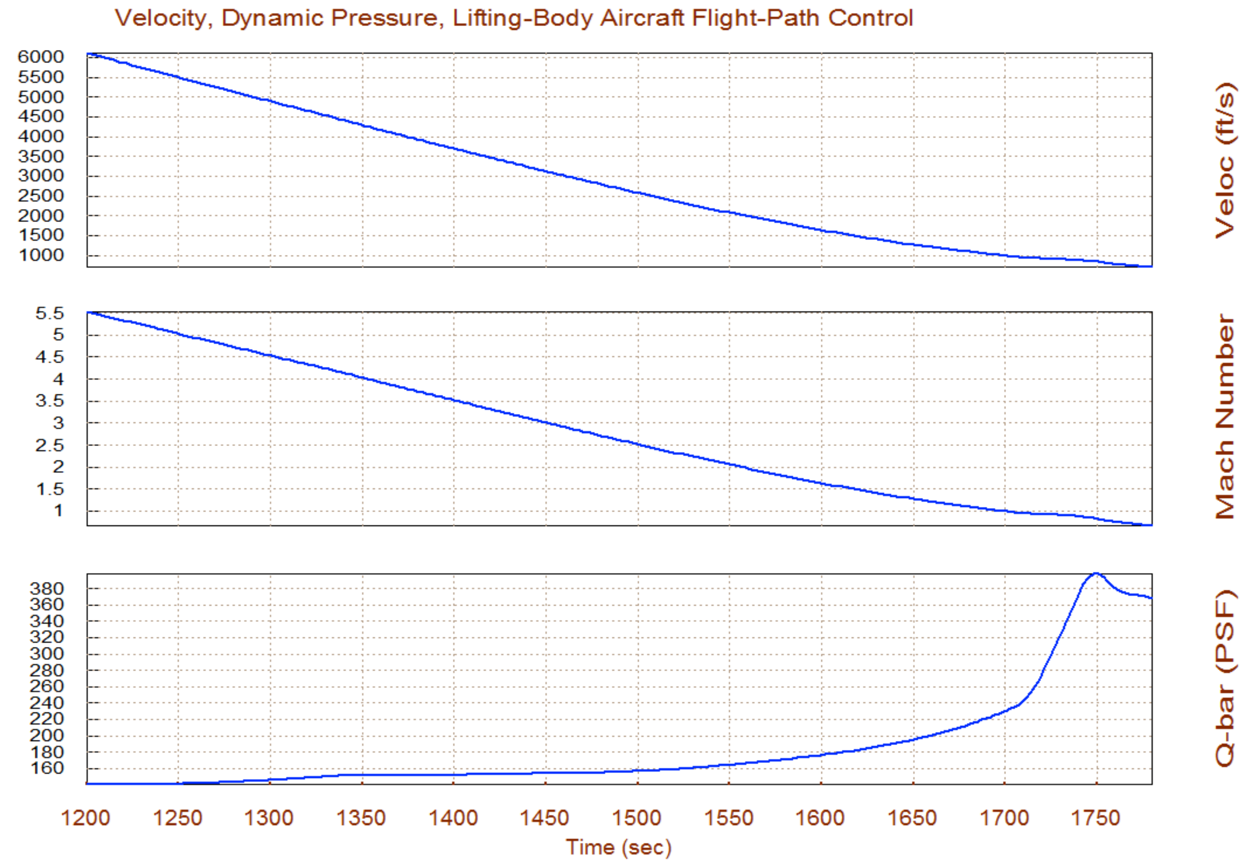

Stability Margin in Roll
Roll Axis Loop Opened, Pitch & Yaw Loops Are Closed
Open-Loop Gain (dB)
40
20
0
-20
-40
-60
-80
-180
-135
-90
-45
Open-Loop Phase (deg)

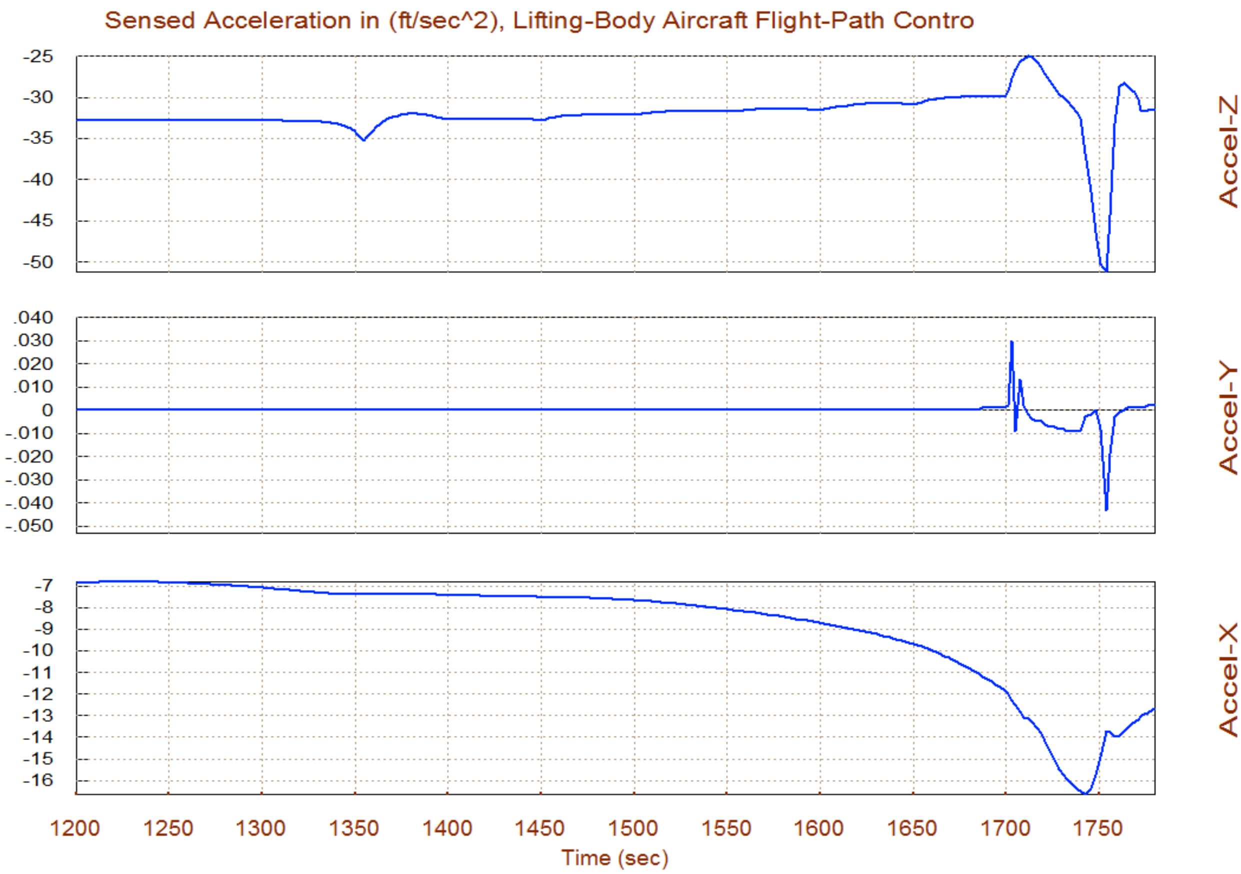

Roll Axis Bode Plot
Roll Axis Loop Opened, Pitch & Yaw Loops Are Closed
Magnitude (dB)
100
50
0
-50
-100
-150
Phase (deg)
0
-45
-90
-135
-180
10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4}
Frequency (rad/sec)

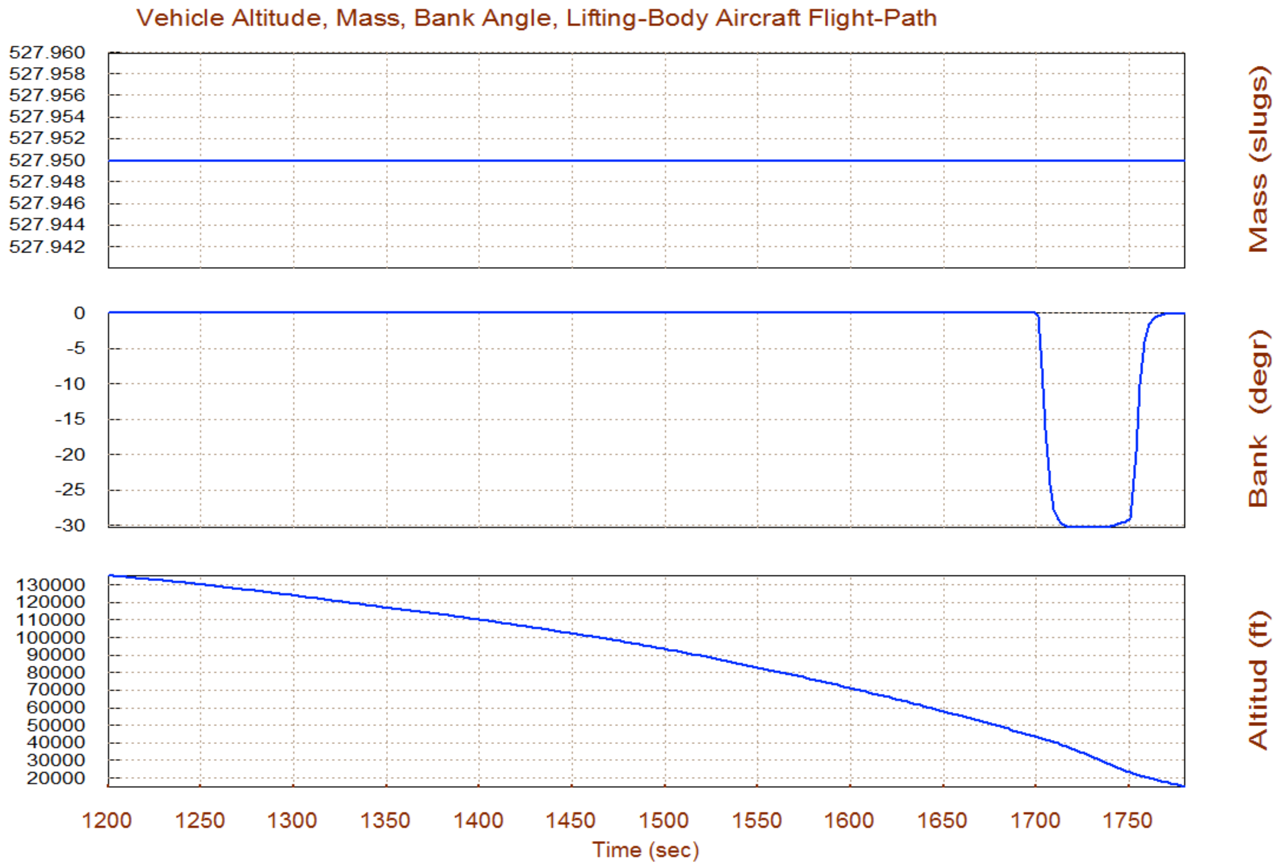
1.3 Flight-Path Angle Control Mode

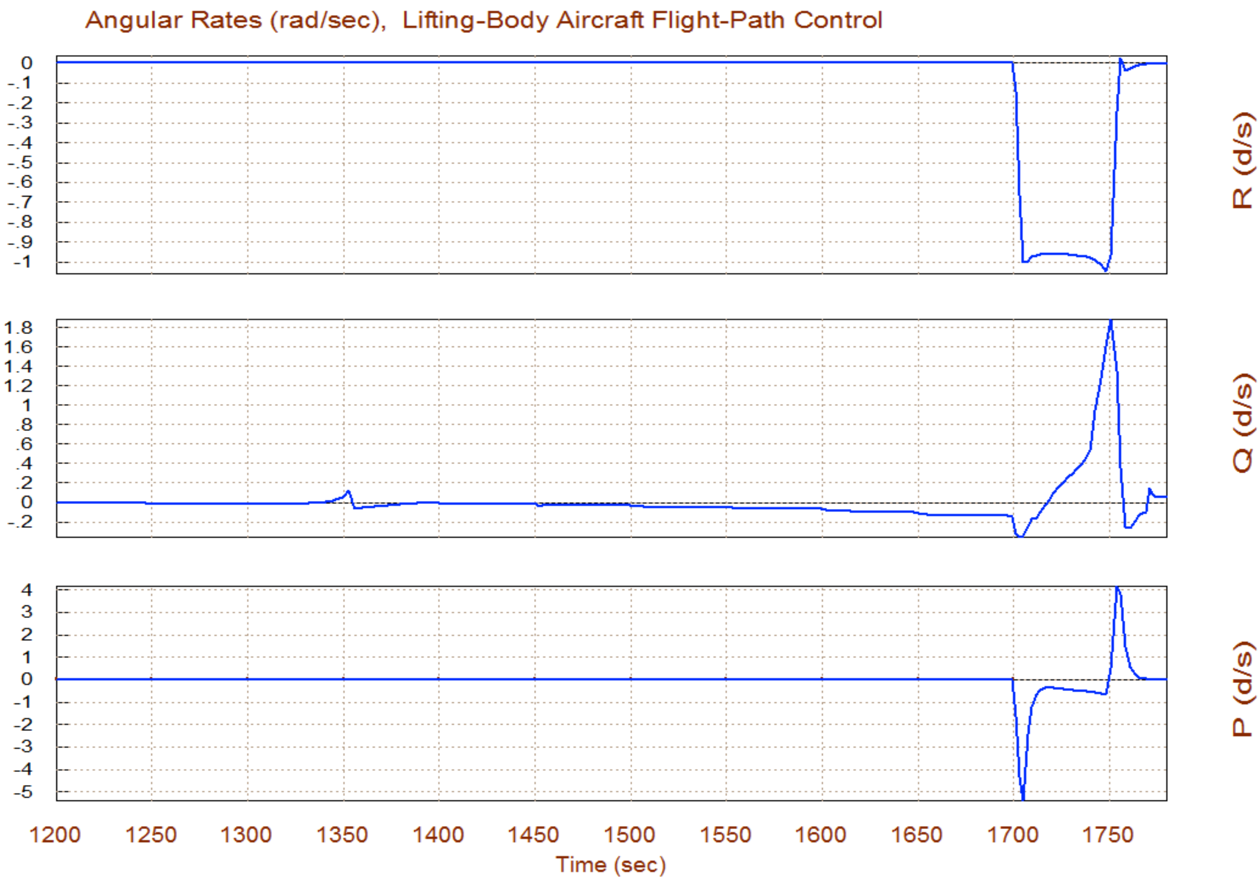
From the Nz-control mode the flight control system gradually transitions, in order to avoid transients, to the flight-path γ control mode. Direct γ-control is commanded by the closed-loop guidance system which calculates the required flight-path angle for controlling the vehicle descent rate, as a function of range, altitude, and speed. Guidance, however, is beyond the scope of this example. We will design a flight control system that receives open-loop guidance commands from a table. The files for the gamma-control section of the trajectory are located in: "*C:\Flixan\Trim\Examples\Lifting-Body Aircraft\Reentry from Space\Trim_Anal\Gamma_Control*". The trajectory is in file "*Gamma-Cntl.Traj*". The surface mixing matrix "KmixM2" has already been calculated and saved in file "*Kmix.Qdr*". The remaining files are the same as in the α-control section. The following figures show some of the trajectory parameters in the γ-control region, between Mach (5 to 0.9). The flight-path angle drops significantly towards the end of this phase, at t=1700, in order to gain sufficient speed after the vehicle performs a 30° roll maneuver to align its direction with the runway. Then in the next section it performs the pitch-up flare and lands. The dynamic pressure increases significantly in this final period as it approaches for landing, below Mach 1 at 20,000 (feet) altitude.




Velocity, Dynamic Pressure, Lifting-Body Aircraft Flight-Path Control
Veloc (ft/s)
Mach Number
Q-bar (PSF)
Time (sec)


Sensed Acceleration in (ft/sec^2), Lifting-Body Aircraft Flight-Path Contro
Accel-Z
Accel-Y
Accel-X
Time (sec)

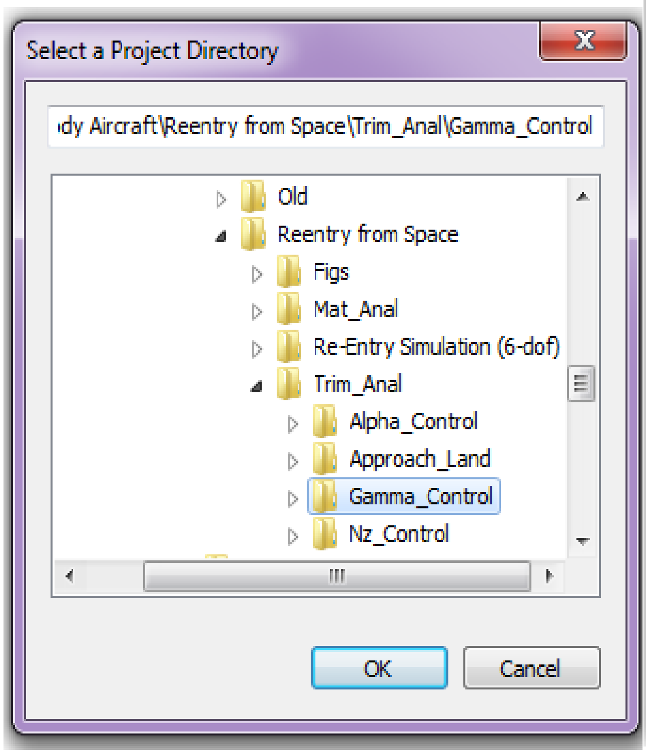

Vehicle Altitude, Mass, Bank Angle, Lifting-Body Aircraft Flight-Path
527.960
527.958
527.956
527.954
527.952
527.950
527.948
527.946
527.944
527.942
Mass (slugs)
0
-5
-10
-15
-20
-25
-30
Bank (degr)
130000
120000
110000
100000
90000
80000
70000
60000
50000
40000
30000
20000
Altitud (ft)
1200 1250 1300 1350 1400 1450 1500 1550 1600 1650 1700 1750
Time (sec)

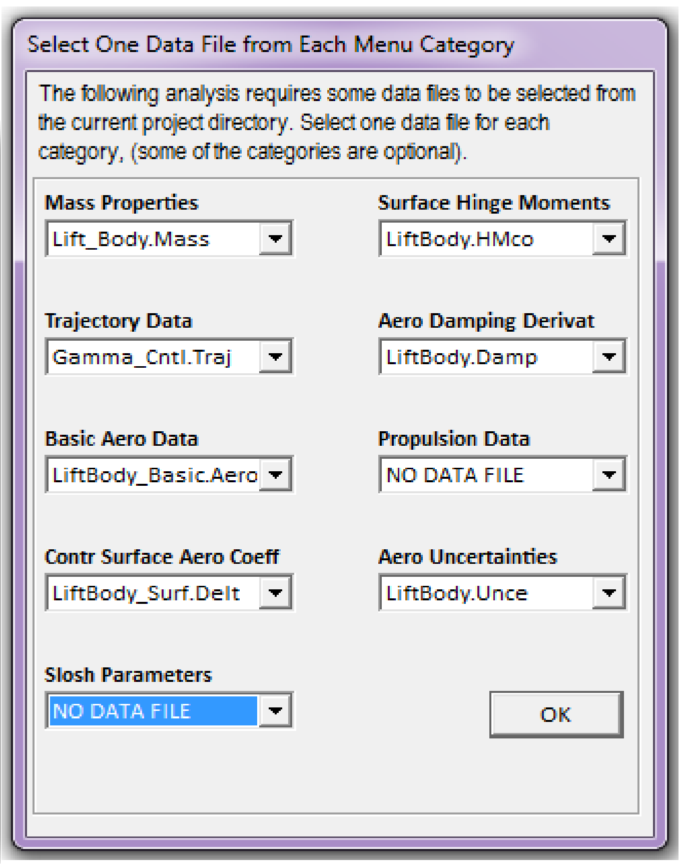

Angular Rates (rad/sec), Lifting-Body Aircraft Flight-Path Control
0
-.1
-.2
-.3
-.4
-.5
-.6
-.7
-.8
-.9
-1
R (d/s)
1.8
1.6
1.4
1.2
1
.8
.6
.4
.2
0
-.2
Q (d/s)
4
3
2
1
0
-1
-2
-3
-4
-5
P (d/s)
1200 1250 1300 1350 1400 1450 1500 1550 1600 1650 1700 1750
Time (sec)

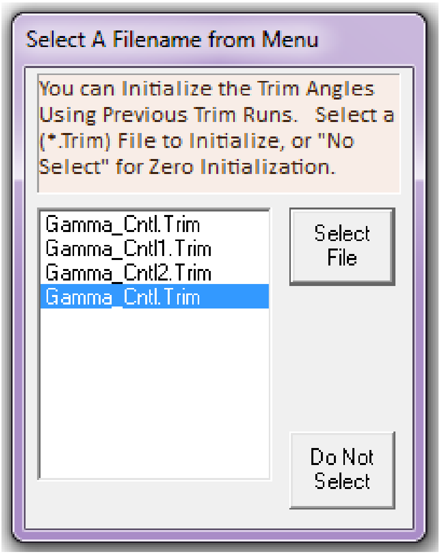
Aerosurface Trimming

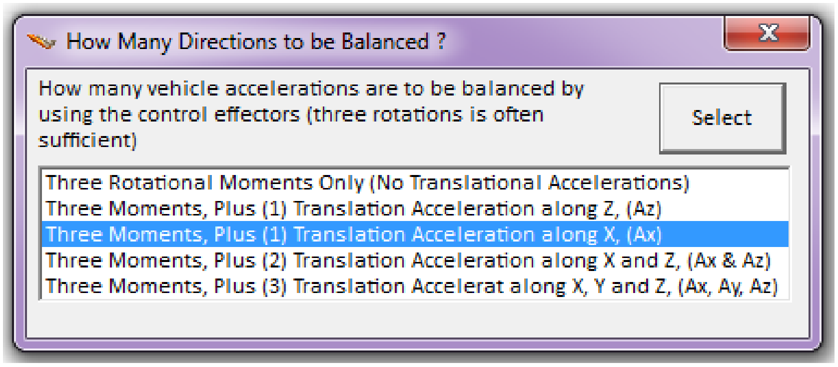
We will now trim the aero-surfaces along the gamma-control section of the trajectory to balance the vehicle moments. We will also include trimming in the x direction this time since we approach towards the approach and landing phase, and drag is beginning to become a control factor, although drag-modulation control will be introduced only in the approach and landing section.

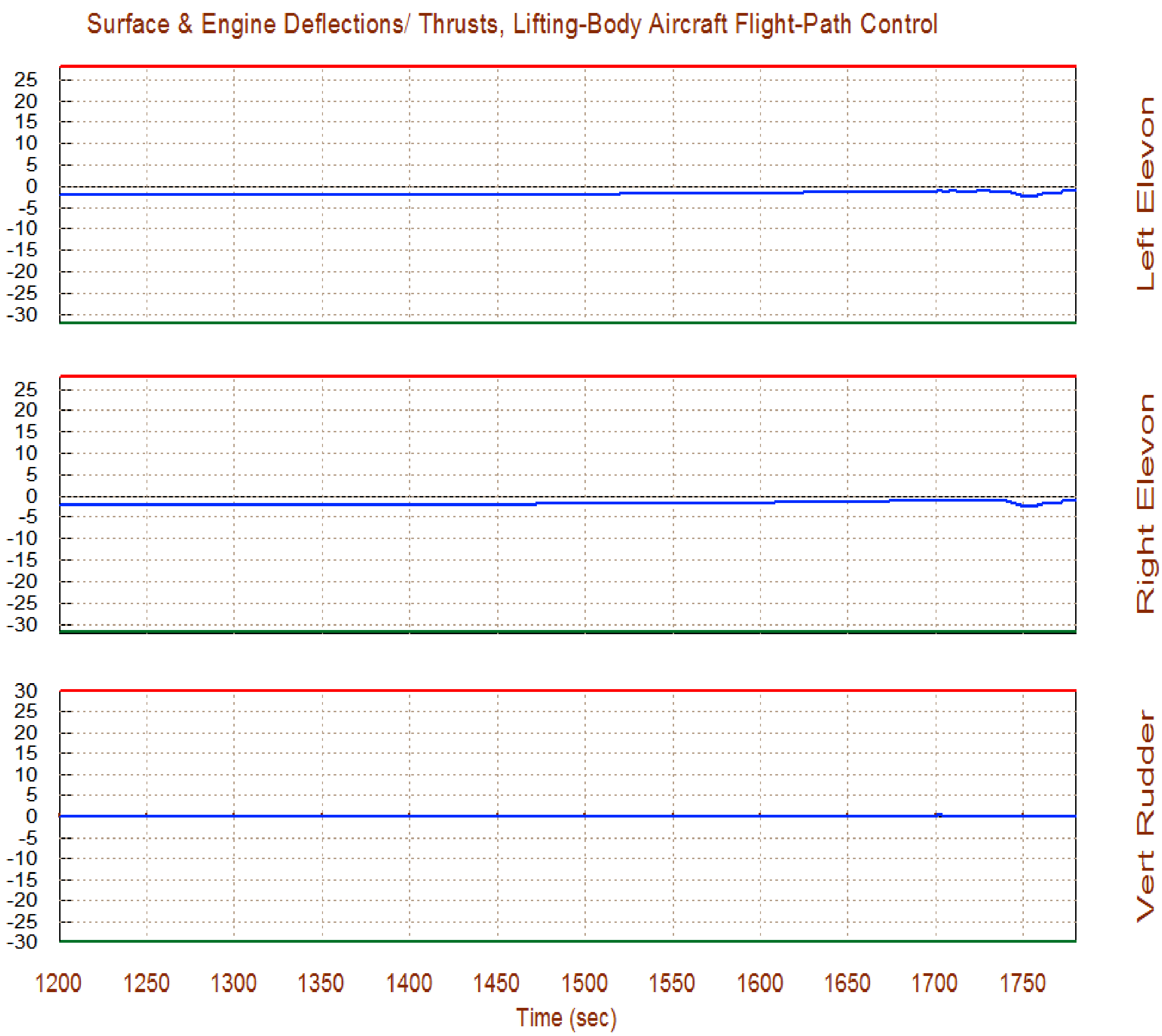
Start Flixan and select the applicable files in folder: "*C:\Flixan\ Trim\ Examples\ Lifting-Body Aircraft\ Reentry from Space\Trim_Anal\Gamma_Control*". From the Trim main menu choose option-3 for trimming, do not select a trim initialization file, and select to trim the three moments, roll, pitch, and yaw, plus the x-acceleration. The program will calculate a combination of surface deflections that balance the 3 moments and x-acceleration based on the individual surface capabilities. The trim deflections are saved in file "*Gamma_Control.Trim*".

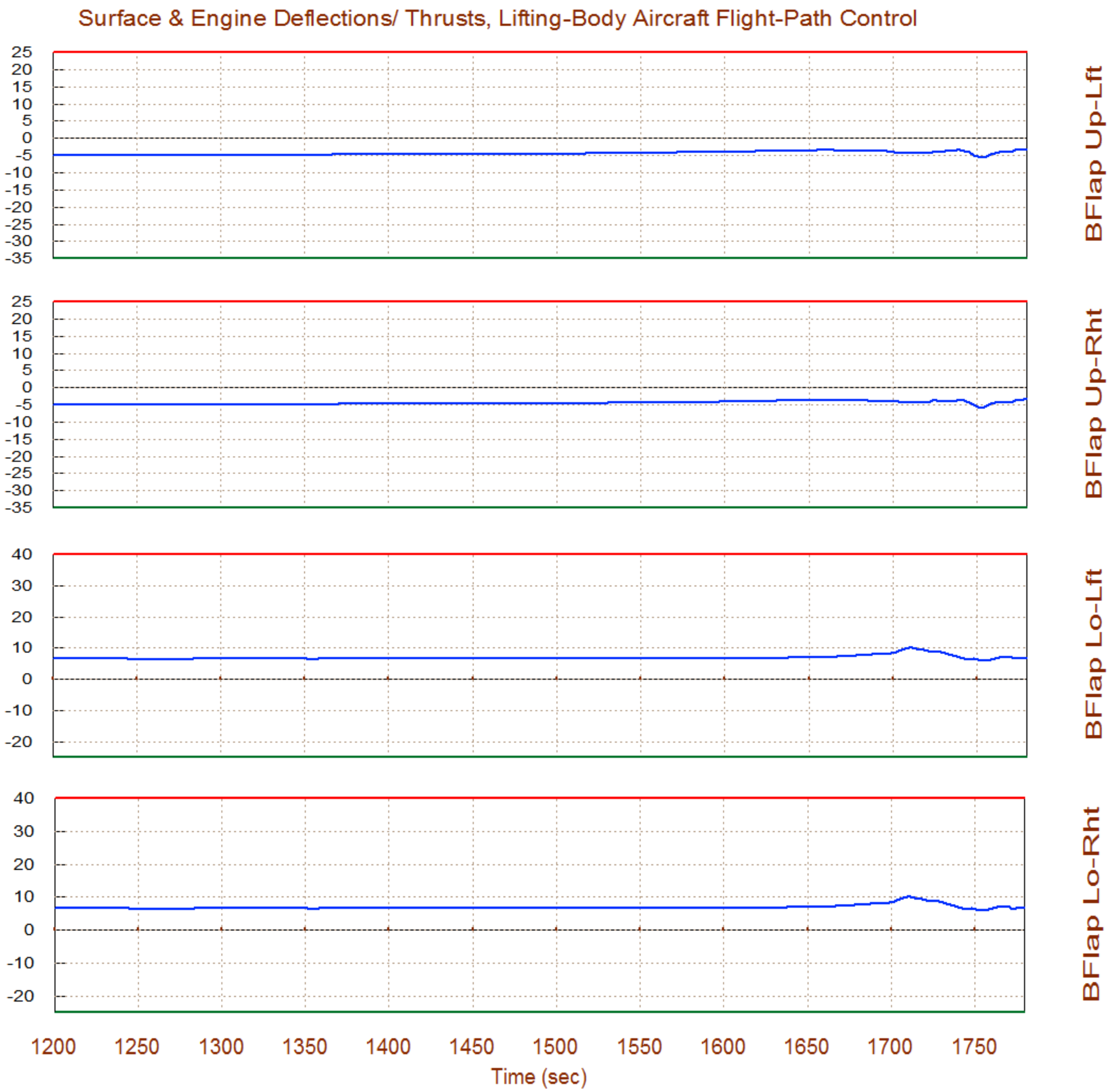





Select A Filename from Menu
You can Initialize the Trim Angles Using Previous Trim Runs. Select a (*.Trim) File to Initialize, or "No Select" for Zero Initialization.
Gamma_Cntl.Trim
Gamma_Cntl1.Trim
Gamma_Cntl2.Trim
Gamma_Cntl.Trim
Select File
Do Not Select


How Many Directions to be Balanced ?
How many vehicle accelerations are to be balanced by using the control effectors (three rotations is often sufficient)
Select
Three Rotational Moments Only (No Translational Accelerations)
Three Moments, Plus (1) Translation Acceleration along Z, (Az)
Three Moments, Plus (1) Translation Acceleration along X, (Ax)
Three Moments, Plus (2) Translation Acceleration along X and Z, (Ax & Az)
Three Moments, Plus (3) Translation Accelerat along X, Y and Z, (Ax, Ay, Az)

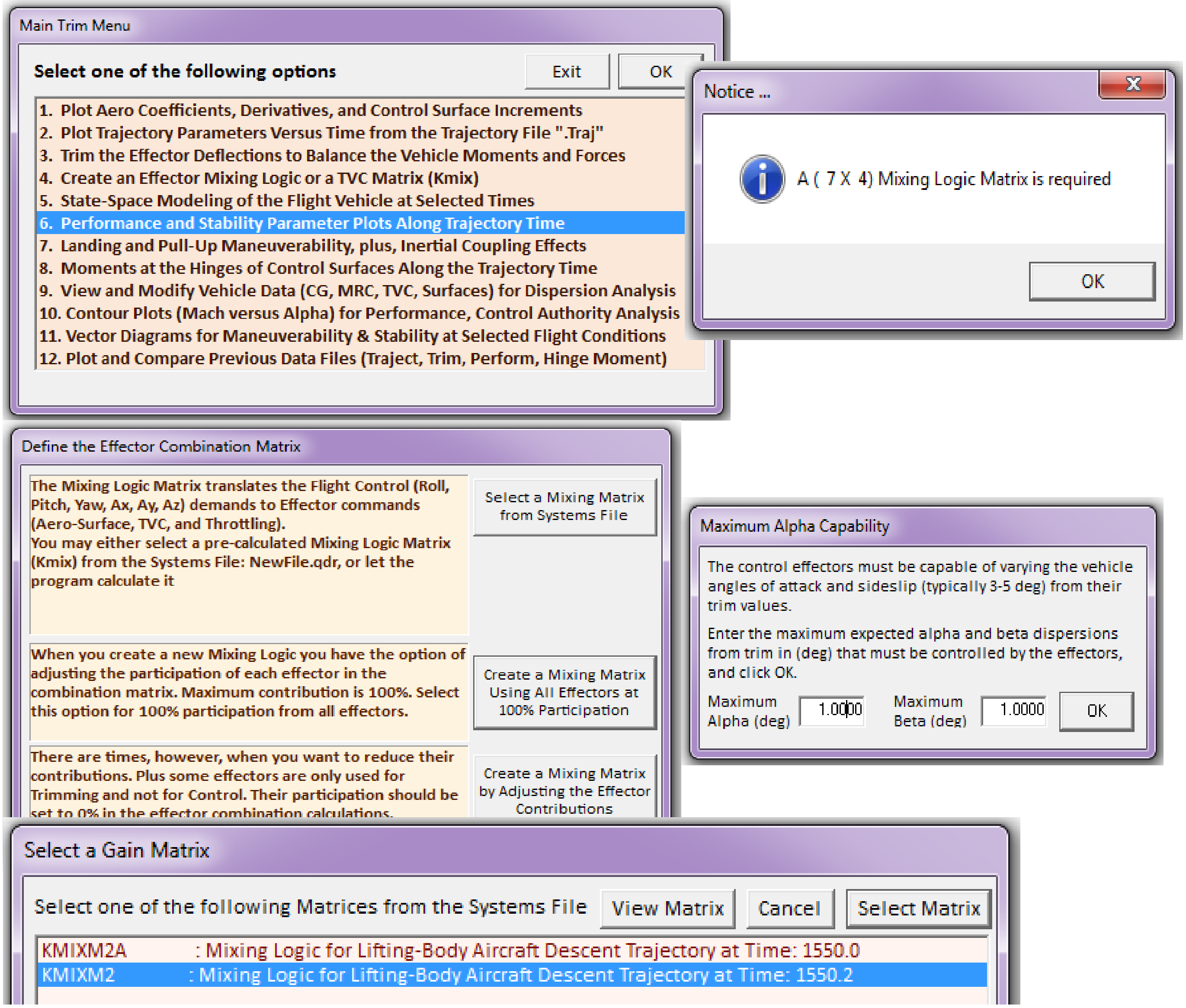

Surface & Engine Deflections/ Thrusts, Lifting-Body Aircraft Flight-Path Control
Left Elevon
Right Elevon
Vert Rudder
Time (sec)

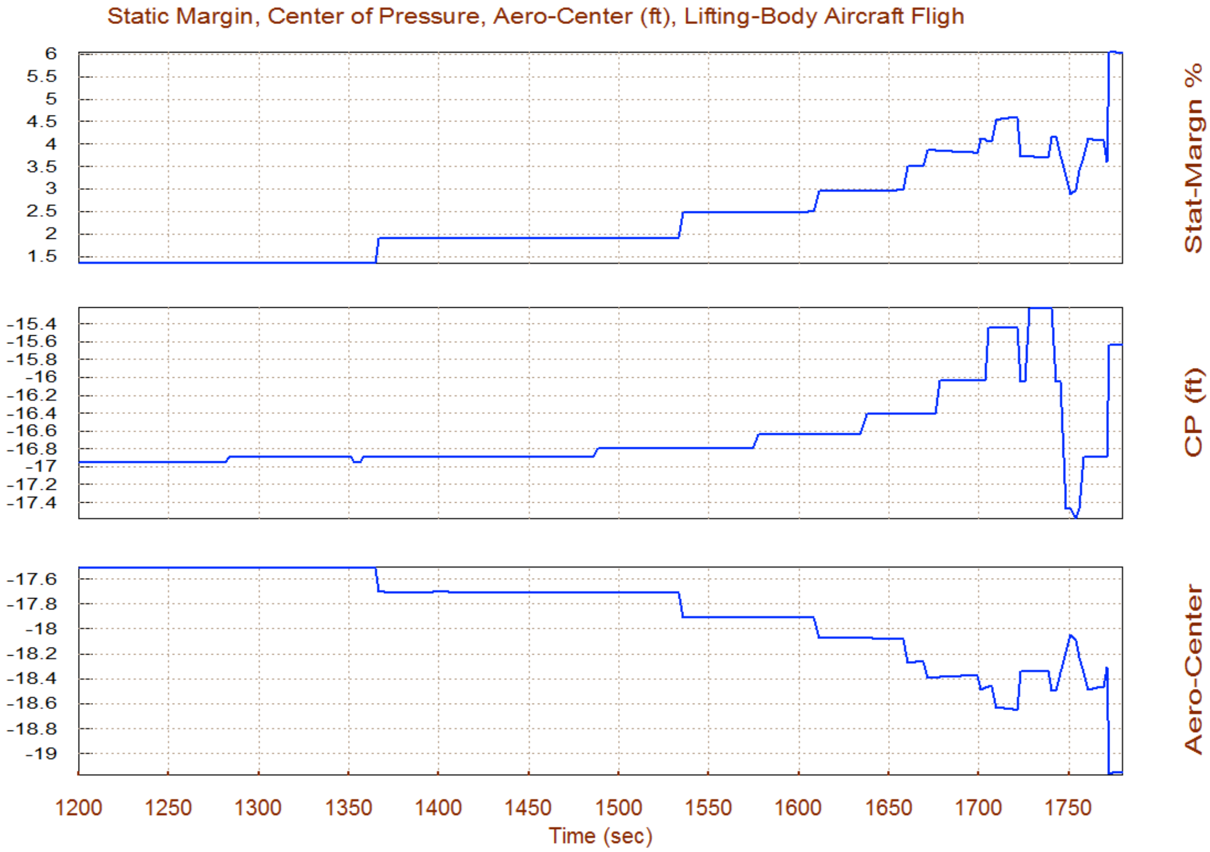


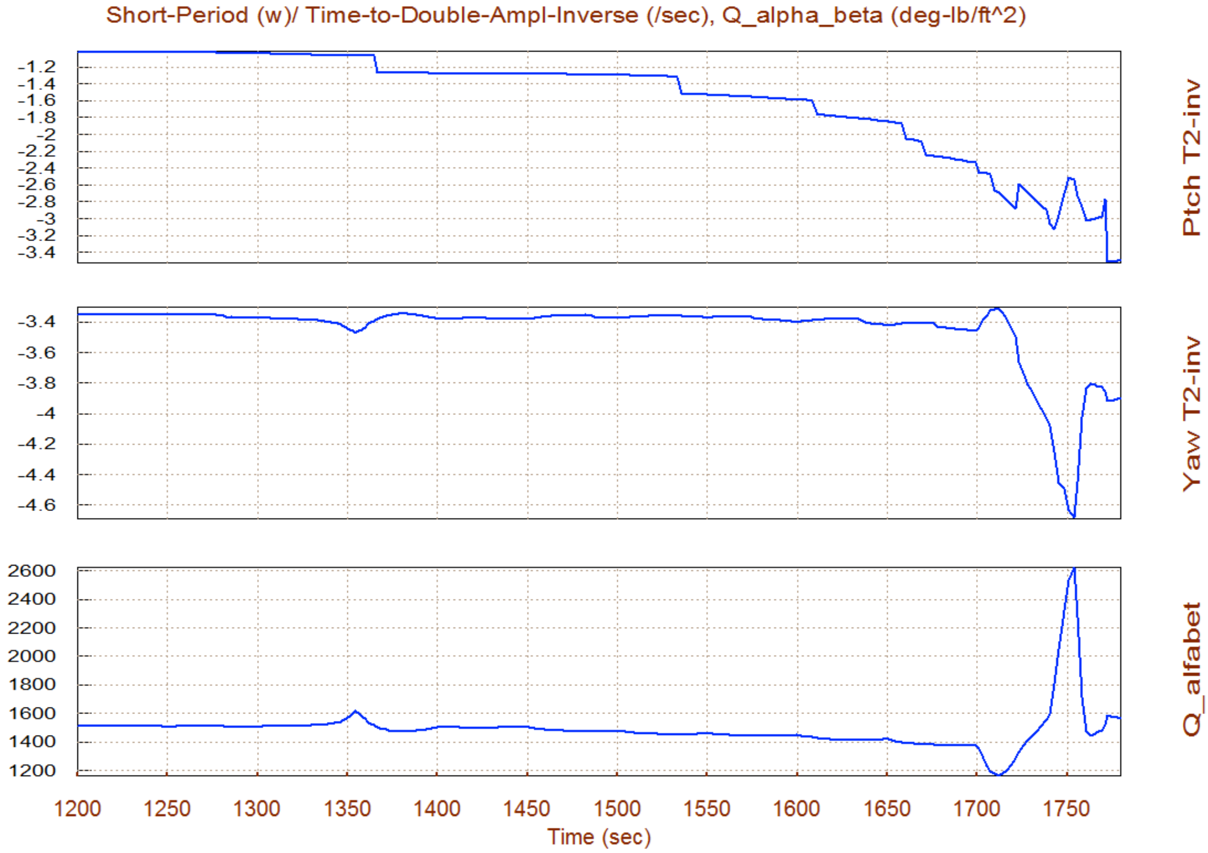
Note, the trim analysis is an iterative process. The aero-surface trim angles are not entirely determined by the trim algorithm without any inputs from the designer, but their positions are often biased or constrained prior to trimming by adjusting the initial surface positions and the deflection limits in the aerosurface coefficients file "*LiftBody_Surf.Delt*". This facilitates the trimming process in order to accommodate other design constraints and performance factors. It also helps to generate dynamic models with the proper trim angles for control design.

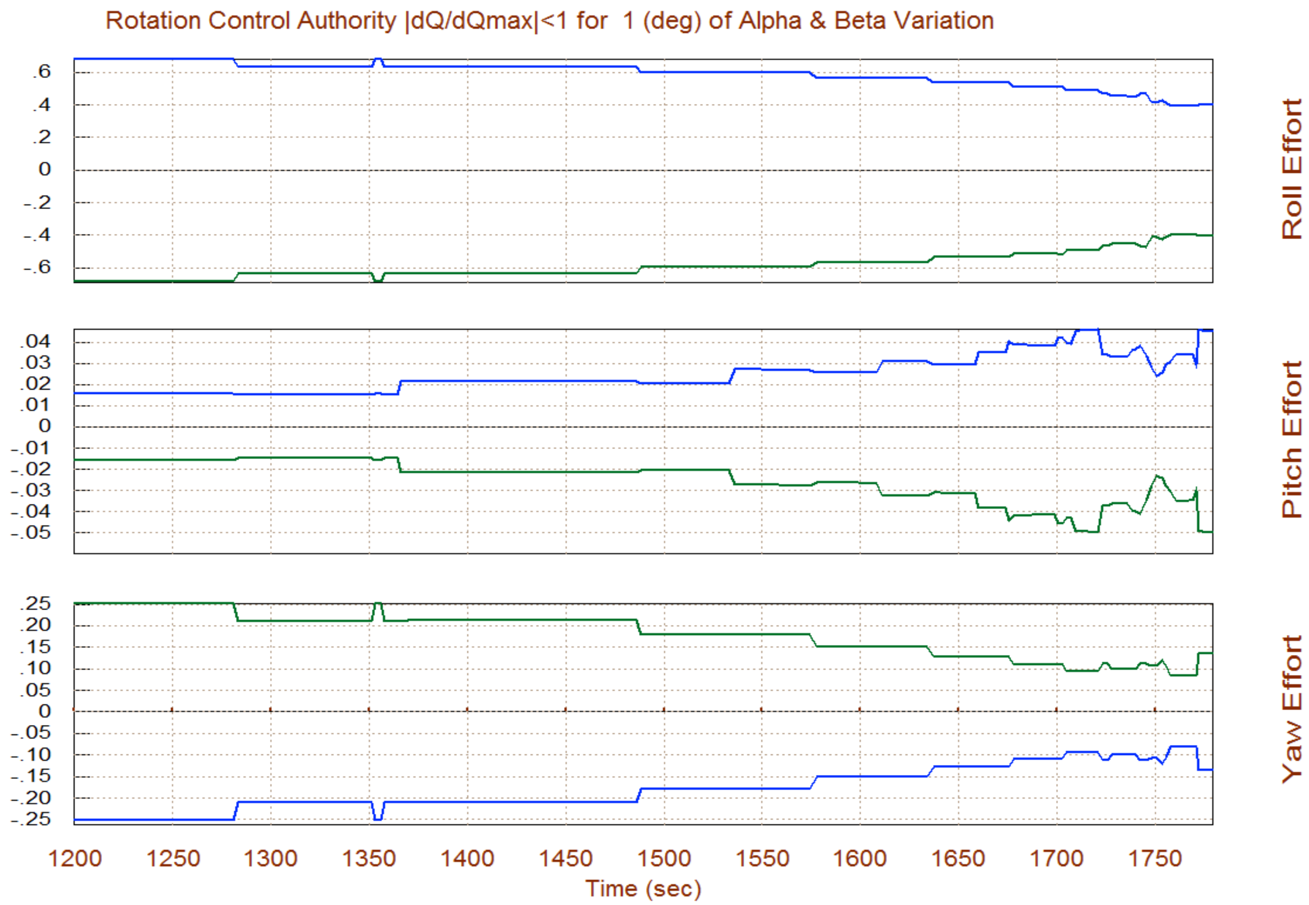
Performance Parameters along the Trajectory

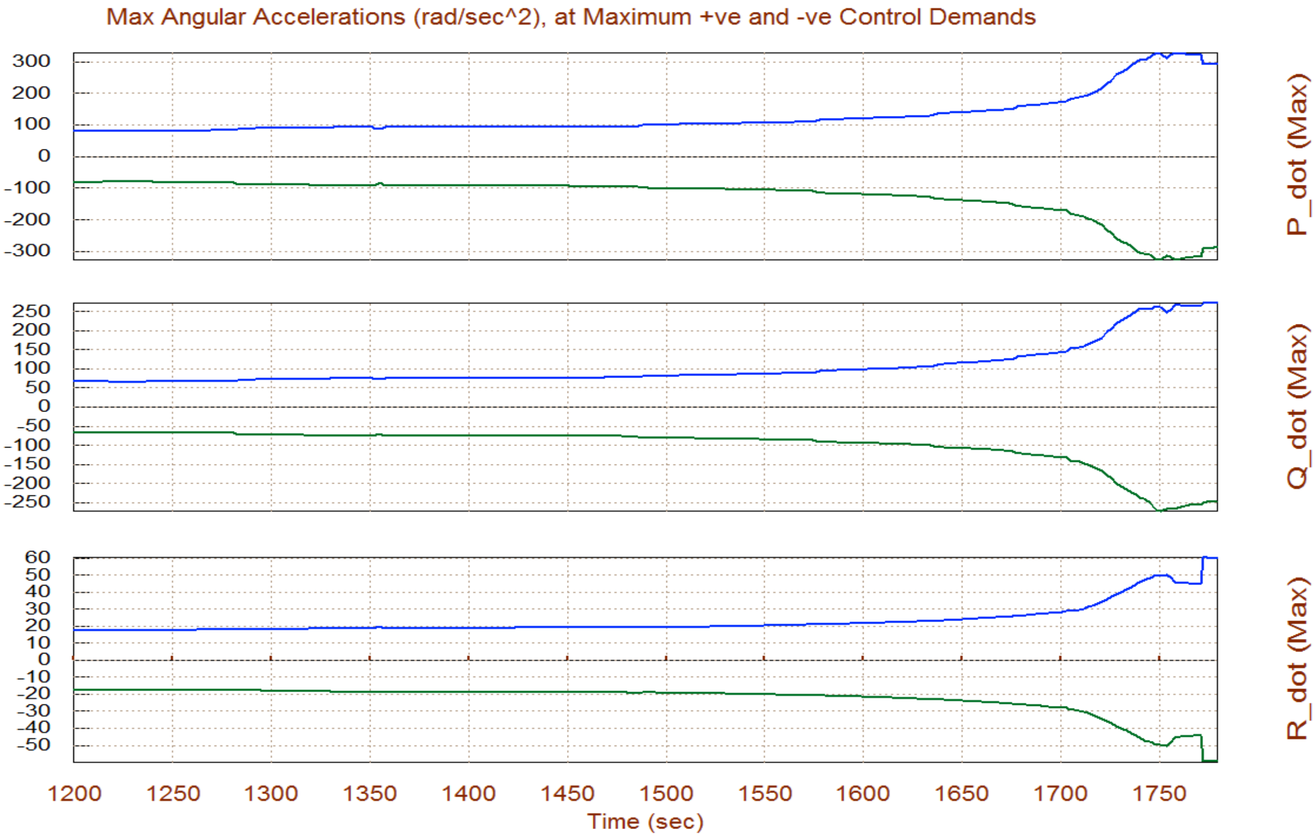
The static performance analysis requires a mixing logic matrix and a different matrix KmixM2 was designed by the mixing-logic program for this phase based on vehicle data from a fixed flight condition. You must remember, therefore, to select the systems file "Kmix.Qdr" which includes the control surface mixing matrix KmixM2 before beginning the analysis. The mixing logic matrix defines how the aero-surfaces combine together to allocate control in roll, pitch, yaw, and Ax-control, and the control effectiveness parameters strongly depend upon this matrix. Notice, the fourth column for Ax-control in KmixM2 has been zeroed and it is just a place holder for the next phase where we will control altitude and velocity independently. From the Trim main menu, the static performance analysis option-6 is selected. The program requests a (7x4) mixing matrix because we trimmed along 4 directions, including Ax. But although we included Ax in trimming, however, we are not interested in controlling it yet, and we will ignore its performance. Therefore, the fourth column in the (7x4) matrix KmixM2 in file "Kmix.Qdr", corresponding to Ax-control was set to zero. We must also define the maximum wind disturbance in terms of (α_{max} and β_{max}) angles which are both set to 1°.

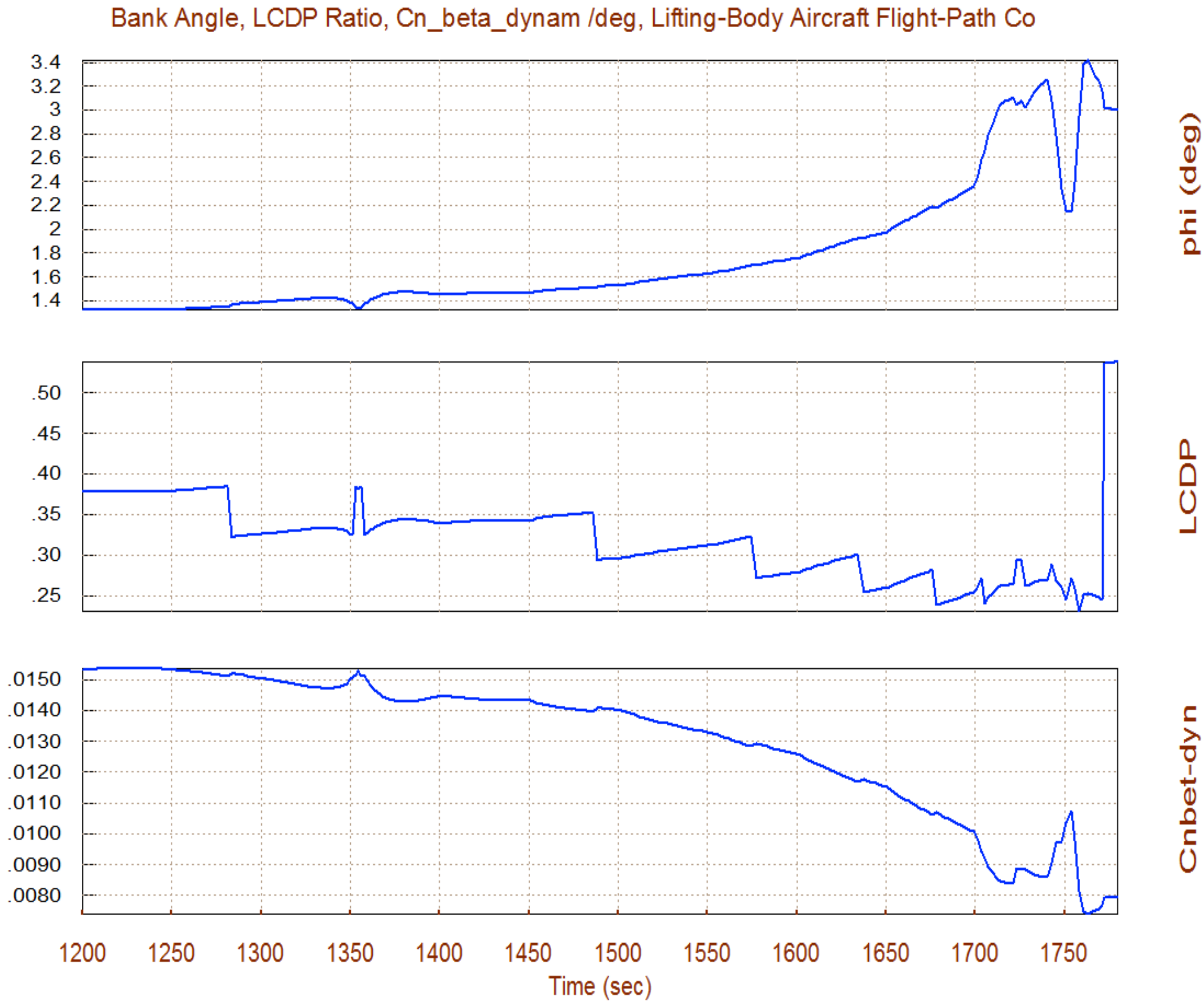



Static Margin, Center of Pressure, Aero-Center (ft), Lifting-Body Aircraft Fligh
Stat-Margn %
CP (ft)
Aero-Center
Time (sec)


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)


Rotation Control Authority |dQ/dQmax|<1 for 1 (deg) of Alpha & Beta Variation
Roll Effort
Pitch Effort
Yaw Effort
Time (sec)

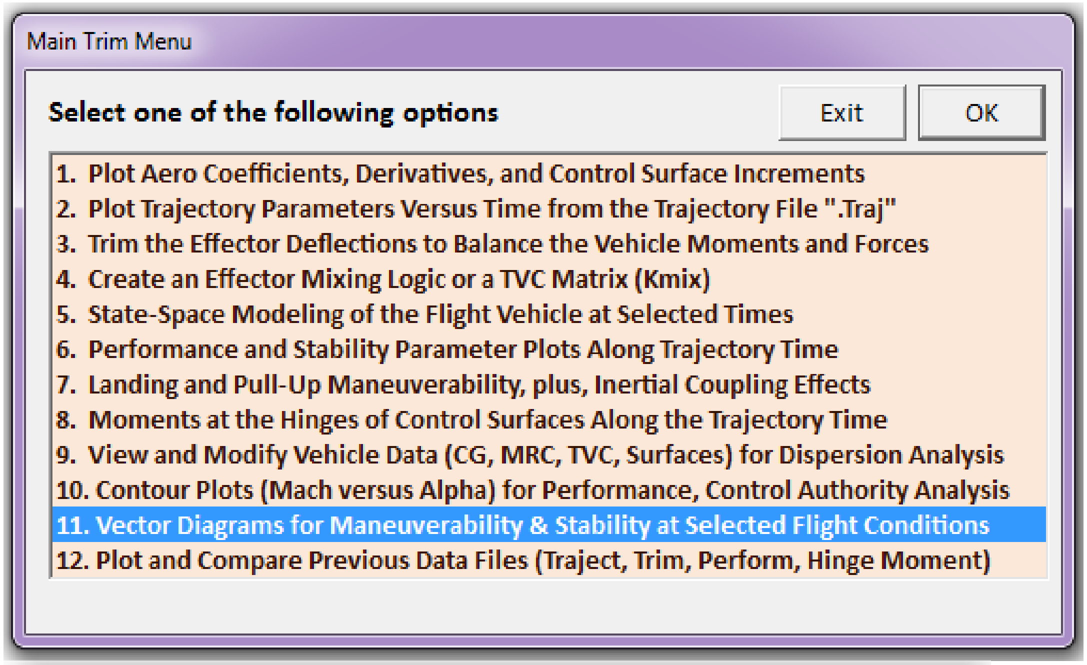

Max Angular Accelerations (rad/sec^2), at Maximum +ve and -ve Control Demands
P_dot (Max)
Q_dot (Max)
R_dot (Max)
Time (sec)

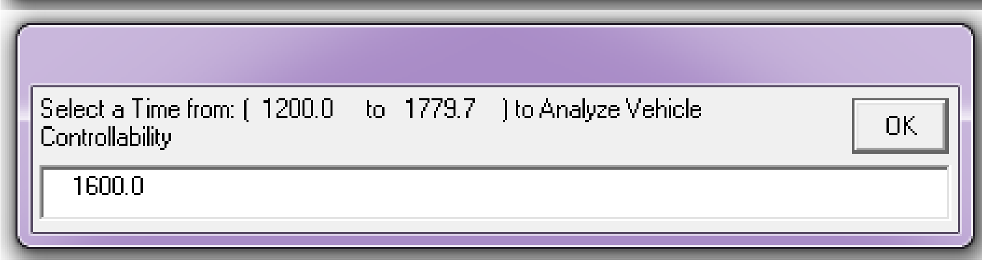


The performance results indicate that the longitudinal axis in this phase is statically stable due to the reduction in the angle of attack. The short-period resonance varies between: 1.2 to 3.2 (rad/sec) and the static margin peaks to 6%. In the lateral direction it is always statically stable with the Dutch-roll resonances peaking to 4.6 (rad/sec) during the roll maneuver. The ($Q\alpha$, $Q\beta$) loading is reasonably low but it spikes to 2600 (psf-deg) during the roll maneuver. Remember, that this parameter assumes 1° dispersions in α_{max} and β_{max} due to wind-shear. The control efforts against the wind dispersions are sufficiently small in pitch and yaw. They are symmetrical relative to zero which implies that the vehicle is perfectly trimmed with equal authority in positive and negative directions. In roll, however, the control authority was slightly compromised because the control effort parameter is 0.65. We normally like to see the control effort below 0.5, but it was traded-off, for improving the LCDP which would have been too low otherwise. The mixing logic KmixM2 is a modified version of the matrix obtained by the Flixan algorithm. The rudder contribution towards roll was slightly increased against reducing the aileron contribution in order to increase the LCDP which now is sufficiently positive without any sign (roll) reversals. The $Cn\beta$-dynamic is positive which means that the vehicle is directionally stable. The bank angle parameter (ϕ) is the bank angle due to a β_{max}= 1°. It is useful near landing.

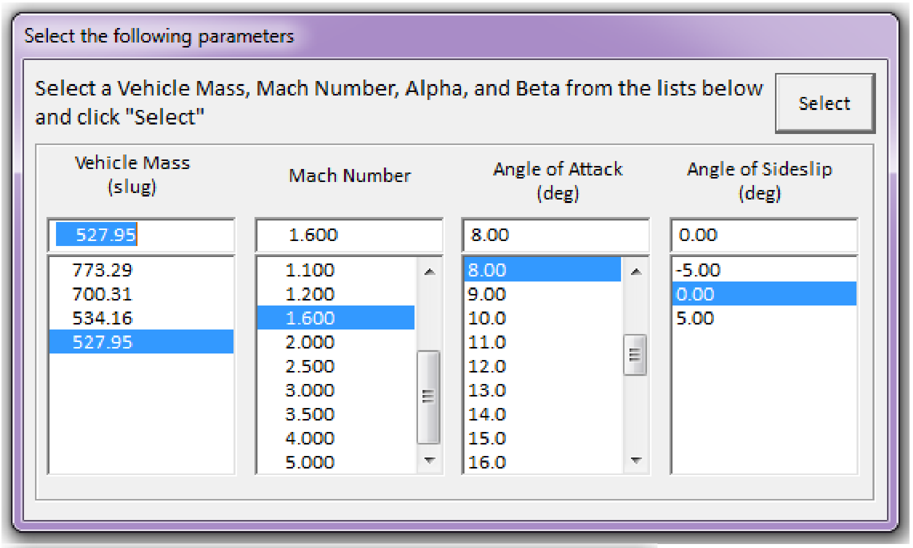
Controllability Analysis by Using Vector Diagrams

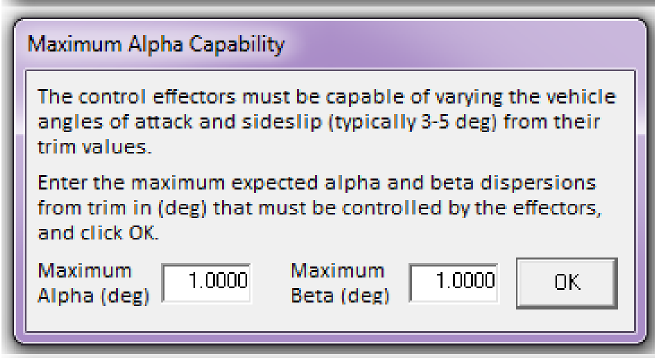
Vector diagrams help us determine the vehicle maneuverability, control authority, and orthogonality of the effectors system at a fixed flight condition against wind-shear disturbances in the steady-state. From the Trim menu select option-11, and then an arbitrary flight condition at t=1600 sec, near the middle of the γ-controlled section of the trajectory, corresponding to Mach 1.6.

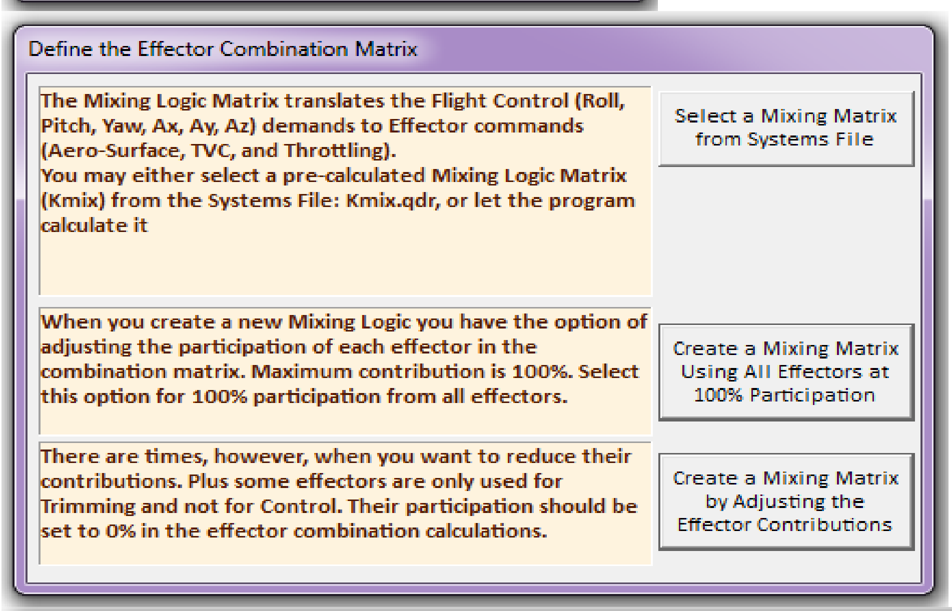


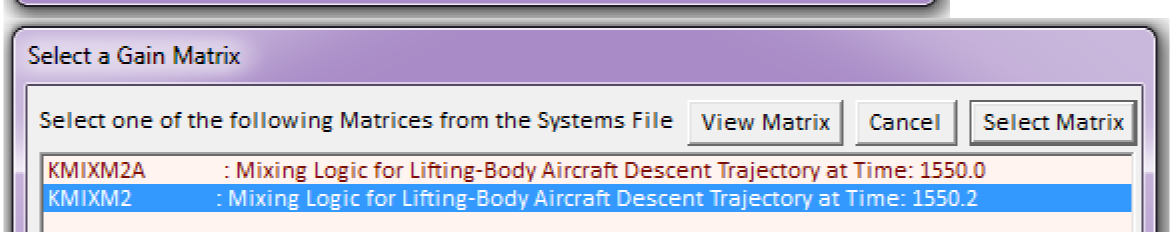


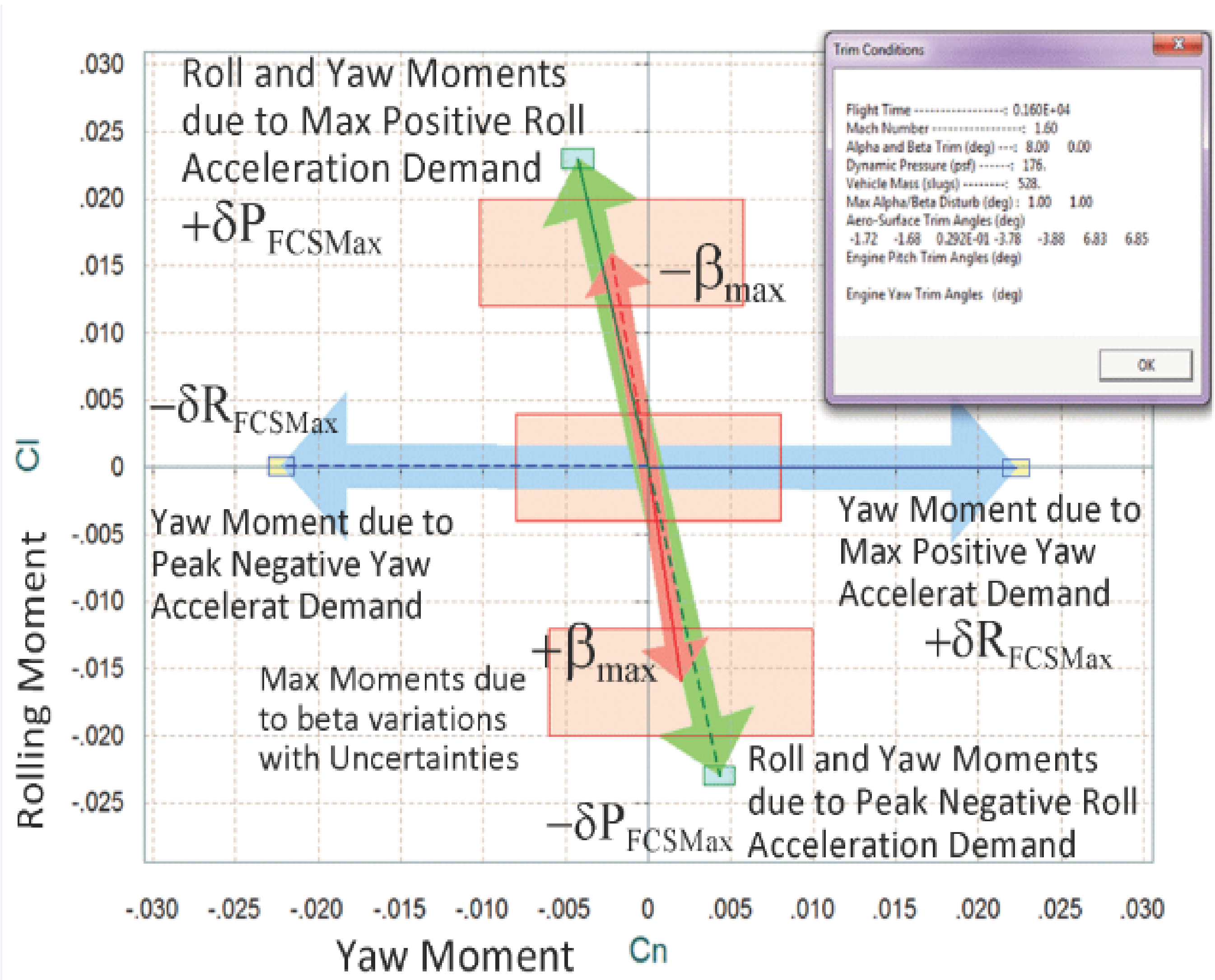
The following dialog consists of menus used for selecting the vehicle mass, Mach number, alpha, and beta. The default values correspond to the selected flight time. You may keep those parameters or change them to something different. In this case we select the default values and click "*Select*". Notice that Mach 1.6 and α=8° are the nearest Mach number and angle of attack at the selected time. The disturbances are caused by wind-shear defined by the maximum alpha and beta produced. In the following dialog enter the maximum disturbance angles (α_{max} and β_{max})=1°, and then select the (7x4) control surface combination matrix "KmixM2" from file Kmix.Qdr, as shown.


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)
527.95
1.600
8.00
0.00
773.29
700.31
534.16
527.95
1.100
1.200
1.600
2.000
2.500
3.000
3.500
4.000
5.000
8.00
9.00
10.0
11.0
12.0
13.0
14.0
15.0
16.0
-5.00
0.00
5.00

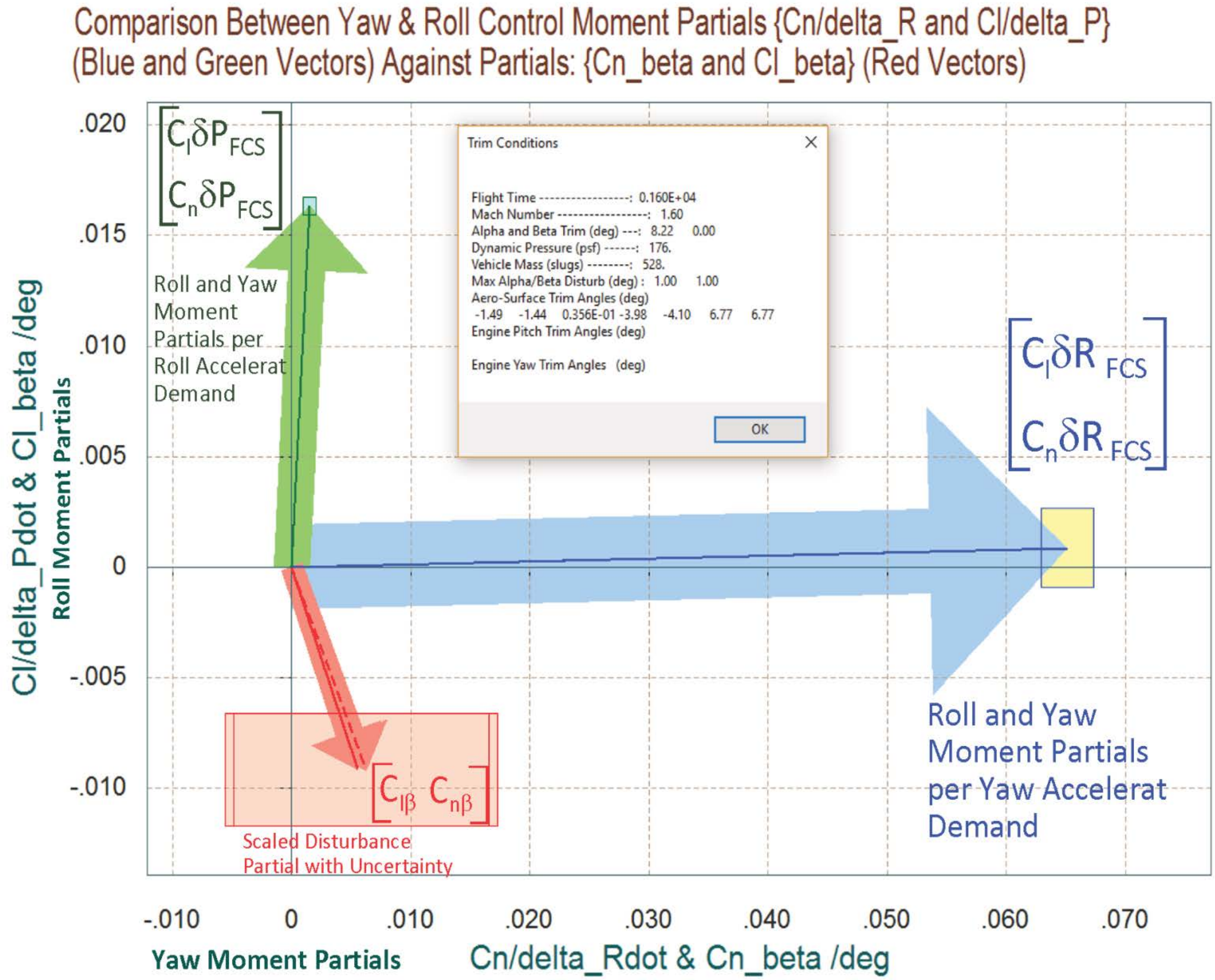

Maximum Alpha Capability
The control effectors must be capable of varying the vehicle angles of attack and sideslip (typically 3-5 deg) from their trim values.
Enter the maximum expected alpha and beta dispersions from trim in (deg) that must be controlled by the effectors, and click OK.
Maximum Alpha (deg)
1.0000
Maximum Beta (deg)
1.0000
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 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


Select a Gain Matrix
Select one of the following Matrices from the Systems File
View Matrix
Cancel
Select Matrix
KMIXM2A : Mixing Logic for Lifting-Body Aircraft Descent Trajectory at Time: 1550.0
KMIXM2 : Mixing Logic for Lifting-Body Aircraft Descent Trajectory at Time: 1550.2



The above vector diagram shows the non-dimensional roll and yaw moments, (C_l & C_n), produced when the roll and yaw FCS demands are maximized to the saturation limits of the aerosurfaces. The solid blue vector represents the yaw moment produced when the yaw FCS demand is at its maximum positive position $\delta R_{+FCSMax}$, and the dashed blue vector in the opposite direction indicates the negative moment produced when the yaw demand is at its peak negative position $\delta R_{-FCSMax}$. It shows that the yaw control produces only yaw, and not any rolling moment. Similarly, the two green vectors in the opposite up and down directions are the maximum moments produced when the roll FCS demand is maximized in the positive (solid green), and in the negative (dashed) directions $\delta P \pm_{FCSMax}$. The two smaller red vectors symbolize the roll and yaw moments generated by the angle of sideslip $\pm\beta_{max}$ variations and it is mainly in roll. A positive β_{max} generates a negative rolling moment because this lifting-body airframe has significant amount of dihedral. The rectangles at the tips of the arrows represent the moment uncertainties in the disturbance and control vectors. They are calculated from the uncertainties in the basic aerodynamic coefficients and in the aero-surface increment coefficients which are located file "*LiftBody.Unce*".



This figure is a moment partials vector diagram showing the variation in roll and yaw moments per acceleration demands in roll and yaw which is in (rad/sec^2). The blue vector is the moments per yaw control demand {CnδR, ClδR} which is mainly in the yaw direction, and the green vector is the moments per roll control demand {CnδP, ClδP} which is mostly in roll. The red vectors pointing downward are the scaled {Cnβ, Clβ} partials. They are scaled to be made comparable to the control vectors. Notice that Clβ is negative and large due to the dihedral in the airframe, and it is bigger in magnitude than Cnβ. The red rectangle centered at the tip of the {Cnβ, Clβ} vector represents the uncertainties in these partials. Similarly the yellow rectangle at the tip of the yaw control partial represents the uncertainties in {CnδR, ClδR}, and the cyan rectangle at the tip of the roll control partial is the uncertainties in {CnδP, ClδP}. The uncertainties are obtained from file "*LiftBody.Unce*".

The next two pages analyze controllability in the longitudinal directions by maximum controls and by partial vector diagrams. However, in the longitudinal axes and in this control mode there is only one control which is pitch acceleration demand δQ_{FCS}. The pitch control, in addition to pitching moment it generates also force variations in the x and z directions, so even though we have only one pitch control we must still examine its effect in all three directions. Figure 3.1 may be interpreted as a 3-dimensional vector diagram with axes (C_X, C_Z, and C_m), showing the pitching moment Cm plotted against the CZ and the CX forces in non-dimensional form. The blue vectors show the maximum pitching moment and forces produced when the pitch acceleration demand is maximized to saturation levels in both positive and negative directions. The solid blue vector represents the moment and forces due to max positive pitch acceleration demand $\delta Q_{+FCSMax}$, and the dashed blue vector is the moment and forces due to max negative pitch acceleration demand $\delta Q_{-FCSMax}$. Unlike the lateral directions, there is no symmetry in the longitudinal axes because the peak positive control demand $\delta Q_{+FCSMax}$ produces a larger moment and z-force variation than the peak negative control demand $\delta Q_{-FCSMax}$. The aerosurfaces can provide bigger moment and z-force in the positive pitch direction than in the negative. The x-force variation from trim is also asymmetric between positive and negative pitch demands. Notice how either a positive or negative pitch control demand has a negative effect on CX (drag increase). The pitch moment is balanced in pitch because C_{m0}=0 when the control δQ_{FCS}=0. However, the vehicle is accelerating in both -x and -z directions because C_{X0} and C_{Z0} are both negative when δQ_{FCS}=0. Notice also that a +pitch control demand reduces the magnitude of CZ, reducing lift as the Elevons rotate upwards to increase the pitching moment. The two red vectors pointing up and down represent the forces and moments generated by the variations $\pm\alpha_{max}$ and $\pm\beta_{max}$ from trim (α_0 and β_0), which in this case they are both ±1°. If you Increase α makes the z-force more negative (up). The red rectangles represent the uncertainty in the moment and force coefficients.

Figure (3.2) shows the partials in the longitudinal directions which are: pitch moment and forces per pitch control and pitch moment per alpha. The two figures can also be interpreted as a 3-dimensional vector diagram. The blue vectors represent the pitching moment, normal and axial force partials per pitch acceleration demand {$Cm\delta Q_{FCS}$, $Cz\delta Q_{FCS}$, $C_X\delta Q_{FCS}$}. It shows that a small increase in pitch demand produces a positive effect in pitching moment and in z force. The variations in the x and z forces are mainly due to the Elevon up deflections. The red vectors are the scaled {$C_{m\alpha}$, $C_{Z\alpha}$, $C_{X\alpha}$} partials. They are scaled to be made comparable to the control vectors, as already described, and two because they are calculated at the two extreme values of $\pm\beta_{max}$. The control vectors are clearly more dominant than the disturbance partials. Negative $C_{m\alpha}$ is indicative that the vehicle is statically stable at t=1600 sec.

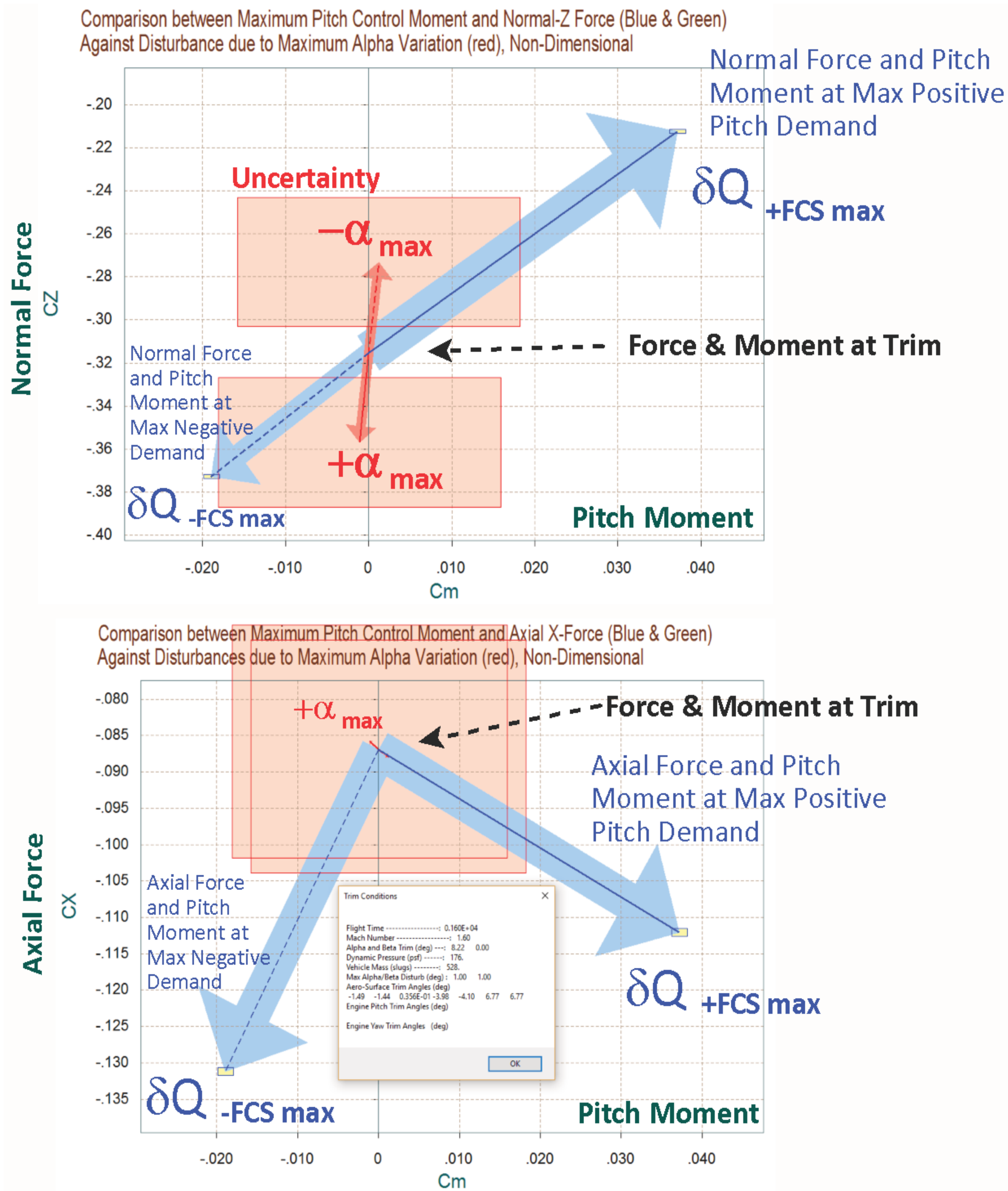


Figure 3.1 Maximum Moments and Forces Diagram in the Longitudinal Directions

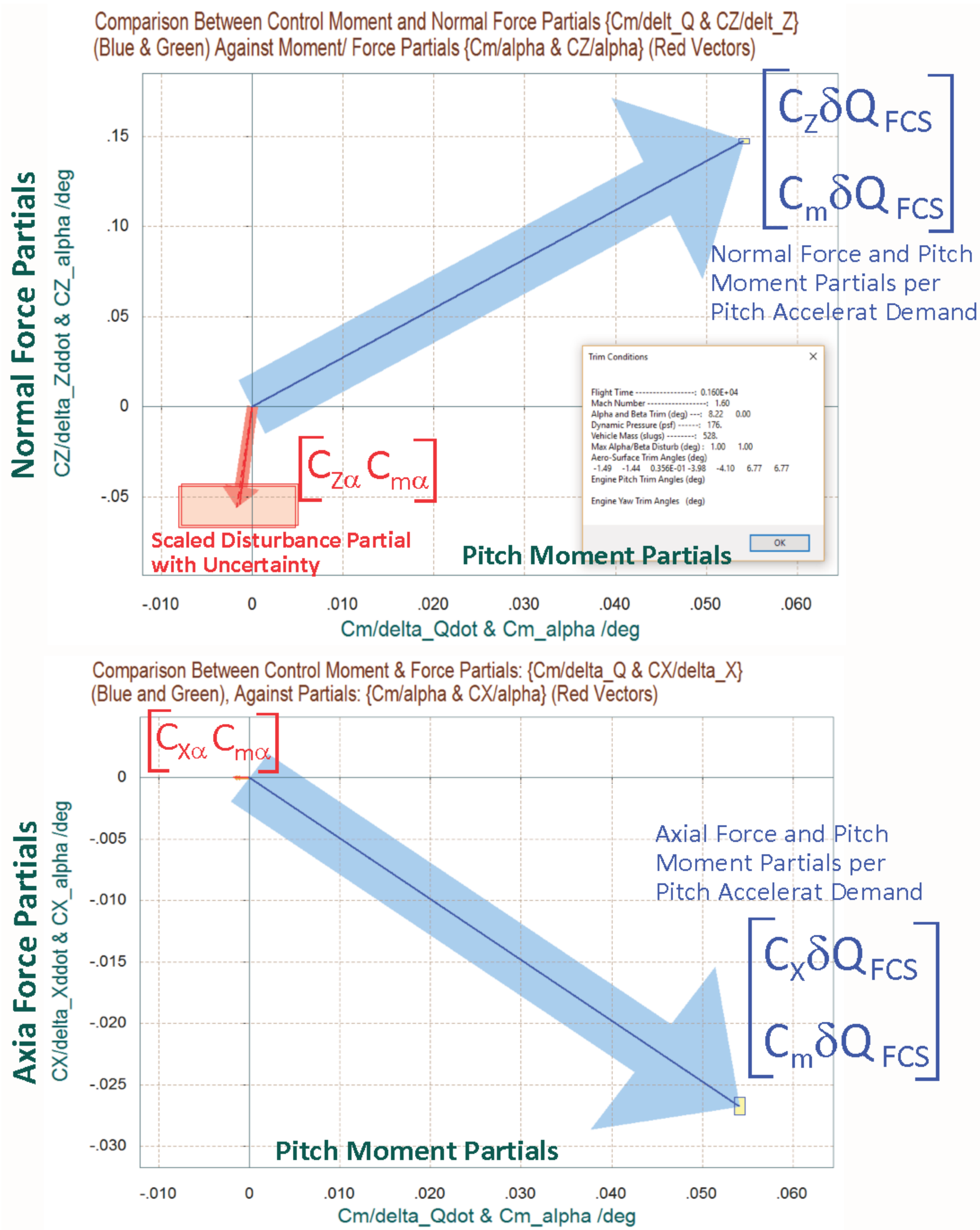


Figure 3.2 Moments and Forces Partials in the Longitudinal Directions

The next figure shows the partials of accelerations per acceleration demands in roll and yaw. The green vector is the accelerations per roll demand $\{\dot{P}/\delta P_{FCS}, \dot{R}/\delta P_{FCS}\}$, and the blue vector is the accelerations per yaw demand $\{\dot{P}/\delta R_{FCS}, \dot{R}/\delta R_{FCS}\}$. The axis units are in (rad/sec^2) per (rad/sec^2). Ideally they should be unit vectors, decoupled, and pointing in the demanded directions (green vector along the +vertical axis and blue vector along +horizontal), but this is not an absolute requirement, as we have already explained. In this case, however, they are pretty close to being a decoupled system. It is an indication that the effector mixing matrix is properly designed.

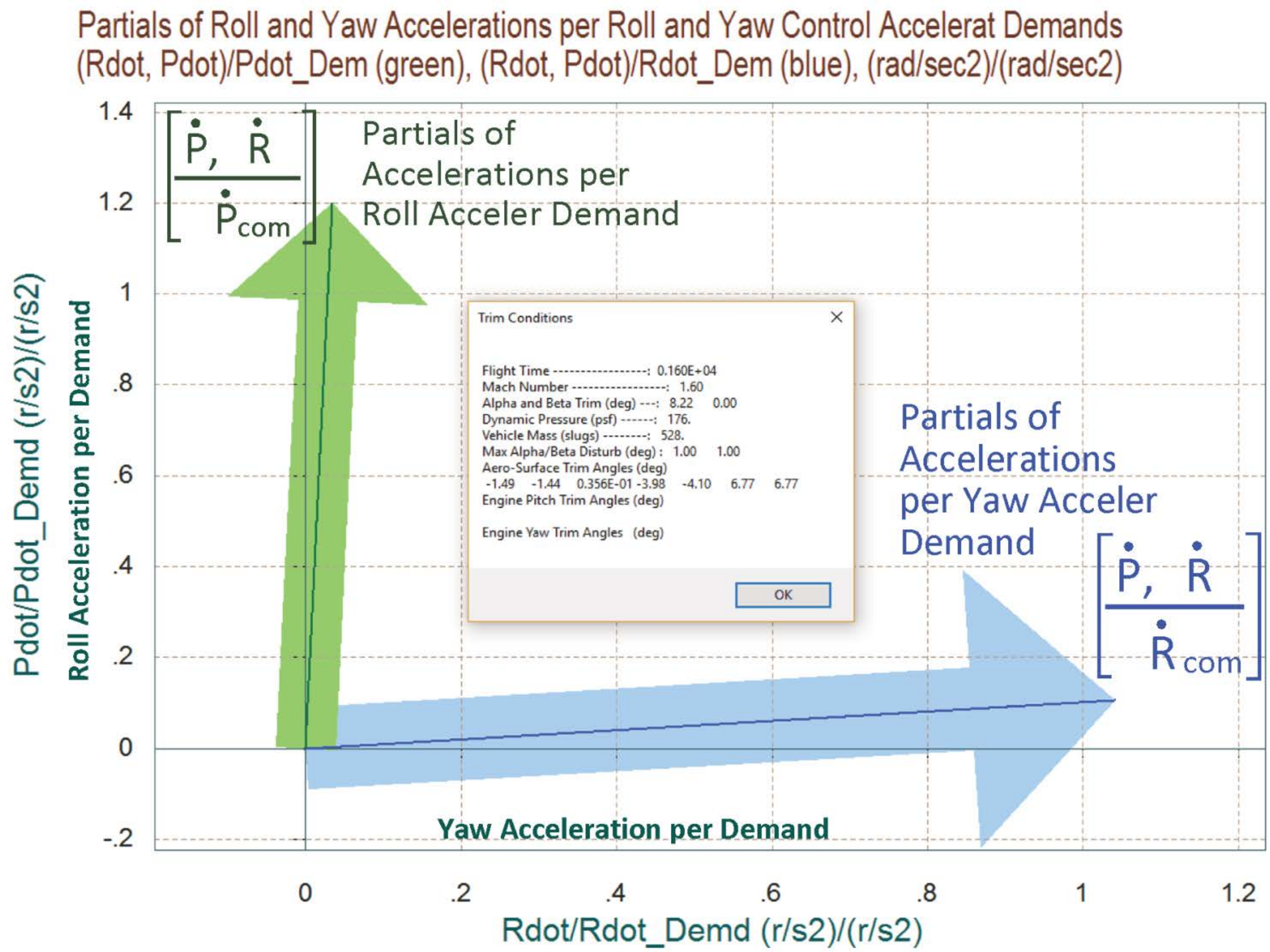


Figure 3.3 shows the effects of yaw control in yaw moment and in side-force. The blue vectors in the top diagram show the yaw moment and side-force produced when the yaw control demand saturates at $\delta R_{\pm FCSMax}$. The red vectors show the effect due to $\pm\beta_{max}$ dispersions. The bottom figure is a partials diagram showing the side-force and yaw moment partials per yaw demand $\{C_Y\delta R_{FCS}, Cn\delta R_{FCS}\}$. The red vectors are the scaled $\{C_{Y\beta}, Cn_\beta\}$ partials. An increase in β indicates a positive yaw moment and a negative side-force which implies that the vehicle is statically stable in yaw. The rectangles centered at the vector tips represent the uncertainties in the aero coefficients.

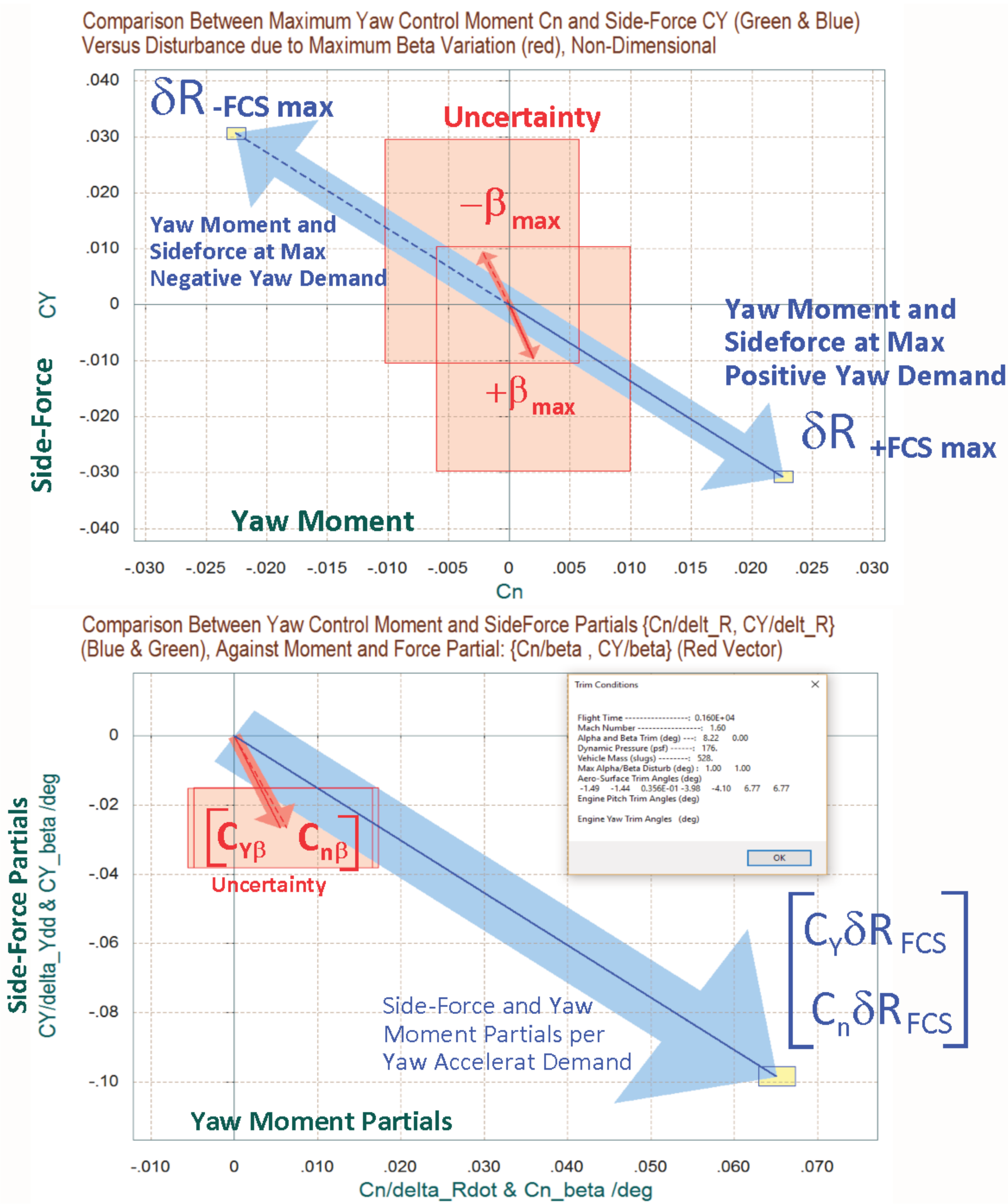
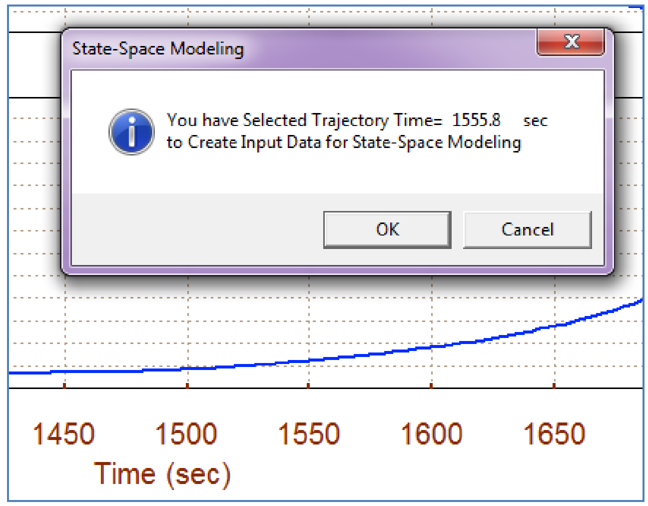
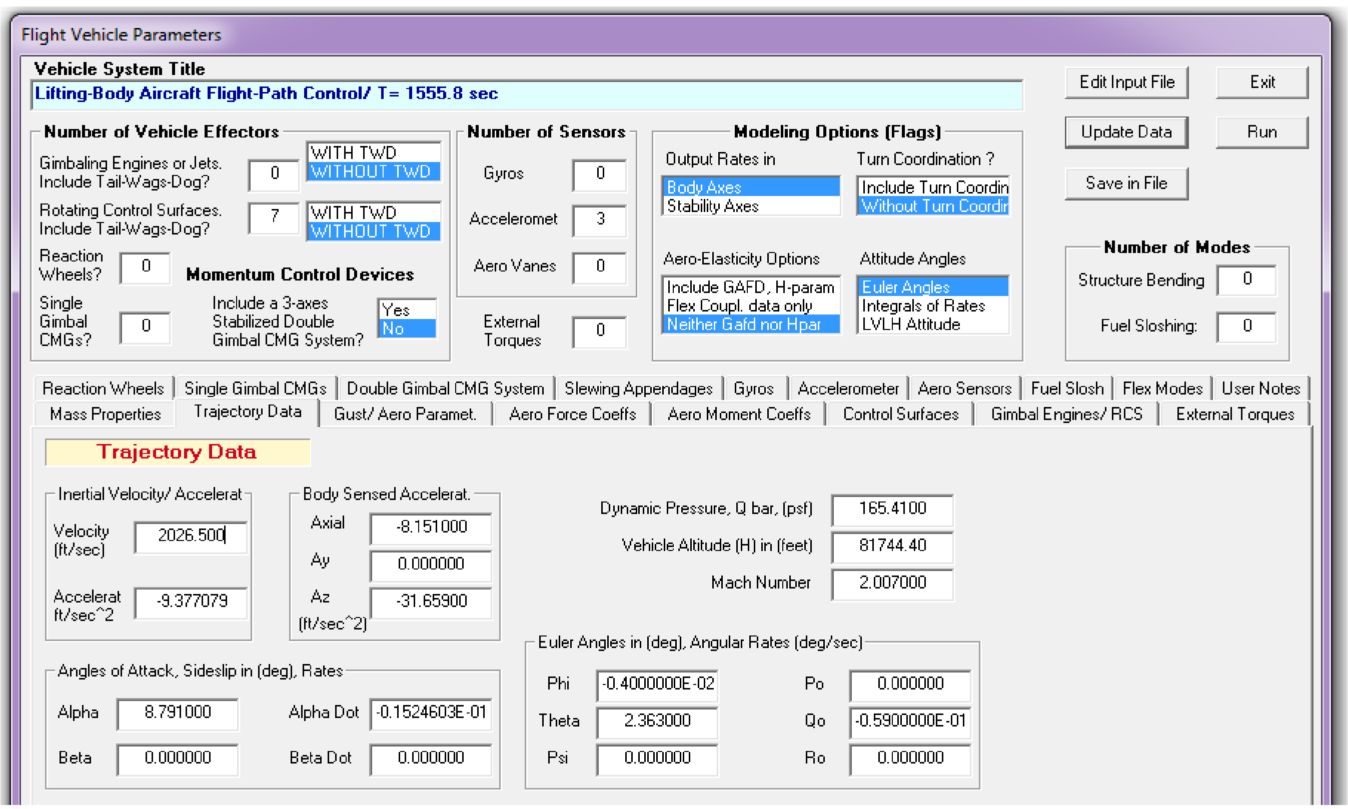


Figure 3.3 Effects of Yaw Control in Yaw and Side-force directions

Dynamic Modeling, Control Design, and Stability Analysis

We will now create a dynamic model at a fixed flight condition, at time t=1556 sec, that corresponds to Mach 2 in the gamma-controlled region, design control laws and a control surface mixing logic KmixM2, analyze stability in the frequency domain, and simulate its performance when tracking gamma and phi commands. The process, systems and analysis are very similar to the previous cases so we will skip the details. To create a dynamic model, plot the trajectory, and from one of the trajectory plots, go the top menu bar and choose "*Graphic Options*". Then from the vertical pop-up menu click on "*Select Time to Create State-Space System*". Then using the mouse click at time t=1556 sec, along the x axis of the plot to select the flight condition. The program confirms the flight time and prepares the dynamic model.

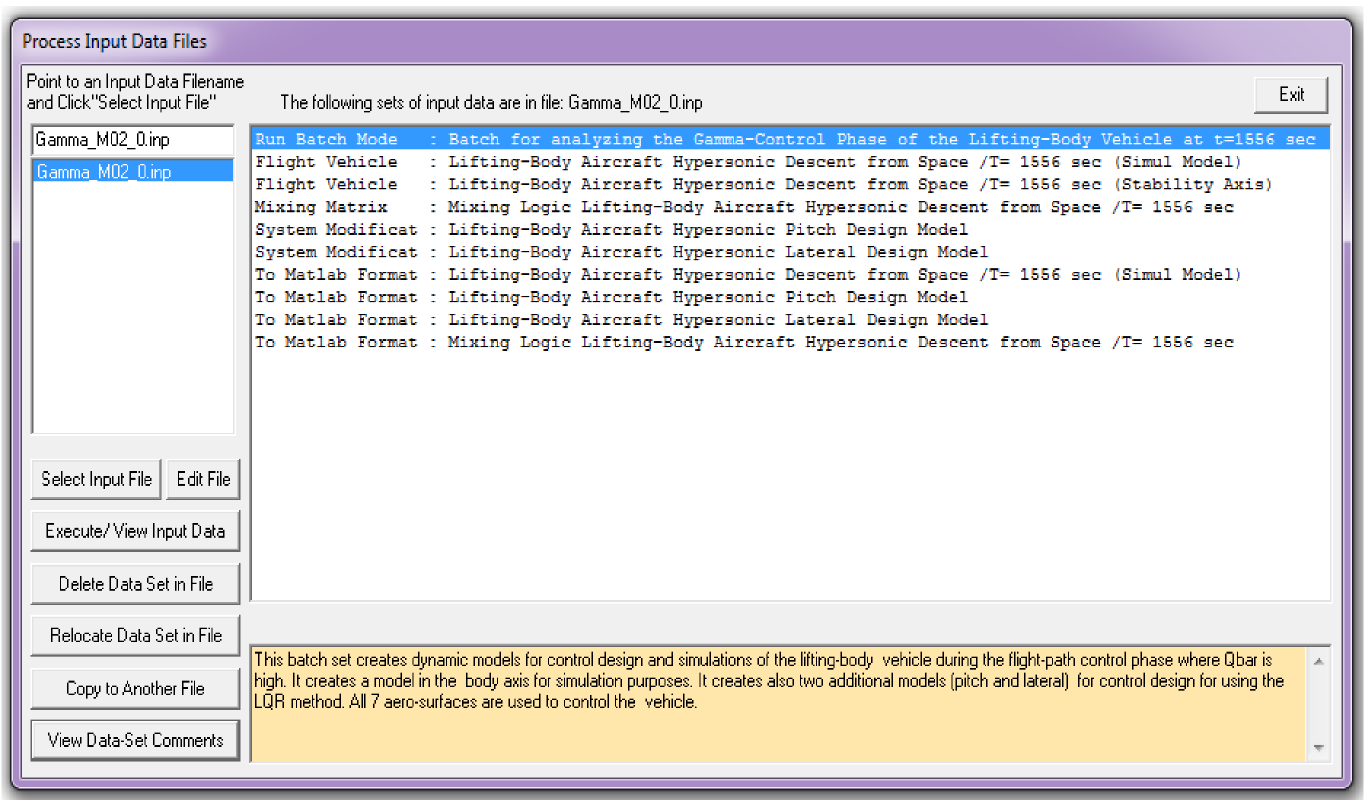




The vehicle input data, however, at trajectory time t=1556 (sec) which corresponds to Mach 2 is already created in file "*Gamma_M02_0.Inp*". The Matlab analysis for this flight condition is performed in folder "*C:\Flixan\Trim\Examples\Lifting-Body Aircraft\Reentry from Space\Mat_Anal\Mch_2*".

Processing the Input Data

The input data file "*Gamma_M02_0.Inp*" will now be processed by Flixan to create a vehicle simulation model "*Lifting-Body Aircraft Hypersonic Descent from Space /T= 1556 sec (Simul Model)*" in file "*vehicle_sim*", and the pitch and lateral stability axis design models "*Lifting-Body Aircraft Hypersonic Pitch Design Model*" and "*Lifting-Body Aircraft Hypersonic Lateral Design Model*" in files "*pitch_des.m*" and "*later_des.m*" respectively. It also generates a mixing logic matrix KmixM2a corresponding to this flight condition. A different matrix, however, was used in static analysis and it will also be used in the control analysis because it improves roll controllability (LCDP). To process this file, start Flixan and select the project directory containing the input data file. Then go to "*Edit*", "*Manage Input Files*" and "*Process/ Edit Input Data*". When the following dialog appears, select the input data file "*Gamma_M02_0.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 titled "*Batch for analyzing the Gamma-Control Phase of the Lifting-Body Vehicle at t=1556 sec*", and click on "*Execute/ View Input Data*". Flixan will process the input file and save the systems and matrices in file "*Gamma_M2*.Qdr". It will also create the matrices and system functions for Matlab analysis.

LQR Control Design

The Matlab file "init.m", which is similar to the previous cases, loads the simulation and design systems and the surface mixing matrix into Matlab and performs the pitch and lateral LQR designs.

```
% File Init.m for Initialization and Perform Control Design
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
[Ave, Bve, Cve, Dve] = vehicle_sim;              % Simulation Model 6-dof
load KmixM2.mat -ascii; Kmix=KmixM2;             % Load Surfaces Mix Logic (7 x 3)

alfa0=8.791; V0=2026.5; Thet0=2.363; 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
[A14,B14,C14,D14]= linmod('Ldes5x');             % 5-state model {p,r,bet,pint,betint}
A15= C14*A14*inv(C14);   B15= C14*B14;           % Stability axis System
C15= C14*inv(C14);       D15= D14;

% Lateral LQR Design Using Only the RCS Jets
R=[1,2]*0.5; R=diag(R);                          % LQR Weights R=[1,1]*2
Q=[10 2 0.5 10 0.01]*1; Q=diag(Q);               % LQR Weights Q=[1 0.4 0.5 0.2 0.005]*3
[Kpr,s,e]=lqr(A15,B15,Q,R)                       % Perform LQR design on Jets
save Kpr_M02_0.mat Kpr -ascii

% Pitch LQR Design Using the 7 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]; Q=diag(Q);                     % LQR Weights {gami,gama,q,alfa}
[Kq,s,e]=lqr(Ap5,Bp5,Q,R)                        % Perform LQR design on Surf
save Kq_M02_0.mat Kq -ascii
```

Pitch Design

The gamma-control design is different from the previous control modes because it is based on a different state-vector and the flight-path angle is directly commanded from guidance. The pitch design model "*Lifting-Body Aircraft Hypersonic Pitch Design Model*" from file "*pitch_des.m*" consisting of states: {θ, q, and α} is modified (using Simulink file Pdes4x.Mdl). A γ-state and its integral are constructed by combining (θ and α). The state-vector in the pitch design model becomes {γ-integral, γ, q, and α}. The γ-integral feedback helps the flight-path angle error converge to zero. α-integral feedback is not required in this case because we are not tracking α. We also take advantage in this case of the almost linear relationship between α and Nz in the implementation of the control system and replace the α-feedback with Nz-feedback because Nz is directly measurable from the accelerometer but not α. The phugoid states (δh and δV) are not included in the design model because they are not directly controlled. The state-feedback is a (1 x 4) gain matrix "Kq_M2_0.mat" that is generated by the LQR algorithm.

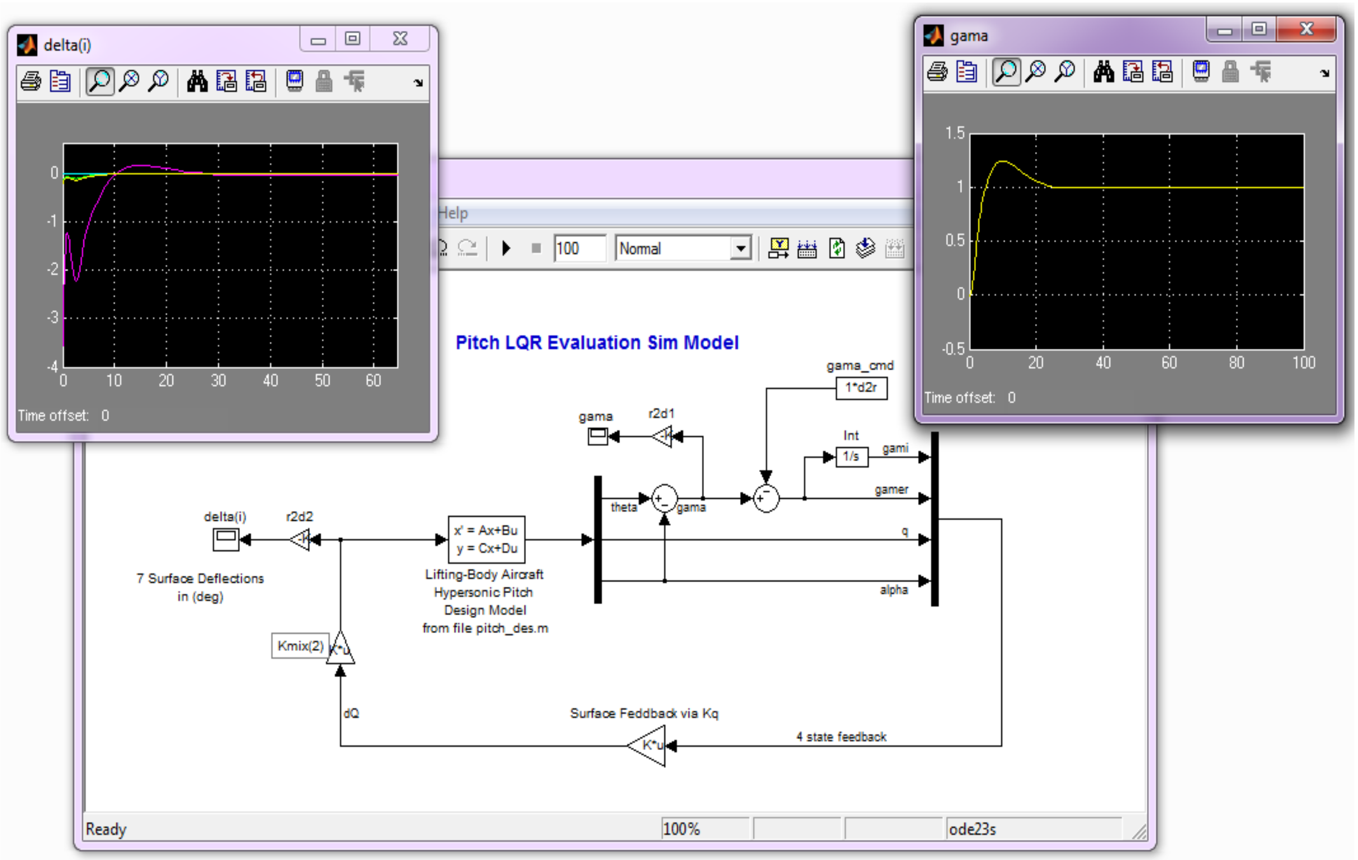


Figure 3.4 Simulink Model "*Sim_Pitch_Simple.Mdl*" for evaluating the Gamma_Control LQR design

The Simulink model "*Sim_Pitch_Simple.Mdl*" in Figure 3.4, is used for evaluating this preliminary LQR design. It includes the state-feedback matrix Kq and the mixing-logic matrix KmixM2. It calculates the system's response to 1° change in alpha. The surface deflections are mainly in the two elevons, but the four body-flaps are also participating by a smaller amount. The Nz feedback is implemented in the 6-dof simulation model.

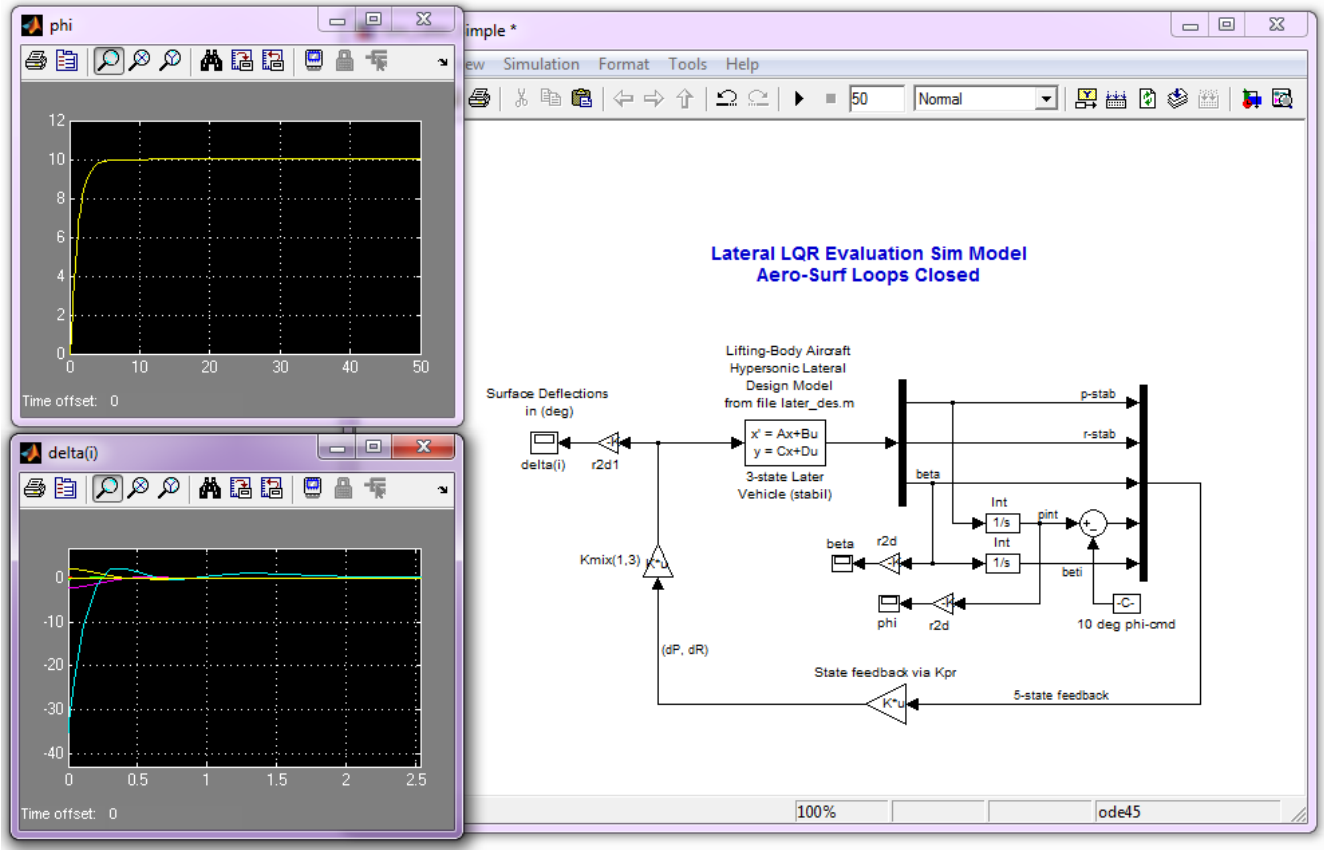


Figure 3.5 Simulink Model "*Sim_Later_Simple.Mdl*" for evaluating the Phi_Control Lateral LQR design

Lateral Design

The lateral design is almost identical to the previous cases. It uses the system "*Lifting-Body Aircraft Hypersonic Lateral Design Model*" from file "*later_des.m*" consisting of states: {p_s, r_s, and β}. The rates are about the velocity vector. The state-vector is augmented (using Simulink file Ldes5x.Mdl) to include also p_s-integral and β-integral. The stability axis model is preferred over the body axis model in the lateral LQR design because the vehicle is commanded to roll about the velocity vector, in order to minimize the beta transients and lateral loads during turns. The lateral dynamic model used in the LQR design also includes the turn-coordination terms. It assumes that turn-coordination is included in the vehicle model. The state-feedback matrix generated by the LQR algorithm using Matlab is a (2 x 5) gain matrix "Kpr_M2_0.mat". The Simulink model "*Sim_Later_Simple.Mdl*", shown in Figure 3.5 is used for evaluating the lateral LQR design. It includes the state-feedback matrix Kpr and the mixing-logic matrix KmixM2.

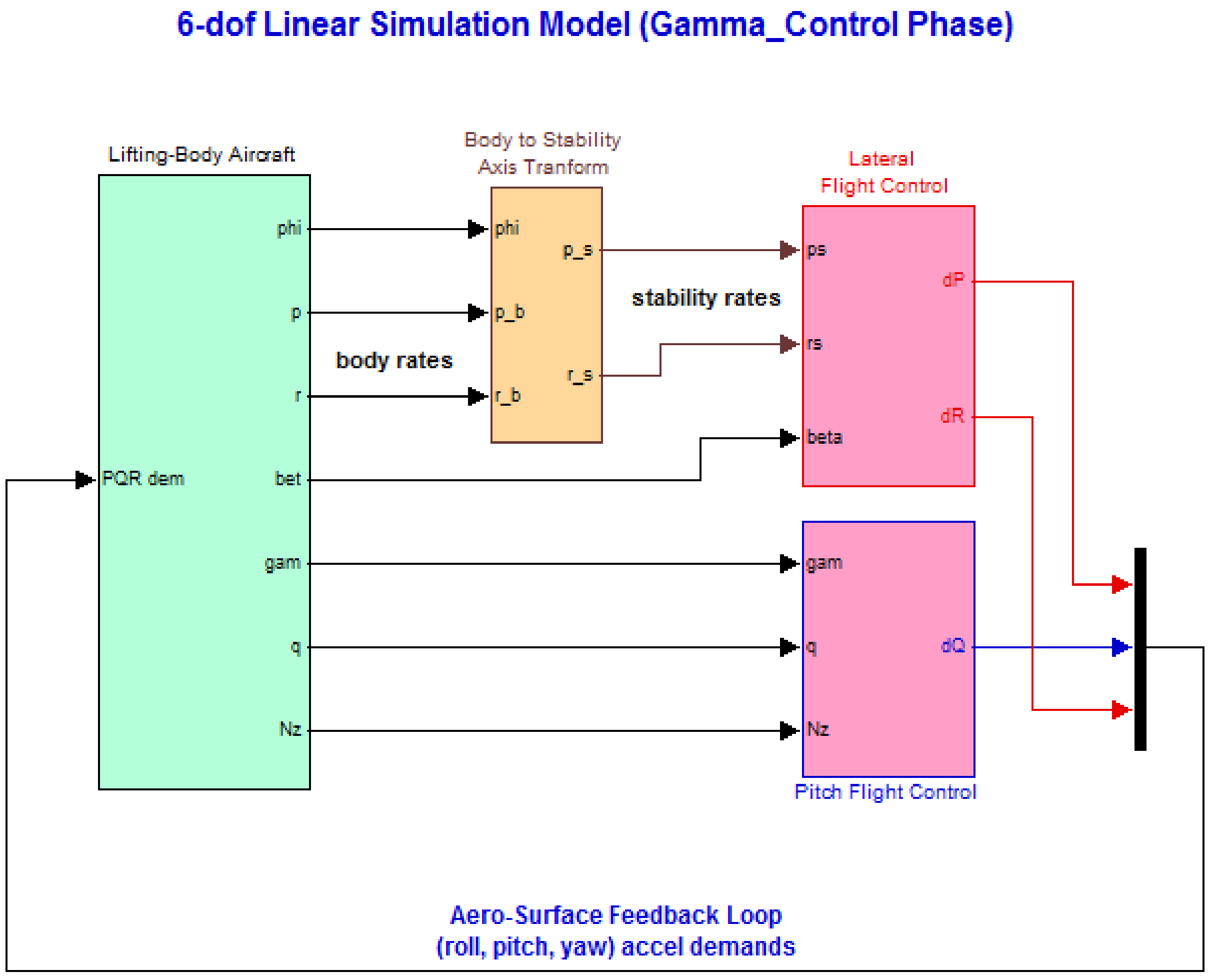


Figure 3.6a Simulation Model in File "Simul_6dof.Mdl"; Notice the pitch controller now uses gamma and Nz feedback.

Linear Simulation Model

The Matlab simulation model for the Mach 2, gamma-control phase, is in file "*Simul_6dof.mdl*" and shown in Figure 3.6. It looks similar to the simulation models of the previous two cases but in the longitudinal direction it uses instead {γ-integral, γ, q, and Nz} feedback, and its input is (γ-command) coming from the closed-loop guidance. This model is used for evaluating the control system's closed-loop response to ϕ and γ commands and also to wind-gusts before implementing it on a non-linear 6-DOF simulation. The vehicle output rates are body rates since the rate-gyro measurements are in body axes and, therefore, a body to stability axis transformation block is included to convert the (p & r) body rates to stability axes rates (p_{stab} & r_{stab}) which are needed by the lateral LQR state-vector feedback, similar to the previous phases. The linearized turn-coordination terms are also included in this block.

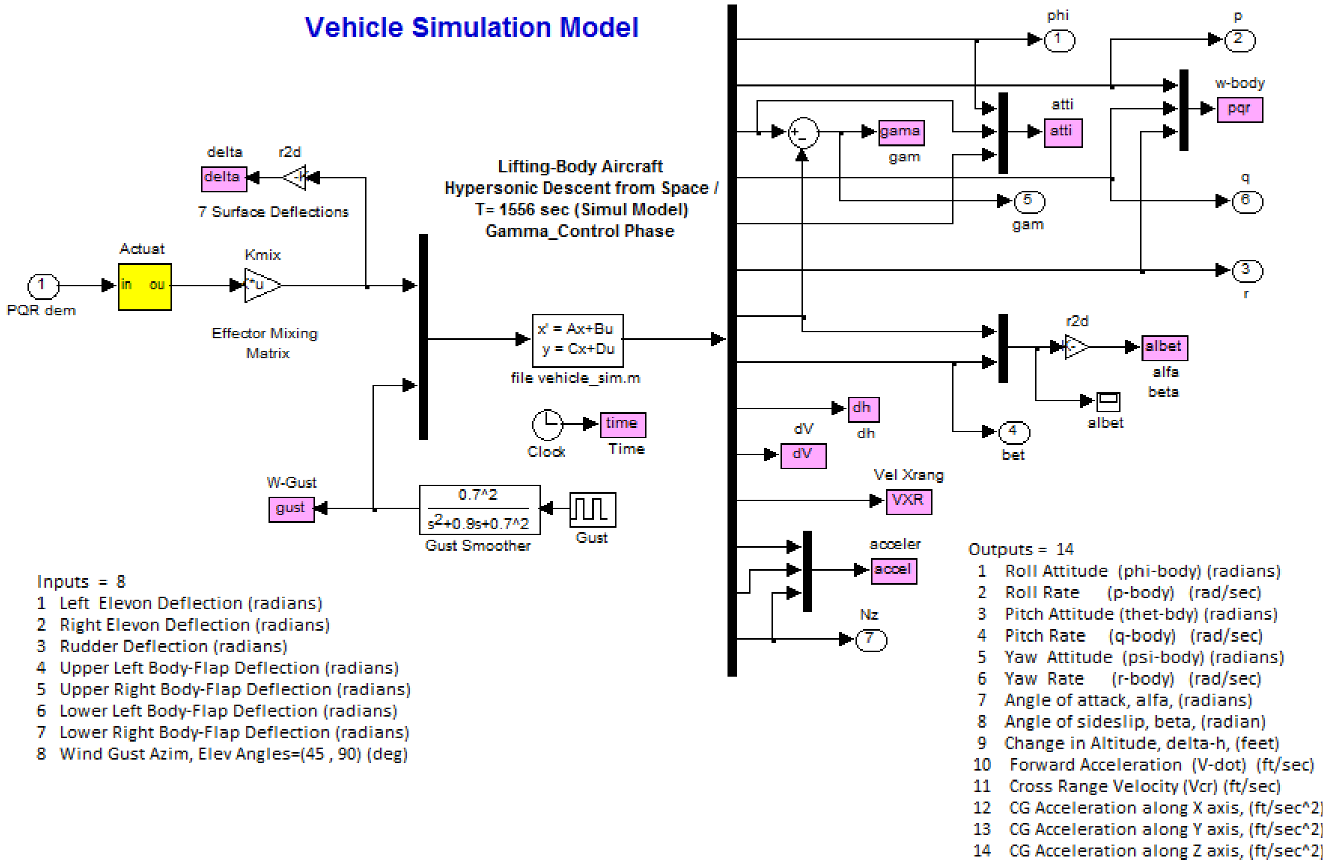


Figure 3.6b Vehicle Dynamics Block including the aero-surface Mixing Logic, Gust disturbance and Actuators

Figure 3.6b shows the vehicle dynamics (green) block expanded. It uses the body-axis vehicle model "*Lifting-Body Aircraft Hypersonic Descent from Space /T= 1556 sec (Simul Model)*" that was generated by Flixan and it is loaded into Matlab from file "*vehicle_sim.m*". The inputs to this block are: roll, pitch, and yaw acceleration demands from flight control which are converted into surface deflections by the surface mixing logic KmixM2. Low-pass filters are also used to model the actuator dynamics. 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 "Gamma_M2.Inp", and it excites both pitch and yaw, perpendicular to the X-body and at 45° between +Y and +Z axes (typical).

The pitch and lateral control laws are state-feedback gains as already described. The pitch controller consists of a (1x4), {γ-integral, γ, q, and Nz} state-feedback gain Kq, (α was replaced with Nz by a gain relationship Nz2a). An Nz-filter was also included. The pitch axis is excited by a γ-command. The lateral controller is a (2x5), (p_s, r_s, β, p_s-integr, β-integr) state-feedback gain Kpr. It is used to perform roll maneuvers by rolling the vehicle about the velocity vector (V_0).

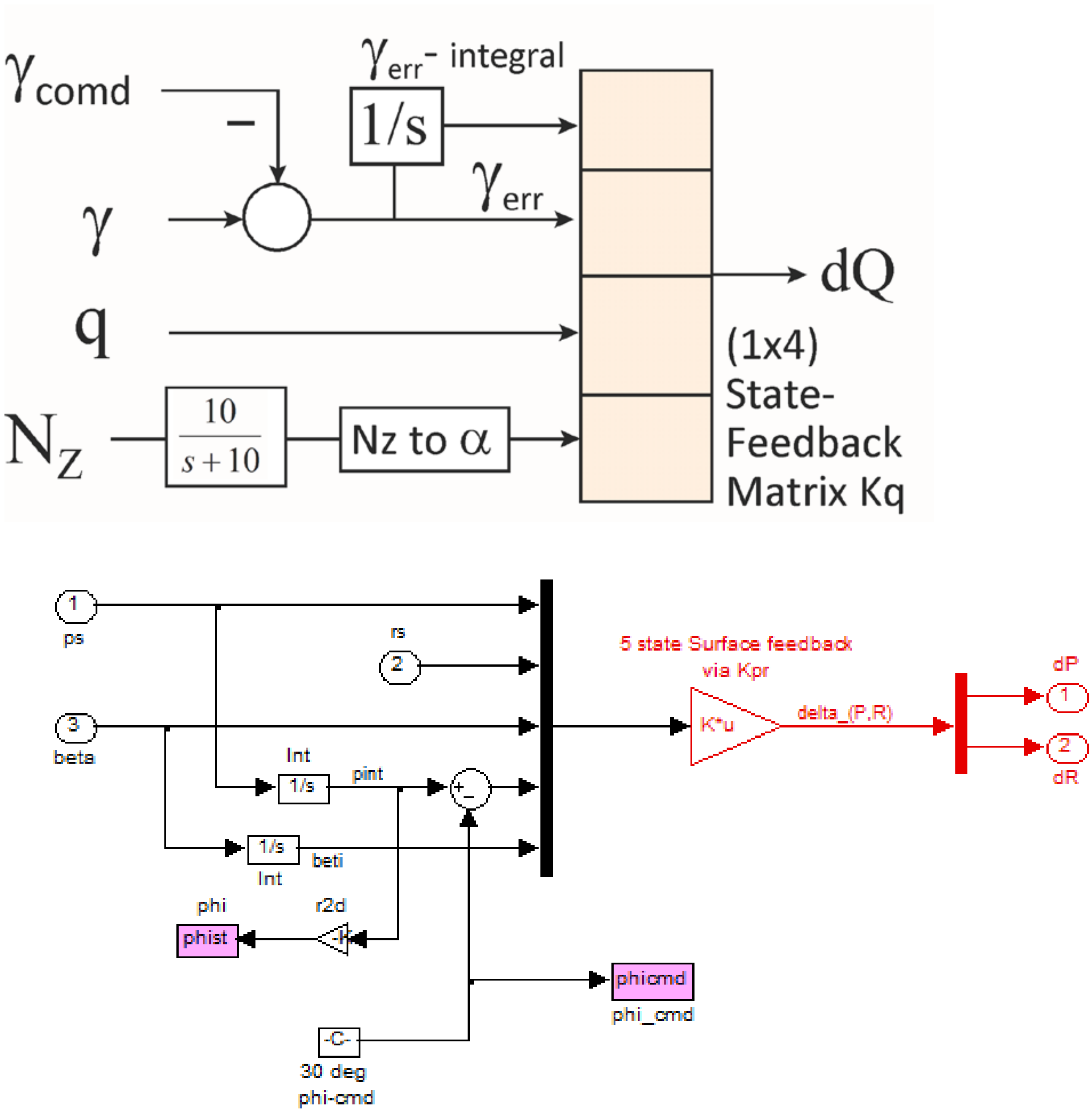


Figure 3.6c Pitch and Lateral state-feedback Control Laws derived by the LQR method

Simulation Results

We will now use the linear simulation model described for the Mach 2 case to perform gamma and roll maneuvers simultaneously. The two commands are: γ_{cmd}=2°, and ϕ_{cmd}=10°. Both variables respond as expected to the step commands. The vehicle rolls 10° about the velocity vector creating a very small sideslip transient in β.

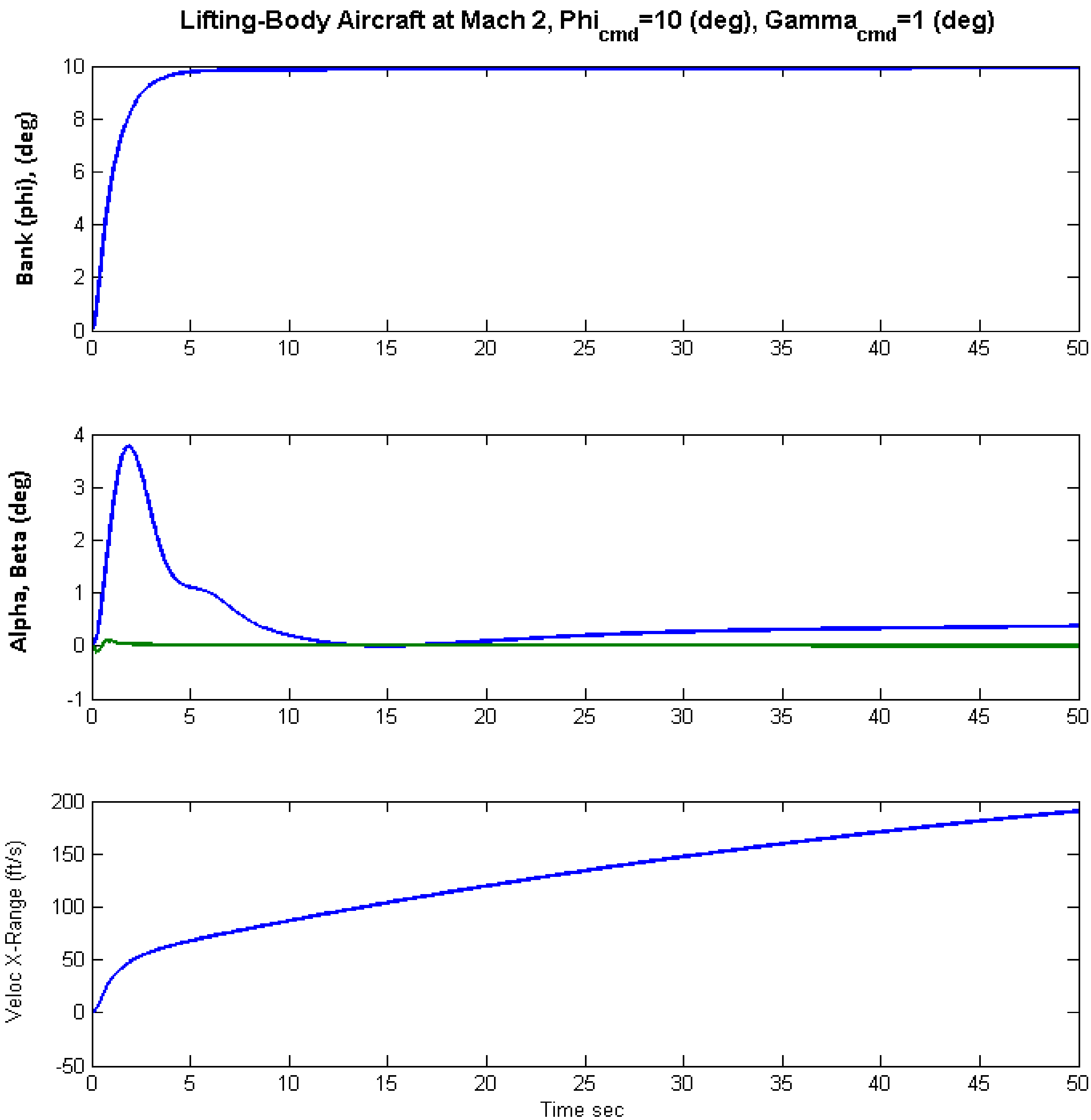


Figure 3.7 Vehicle Response to Simultaneously applied phi and gamma commands at Mach 2

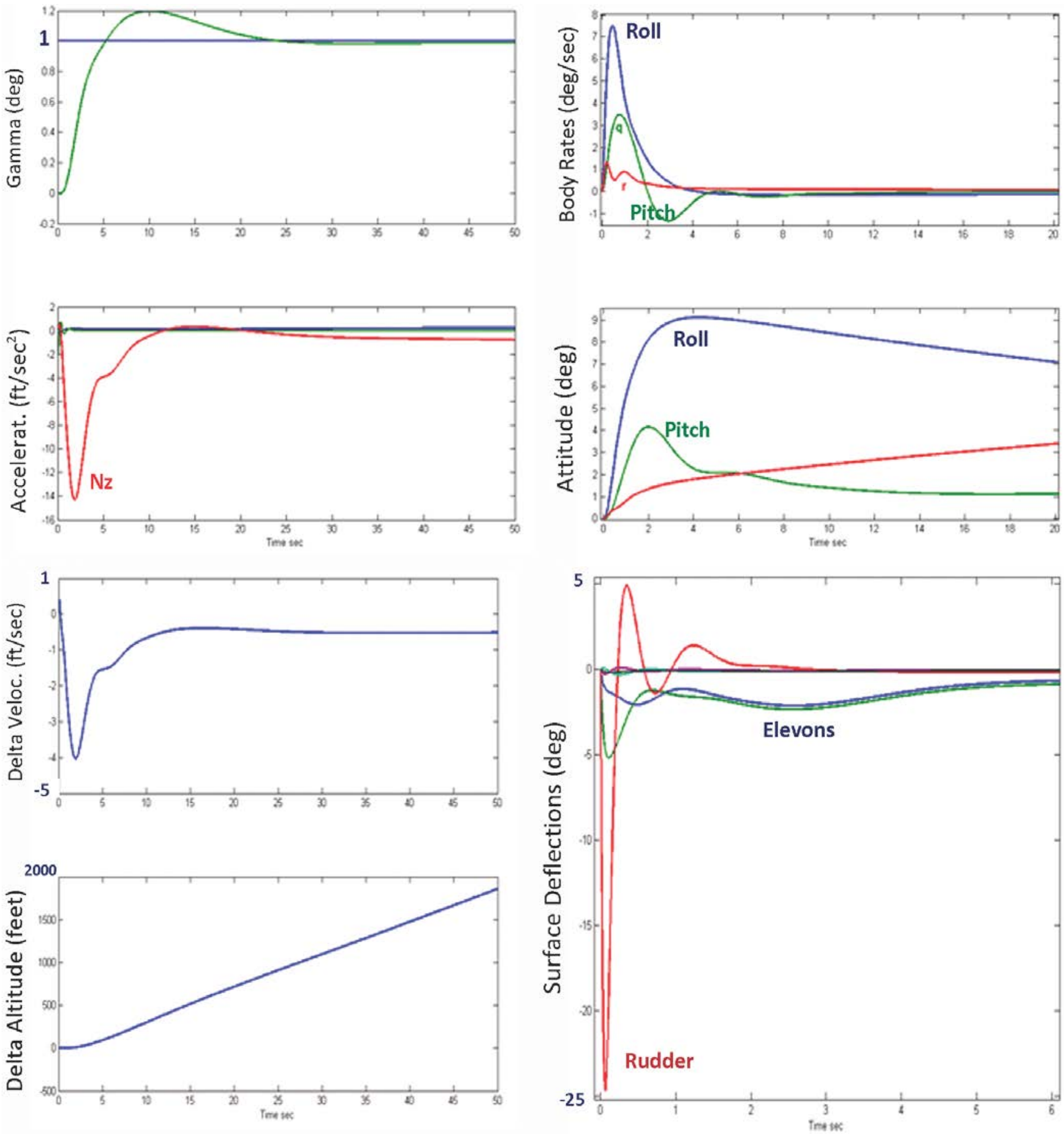


Figure 3.7 Vehicle Response to Simultaneously applied phi and gamma commands at Mach 2

Stability Analysis

Figure 3.8 shows the Simulink model "Stab_Anal.mdl" used for analyzing the stability margins for the Mach 2 case. This model is similar to the simulation "Simul_6dof.Mdl" but it is configured for open-loop analysis. One loop is opened and the other two loops are closed (in the case shown below the roll loop is opened). The Matlab file "Frequ.m" uses this model to calculate the frequency response across the opened loop. The next two figures show the Nichols plots in the pitch and roll directions and the red lines are highlighting the phase margins for the Mach 2 case.

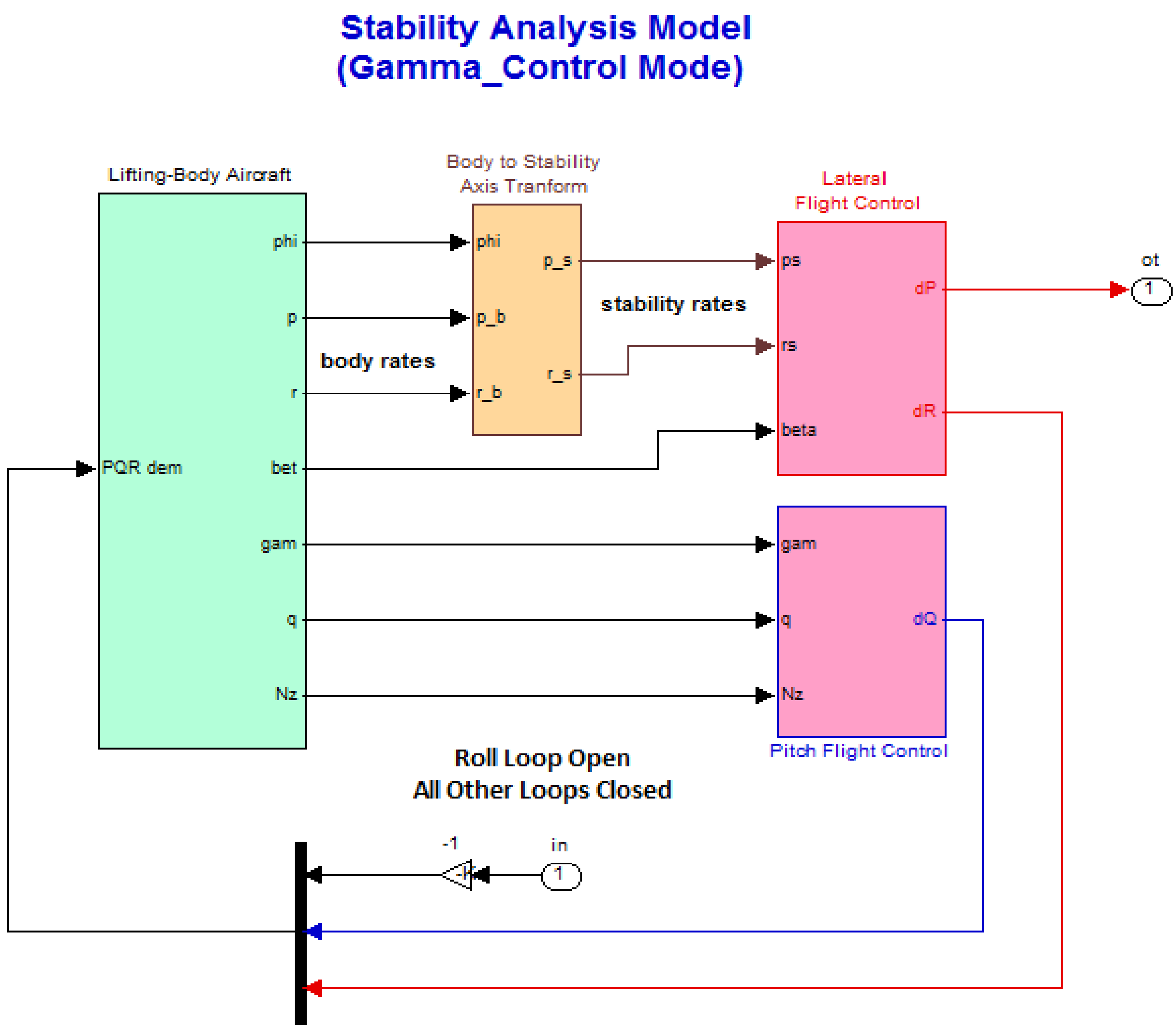
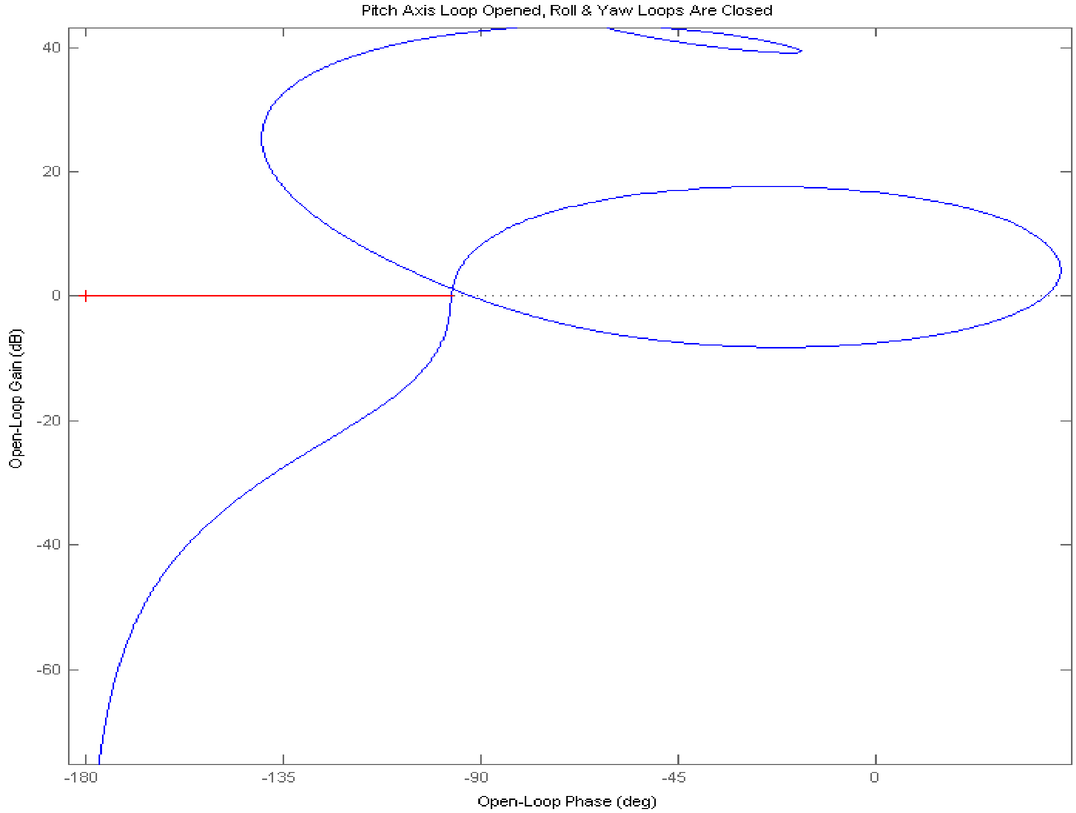
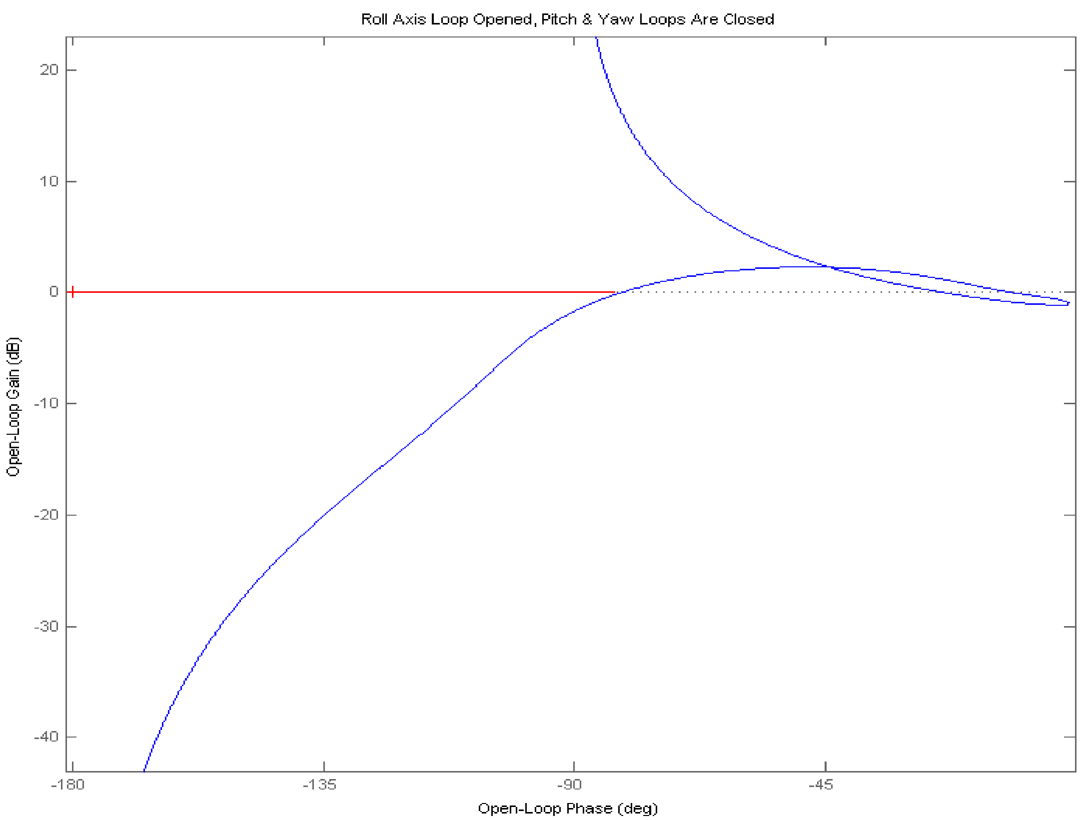


Figure 3.8 Stability analysis model "Stab_Anal.mdl" used for frequency response analysis

Pitch Axis Stability

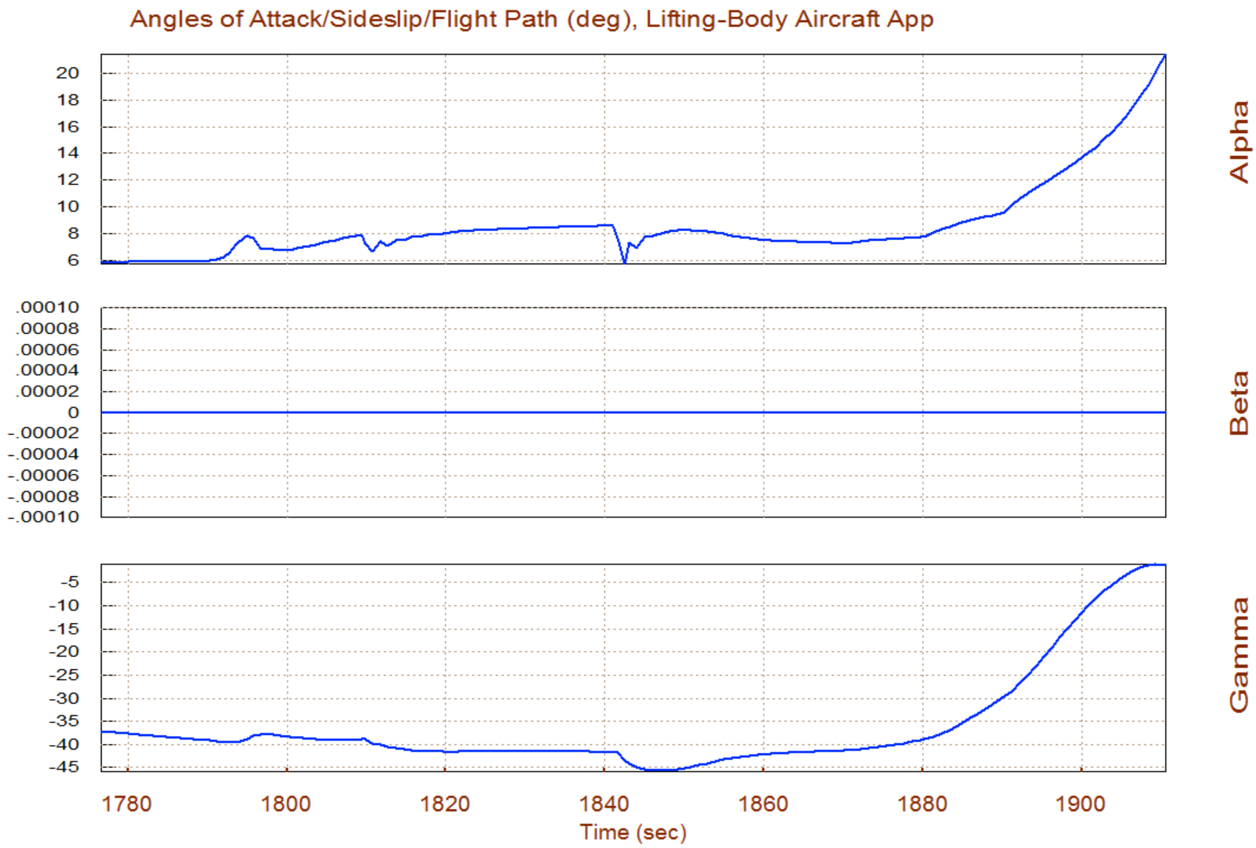


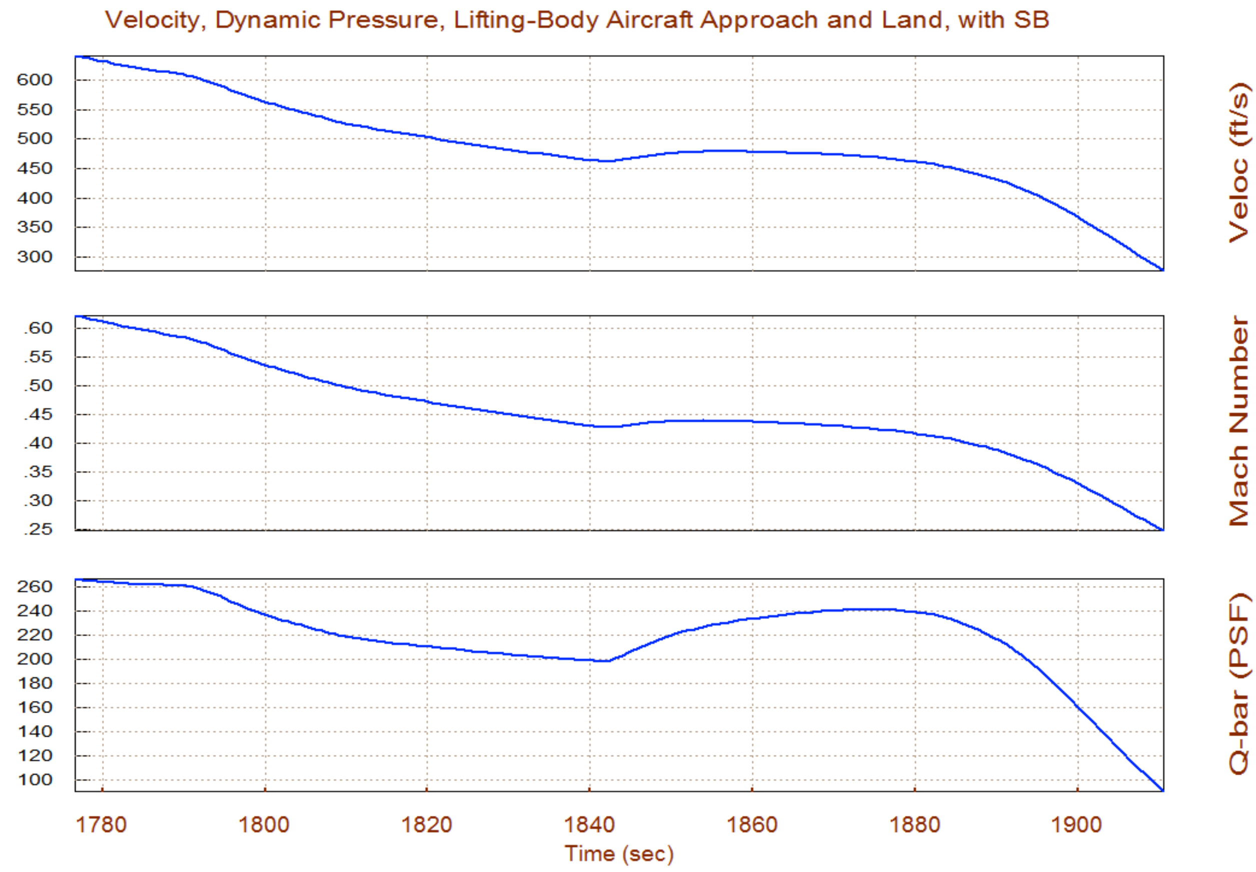
Roll Axis Stability

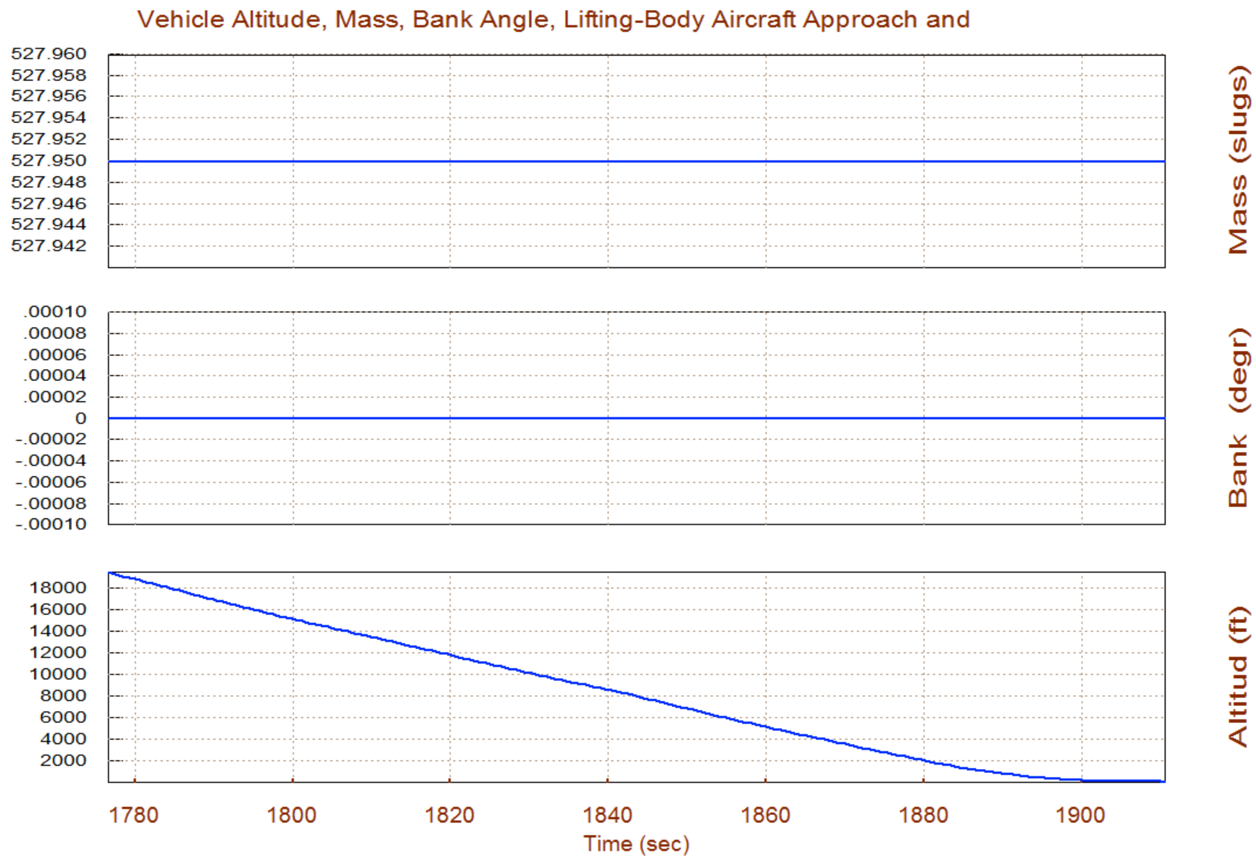


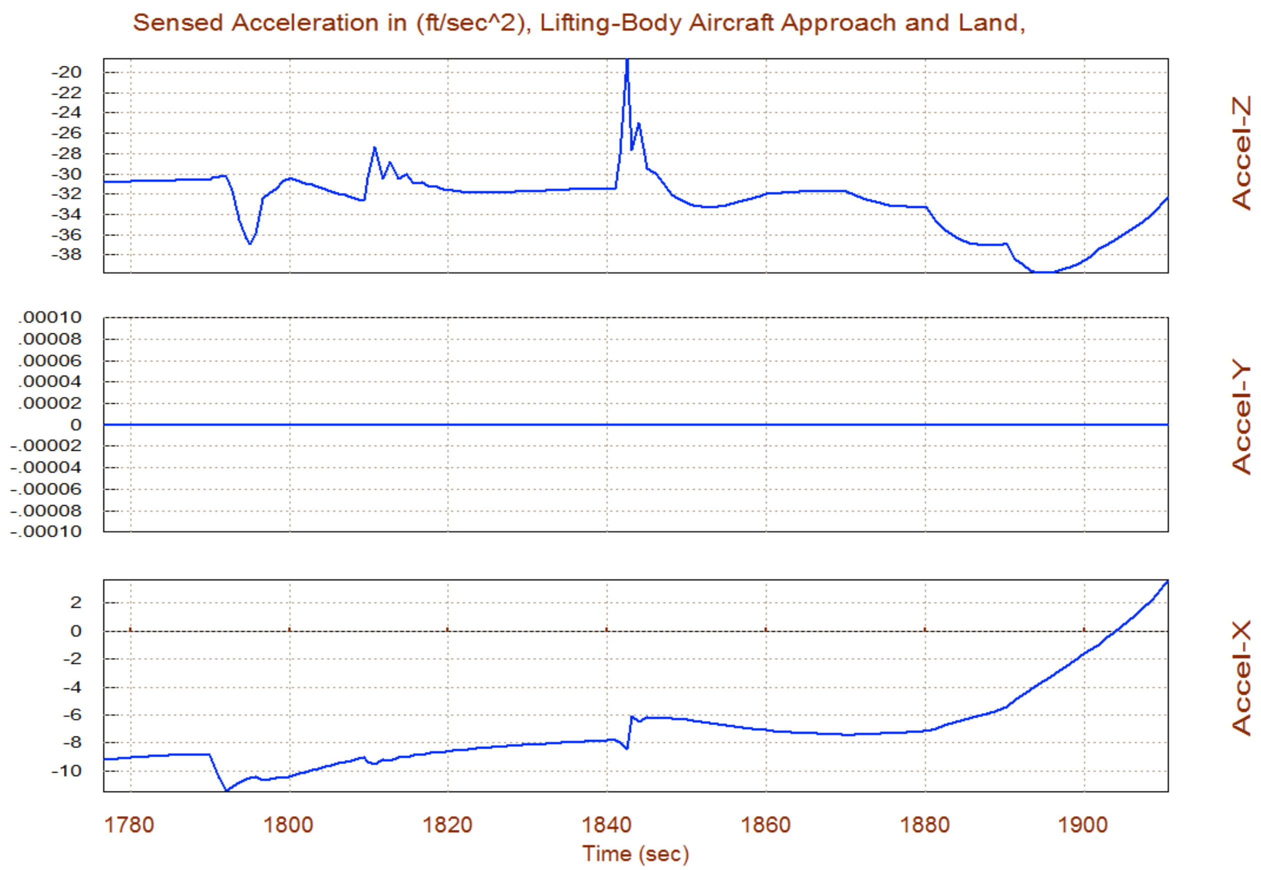
1.4 Approach and Landing Mode

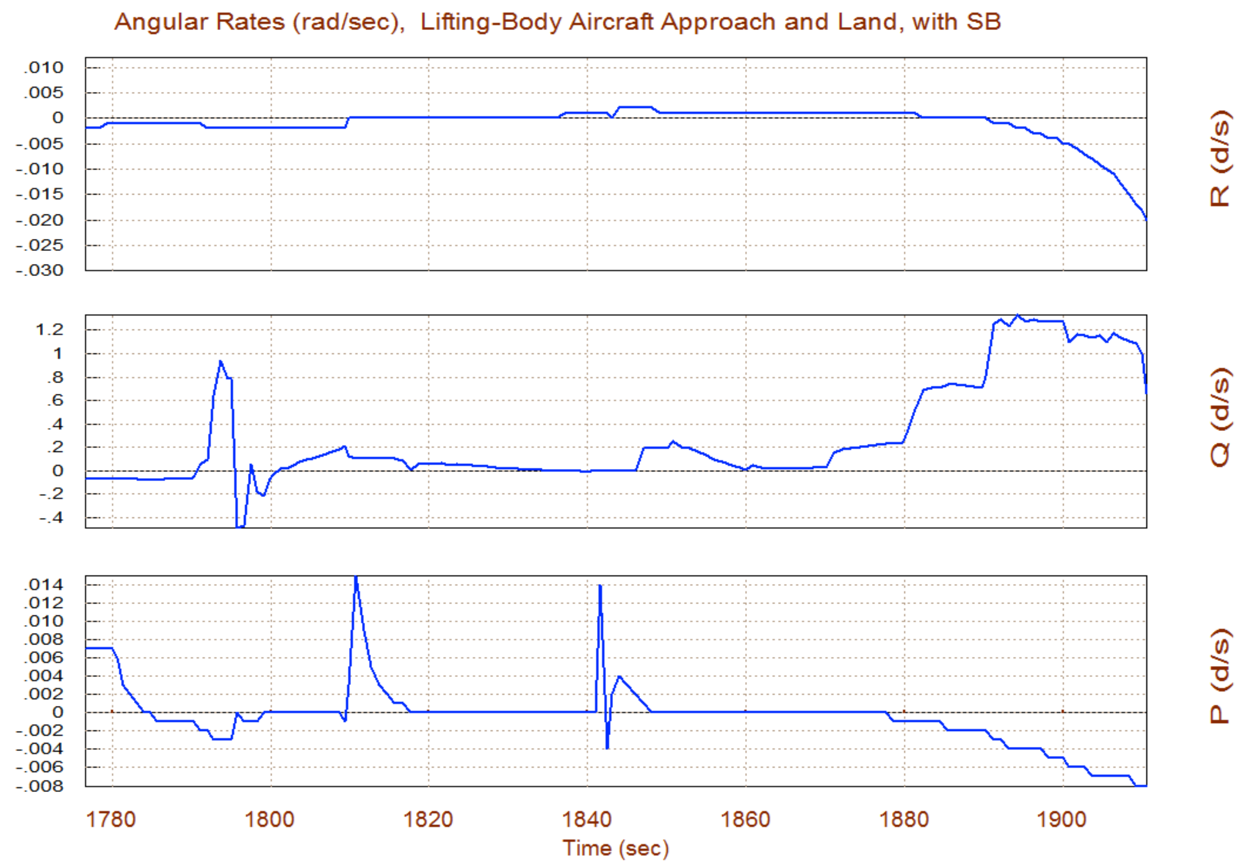
The approach and landing phase is different and more complex in comparison with the previous three phases because it involves additional controls and we will analyze it in more detail. It begins at an altitude of approximately 20,000 (ft) where the vehicle dives at a steep (γ=-50°) angle in order to gain sufficient speed and to be able to perform its final pitch-up flare, where γ must be reduced to almost zero at landing without stalling. The closed-loop guidance system controls altitude and velocity. The flight control system receives changes in altitude and velocity commands from guidance and it translates them to surface deflections. In lateral, there are no major roll maneuvers to perform during this period because the vehicle is already aligned with the runway. Small directional errors detected by the landing system due to cross-winds become commands to the heading control system and they are converted to small roll adjustments that correct the misalignments. The aerosurface mixing logic used in the analysis is a fixed matrix "KmixM0p4b" that was designed for a fixed flight condition. It is already prepared and saved in file "*Kmix.Qdr*". It includes a 4th column, in addition to roll, pitch, and yaw, which provides drag control via the speed-brake. In the non-linear simulation, however, the mixing logic matrix is scheduled just like the control gains. The approach and landing section of the trajectory is analyzed in folder "*C:\Flixan\Trim\ Examples\ Lifting-Body Aircraft\Reentry from Space\Trim_Anal\Approach_Land*". The trajectory is in file "*Apprch_Land.Traj*". The remaining files are the same as in the previous sections. We begin by showing some of the trajectory parameters during the approach and landing phase between Mach (0.7 to 0.3). Notice that the speed-brake is partially deployed for a 55 sec period before landing, between t=1790 to t=1845 sec. The speed-brake is mechanized by differential body-flap deflections controlled by the 4th column of the mixing-logic matrix. By partially deploying the speed-brake it enables the velocity control system to modulate the vehicle drag and thus control speed against wind variations. The speed-brake, however, is re-deployed about a minute before touch-down to enable better pitch/altitude control which is more critical for the final flare. Notice how the speed increases before the pitch-up flare when the speed-brake is re-deployed. Then we trim the aerosurfaces and repeat a similar and performance analysis for this section of the trajectory, design and analyze the landing flight-control system which is significantly different here because in the longitudinal axis we now have two separate control loops for altitude and velocity control. We will also use the Flixan program to generate uncertainty models and analyze the flight control system robustness to structured parameter variations by using μ-analysis.

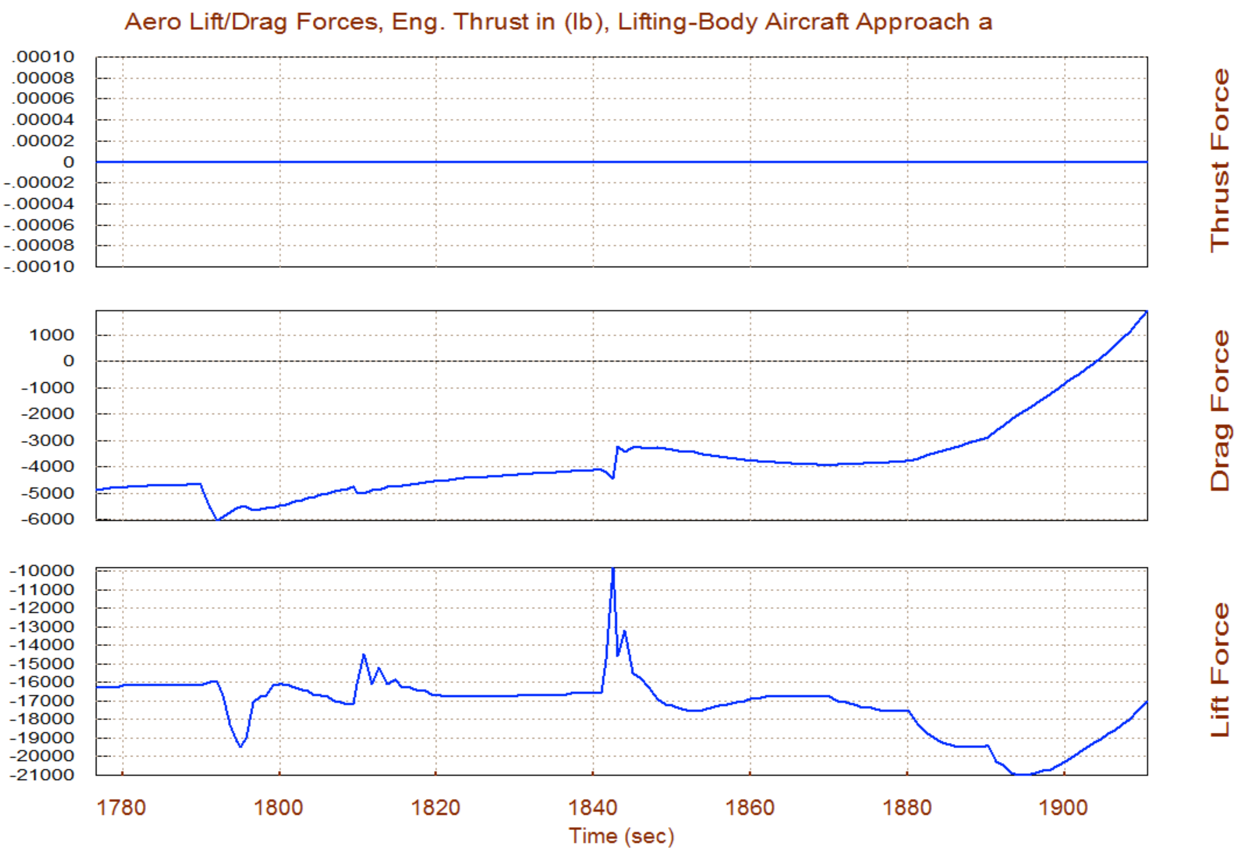

Angles of Attack/Sideslip/Flight Path (deg), Lifting-Body Aircraft App
Alpha
Beta
Gamma
Time (sec)


Velocity, Dynamic Pressure, Lifting-Body Aircraft Approach and Land, with SB
Veloc (ft/s)
Mach Number
Q-bar (PSF)
Time (sec)


Vehicle Altitude, Mass, Bank Angle, Lifting-Body Aircraft Approach and
Mass (slugs)
Bank (degr)
Altitud (ft)
Time (sec)

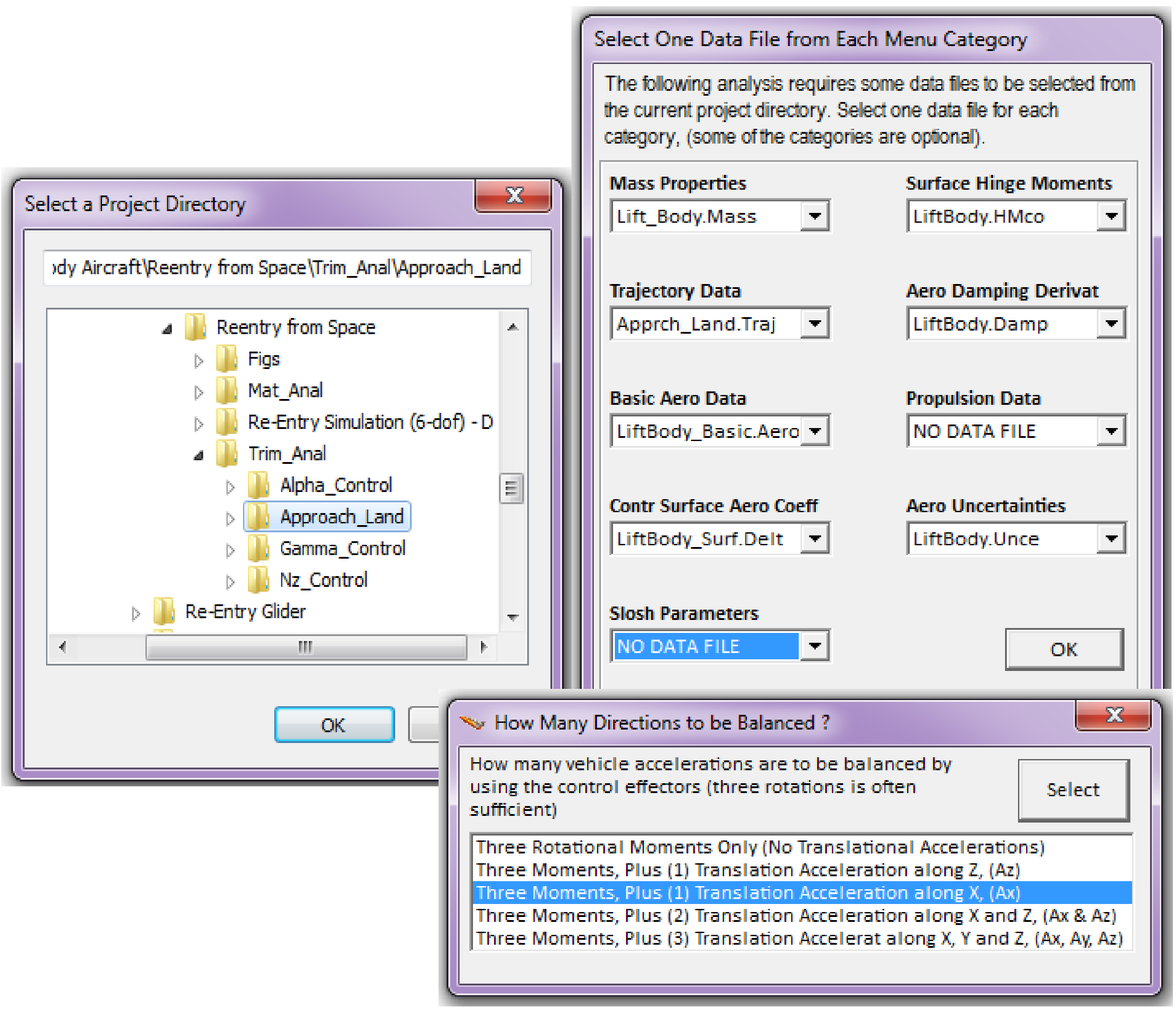

Sensed Acceleration in (ft/sec^2), Lifting-Body Aircraft Approach and Land,
Accel-Z
Accel-Y
Accel-X
Time (sec)

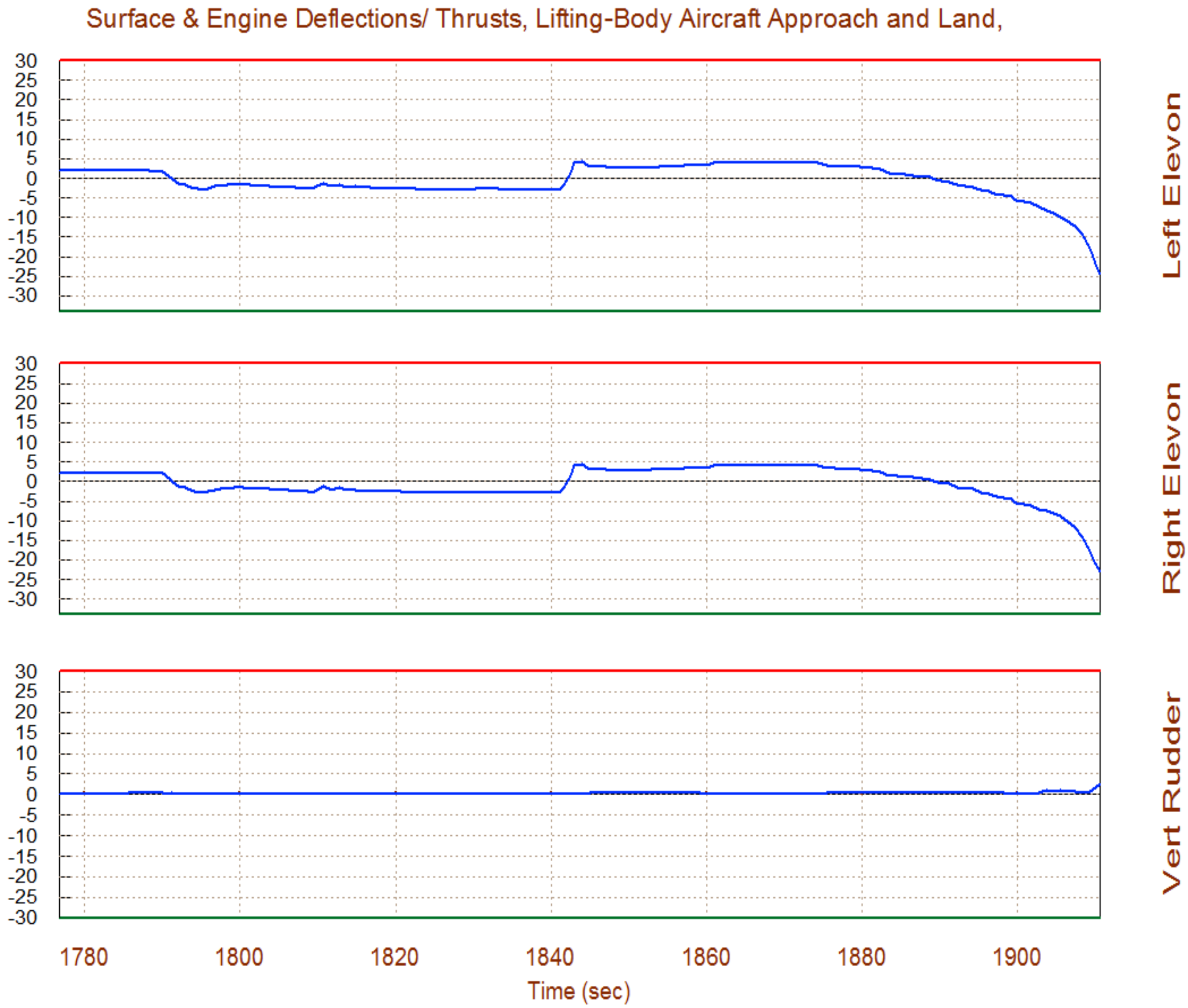

Angular Rates (rad/sec), Lifting-Body Aircraft Approach and Land, with SB
R (d/s)
Q (d/s)
P (d/s)
Time (sec)


Aero Lift/Drag Forces, Eng. Thrust in (lb), Lifting-Body Aircraft Approach a
Thrust Force
Drag Force
Lift Force
Time (sec)

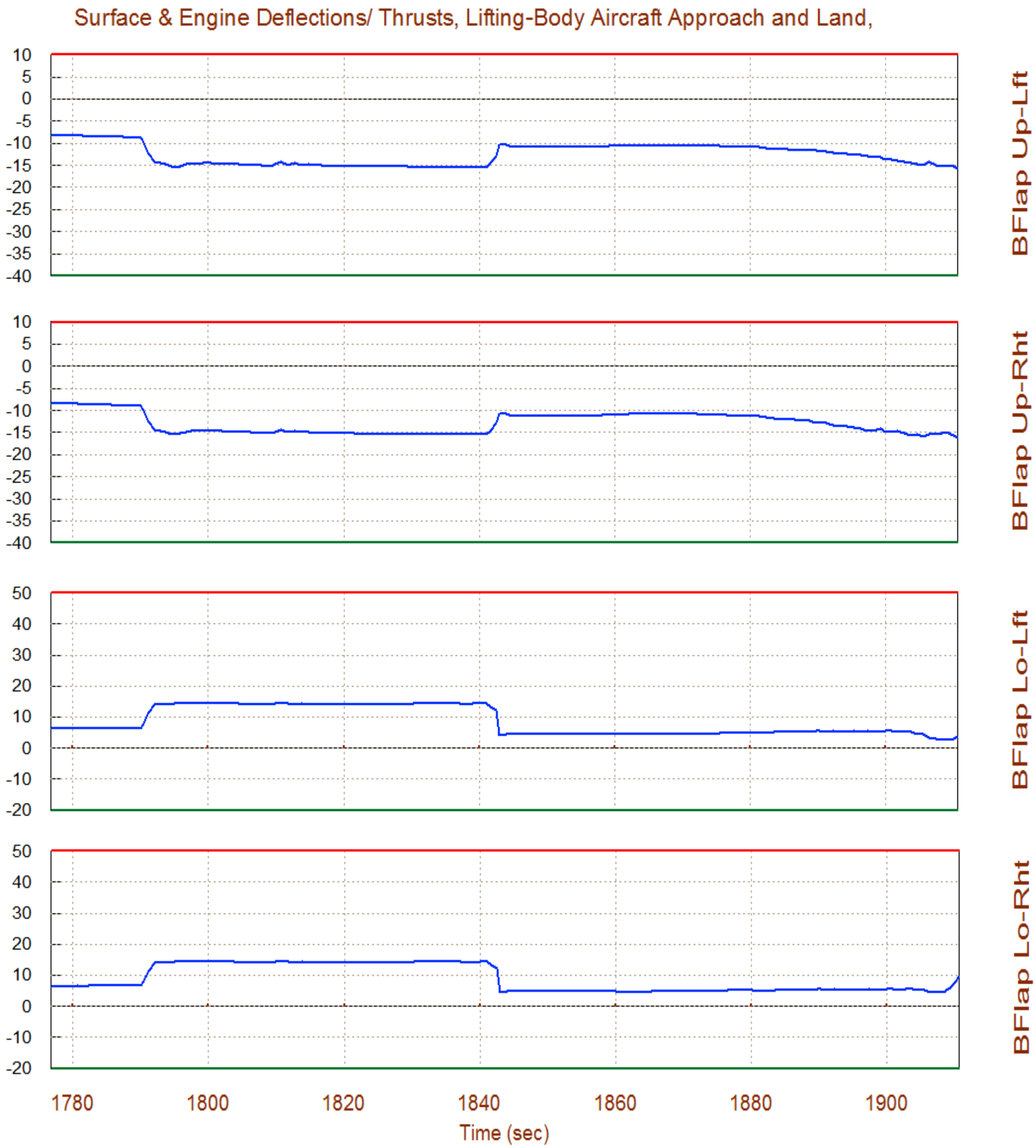
Aerosurface Trimming

We will trim the aero-surfaces along the approach and landing section of the trajectory to balance not only the 3 vehicle moments but also the axial acceleration along the trajectory. The x-acceleration is included in the aero-surface trimming process because a velocity control loop will be included in the control system to provide control in the x-direction. It is modulating drag by means of controlling the opening of the speed-brake. The mixing logic matrix must be designed to receive the deceleration control demand and to translate it to speed-brake opening. The trimming algorithm must balance the 3 moments and also the axial acceleration along the target trajectory according to the control authority of each aerosurface. Start Flixan and select the appropriate files in folder "*C:\Flixan\ Trim\ Examples\Lifting-Body Aircraft\Reentry from Space\Trim_Anal\ Approach-Land*". From the Trim main menu choose option-3 for trimming, do not select a trim initialization file and select to trim along the three rotational moments, roll, pitch, and yaw, plus the x-acceleration. The program will determine a combination of surface deflections that balance the moments and the x-acceleration based on the control capability of each surface. The trim deflections are saved in file "*Apprch_Land.Trim*".





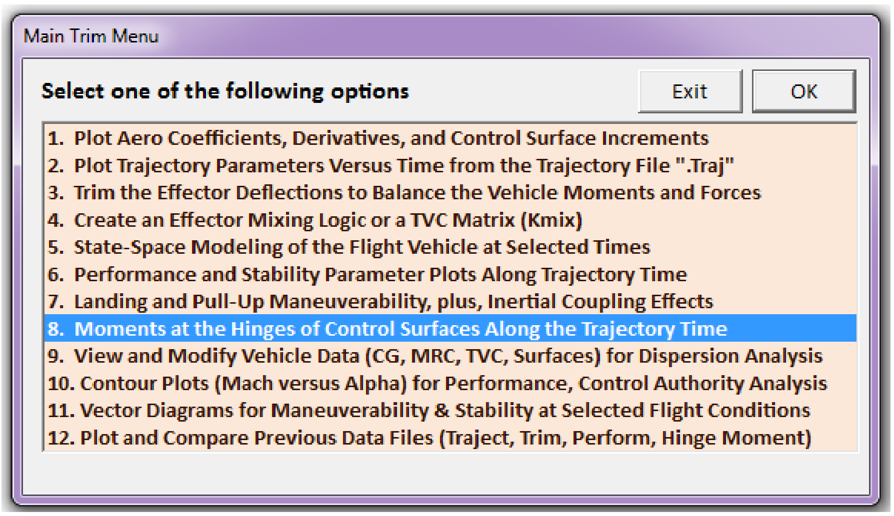
Notice that the Elevon deflections are negative (up) during the final flare in order to generate the required pitching moment to bring γ=0. Notice also the four body-flap deflections during the period of a partial speed-brake deployment (1790 to 1845) sec. Remember that these are trim results and not simulations. The effector deflections are calculated by the Trim program in order to balance the moments and match the x-acceleration along the specified trajectory. The aero-surface bias angles in the surface deflections file "*LiftBody_Surf.Delt*" were preset to fixed values close to the average trim angles obtained from the 6-dof simulation.

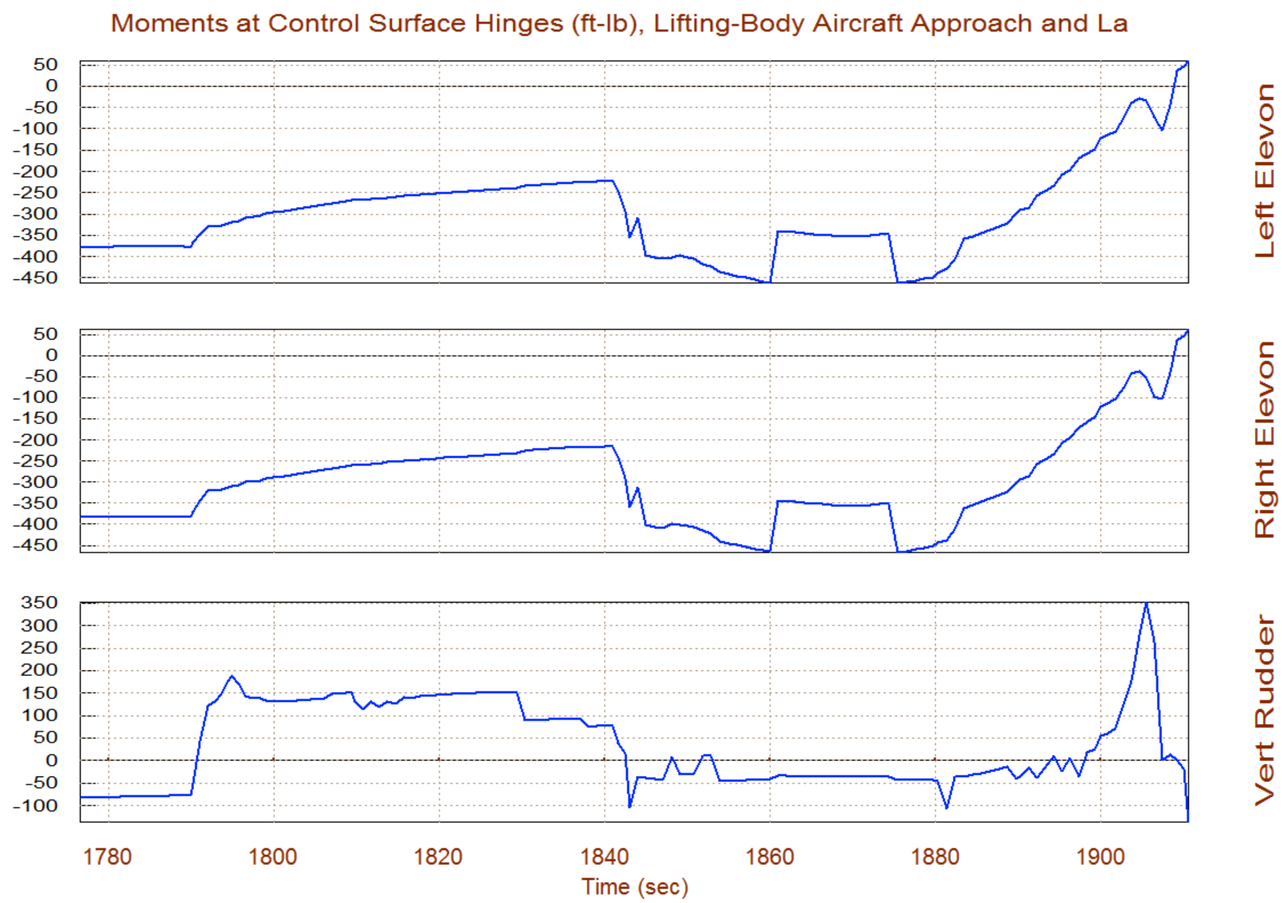


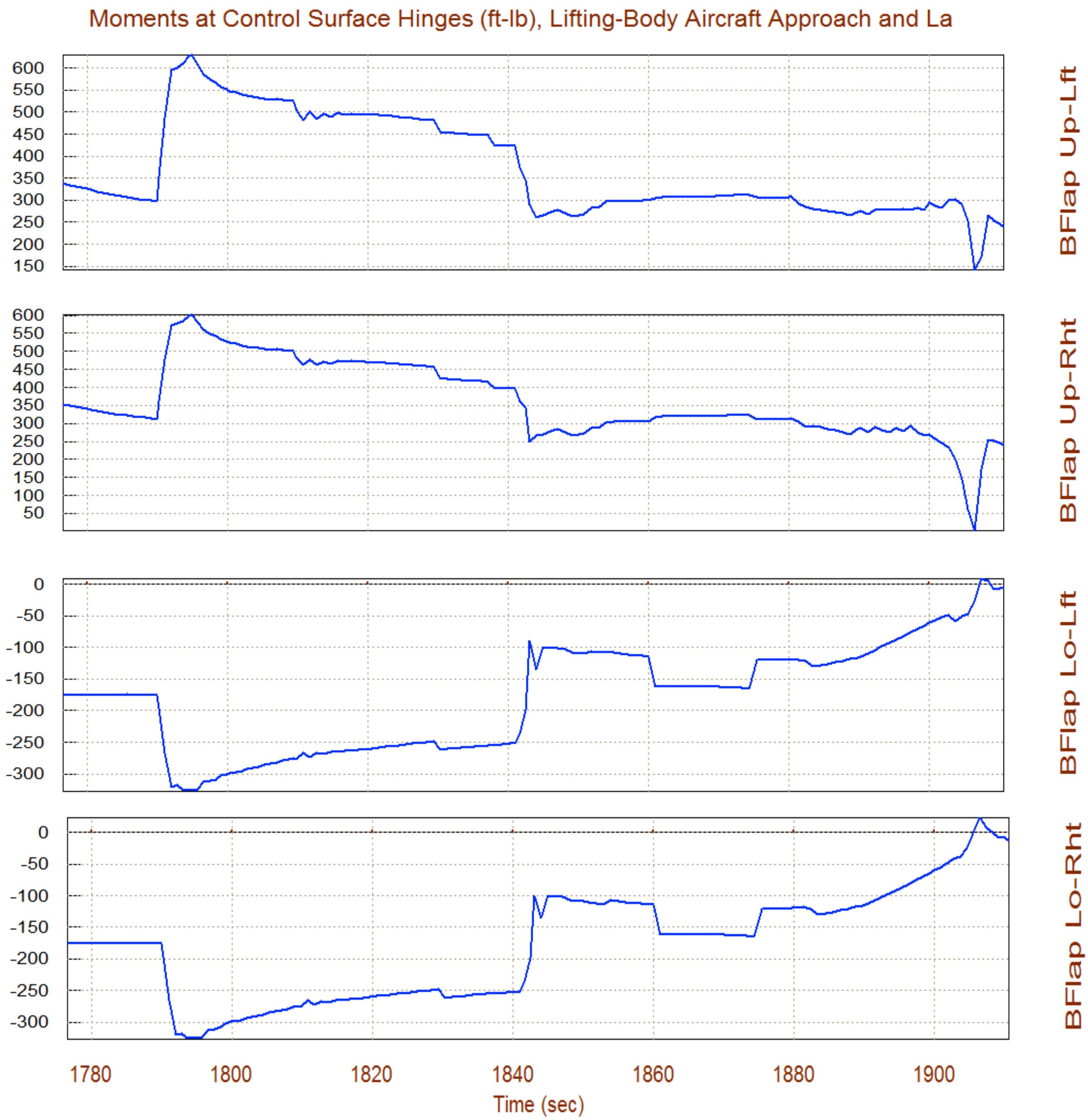
Surface & Engine Deflections/ Thrusts, Lifting-Body Aircraft Approach and Land,
10
5
0
-5
-10
-15
-20
-25
-30
-35
-40
BFlap Up-Lft
BFlap Up-Rht
50
40
30
20
10
0
-10
-20
BFlap Lo-Lft
BFlap Lo-Rht
1780
1800
1820
1840
1860
1880
1900
Time (sec)

Hinge Moments along the Trajectory

The hinge moments, option-8 from the Trim main menu, calculates and plots the moments at the hinges of the 7 aero-surfaces as a function of time, as the vehicle follows the specified trajectory. It uses the hinge-moment coefficients data from file "*LiftBody.HMco*" to calculate the moments as described by equation (3.50). The hinge moments are saved in file "*Apprch_Land.HiMo*", as a function of the trajectory time.



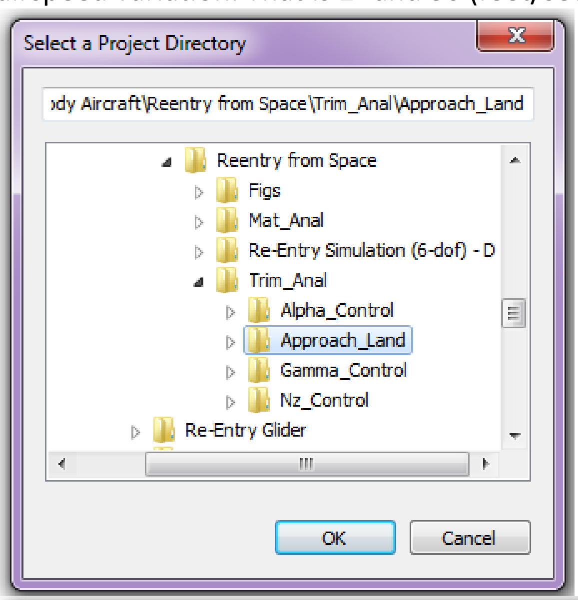


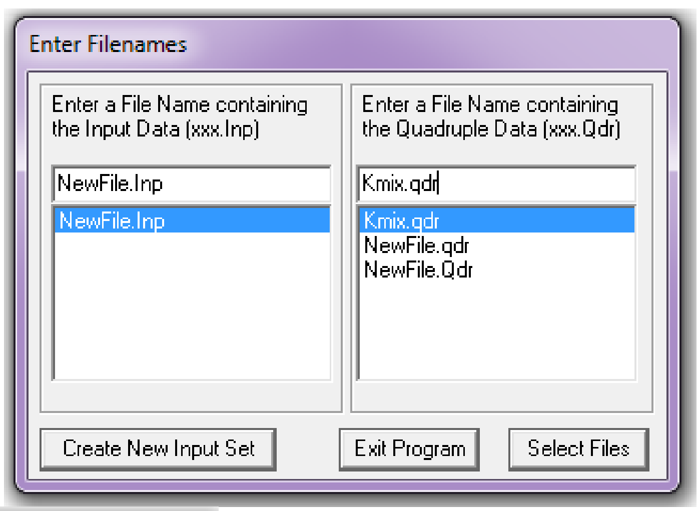


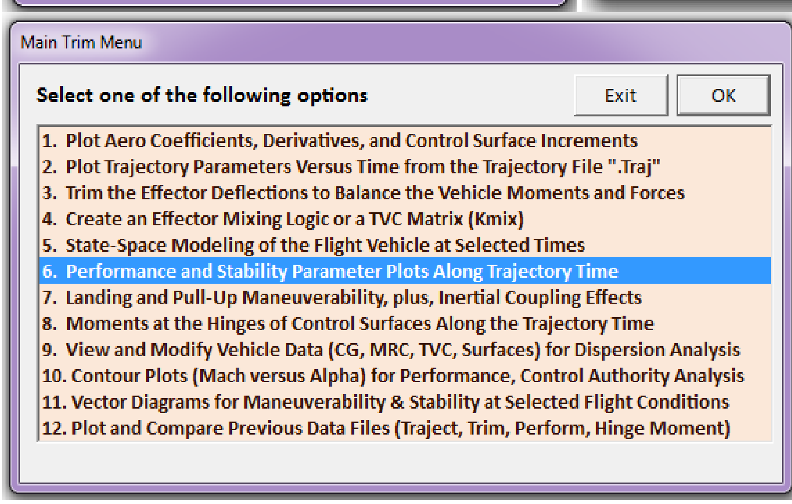
This option is useful in sizing the actuator torques. It is, however, available only when a hinge moment coefficients file (.HMco) is available.

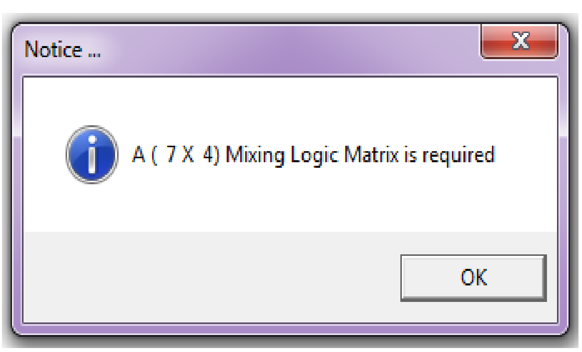
Performance Parameters along the Trajectory

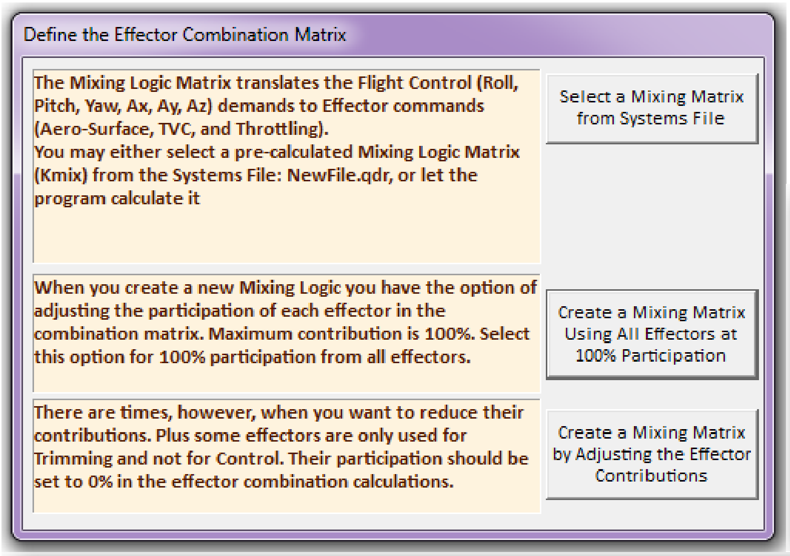
Before beginning the performance analysis it is important to select the systems file "Kmix.Qdr" which includes the control-surface mixing matrix "KmixM0p4b". The mixing logic matrix defines how the aero-surfaces combine together to allocate control along roll, pitch, yaw, and axial control, and the control authority (or effort) parameters strongly depend on this matrix. The fourth column in matrix "KmixM0p4b" is the axial acceleration demand and specifies the opening of the four body-flaps that implement the speed-brake function for axial acceleration control. It is mainly a combination of upper and lower differential body-flap deflections that modulate drag. This axial acceleration control input is of course applicable only during the period where the speed-brake is partially deployed, and a different mixing logic is used otherwise. However, to avoid complicating the analysis we will keep a constant mixing logic matrix in the entire approach and landing trajectory. From the Trim main menu select option-6 to calculate the static performance parameters along the trajectory. The program requests a (7x4) mixing matrix since we have included the axial direction when trimming. The Flixan mixing-logic algorithm was used to generate the mixing matrix. The matrix, however, was slightly modified to improve the LCDP by introducing more rudder participation in roll. We must also define the maximum dispersions from trim in the aerodynamic angles α_{max} and β_{max}, and the maximum airspeed variation. That is 2° and 30 (feet/sec) due to wind-shear disturbances or maneuvering.

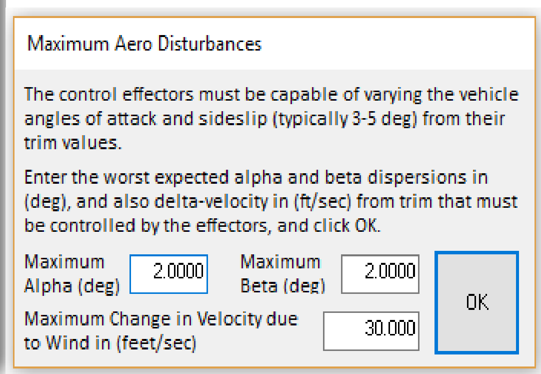


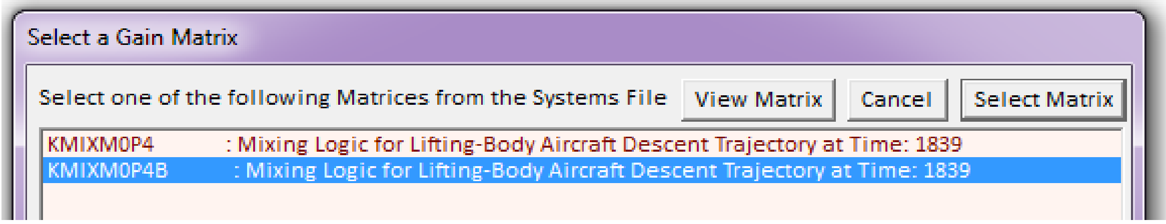


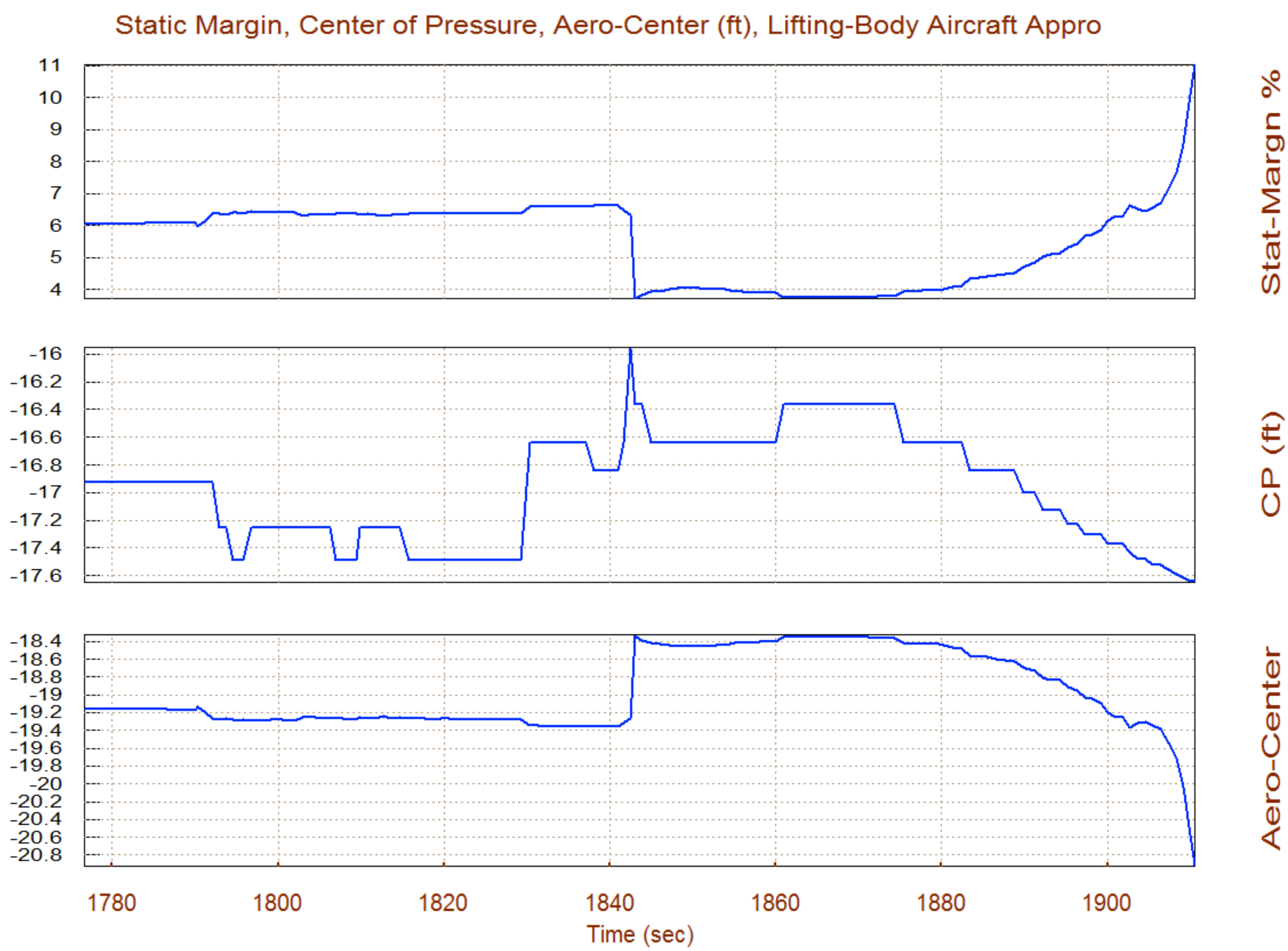


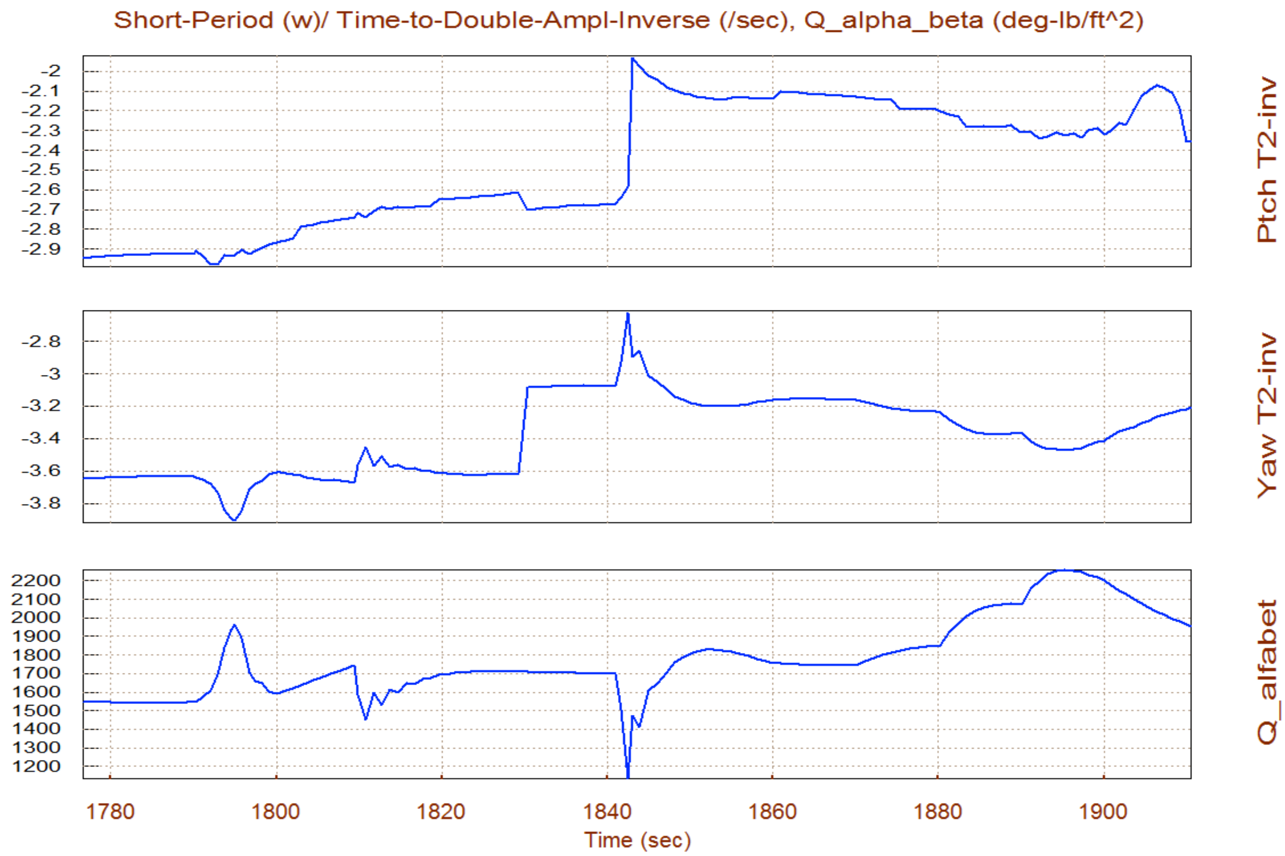



Define the Effector Combination Matrix
The Mixing Logic Matrix translates the Flight Control (Roll, Pitch, Yaw, Ax, Ay, Az) demands to Effector commands (Aero-Surface, TVC, and Throttling).
You may either select a pre-calculated Mixing Logic Matrix (Kmix) from the Systems File: NewFile.qdr, or let the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

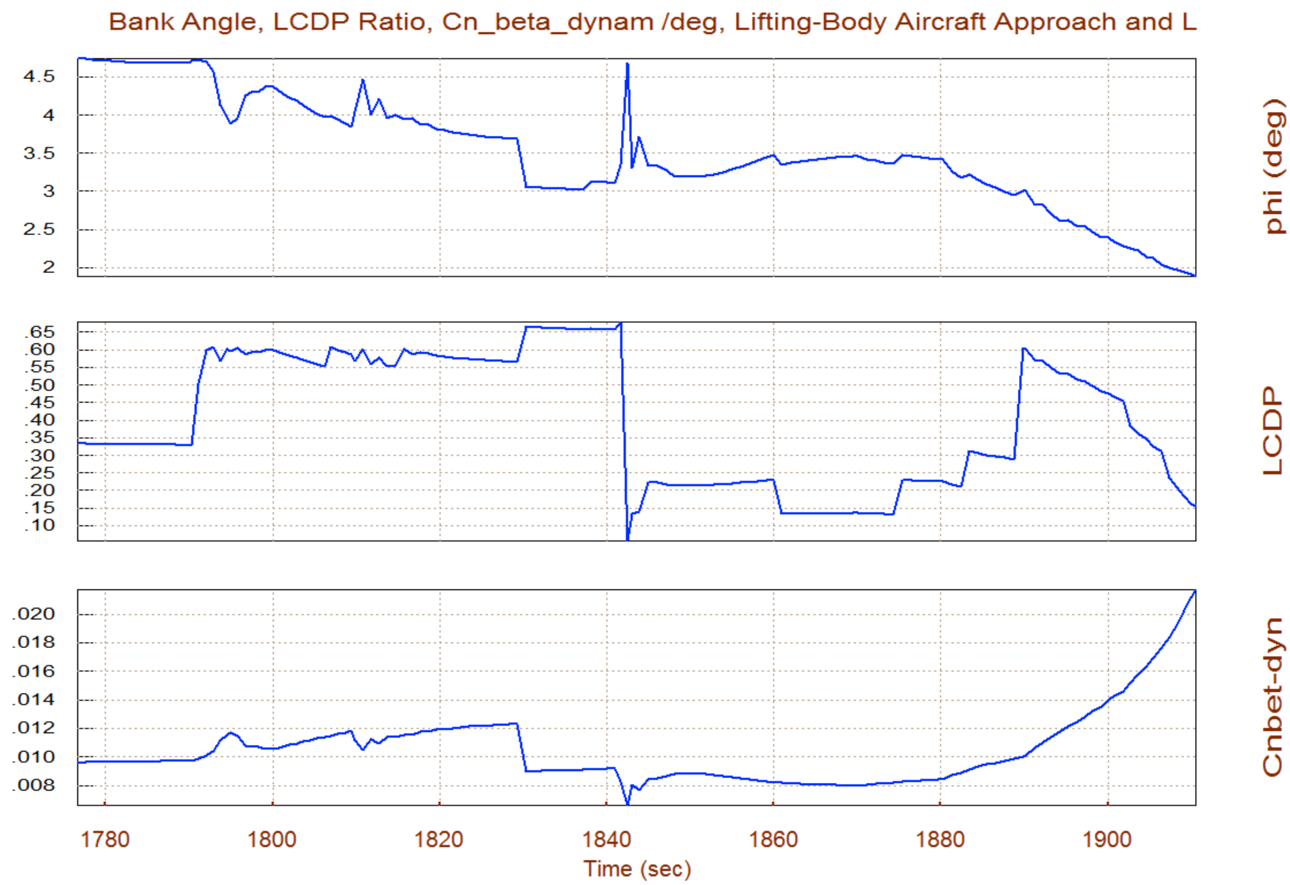

Maximum Aero Disturbances
The control effectors must be capable of varying the vehicle angles of attack and sideslip (typically 3-5 deg) from their trim values.
Enter the worst expected alpha and beta dispersions in (deg), and also delta-velocity in (ft/sec) from trim that must be controlled by the effectors, and click OK.
Maximum Alpha (deg)
2.0000
Maximum Beta (deg)
2.0000
OK
Maximum Change in Velocity due to Wind in (feet/sec)
30.000


Select a Gain Matrix
Select one of the following Matrices from the Systems File
View Matrix
Cancel
Select Matrix
KMIXM0P4 : Mixing Logic for Lifting-Body Aircraft Descent Trajectory at Time: 1839
KMIXM0P4B : Mixing Logic for Lifting-Body Aircraft Descent Trajectory at Time: 1839

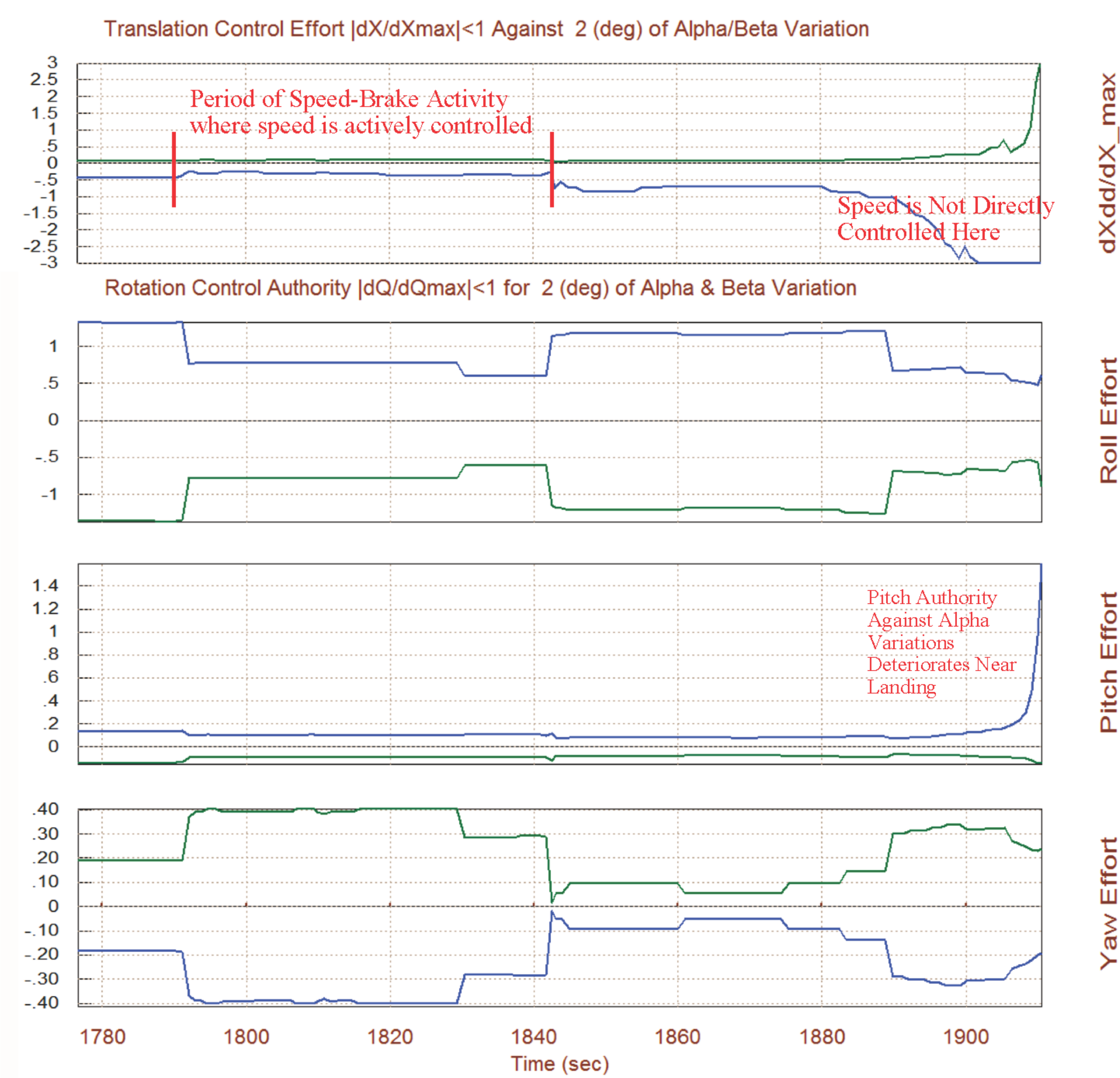

Static Margin, Center of Pressure, Aero-Center (ft), Lifting-Body Aircraft Appro
Stat-Margn %
CP (ft)
Aero-Center
Time (sec)



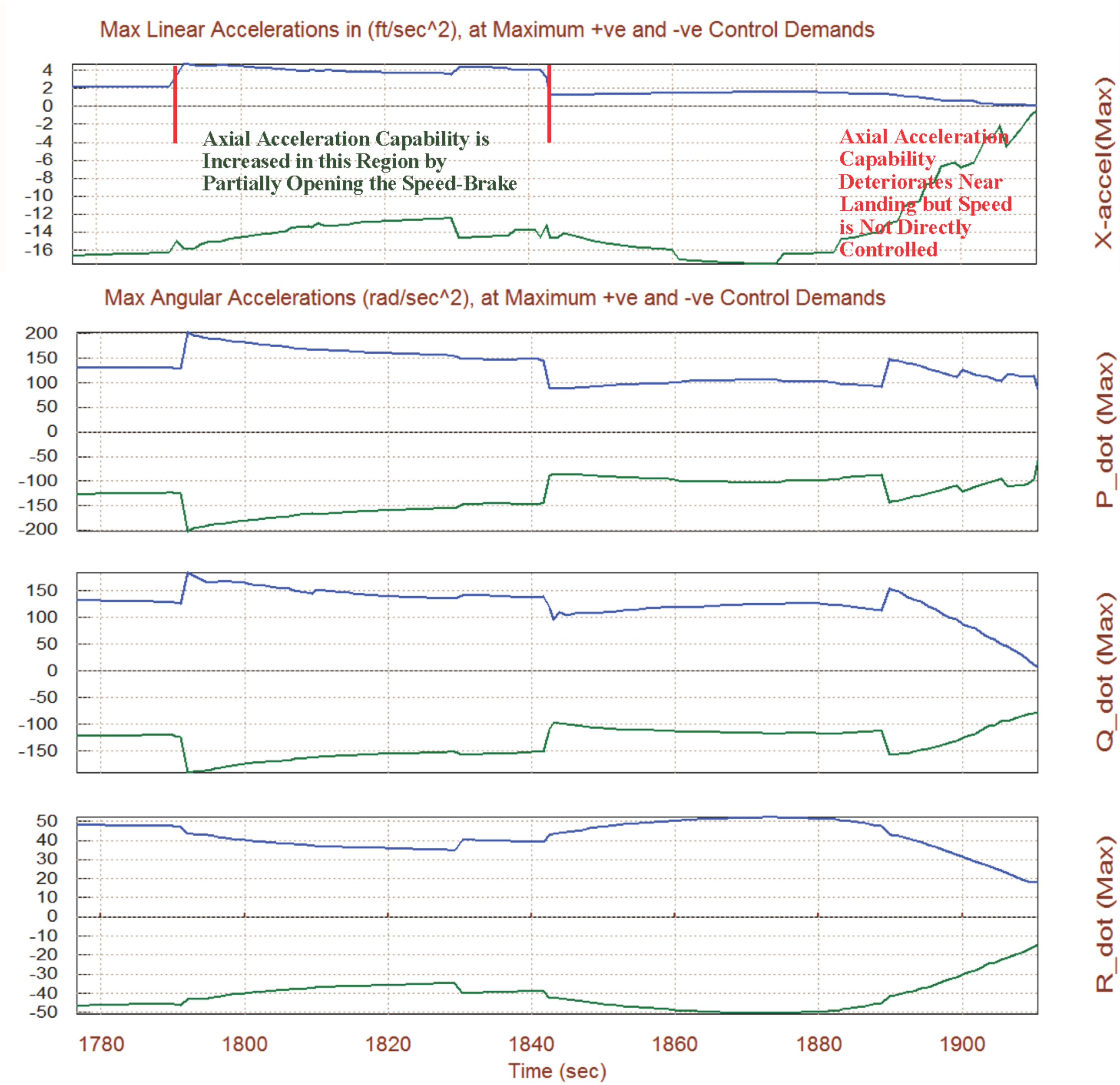
Short-Period (w)/ Time-to-Double-Ampl-Inverse (/sec), Q_alpha_beta (deg-lb/ft^2)
Ptch T2-inv
Yaw T2-inv
Q_alfabet
Time (sec)

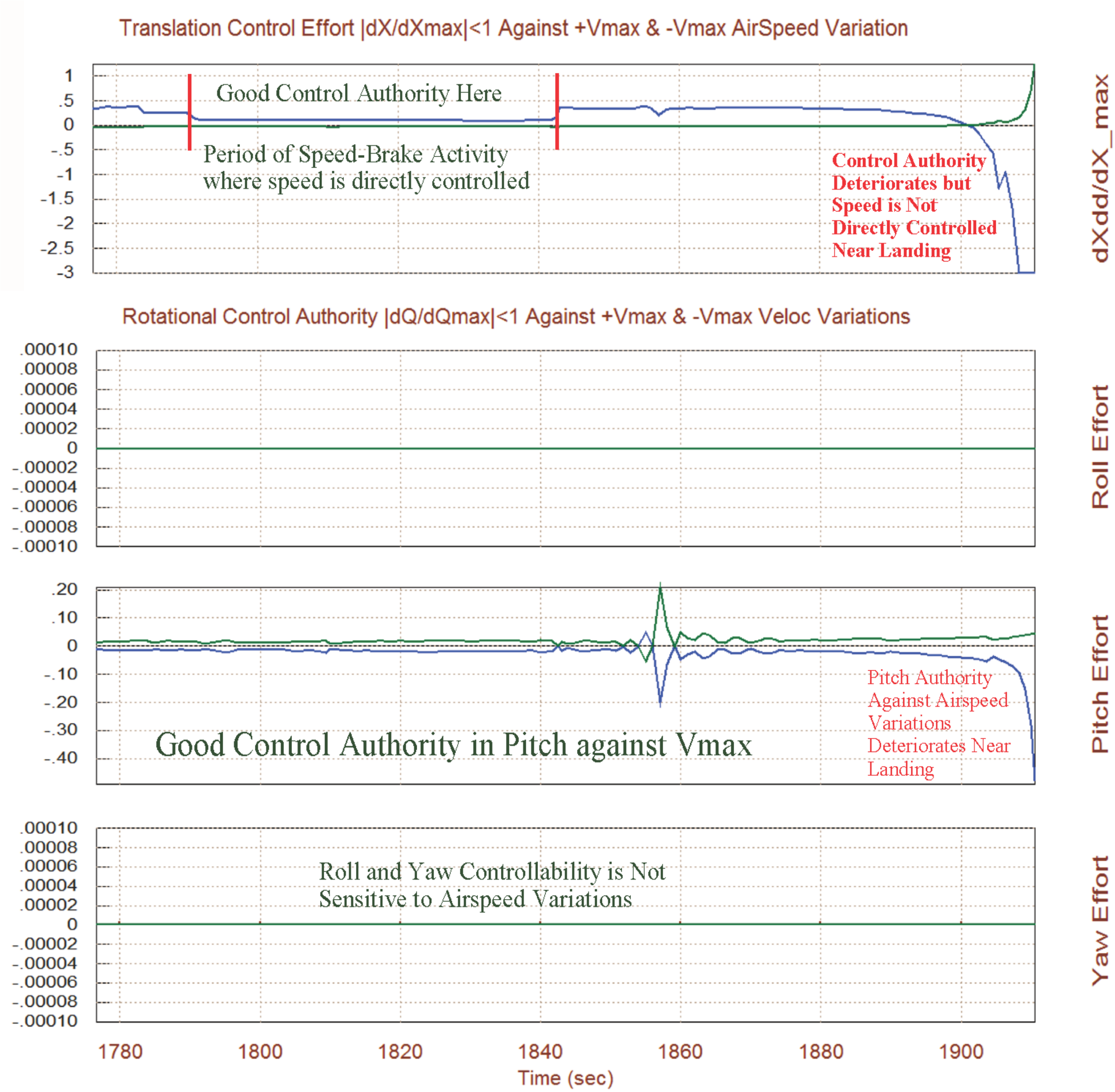


Bank Angle, LCDP Ratio, Cn_beta_dynam /deg, Lifting-Body Aircraft Approach and L
phi (deg)
LCDP
Cnbet-dyn
Time (sec)



The performance results show that during this phase the vehicle is statically stable both in pitch and lateral. The short-period resonance varies between: 1.8 to 3 (rad/sec) and the static margin varies between: 4.5% to 9%. In the lateral direction the Dutch-roll resonance varies between: 2.8 to 3.8 (rad/sec). The maximum ($Q\alpha$, $Q\beta$) loading is 2200 (psf-deg) which is acceptable. This is due to the 2° of α_{max} and β_{max} dispersions. The $Cn\beta$-dynamic is positive which means that the vehicle is directionally stable. The bank angle parameter (ϕ) is due to cross-wind produced by β_{max}= 2°. It is less than 3° near landing, which is acceptable. The control efforts against α_{max} and β_{max} dispersions are sufficiently small in pitch and yaw. In roll, however, the control authority exceeds the acceptable limit. Roll authority was compromised in order to increase the LCDP magnitude and to avoid roll-reversals. It means that in the presence of a strong gust the RCS jets will be energized, since RCS control is always available as an outer loop. The pitch control effort also increases near landing (less authority) due to the dynamic pressure drop and the increased Elevon deflections (near the limits) for the pitch-up flare. The axial control authority is very good (effort below 0.3) in the period where the speed-brake is partially opened and active. It means that we can modulate the speed-brake to regulate speed against the anticipated α_{max} and β_{max} dispersions. The axial control authority deteriorates near landing but we don't care because we are not directly controlling airspeed near landing. The next figure shows the maximum accelerations in the 4 control directions at full control demands, in (deg/sec2) and in (feet/sec2).

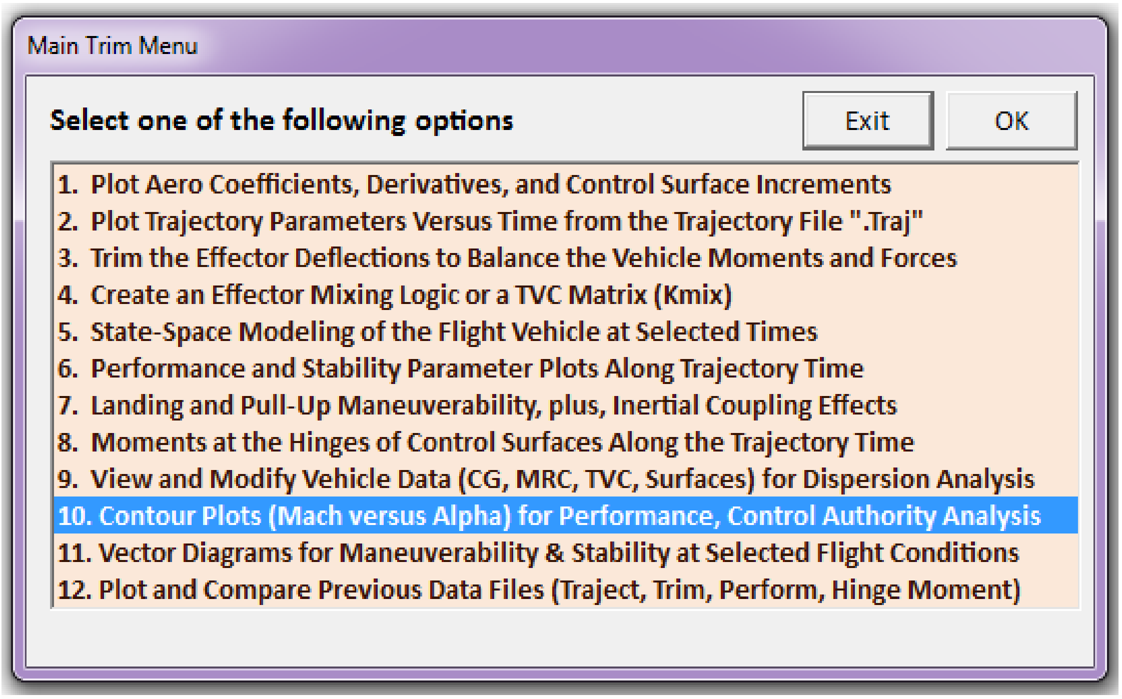


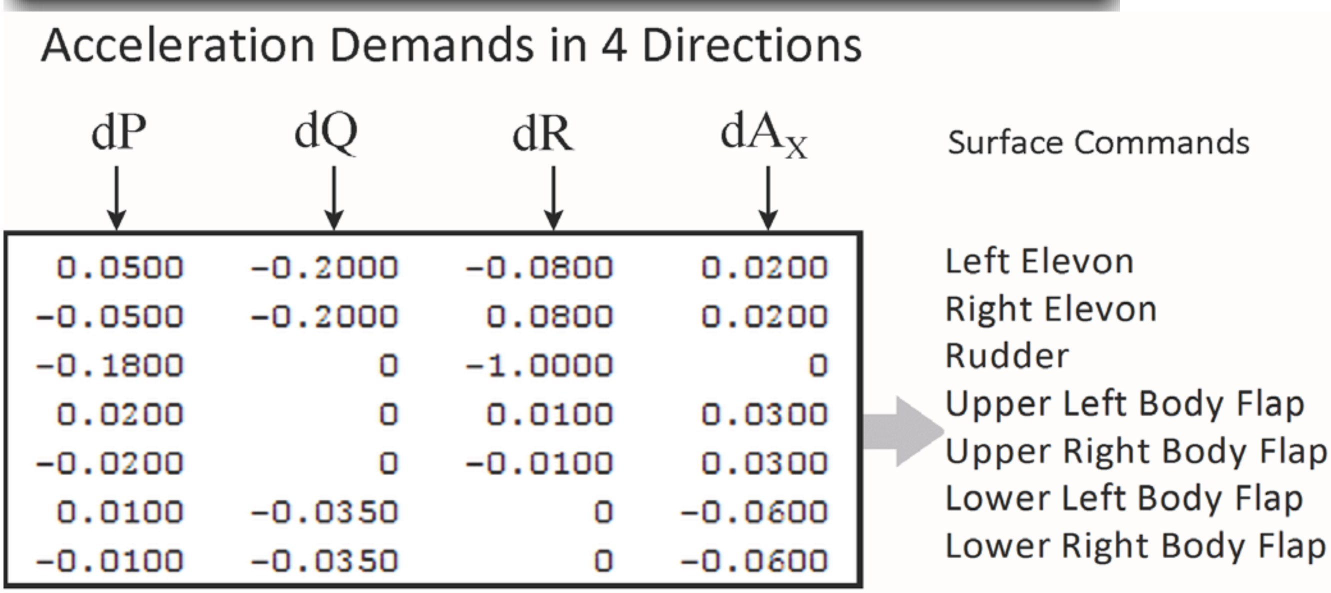


The above figure shows the effectors system control authority against airspeed variations V_{max} = ±30 (feet/sec). The axial control effort is very good (below 0.2) in the period where the speed-brake is partially opened and active. It means that we can modulate the speed-brake to regulate speed against the anticipated V_{max} airspeed variations due to winds. Roll and yaw control authority is not affected by the V_{max} variations because the nominal β_0=0 in this case. The pitch control authority is also very good. It means that the pitch effectors can produce enough moment to counteract the pitch moment produced by the V_{max} variations. That is either tail-wind or head-wind variations.

Contour Plots Analysis

We will now show some important performance parameters by using contour plots. Contour plots allow us to visualize vehicle performance over the entire Mach versus Alpha range, and it is selected by clicking in option-10 from the Trim program main menu. The surface mixing matrix KmixM0p4b is also selected from file "Kmix.Qdr".

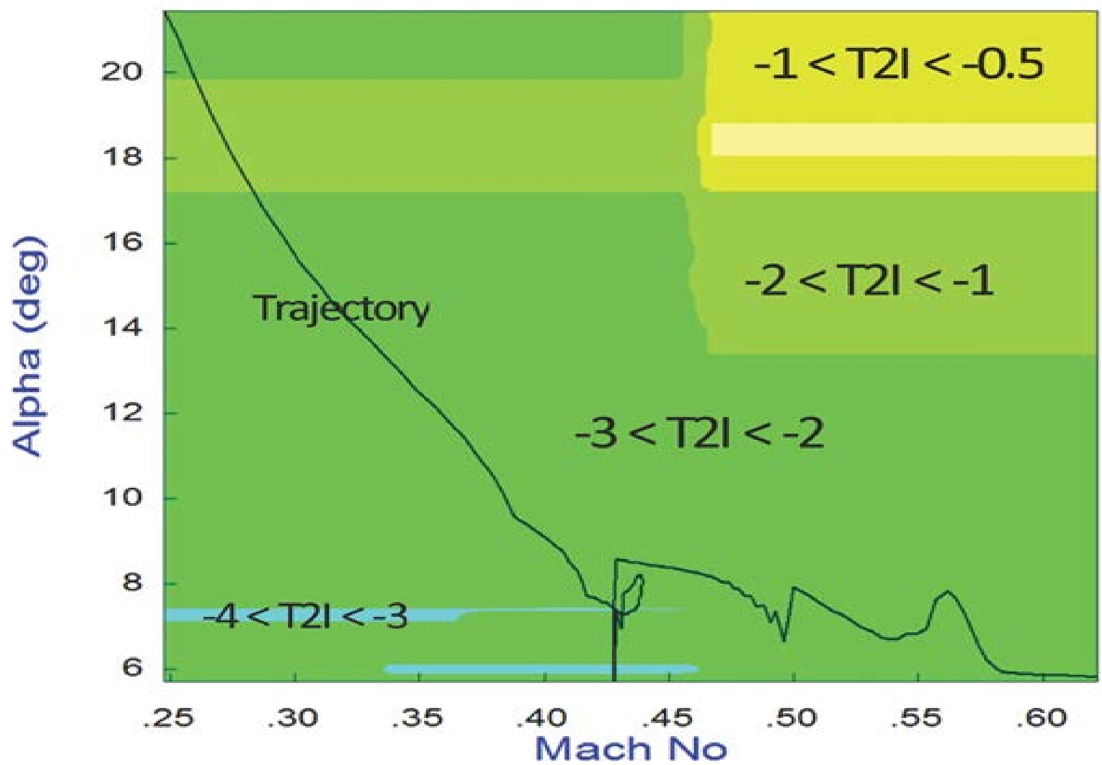




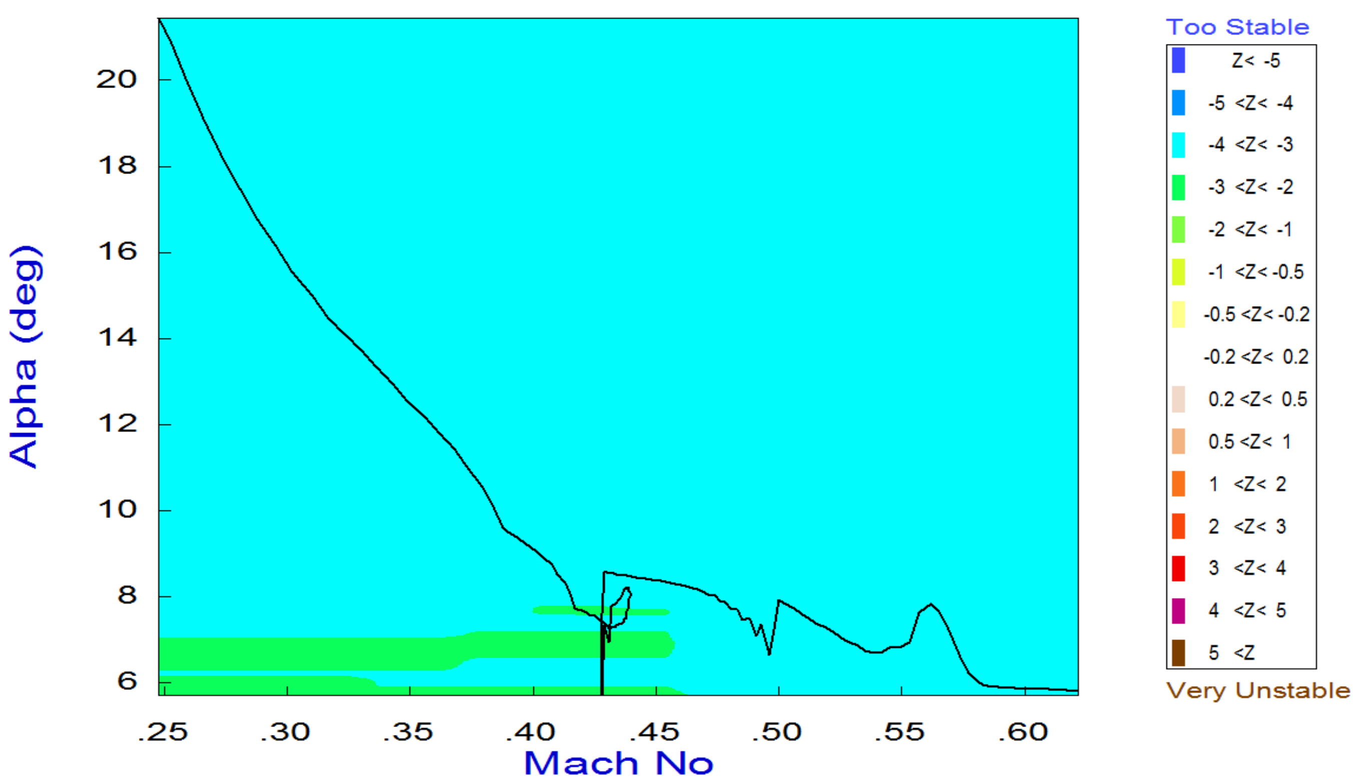
Surface Commands	dP	dQ	dR	dA_X
Left Elevon	0.0500	-0.2000	-0.0800	0.0200
Right Elevon	-0.0500	-0.2000	0.0800	0.0200
Rudder	-0.1800	0	-1.0000	0
Upper Left Body Flap	0.0200	0	0.0100	0.0300
Upper Right Body Flap	-0.0200	0	-0.0100	0.0300
Lower Left Body Flap	0.0100	-0.0350	0	-0.0600
Lower Right Body Flap	-0.0100	-0.0350	0	-0.0600

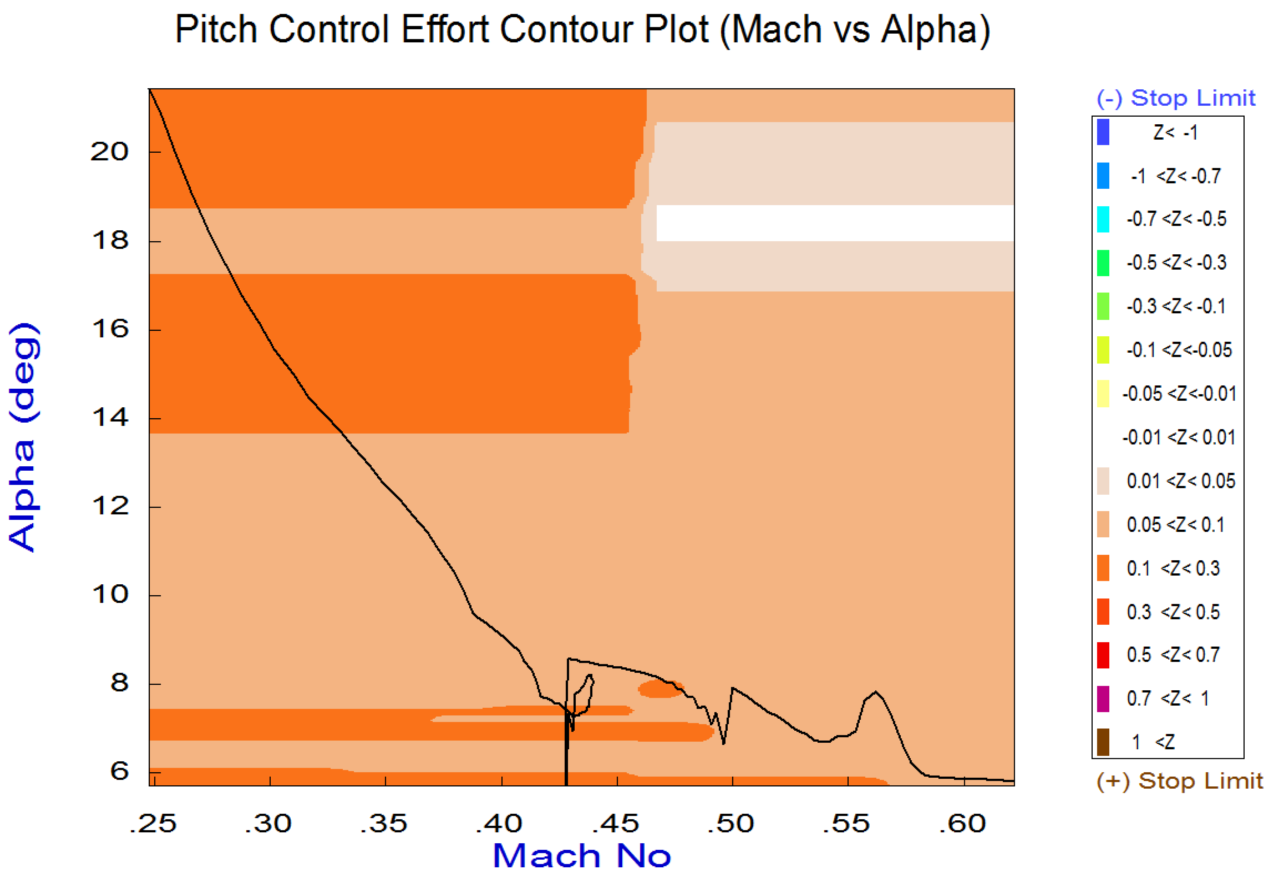
The first two plots show the pitch and lateral stability parameter in the entire Mach versus alpha range. The trajectory is shown by the dark line starting from the lower right-hand corner (Mach 0.65, α=6°) and ending in the upper left-hand side (Mach 0.25, α=22°). The stability parameters show that the vehicle is statically stable in both pitch and lateral. In the lateral direction the stability parameter is almost constant. The next two plots show the pitch and yaw control authority, against 2° of α_{max} and β_{max} disturbances, which is good in both directions. The roll control authority, however, is not sufficient in some regions shown in brown color and it is barely marginal in the purple regions. The LCDP ratio which measures dynamic controllability in roll is good. The surface mixing logic matrix was adjusted to improve the LCDP at the expense of reducing roll control authority, as already discussed. Notice, the following contour plots were calculated using a constant mixing-logic matrix but in actuality the mixing-logic is also scheduled similar to the control gains as a function of Mach and alpha.

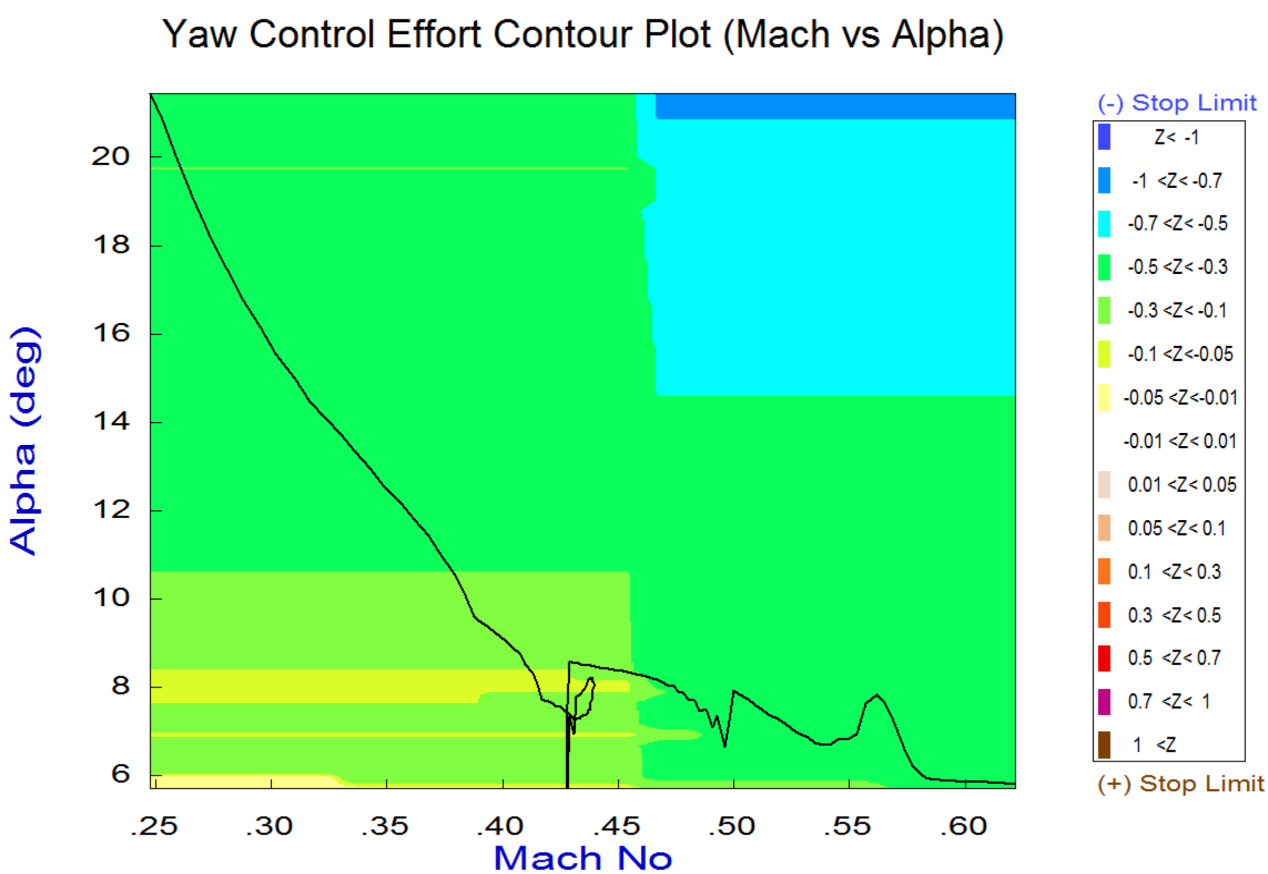
Pitch Stability Contour Plot (Mach vs Alpha)

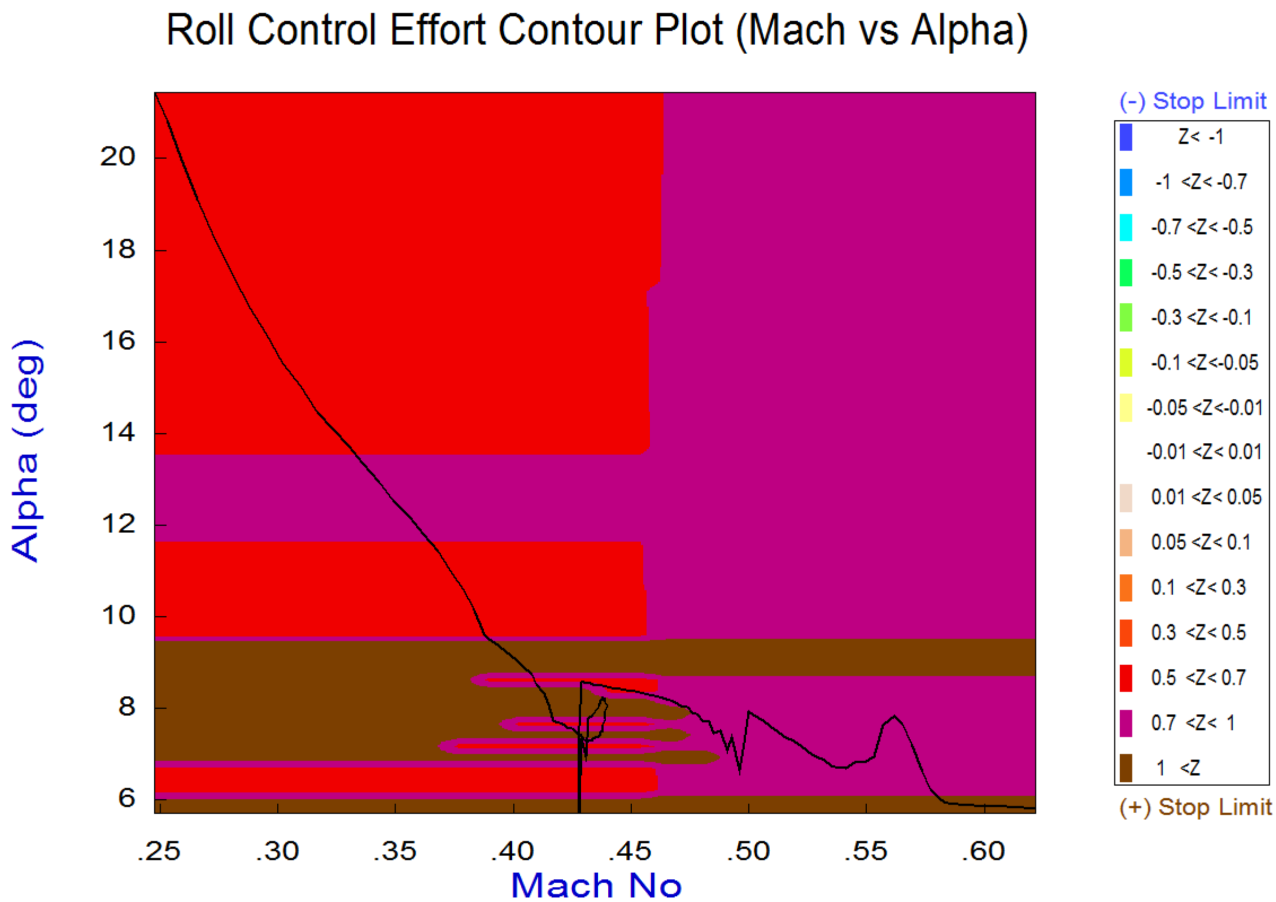


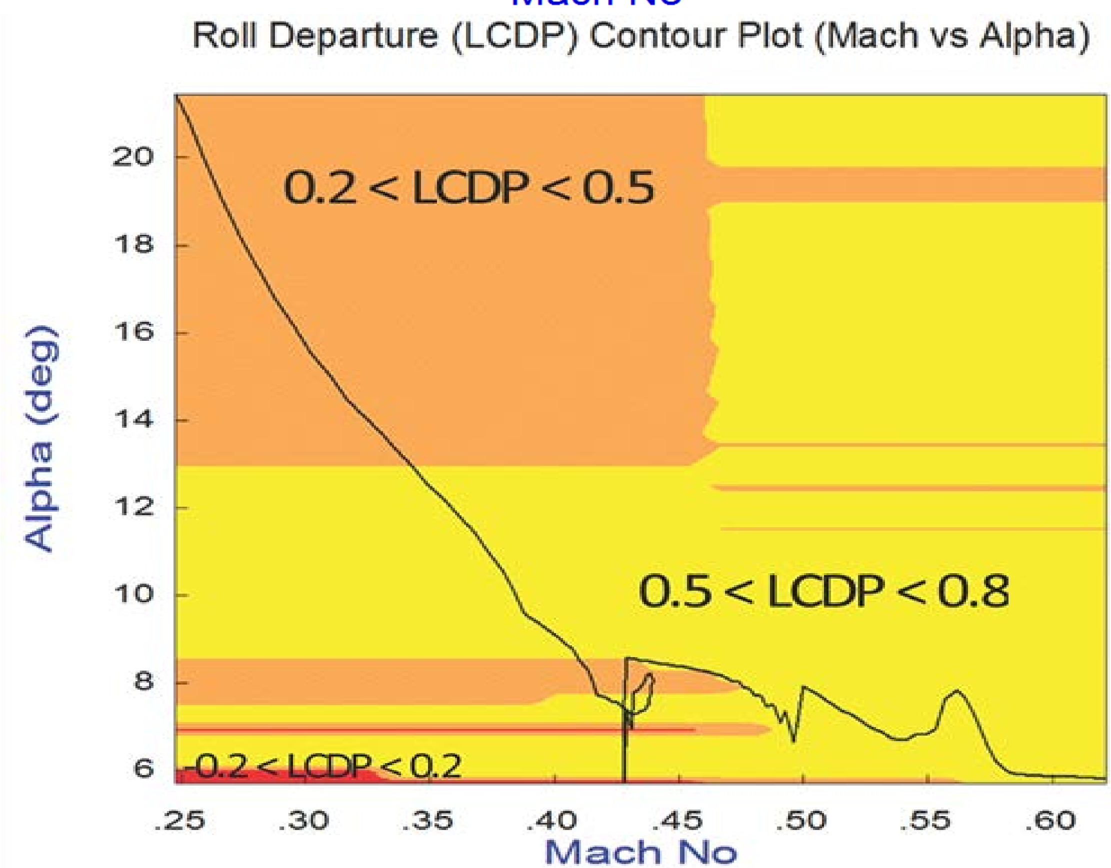
Lateral Stability Contour Plot (Mach vs Alpha)




Pitch Control Effort Contour Plot (Mach vs Alpha)
Alpha (deg)
Mach No
(-) Stop Limit
Z< -1
-1 <Z< -0.7
-0.7 <Z< -0.5
-0.5 <Z< -0.3
-0.3 <Z< -0.1
-0.1 <Z<-0.05
-0.05 <Z<-0.01
-0.01 <Z< 0.01
0.01 <Z< 0.05
0.05 <Z< 0.1
0.1 <Z< 0.3
0.3 <Z< 0.5
0.5 <Z< 0.7
0.7 <Z< 1
1 <Z
(+) Stop Limit

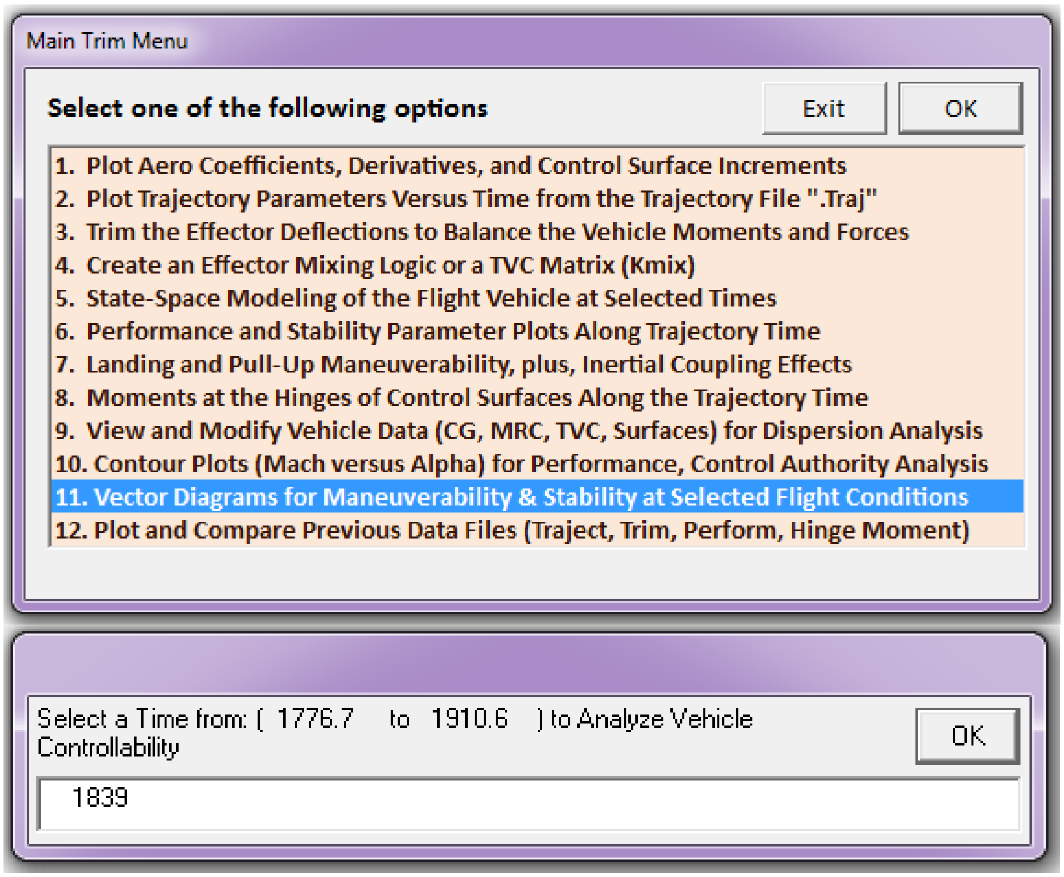

Yaw Control Effort Contour Plot (Mach vs Alpha)
Alpha (deg)
Mach No
(-) Stop Limit
Z< -1
-1 <Z< -0.7
-0.7 <Z< -0.5
-0.5 <Z< -0.3
-0.3 <Z< -0.1
-0.1 <Z<-0.05
-0.05 <Z<-0.01
-0.01 <Z< 0.01
0.01 <Z< 0.05
0.05 <Z< 0.1
0.1 <Z< 0.3
0.3 <Z< 0.5
0.5 <Z< 0.7
0.7 <Z< 1
1 <Z
(+) Stop Limit


Roll Control Effort Contour Plot (Mach vs Alpha)
Alpha (deg)
20
18
16
14
12
10
8
6
.25
.30
.35
.40
.45
.50
.55
.60
Mach No
(-) Stop Limit
Z< -1
-1 <Z< -0.7
-0.7 <Z< -0.5
-0.5 <Z< -0.3
-0.3 <Z< -0.1
-0.1 <Z<-0.05
-0.05 <Z<-0.01
-0.01 <Z< 0.01
0.01 <Z< 0.05
0.05 <Z< 0.1
0.1 <Z< 0.3
0.3 <Z< 0.5
0.5 <Z< 0.7
0.7 <Z< 1
1 <Z
(+) Stop Limit

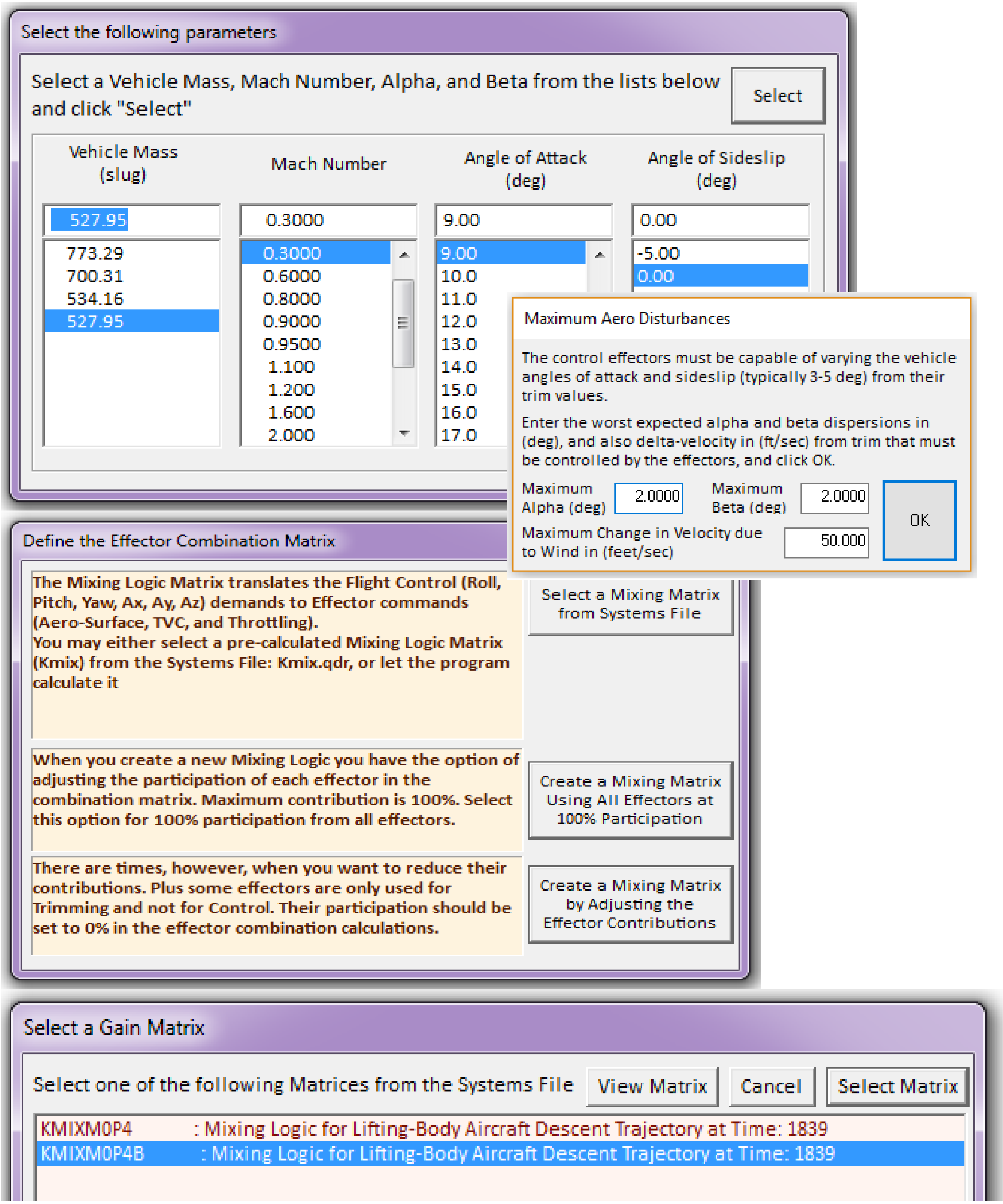

Roll Departure (LCDP) Contour Plot (Mach vs Alpha)
0.2 < LCDP < 0.5
0.5 < LCDP < 0.8
-0.2 < LCDP < 0.2
Alpha (deg)
20
18
16
14
12
10
8
6
.25
.30
.35
.40
.45
.50
.55
.60
Mach No

Controllability Analysis by Using Vector Diagrams

Vector diagrams are used for analyzing vehicle controllability at fixed flight conditions by comparing the control authority of the aerosurfaces against the effects from wind-shear disturbances defined in terms of angles of attack and sideslip dispersions α_{max} and β_{max} from trim. In this case the dispersions are expected to be less than ±2°. Partial vector diagrams also analyze the controllability gain $C_{m\delta}$ against the aerodynamic partials $C_{m\alpha}$, etc. To run the vector diagrams program, from the Trim main menu select option-11, and then enter a flight condition at t=1839 sec, which is in the region where the speed-brake is partially deployed and it is actively controlling the speed by varying drag. The control system in this flight condition is controlling the vehicle motion in four directions, including a velocity control loop.



The following dialog consists of menus for selecting the flight condition which is defined by the vehicle mass, Mach number, alpha, and beta. Select the default values that correspond to this flight condition and click on "*Select*". Notice that Mach 0.3 and α=9° are the nearest Mach number and angle of attack at the selected time. In the following dialog enter the maximum dispersion angles (α_{max} and β_{max})=2° from trim α_0 and β_0, that define the wind-shear disturbances. Enter also the maximum airspeed variation due to winds, 50 (feet/sec). Then select the (7x4) control surface combination matrix "KmixM0p4b" from file Kmix.Qdr, as shown.



The vector diagrams in Figure 1.4.1 show the non-dimensional roll and yaw moments and side-force, (C_l, C_n, C_Y), produced when the roll and yaw FCS acceleration demands are at maximum deflection from trim, before reaching the aerosurface limits. The solid blue vector shows the moments when the yaw FCS demand is at its maximum positive position $\delta R_{+FCSMax}$, and the dashed blue vector in the opposite direction is the negative moment produced when the yaw demand is at its peak negative position $\delta R_{-FCSMax}$. Similarly, the green vectors in the vertical directions show the peak roll and yaw moments produced by maximizing the roll control in both directions $\delta P\pm_{FCSMax}$. The control moment vectors are pointing towards their intended directions with some cross-coupling. They are, however, perfectly orthogonal to each other which is a good property for control. The lower figure shows the maximum side-force produced by maximizing the yaw demand. Positive yaw demand requires a negative rudder deflection which produces a negative side-force. The two red vectors show the roll and yaw moments produced by the angle of sideslip $\pm\beta_{max}$ dispersions from trim and they are mainly in roll. Positive β_{max} produces a positive yawing moment because the vehicle is stable, also a big negative rolling moment because this lifting-body vehicle has substantial dihedral. It also produces a negative side-force. The red rectangles at the tips of the arrows show the roll, yaw, and side-force uncertainties in the dispersion and in the control vectors. The uncertainties are defined in file "*LiftBody.Unce*".

The vector diagrams in Figure 1.4.2 analyze controllability in the longitudinal direction when the two control demands are maximized. In addition to pitch control the vehicle uses the speed-brake to modulate drag and vary the negative acceleration. The flight control produces two longitudinal demands: pitch (δQ_{FCS}) and axial (δX_{FCS}) accelerations. The actual deflections are determined by the surface mixing matrix. The figures show the pitch moment Cm plotted against the CZ and the CX forces in coefficient form. The blue vectors represent the maximum pitch moment and forces produced when the pitch control demand is maximized. The solid blue vector is due to max positive $\delta Q_{+FCSMax}$, and the dashed blue vector is due to max negative $\delta Q_{-FCSMax}$ pitch demand. The pitch control, in addition to producing a pitching moment, it produces also significant force variations in z, and to a lesser extent in the x direction. Unlike the lateral directions, the vectors here are not symmetrical because the positive control demand $\delta Q_{+FCSMax}$ produces a larger moment and z-force variation than the negative control demand. The vehicle is trimmed in pitch because Cm is almost zero when the control δQ_{FCS}=0. It is, however, accelerating in both -x and -z directions because CX and CZ are negative when δQ_{FCS}=0. Notice that a +pitch control demand reduces the magnitude of CZ, reducing lift because the Elevons rotate upwards to increase the pitching moment. The green vectors show the effects of the axial control δX_{FCS} via the speed-brake on C_X and Cm. The effect is mainly in the demanded x direction but it also couples in pitch. At the partially deployed speed-brake position the aft force -CX has a nominal value of 0.07, and it can be varied between: 0.04 to 0.12. The red vectors represent the pitch moment, axial and z forces generated by the ±2° variations in the angles of attack and sideslip $\pm\alpha_{max}$ and $\pm\beta_{max}$ from their trim positions. The disturbance in this case is mainly due to the $\pm\alpha_{max}$ variations, positive α_{max} generates negative pitching moment because the vehicle is stable in this flight condition. It also produces a negative z-force and a less negative x-force, increasing α makes the z-force more negative (up). The rectangles centered at the vector tips represent the possible variations due to the uncertainties in the aero-coefficients.

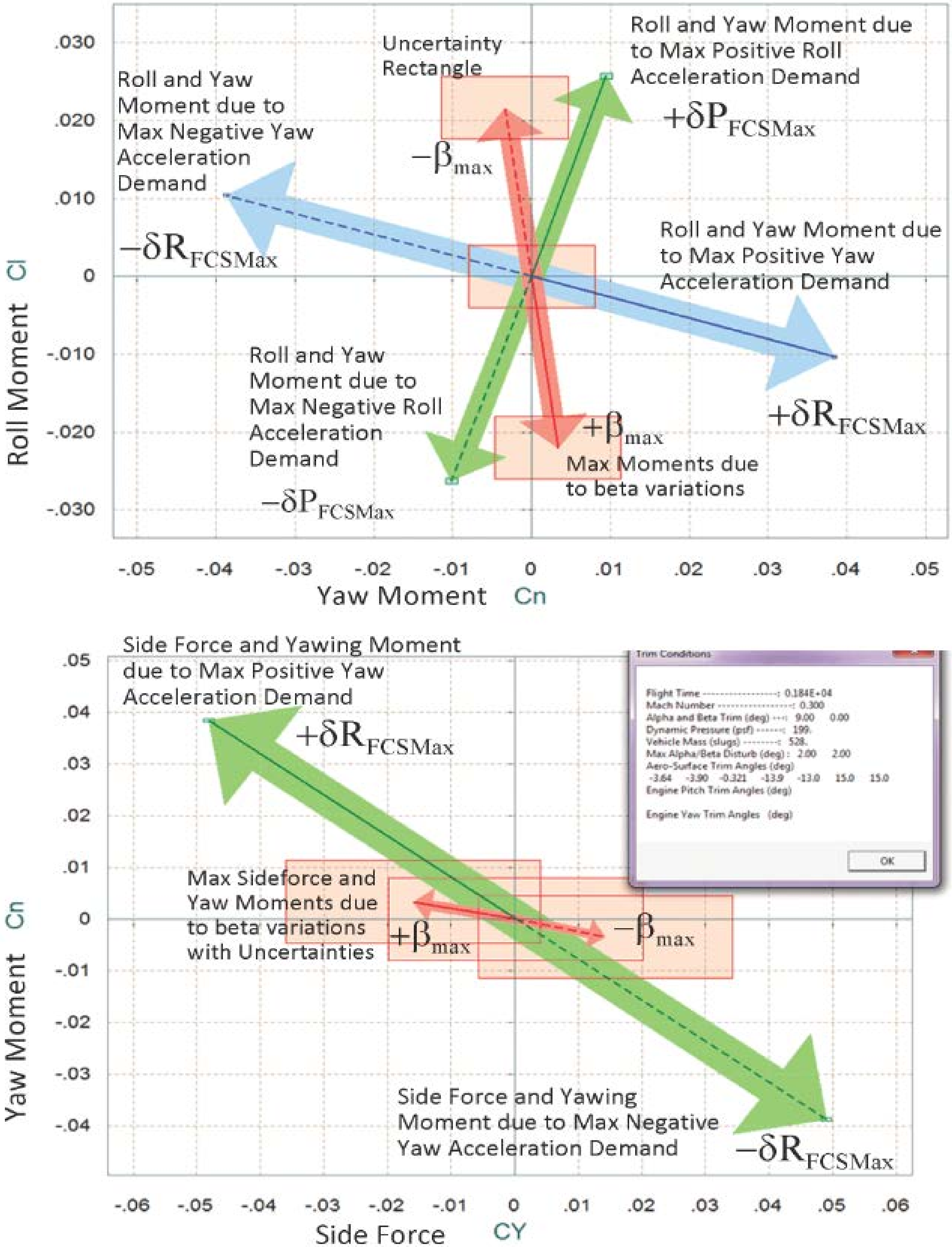


Figure 1.4.1 Lateral Moments and Side-Force produced by maximizing the Controls and also due to $\pm\beta_{max}$

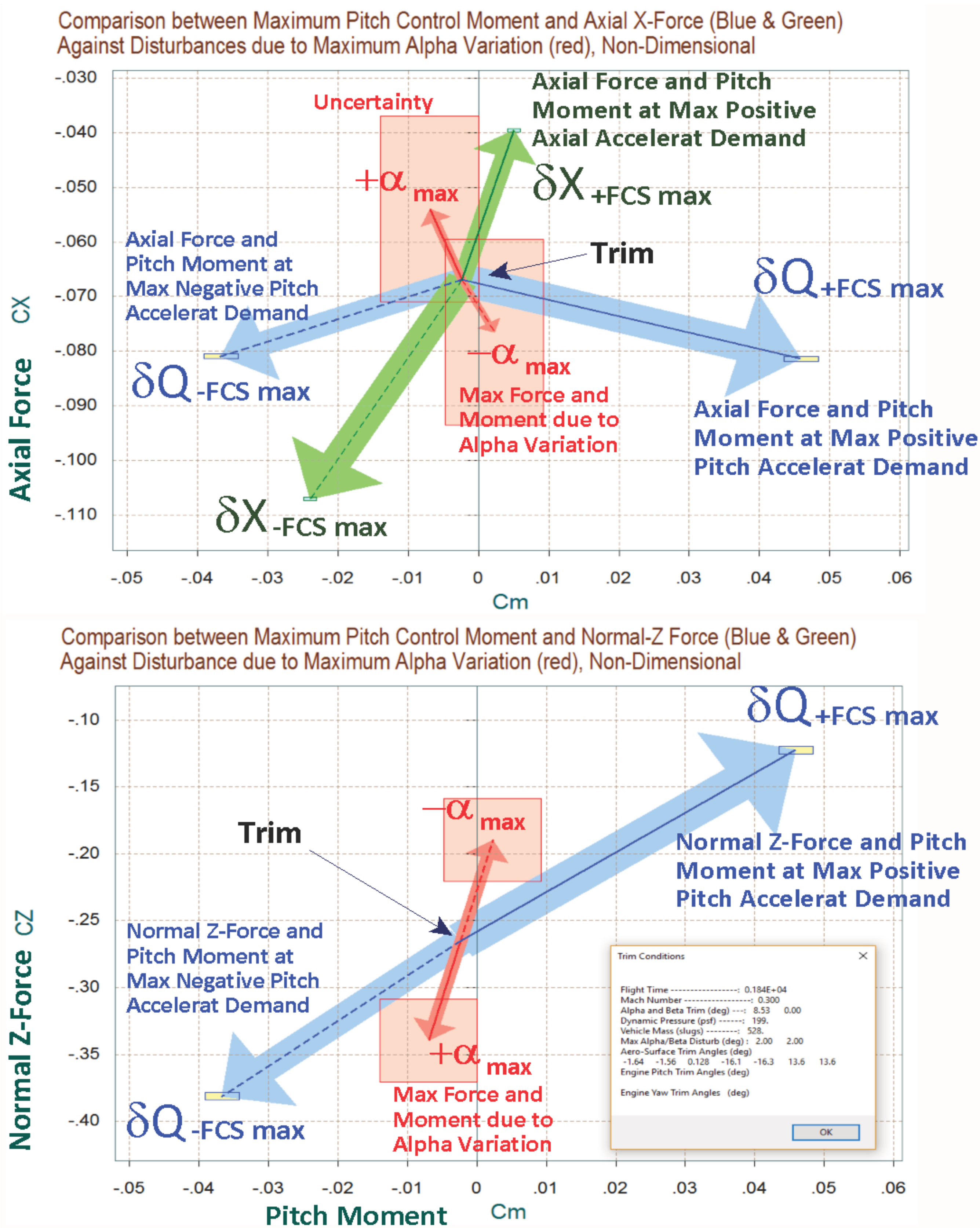


Figure 1.4.2 Pitch Moment, Normal and Axial Forces produced by maximizing the Longitudinal Controls and also due to $\pm\alpha_{max}$

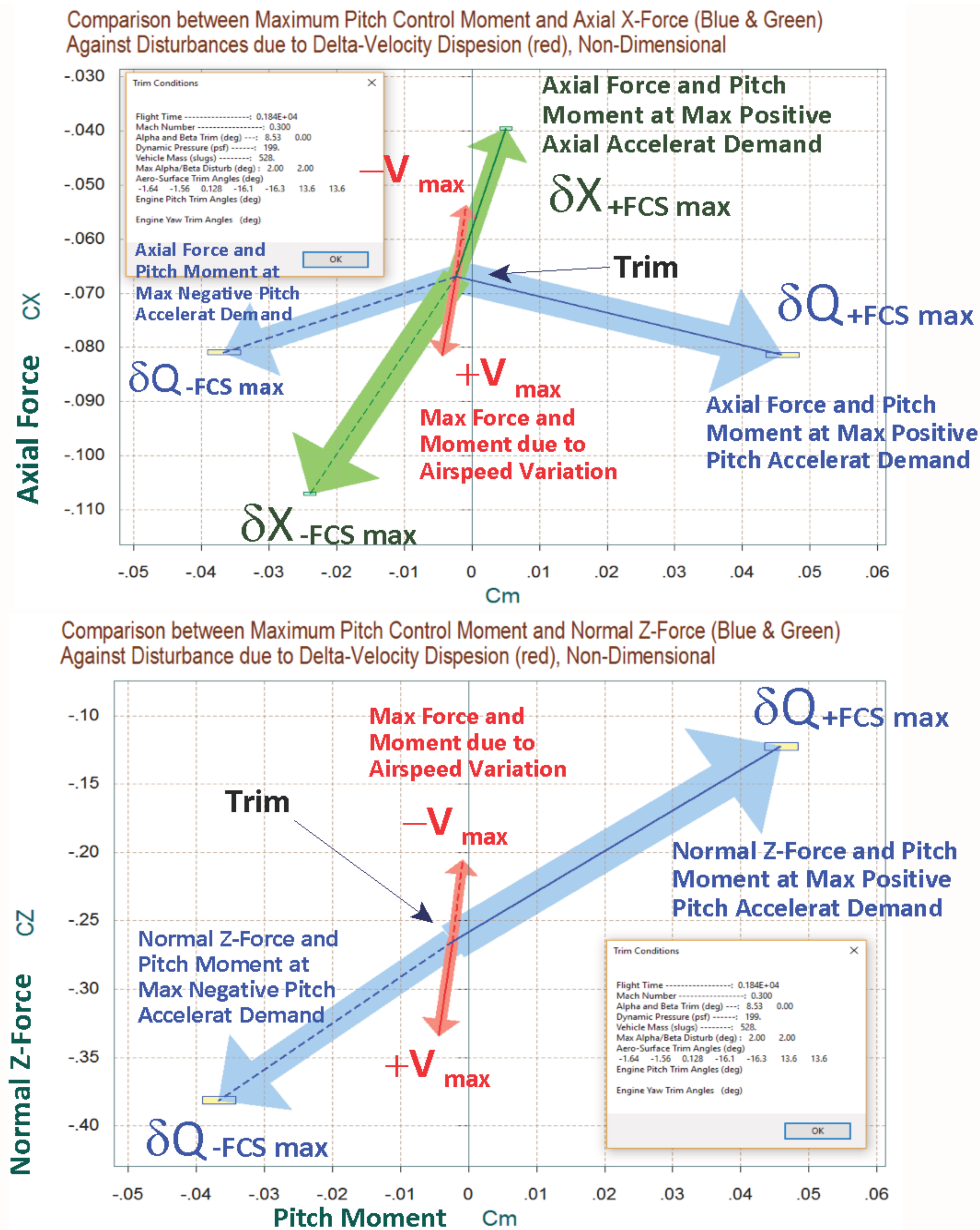


Figure 1.4.3 Pitch Moment, Normal and Axial Forces produced by Air-Speed Variations $\pm V_{max}$

Figure 1.4.3 is similar to Figure 1.4.2. The control vectors are the same but the red dispersion vectors are different. They represent the pitch moment and forces on the vehicle produced by variations in the airspeed due to winds, V_{max}= ±50 (feet/sec). An increase in airspeed due to head-wind $+V_{max}$ produces negative pitching moment (statically stable), negative z-force (upwards), and more negative axial acceleration (drag).

The vector diagrams in Figure 1.4.4 show the moment and force partials in the lateral directions. The top figure shows the roll and yaw moment variations per acceleration demands in roll and yaw in (rad/sec^2). The blue vector is the moments partial per yaw demand $\{Cn\delta R_{FCS}, Cl\delta R_{FCS}\}$ and it is pointing towards the yaw direction. The green vector is the moments partial per roll demand $\{Cn\delta P_{FCS}, Cl\delta P_{FCS}\}$ and it is pointing mainly in roll. The two vectors couple into each other's directions but they are nearly orthogonal to each other. The blue vector in the bottom diagram is the yaw moment and side-force partial per yaw demand. The red vectors pointing downward are the scaled $\{Cn\beta, Cl\beta, Cy\beta\}$ partials. Notice that $Cn\beta$ is positive because the vehicle is stable, and $Cl\beta$ is negative due to the dihedral and it is bigger in magnitude than $Cn\beta$. The red rectangles centered at the tips of the $\{Cn\beta, Cl\beta, Cy\beta\}$ vectors represent the uncertainties in the partials. Similarly, the rectangles at the tips of the control partials represent possible variations in the partials due to aero uncertainties. The uncertainties are obtained from file "*LiftBody.Unce*".

The vector diagrams in Figure 1.4.5 show the moment and force partials in the longitudinal directions. The blue vectors represent the pitch moment, axial and normal force partials per pitch acceleration demand in (rad/sec^2), $\{CX\delta Q_{FCS}, Cm\delta Q_{FCS}, CZ\delta Q_{FCS}\}$. The pitch control vector partial is pointing mainly in the pitch direction but it also couples in the X and Z directions. The green vector in the top diagram represents the pitch and axial force partials: $\{CX\delta X_{FCS}, Cm\delta X_{FCS}\}$ per axial acceleration demand in (feet/sec^2), and it is mainly in the vertical axial force direction. The two control partials are almost orthogonal to each other, pointing towards the intended directions, and they are not coupling very much into each other's direction. The red vectors represent the $\{C_{X\alpha}, C_{m\alpha}, C_{Z\alpha}\}$ partials. Notice that $Cm\alpha$ is negative because the vehicle is stable in this flight condition. The red rectangle centered at the tips of the $\{C_{X\alpha}, C_{m\alpha}, C_{Z\alpha}\}$ partials represents the uncertainties in the partials. Similarly the yellow rectangle at the tip of the pitch control partial represents the uncertainties in $\{CX\delta Q_{FCS}, Cm\delta Q_{FCS}, CZ\delta Q_{FCS}\}$, and the cyan rectangle at the tip of the axial control partial is the uncertainties in $\{CX\delta X_{FCS}, Cm\delta X_{FCS}\}$. The uncertainties are obtained from file "*LiftBody.Unce*".

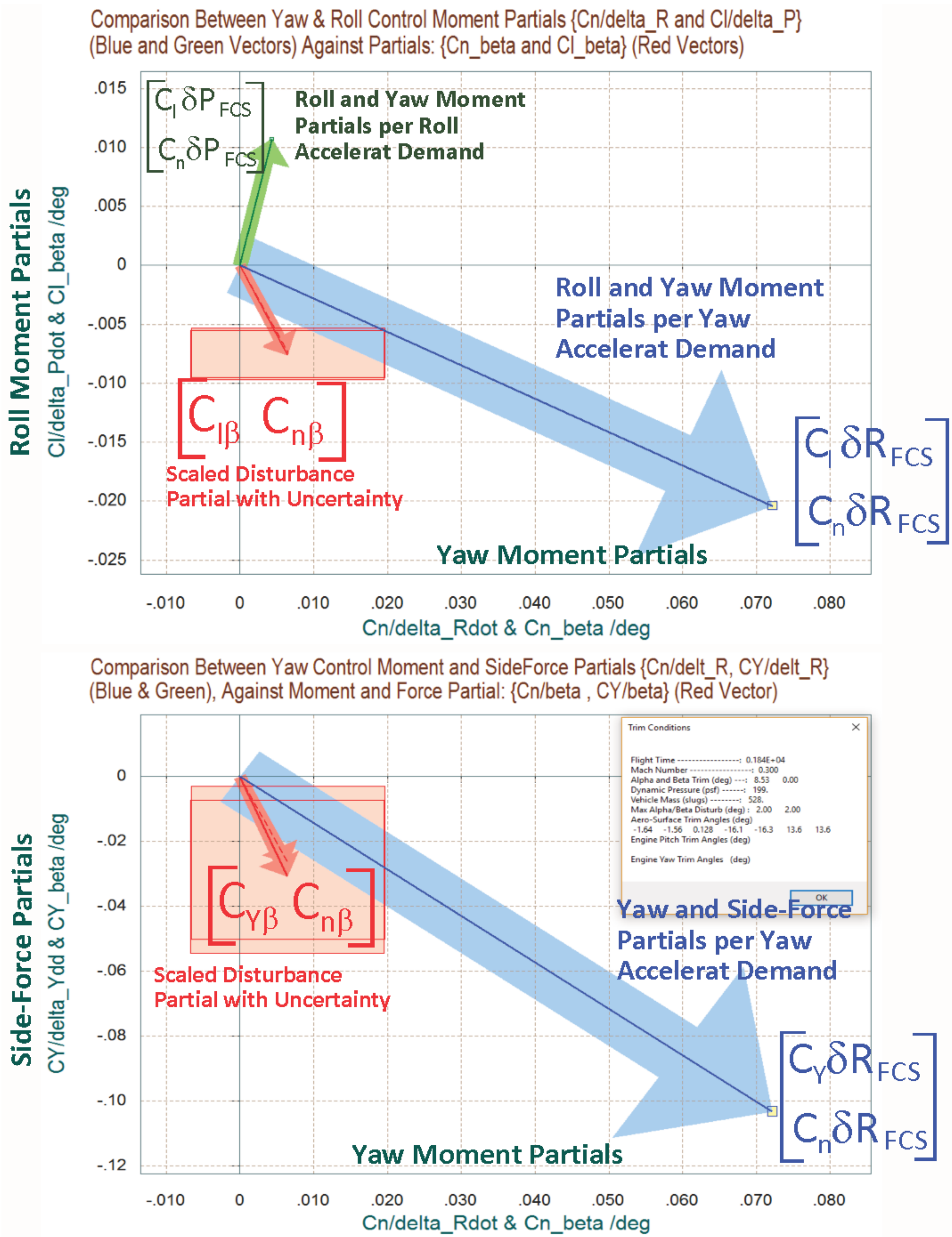


Figure 1.4.4 Roll, Yaw Moment, and Side-Force Partials per Roll and Yaw Demands, Including β Partials

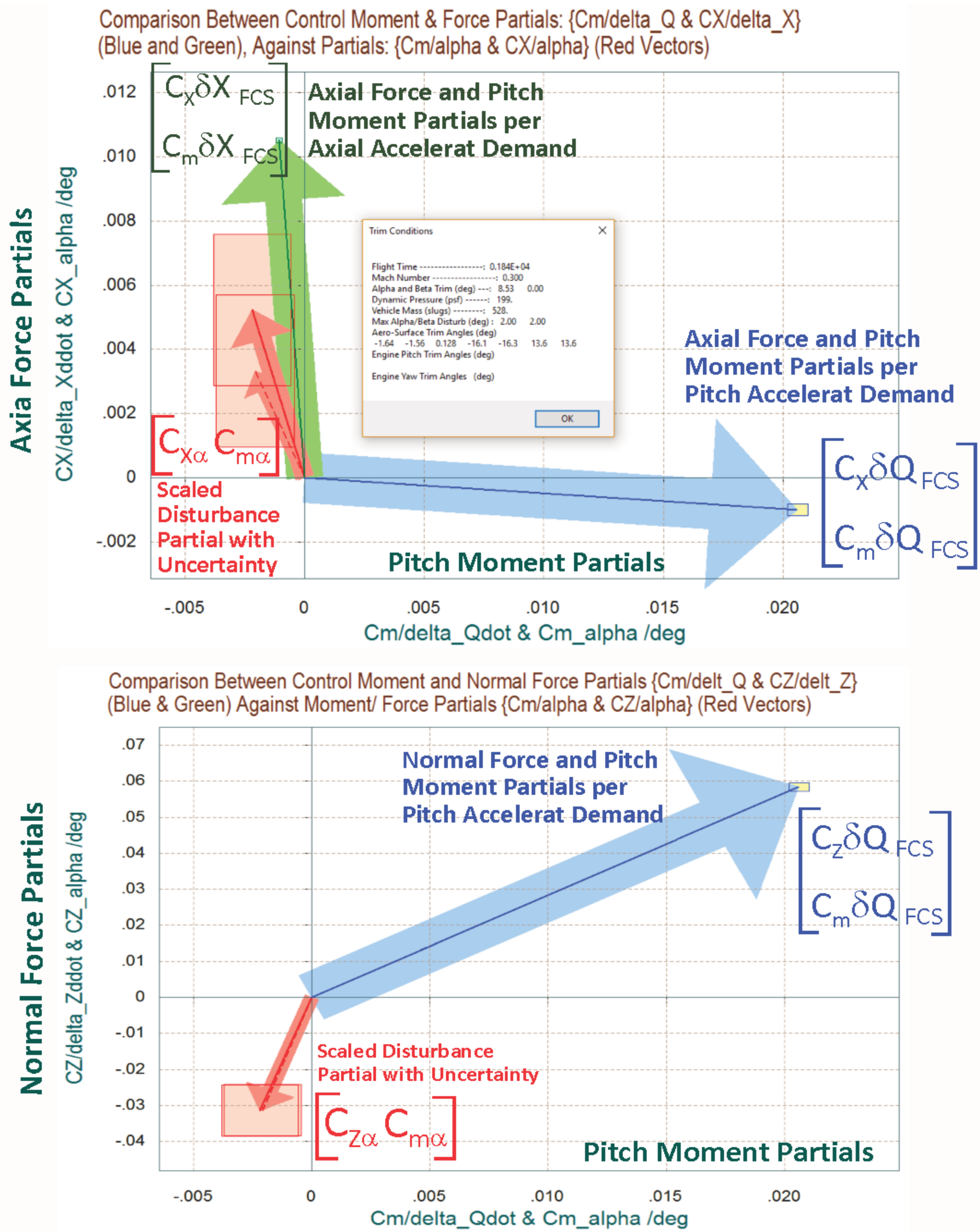


Figure 1.4.5 Longitudinal Moment and Force Partials per Pitch and Axial Demands, Including α Partials

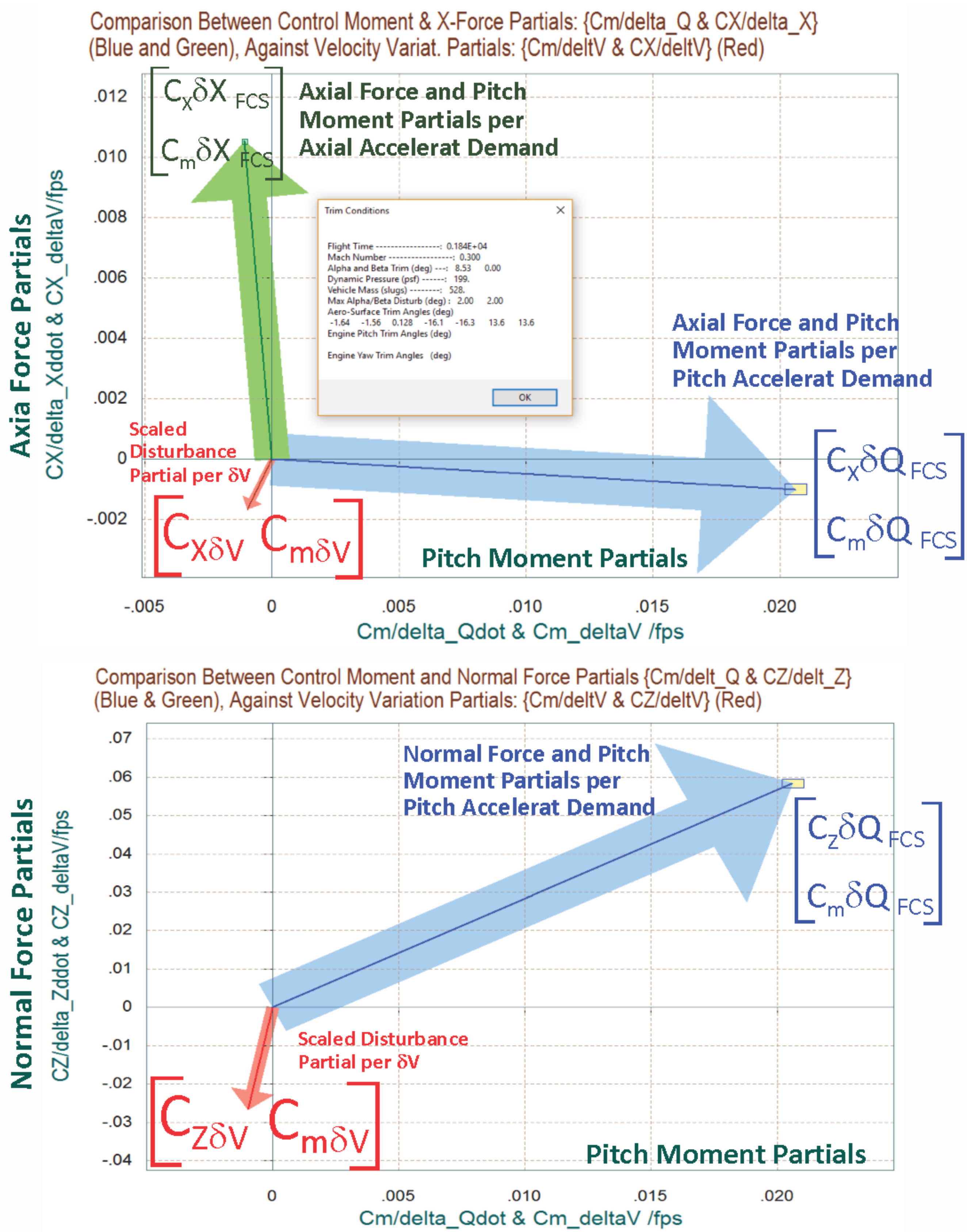


Figure 1.4.6 Longitudinal Moment and Force Partials, Including Partials per Airspeed Variation

The control vector partials in Figure 1.4.6 are the same as Figure 1.4.5 but the red disturbance partials are different. They are pitch moment and x and z forces per air-speed variations. The vectors compare controllability versus disturbability gains. That is, vehicle static response to control demands against its response to wind variations and obviously the controls must be stronger than the vehicle responses to air-speed variations along the two control directions. The disturbance partials are scaled as it is described in equation (3.24d) in order to be made comparable with the control partials.

The two vector diagrams in Figure 1.4.7 show the partials of accelerations per acceleration demands in the four control directions. The top diagram is the partials of pitch and axial accelerations per acceleration demands in the two longitudinal directions. The green vector pointing upwards is accelerations per axial demand $\{\ddot{X}/\delta\ddot{X}_{FCS}, \dot{Q}/\delta\ddot{X}_{FCS}\}$, and the blue vector pointing towards the right is accelerations per pitch demand $\{\ddot{X}/\delta\dot{Q}_{FCS}, \dot{Q}/\delta\dot{Q}_{FCS}\}$. The directions of the vectors imply that the two longitudinal axes are almost perfectly decoupled, because the acceleration partials are pointing in the corresponding directions, they are almost unit vectors and orthogonal to each other, which imply good longitudinal controllability.

The bottom diagram in figure 1.4.7 shows the vector partials of roll and yaw accelerations per acceleration demands in roll and in yaw. The green vector is accelerations per roll demand $\{\dot{P}/\delta P_{FCS}, \dot{R}/\delta P_{FCS}\}$, and the longer blue vector is accelerations per yaw demand $\{\dot{P}/\delta R_{FCS}, \dot{R}/\delta R_{FCS}\}$. The axis units are in (rad/sec^2) per (rad/sec^2). They are almost orthogonal to each other, which is good, but the green vector is smaller which indicates reduced controllability in roll.

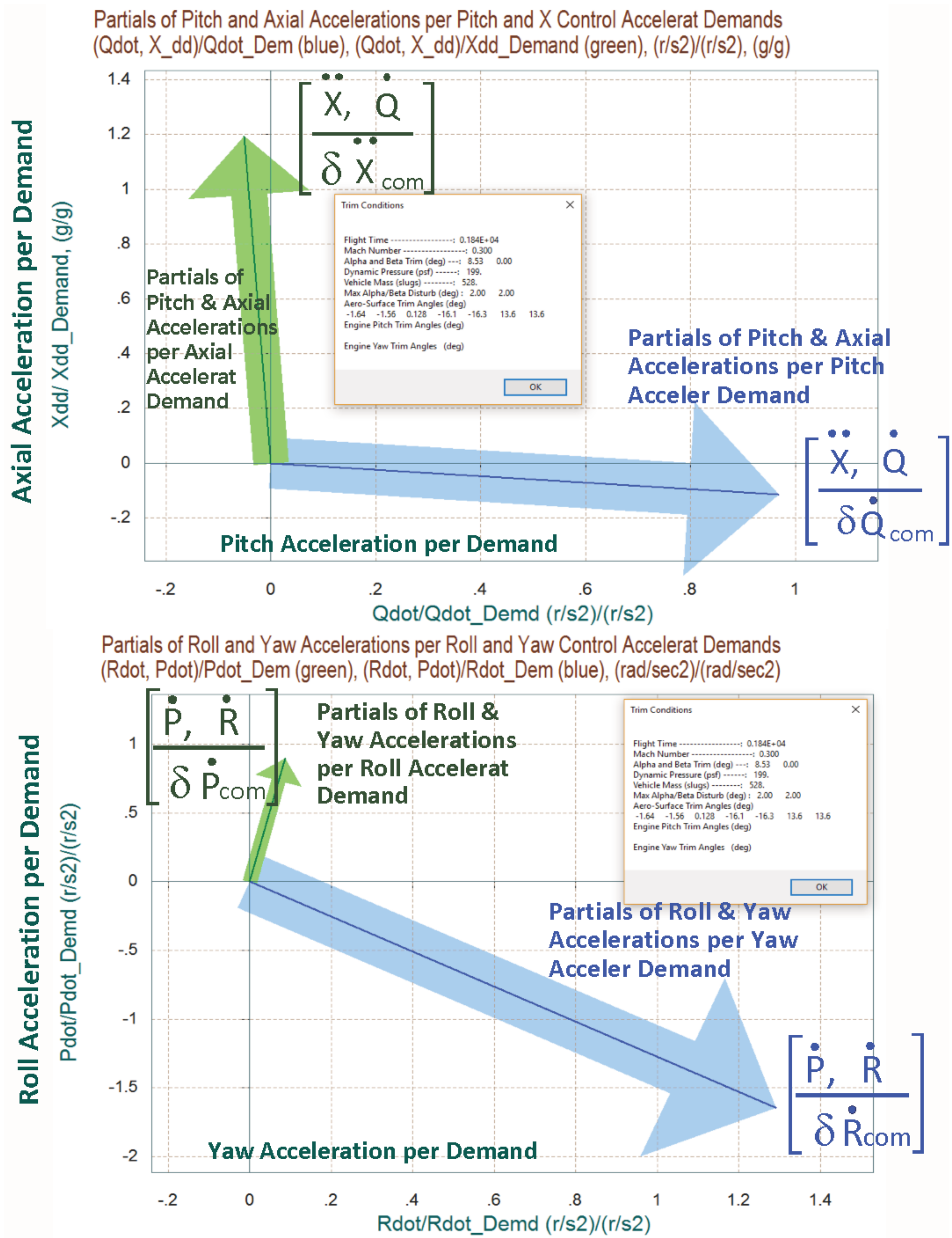


Figure 1.4.7 Acceleration Vector Partials in the Longitudinal and Lateral Directions

Dynamic Modeling, Control Design, and Stability Analysis

We will now create dynamic models for the approach and landing phase at a fixed flight condition (Mach 0.4). We will also use these models to design control laws, a control surface mixing logic, analyze stability in the frequency domain, check the system's robustness to uncertainties by μ-analysis, and evaluate the system's landing capability in a simulation by tracking altitude and speed commands. The vehicle dynamic model is created using Flixan. From one of the trajectory plots, go the top menu bar and choose "*Graphic Options*". Then from the vertical pop-up menu click on "*Select Time to Create State-Space System*". Then using the mouse click at time t=1839 sec, along the x axis to select the flight condition. This flight condition was selected because the speed-brake which allows us to do speed control is deployed at that time. The program confirms the flight time and prepares the dynamic model. In this case, however, we will skip the details because the input data at trajectory time t=1839 (sec) which corresponds to Mach 0.4 is already prepared and the input data is in file "*Land_M0,4_0.Inp*". The Matlab analysis for this flight condition is performed in folder "*C:\Flixan\Trim\Examples\Lifting-Body Aircraft\Reentry from Space\Mat_Anal\Mch_0.4*".

Processing the Input Data

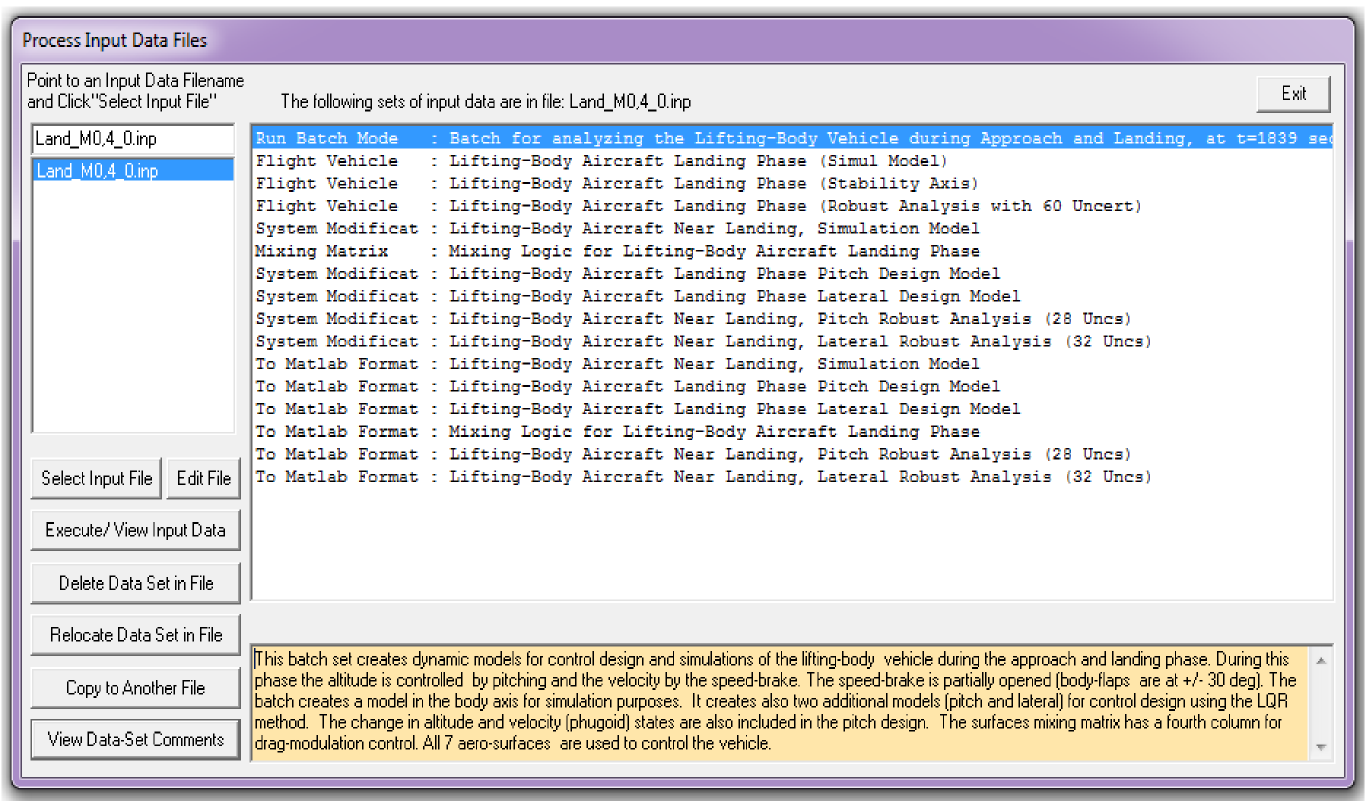
We will now describe the contents of the input data file "*Land_M0,4_0.Inp*" and process it using Flixan. It creates the following systems and matrices that will be used in the Matlab control design and analysis:

- A vehicle simulation model "*Lifting-Body Aircraft Landing Phase (Simul Model)*". This model is augmented to include one additional output (change in velocity). This output is required for speed control. It is not included in the original system outputs, although it is in the state-vector. The modified simulation system title is "*Lifting-Body Aircraft Near Landing, Simulation Model*" and it is also saved in file "*vehicle_sim*" for Matlab analysis.
- A stability axis model "*Lifting-Body Aircraft Landing Phase (Stability Axis)*". This model is used for control design. The body rates are measured with respect to the velocity vector. It has the turn coordination terms included in the dynamics. This model is split in two separate pitch and lateral subsystems "*Lifting-Body Aircraft Landing Phase Pitch Design Model*" and "*Lifting-Body Aircraft Landing Phase Lateral Design Model* " which are also saved in files "*pitch_des.m*" and "*later_des.m*" respectively and used for control design using Matlab.
- A model with 60 uncertainties used for robustness analysis "Lifting-Body Aircraft Landing Phase (Robust Analysis with 60 Uncert)". This model is used for μ-analysis. It is split, however, in two separate pitch and lateral subsystems "*Lifting-Body Aircraft Near Landing, Pitch Robust Analysis (28 Uncs)*" and "*Lifting-Body Aircraft Near Landing, Lateral Robust Analysis (32 Uncs)".* The uncertainties of the pitch parameters are included in the pitch model and the uncertainties of the lateral parameters are included in the lateral model. These two

uncertainty systems are also saved in files "*pitch_unc.m*" and "*later_unc.m*" respectively and used for robustness analysis in Matlab.

- A (7x4) mixing logic matrix "KmixM0p4a" is also created. It converts the roll, pitch, yaw, and axial acceleration flight control demands to 7 aero-surface deflection commands. Its title is "*Mixing Logic for Lifting-Body Aircraft Landing Phase*". Notice that the 4 body-flaps are de-emphasized in the mixing-logic matrix calculation because their maximum deflections from nominal in the vehicle input data are reduced to 10° instead of 30°. This places higher demands on the elevons and rudder. This matrix is saved in file KmixM0p4a.Mat. In the control analysis, however, it is replaced with a different surface combination matrix KmixM0p4 which improves the LCDP performance.

To process this file, start Flixan and select the project directory containing the input data file. Then go to "*Edit*", "*Manage Input Files*" and "*Process/ Edit Input Data*". When the following dialog appears, select the input data file "*Land_M0,4_0.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 describing 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 already created to process the entire file. In order to process the batch, highlight the first line titled "*Batch for analyzing the Lifting-Body Vehicle during Approach and Landing, at t=1839 sec*", and click on "*Execute/ View Input Data*". Flixan will process the input file and save the systems and matrices in file "*Land_M0,4_0*.Qdr". It will also create the matrices and system functions used for Matlab analysis.

LQR Control Design

The Matlab file "init.m" loads the simulation and design systems and the surface mixing matrix in Matlab and performs the pitch and lateral LQR designs.

```
% 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 KmixM0p4.mat -ascii; Kmix=KmixM0p4;         % Load Surfaces Mix Logic (7 x 4)

alfa0=8.531; V0=466.4; Thet0=-33.133; 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
[A14,B14,C14,D14]= linmod('Ldes5x');             % 5-state model {p,r,bet,pint,betint}
A15= C14*A14*inv(C14);   B15= C14*B14;           % Stability axis System
C15= C14*inv(C14);       D15= D14;

% Lateral LQR Design Using Only the RCS Jets
R=[1,10]*0.4; R=diag(R);                         % LQR Weights R=[1,1]*2
Q=[10 2 0.5 20 0.01]*1; Q=diag(Q);               % LQR Weights Q=[1 0.4 0.5 0.2 0.005]*3
[Kpr,s,e]=lqr(A15,B15,Q,R)                       % Perform LQR design on Jets
save Kpr_M0p4_0.mat Kpr -ascii                   % Lateral State-Feedback Gain

% Pitch LQR Design Using the 7 Aero-Surfaces, States: {theta,q,alfa,dH,dV}
[Ap4,Bp4,Cp4,Dp4]= linmod('Pdes5x');             % Include Kmix in design model
R=[5,1]; R=diag(R);                              % Pitch LQR Contrl Weights
Q=[0.00001 0.01 0.001 7 5]; 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_M0p4_0.mat Kq -ascii                     % Longitudinal State-Feedback Gain

% Load Linear Sim Parameters
load THV.mat -ascii;
t=THV(:,1)'-THV(1,1); h=THV(:,2)'; v=THV(:,3)';
x0=[0 0 -2 -2 0 0 18 0 0 0]'*d2r;                 % State Initialization
```

Longitudinal Design

The longitudinal control design is significantly different now from the previous three modes because it is now using two control loops: pitch to control altitude, and speed-brake to control velocity. Although there is significant amount of coupling between the two control loops, it is, however, possible to achieve a certain amount of independent control in the two directions without saturating the control limits. The pitch design plant "*Lifting-Body Aircraft Landing Phase Pitch Design Model*" in file "*pitch_des.m*" now includes 5 states: {θ, q, α, δh, and δV}. The phugoid states (δh and δV) are now included in the design plant because we intend to control them. There is no need for α-integral feedback in this case. The surface mixing matrix Kmix is also added in the design plant (by including it in file "Pdes5x.Mdl"), so the plant inputs are reduced to: pitch and axial acceleration demands. In the control law implementation the α-feedback is replaced with Nz-feedback because Nz is directly measurable and the relationship between α and Nz is almost proportional. The state-feedback generated by the LQR algorithm is a (2x5) gain matrix "Kq_M0p4_0.mat". The Simulink model "*Sim_Pitch_Simple.Mdl*", shown in figure (1.4.4), is used for a preliminary evaluation of the LQR design. It includes the state-feedback matrix Kq and the mixing-logic matrix. It calculates the system's response to altitude and velocity change commands. In the case shown below it calculates the system's response to a 2° command in altitude. Instead of alpha, Nz feedback is implemented in the 6-dof simulation model.

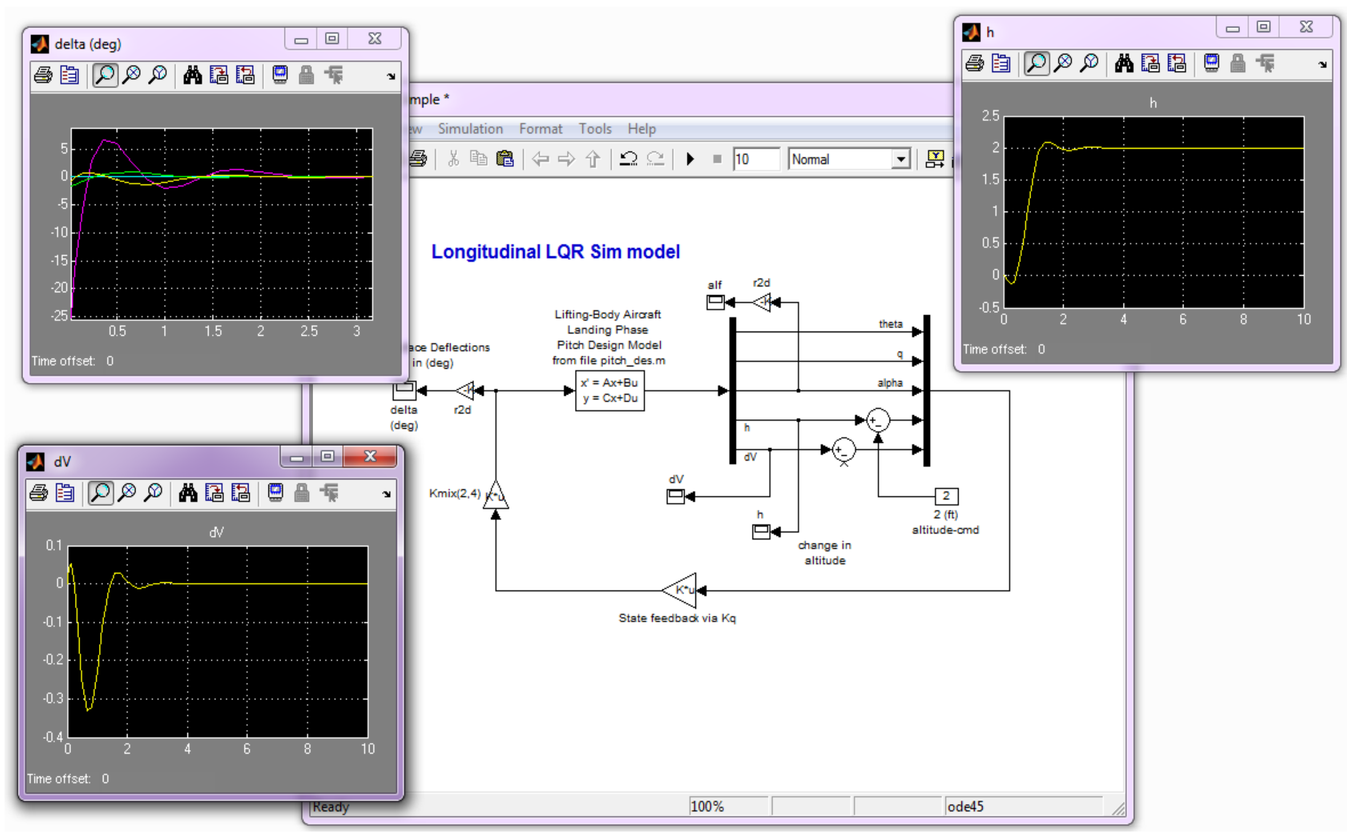


Figure 1.4.4 Simulink Model "*Sim_Pitch_Simple.Mdl*" for evaluating the Approach and Landing LQR design

Lateral Design

The lateral design is almost identical to the previous modes. It uses the system "*Lifting-Body Aircraft Landing Phase Lateral Design Model*" from file "*later_des.m*" consisting of states: {p_s, r_s, and β}. The lateral design model is in the stability axis and includes also the turn-coordination terms for reasons already explained. It is augmented (using Simulink file Ldes5x.Mdl) to include also p_s-integral and β-integral in the state-vector. The state-feedback matrix generated by the LQR algorithm is a (2 x 5) gain matrix "Kpr_M0p4_0.mat". The Simulink model "*Sim_Later_Simple.Mdl*" is used for evaluating the preliminary lateral design. It includes the state-feedback matrix Kpr and the mixing-logic matrix KmixM0p4.

Linear Simulation Model

The Matlab simulation model for the approach and landing mode is in file "*Landing_Sim.Mdl*", shown in figure (1.4.5). The longitudinal axis is different from the previous control modes because now the FCS uses altitude and velocity feedback affecting pitch and speed-brake controls respectively. In the lateral axis directional errors are converted to roll commands. Control in the 4 axes is implemented by combinations of surface deflections as defined in the surface mixing matrix. The simulation model is used for evaluating the system's response to ϕ , δh, and δV commands and also to wind-gust disturbances. Notice, the α-feedback is replaced with Nz feedback in this model. The output rates are body rates since the rate-gyro measurements are in body axes. The controller, however, was designed based on the stability axis model and it expects to see roll and yaw rates about the velocity vector V_0. A body to stability axis transformation block is, therefore, included in the simulation to convert the (p & r) body rates to stability rates (p_{stab} & r_{stab}) which are required in the lateral LQR state-vector feedback. The linearized turn-coordination terms are also included in this block.

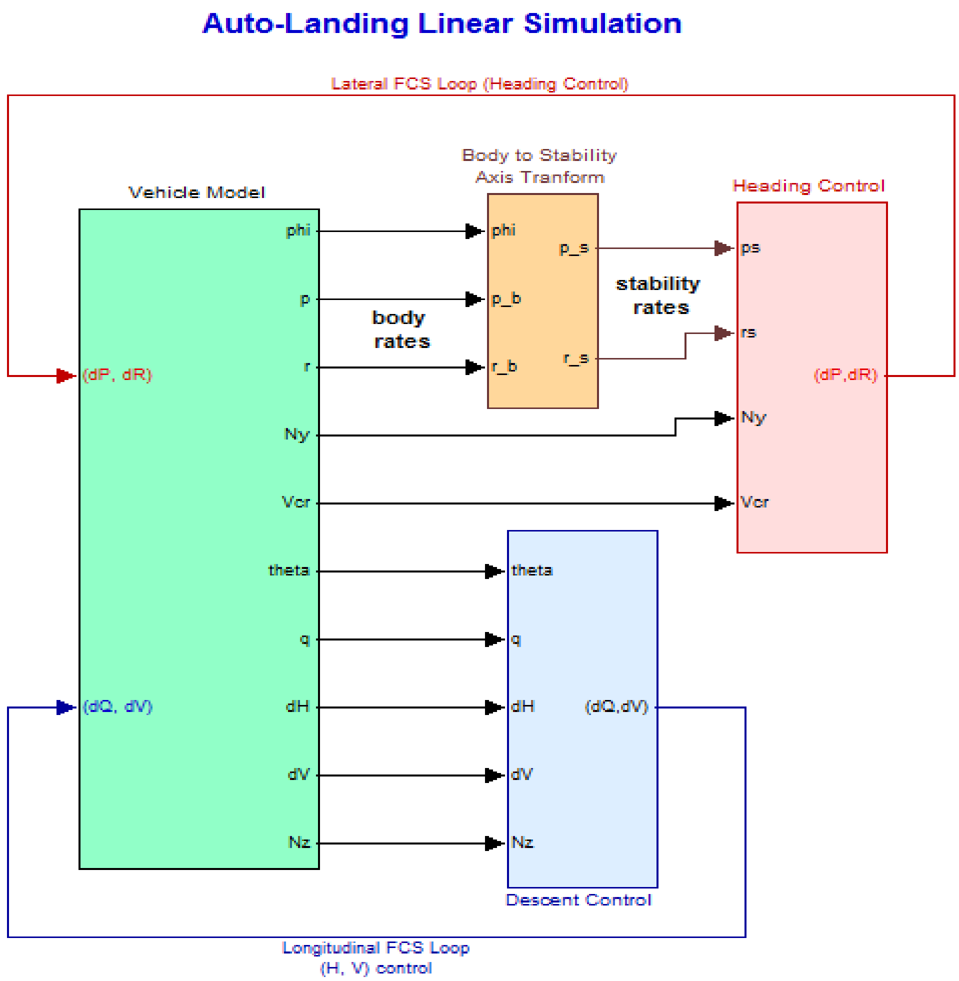


Figure 1.4.5a Simulation Model in File "Landing_Sim.Mdl". The pitch controller now uses altitude and velocity feedback.

Figure (1.4.5b) shows the vehicle dynamics (green) block expanded. It uses the body-axis vehicle model "*Lifting-Body Aircraft Near Landing, Simulation Model*" that was generated by Flixan and has the additional δV output #15. It is loaded in Matlab from file "*vehicle_sim.m*". The lateral inputs to this block from flight control are: roll, and yaw acceleration demands (red), and the longitudinal inputs are: pitch and axial accelerations (blue). The 4 control demands are converted to surface deflections by the surface mixing logic KmixM0p4. Actuator dynamics are included in the yellow block. 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 "*Land_M0,4_0.Inp*", and it excites both pitch and yaw, perpendicular to the X-body and at 45° between +Y and +Z axes (typical).

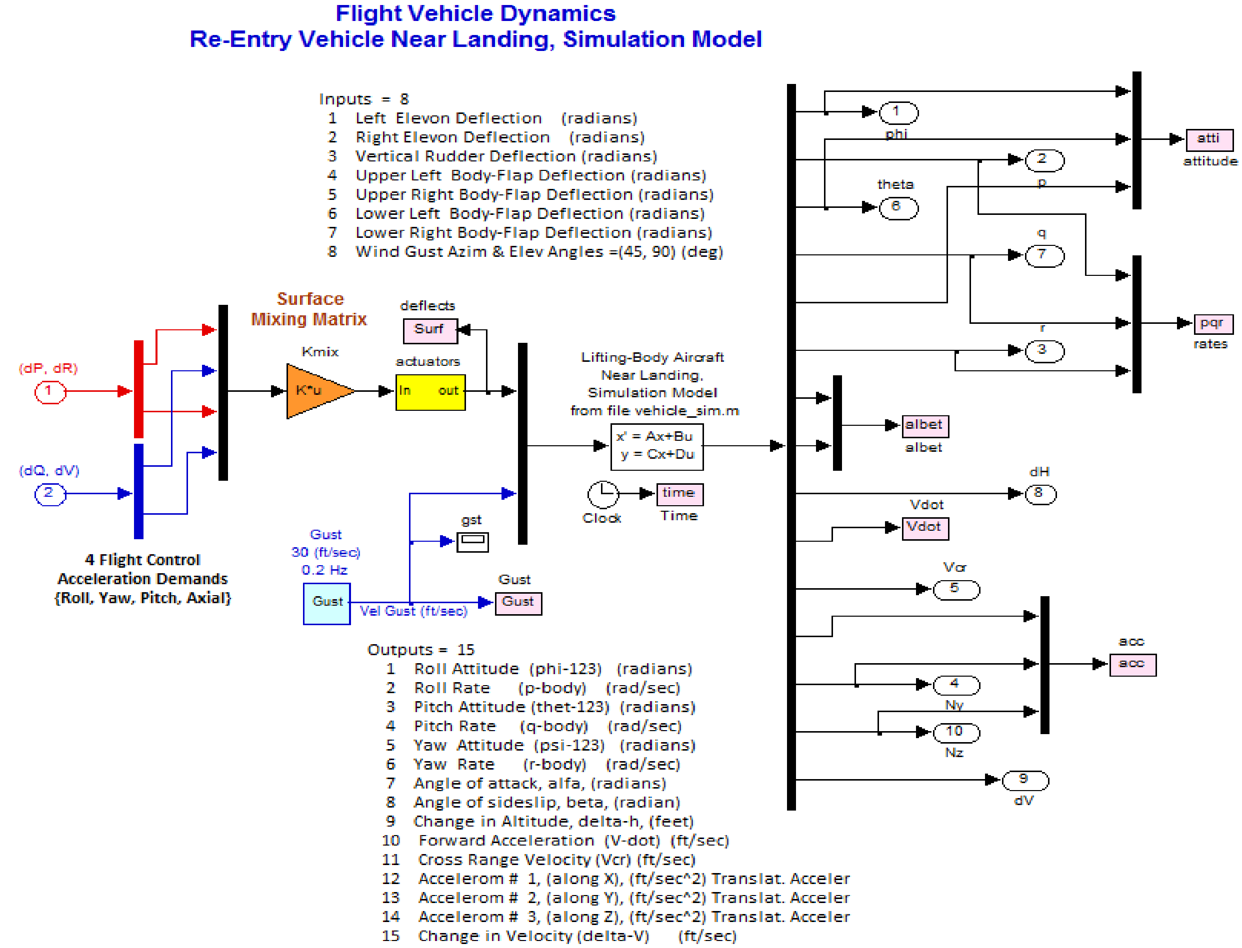


Figure 1.4.5b Vehicle Dynamics Block including the aero-surface Mixing Logic, Gust disturbance and Actuators

The following figure shows the pitch and lateral control laws which are state-feedback gains as already described. In the longitudinal axis the controller consists of a (2x5), {θ, q, Nz, δh, and δV} state-feedback gain Kq, (α was replaced with Nz by a gain relationship Nz2a). An Nz-filter is also included. The guidance command inputs are time histories of altitude and velocity, see Figure (1.4.6b). The two inputs are not for maneuvering since the aircraft is unpowered but they are coordinated from guidance as a function of energy. The control loops also compensate against wind disturbances. In the lateral direction the controller is a (2x5), (p_s, r_s, β, p_s-integr, β-integr) state-feedback gain Kpr. Its purpose is to perform roll maneuvers for direction control. The roll command is a function of the heading error which is calculated from the cross-range velocity error.

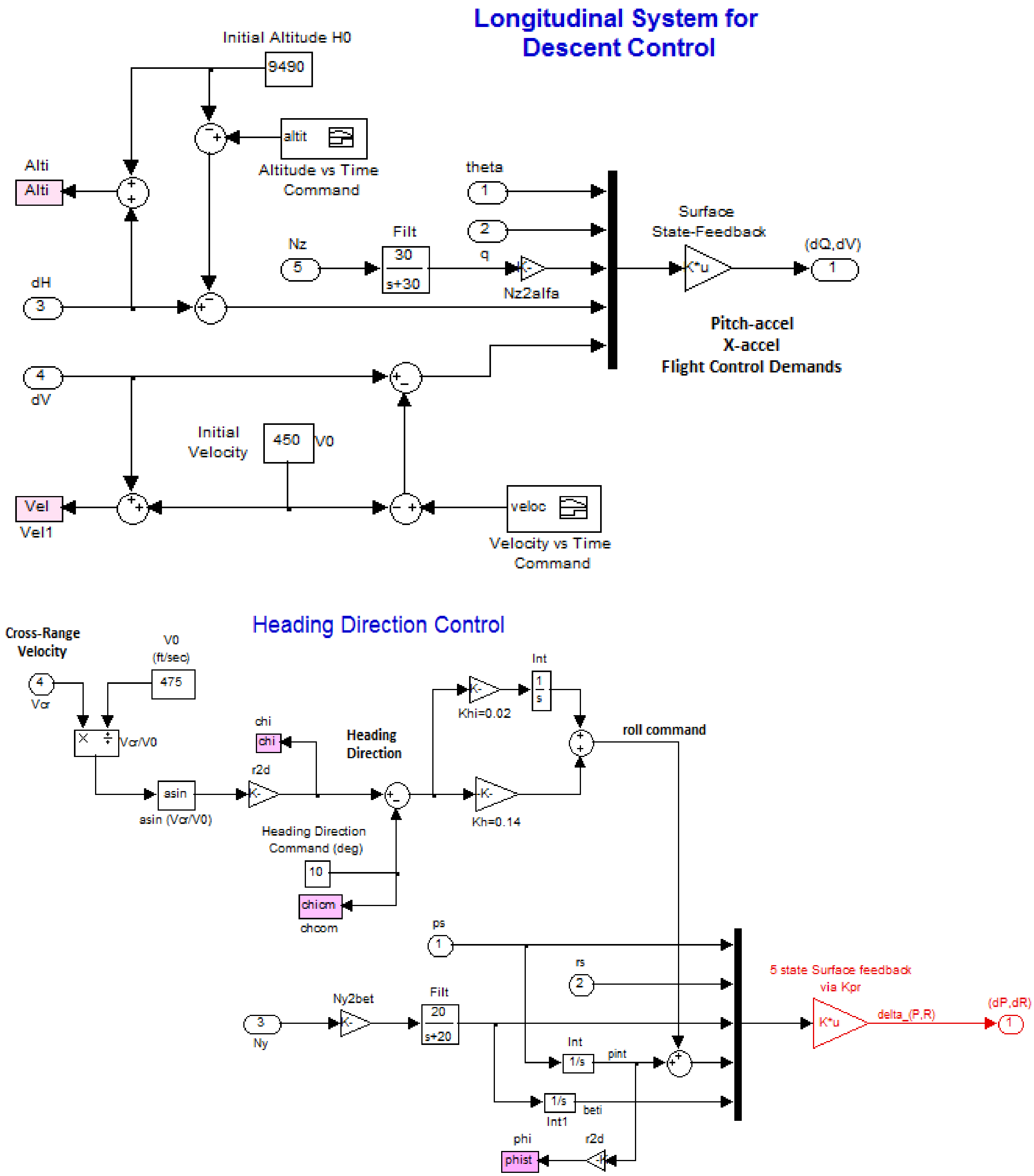


Figure 1.4.6 Longitudinal and Lateral State-Feedback Control Laws for the Approach and Landing Phase

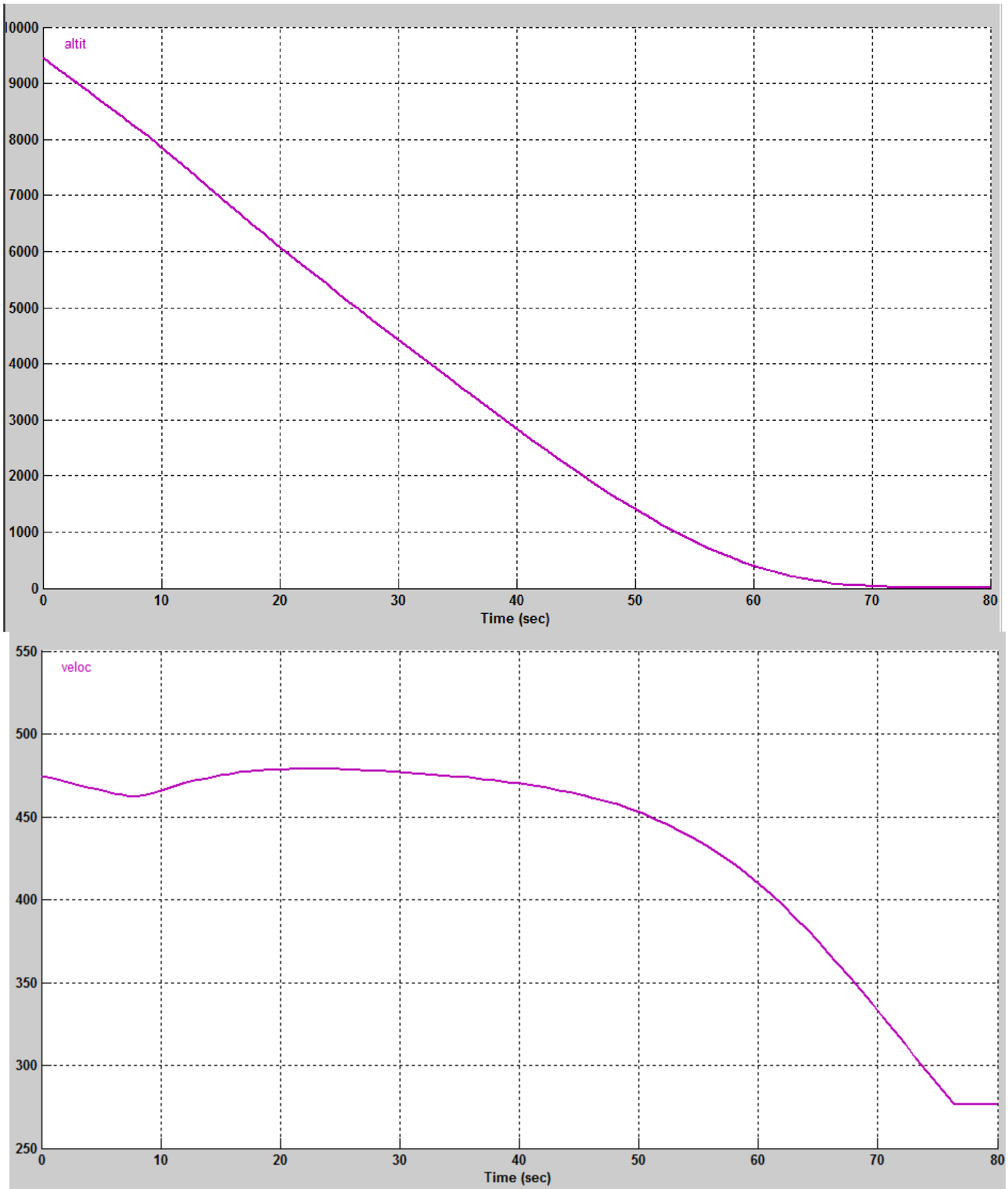


Figure 1.4.6b Altitude and Velocity Coordinated Commands versus Time used in the Simulation

Simulation Results

Let us now use the linear simulation model for the Mach 0.4 case "*Landing_Sim.Mdl*" and command it to track the coordinated altitude and velocity time histories of Figure (1.4.6). The lateral directions are also excited at the same time by commanding a 10° change in the heading direction. At the same time the model is also excited with a wind disturbance noise shown in Figure (1.4.8). This linear model is used for a preliminary evaluation of the flight control system performance. A better evaluation of the design will be obtained from the 6-dof non-linear simulation. Figure (1.4.7a) shows the altitude and velocity response to the longitudinal commands. Figure (1.4.8) shows the heading direction response to the 10° command.

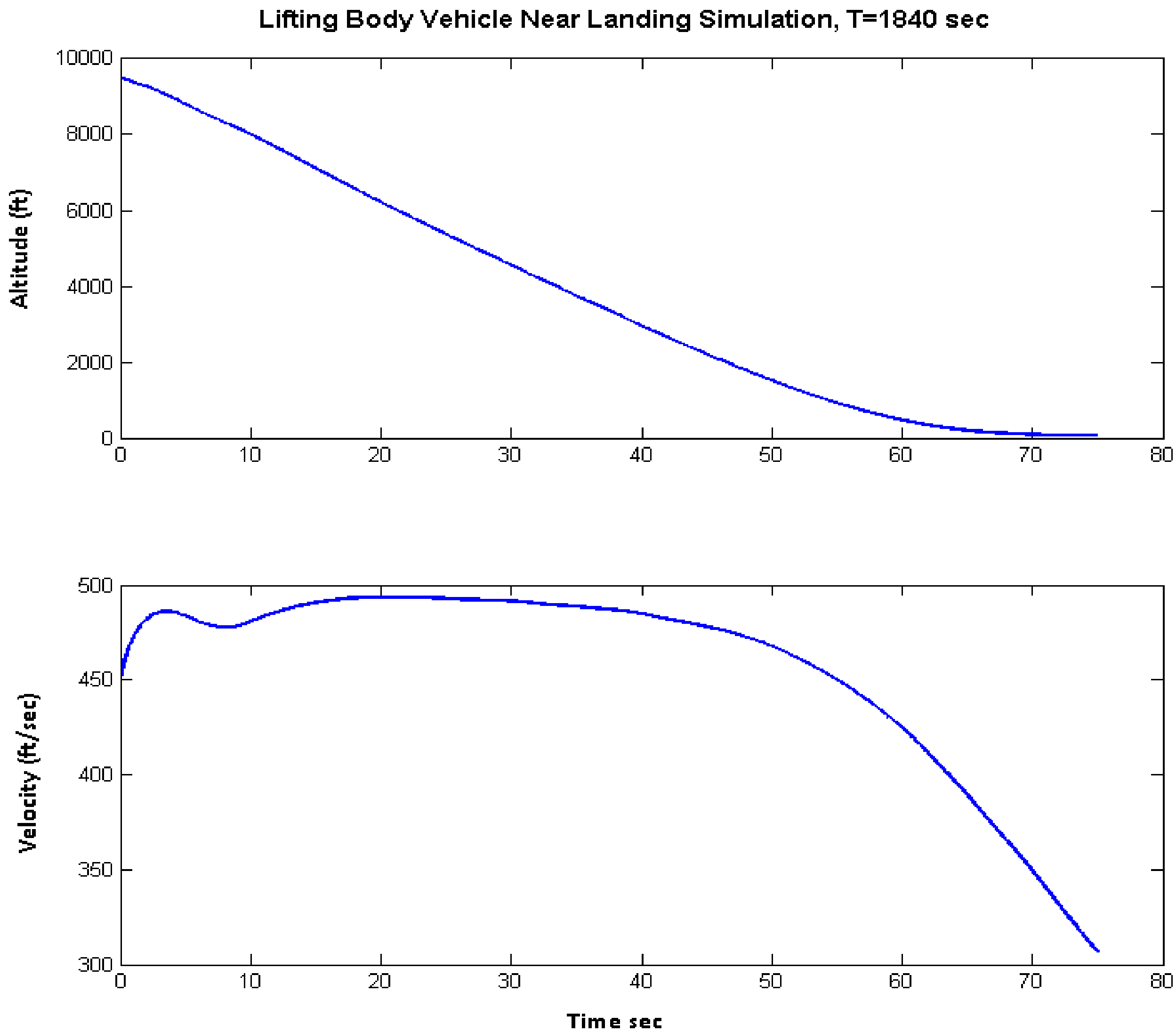
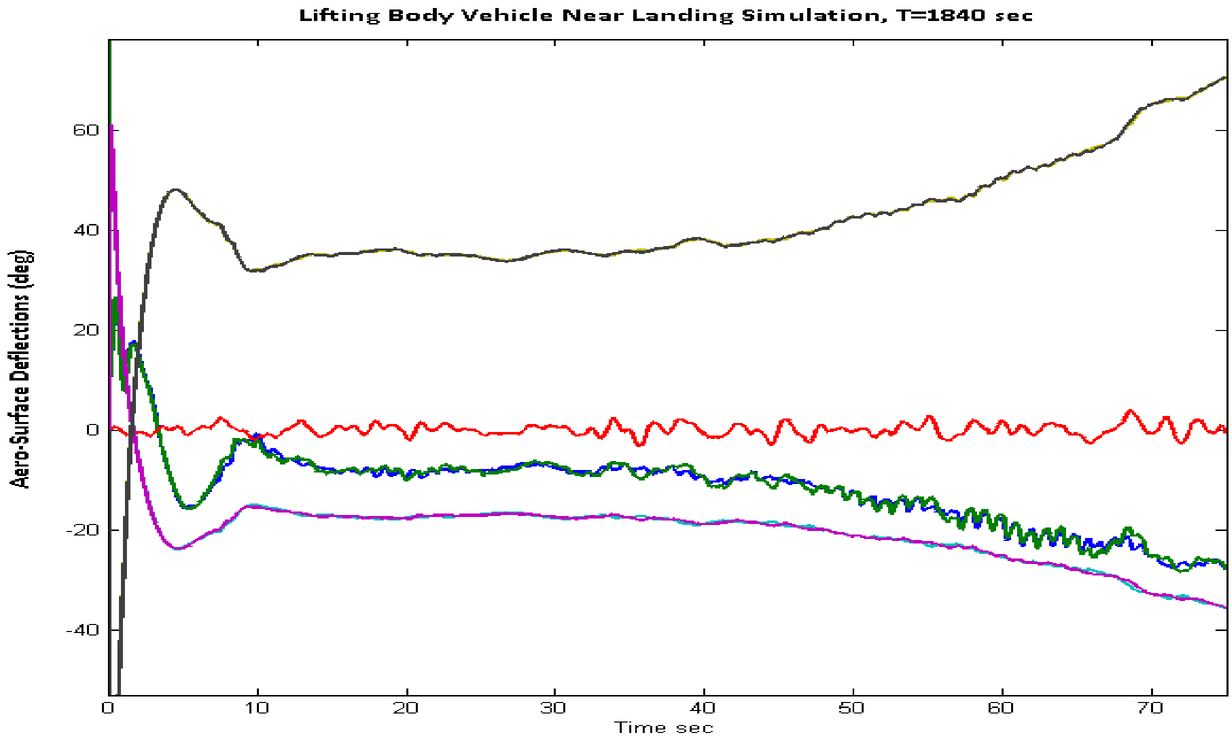
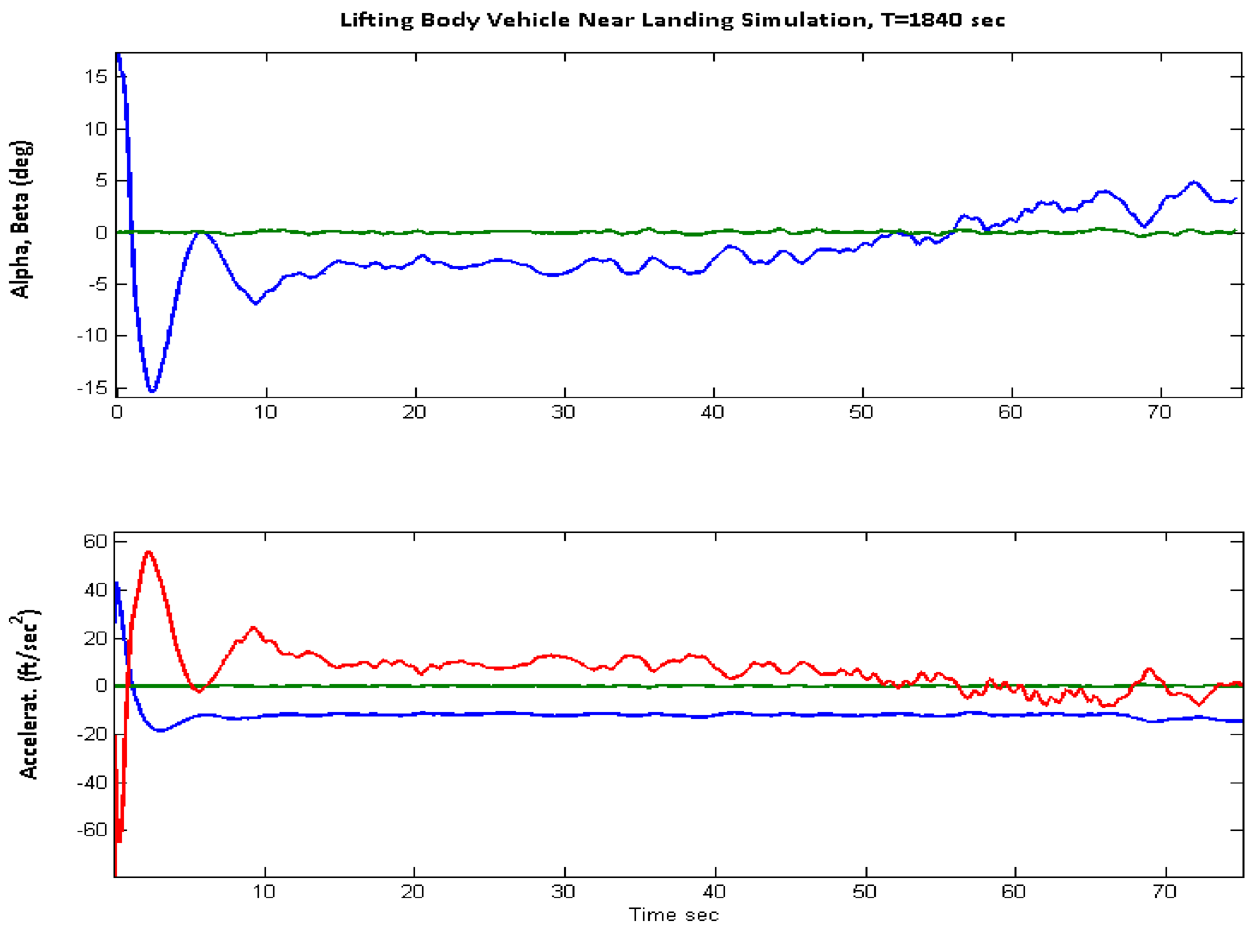


Figure 1.4.7a Response of the Simulation model "Landing_Sim.Mdl" to the Altitude and Velocity Commands


Lifting Body Vehicle Near Landing Simulation, T=1840 sec
Aero-Surface Deflections (deg)
60
40
20
0
-20
-40
0
10
20
30
40
50
60
70
Time sec


Lifting Body Vehicle Near Landing Simulation, T=1840 sec
Alpha, Beta (deg)
15
10
5
0
-5
-10
-15
0
10
20
30
40
50
60
70
Accelerat. (ft/sec^2)
60
40
20
0
-20
-40
-60
10
20
30
40
50
60
70
Time sec

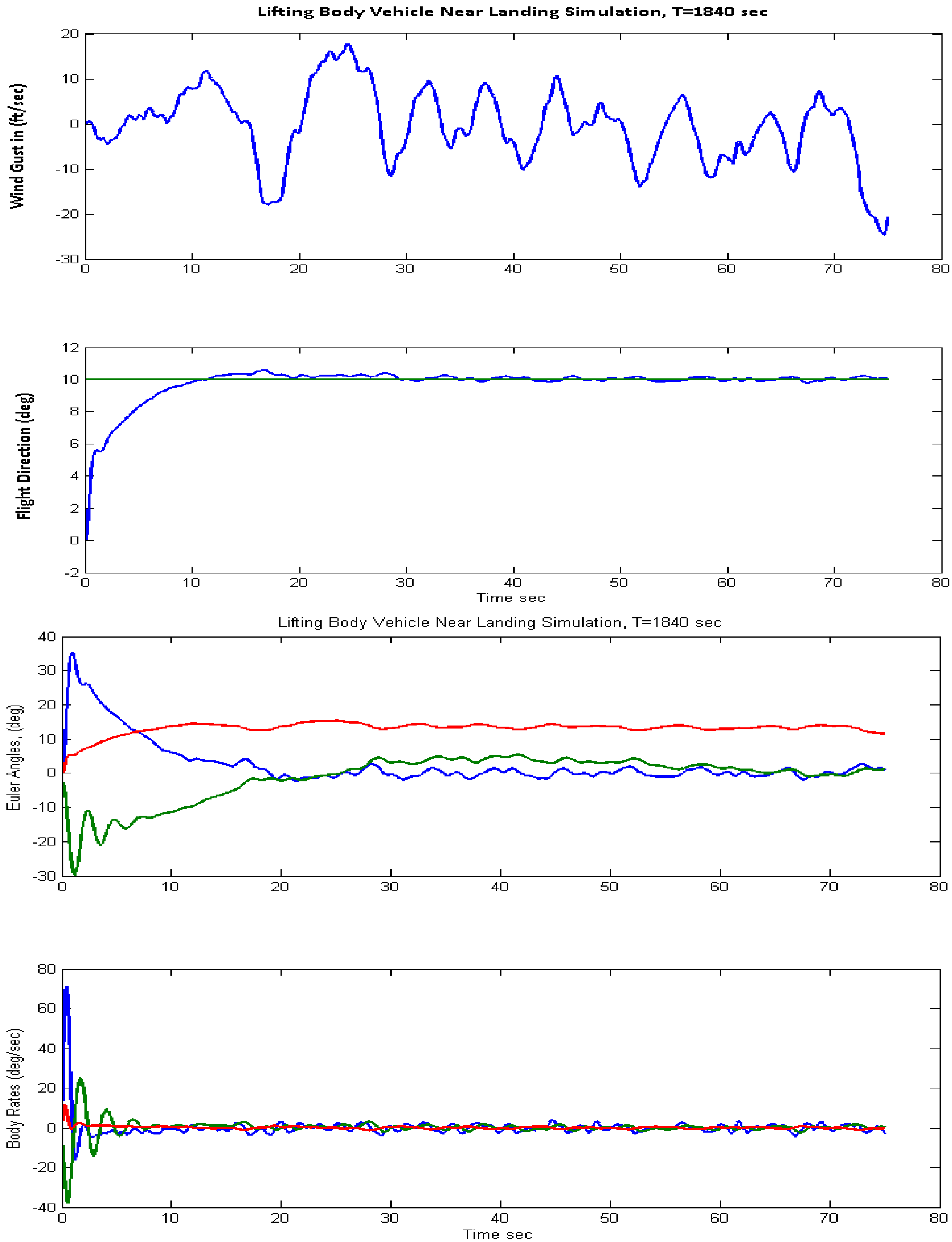


Figure 1.4.8 Lateral System Response to a 10 (deg) change in the heading direction

Stability Analysis

Figure (1.4.9) shows the Simulink model "*Stab_Anal.Mdl*" used for analyzing the stability margins in the four control loops. This model is similar to the simulation "*Simul_6dof.Mdl*" but it is configured for open-loop analysis. One loop is opened at a time and the other three loops are closed (in the case shown below the pitch loop is opened for analyzing pitch axis stability). The Matlab file "Frequ.m" uses this model to calculate the frequency response across the opened loop.

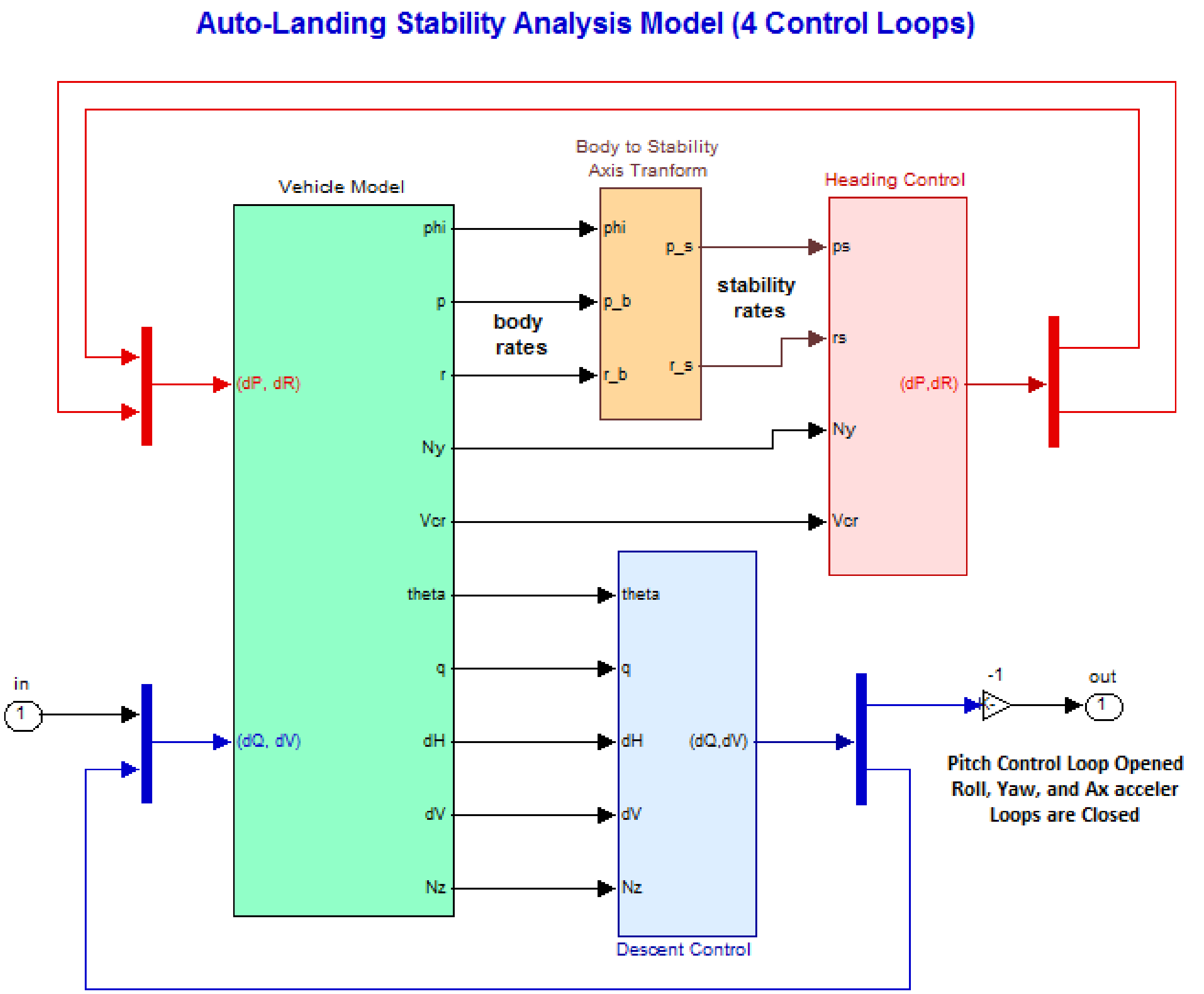
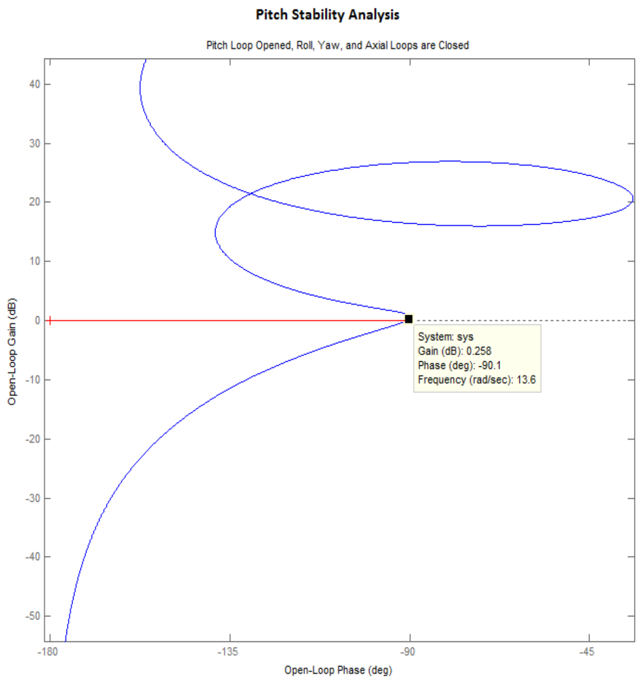
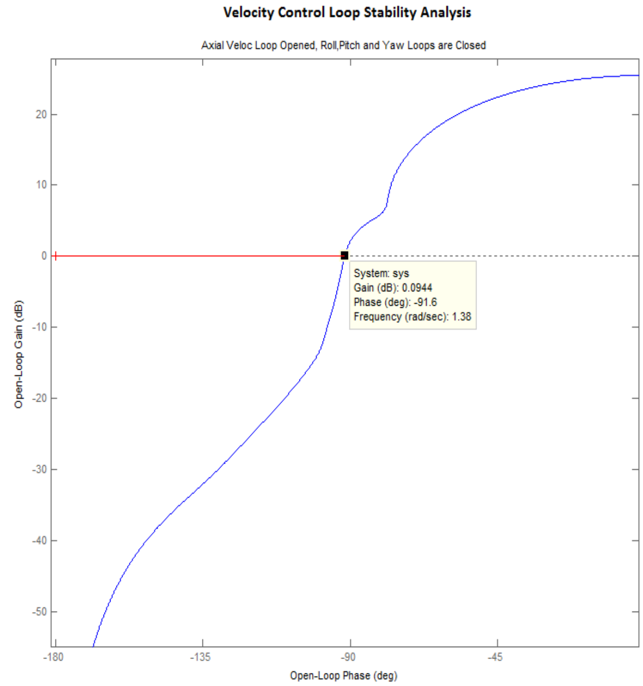
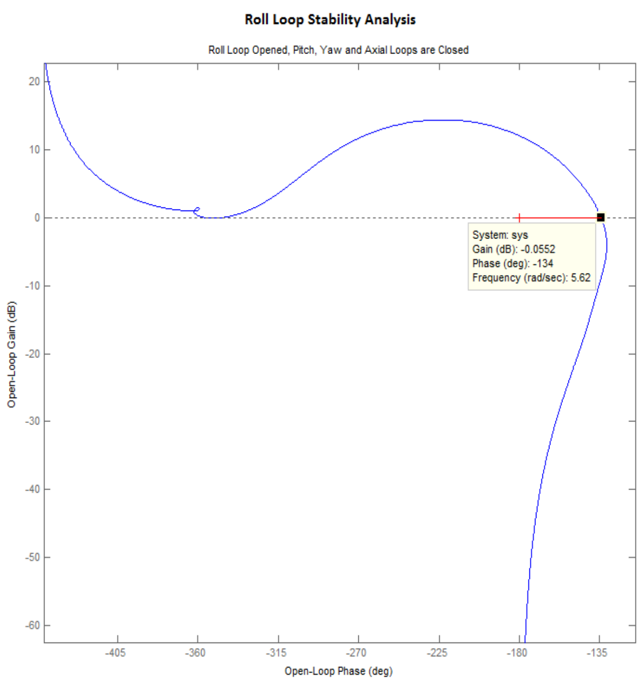
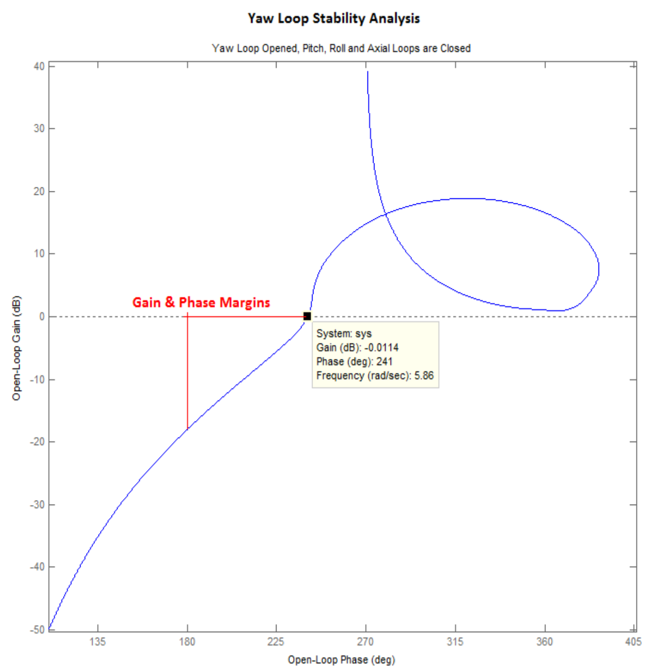


Figure 1.4.9 Stability Analysis model "Stab_Anal.mdl" used for frequency response analysis



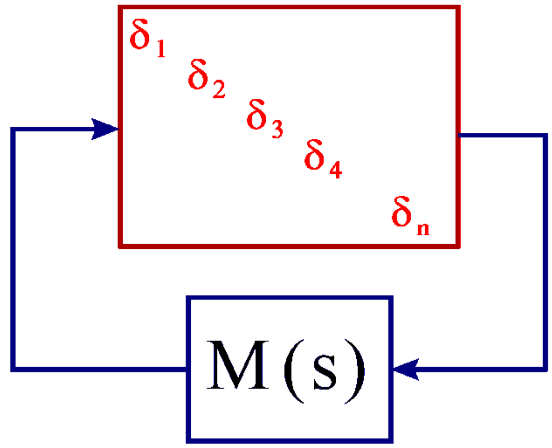






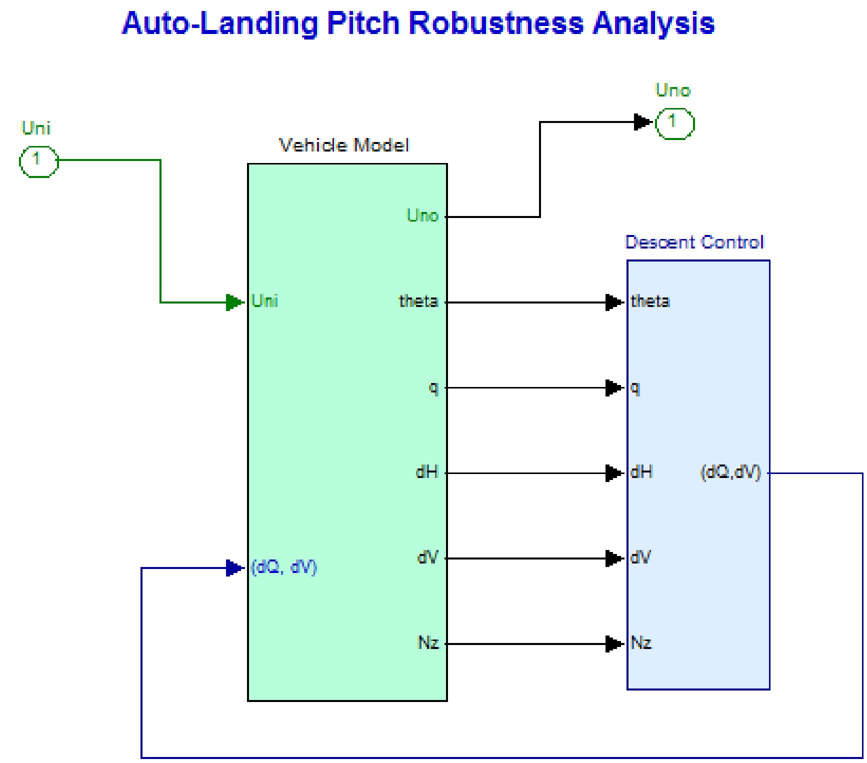
The above figures show the Nichols plots in the four controlled directions (roll, pitch, yaw, and velocity control) for the Mach 0.4 case. The red lines show the phase and gain margins. The cross-over frequency points are also highlighted.

Robustness Analysis to Parameter Uncertainties



Structured singular value (SSV) or μ-analysis is a very powerful tool for analyzing robustness of the flight control system with respect to structured uncertainties. We will, therefore, include μ-analysis in this design example. In the vehicle input data file "*Land_M0,4-0.Inp*" we have created a system with 60 structured uncertainties. Its title is "*Lifting-Body Aircraft Landing Phase (Robust Analysis with 60 Uncert)*". Each uncertainty is defined by an input/ output pair in addition to the ordinary vehicle model inputs and outputs. The amount of uncertainty of each parameter is defined in a separate data-set which is also located in "*Land_M0,4_0.Inp*". The data-set title is "*Uncertainties at Mach=0.43, Alpha=10*" and it is processed by Flixan together with the vehicle data to generate the multi-input-output uncertainties state-space model. The uncertainties model dynamically is the same as the simulation model with the exception that it has a lot of additional inputs and output pairs, each pair representing one of the uncertainties, thus allowing the uncertainties to be pulled out of the model in a separate Δ block, see figure. The remaining block M(s) now represents the stabilized vehicle model with its control loops closed (not shown). It is not uncertain because its uncertainties were pulled out and placed in the diagonal Δ block. It is only connected to the uncertainties Δ block by the input and output vectors. We should also mention that the closed-loop vehicle model M(s) should be stable and that it is also properly scaled so that its diagonal Δ block now has elements that can only vary between ±1. Robustness is measured by calculating the SSV across the M(s) block and the closed-loop system cannot be destabilized by any combination of the uncertainties, as long as $\mu[M(j\omega)]<1$, at all frequencies.

Separate μ-analysis will be performed for the longitudinal and lateral directions. The dynamic model with the 60 uncertainties is separated in two subsystems. The uncertainties were also separated into longitudinal and lateral uncertainties. The longitudinal model has 28 uncertainties and its title is "*Lifting-Body Aircraft Near Landing, Pitch Robust Analysis (28 Uncs)*". The lateral model has 32 uncertainties and its title is "Lifting-Body Aircraft Near Landing, Lateral Robust Analysis (32 Uncs)". They are saved in files "*pitch_unc.m*" and "*later_unc.m*" respectively and used in the μ-analysis. The model separation is defined in "*Land_M0,4_0.Inp*" and it is automatically executed when running the batch set. Most of the uncertainties are rank-1, meaning that they create a single input/output pair. The X-cg, however, affects both longitudinal and lateral models and it creates 3 input/output pairs. The input/ output pairs must be separated carefully by observing the states with which they are coupling. It seems that two X-cg uncertainty pairs are affecting the longitudinal states and one X-cg pair affects the lateral states. The Y-cg is only affecting the lateral directions. The following two models in Figure (1.4.10) are used to calculate the SSV of the longitudinal and lateral systems with the control loops closed, and the next two figures show the longitudinal and lateral (green) vehicle blocks in detail.



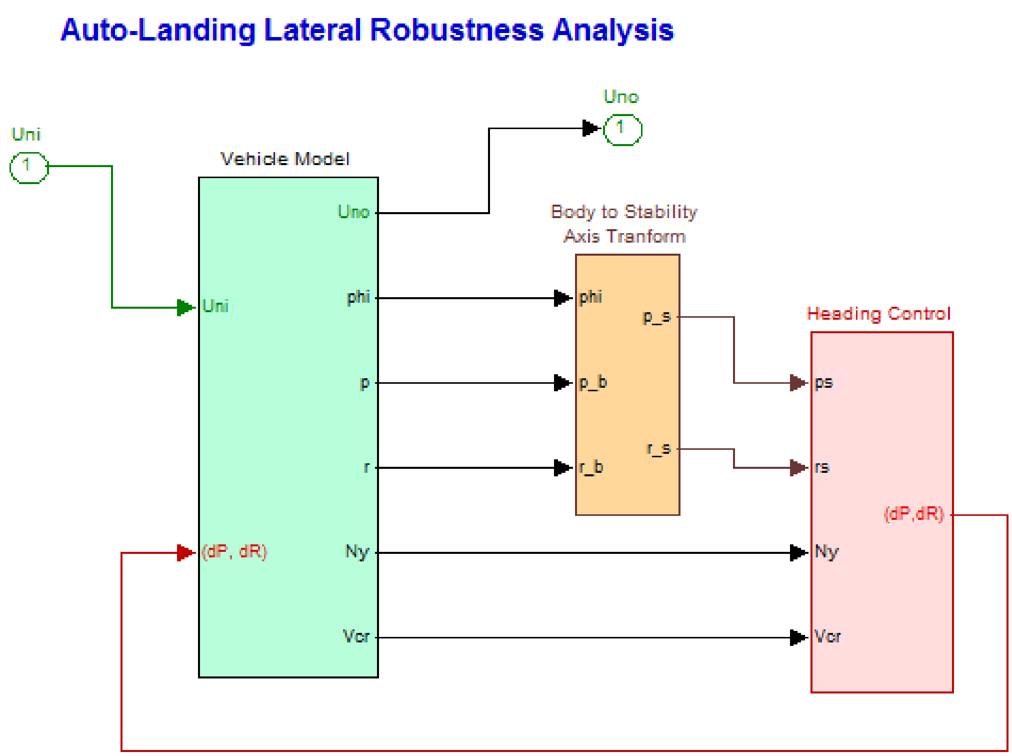
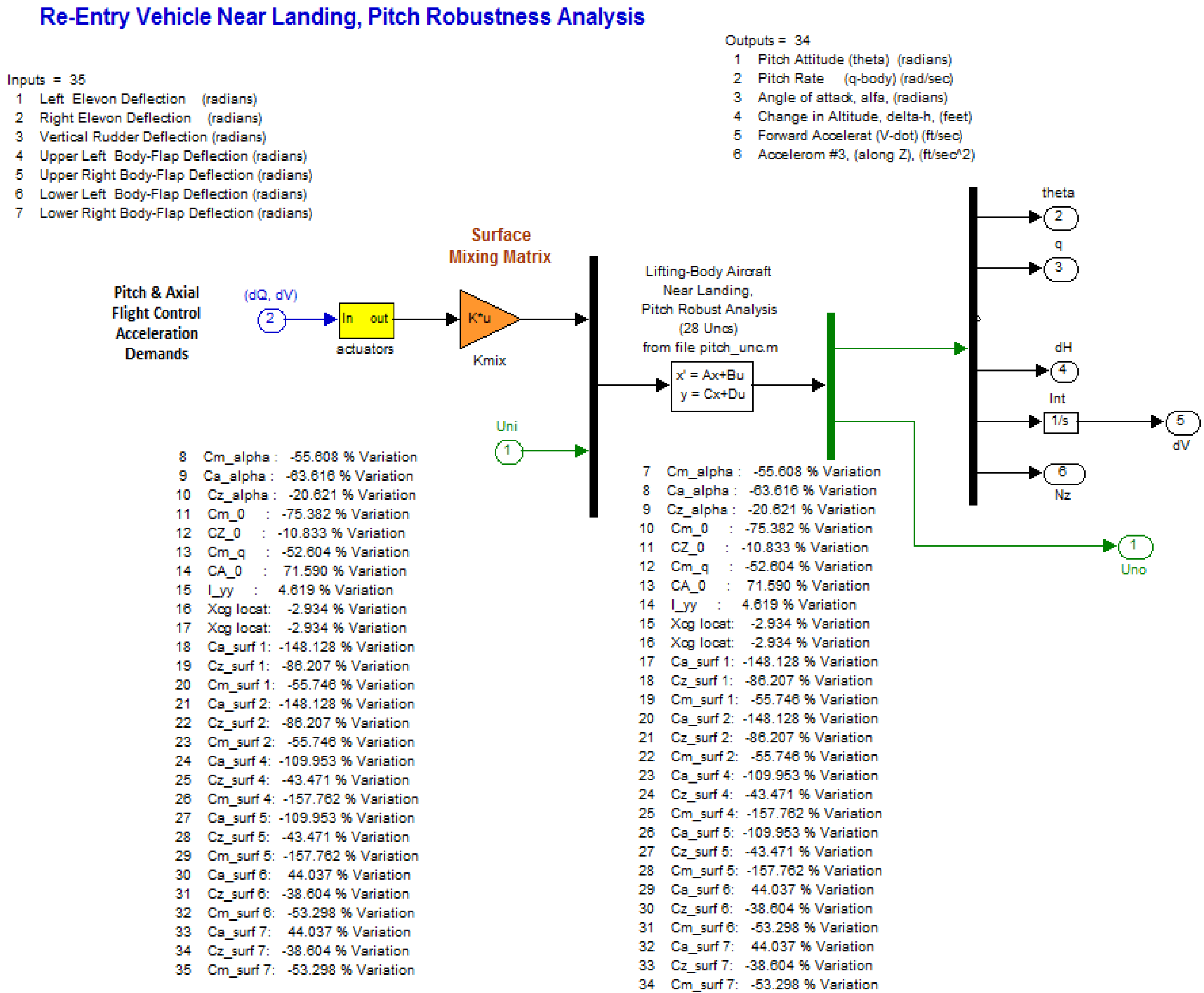
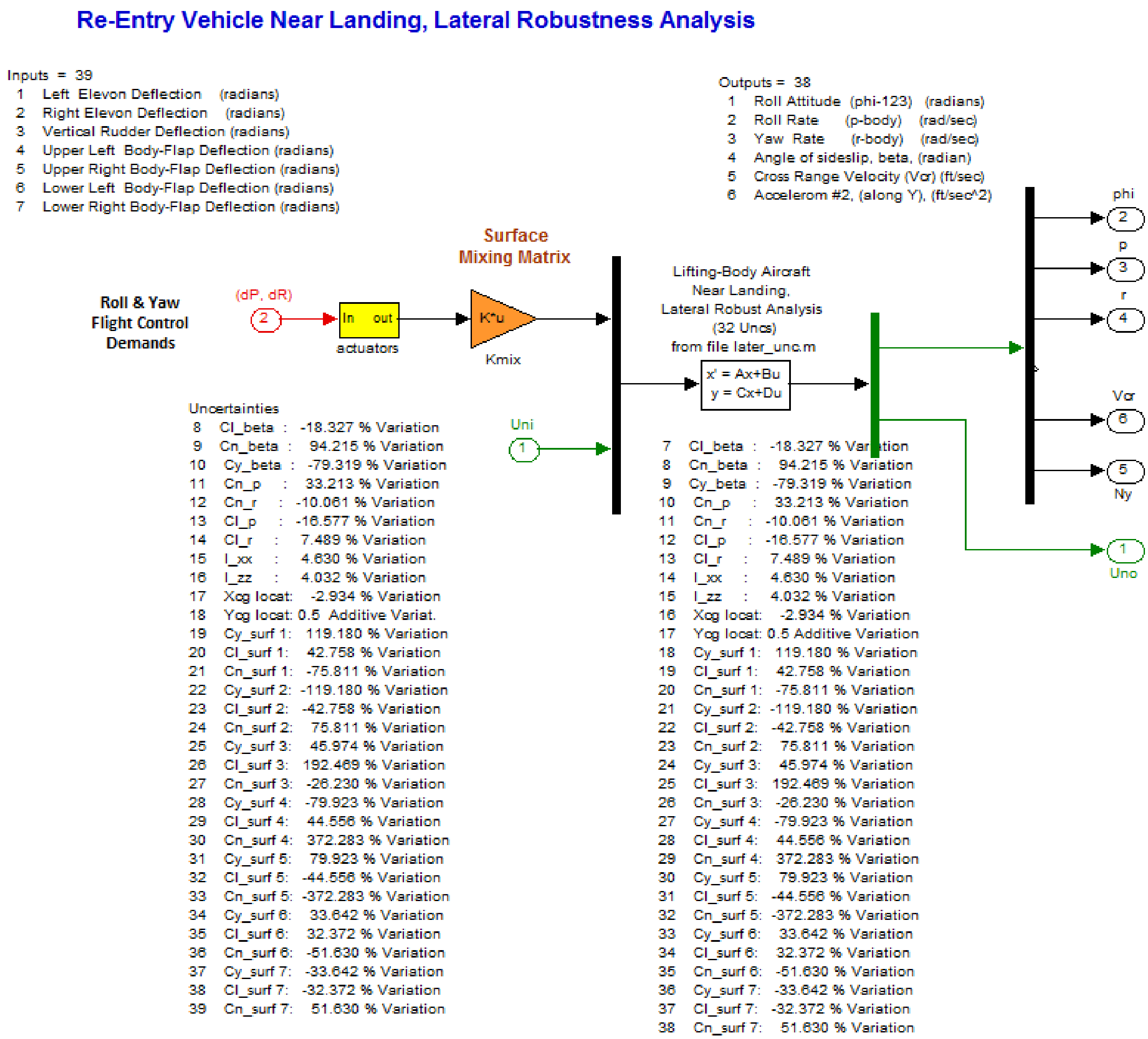


Figure 1.4.10 Simulink Models "Pitch_Robust_Anal.Mdl" and "Lateral_Robust_Anal.Mdl" used in the μ-analysis



This figure shows the longitudinal vehicle block in the Simulink model "Pitch_Robust_Anal.Mdl" used for calculating the SSV in the longitudinal directions. It includes the longitudinal vehicle model with the 28 uncertainties from file "*pitch_unc.m*". It includes also the effectors mixing matrix and actuators. The pitch and axial acceleration controls are converted to 7 aero-surface deflections. The inputs (Uni) and outputs (Uno) are theoretically connecting with the normalized uncertainty block Δ. The SSV is calculated across those input and output vectors. They are labeled to show which uncertainty they represent and also the percentage of each variation.

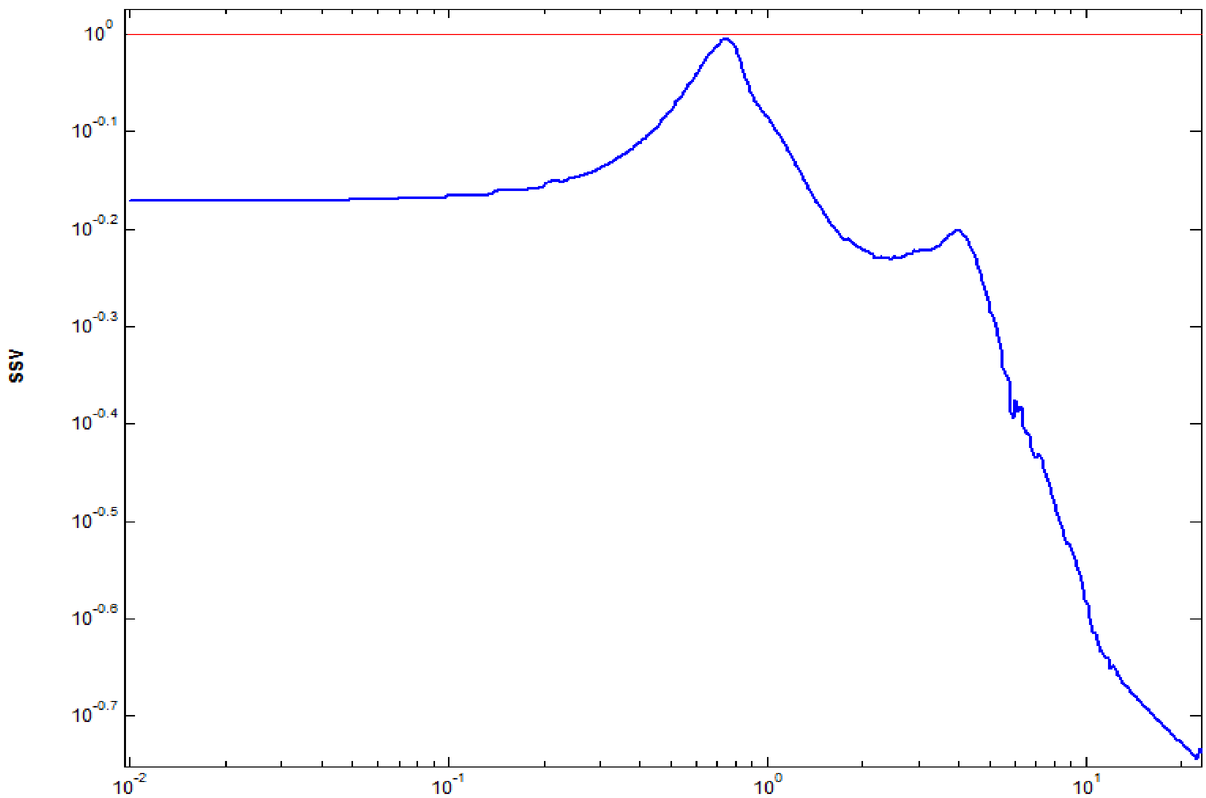


This figure shows the lateral vehicle block in the Simulink model "Lateral_Robust_Anal.Mdl" used for calculating the SSV in the lateral directions. It includes the lateral vehicle model with the 32 uncertainties from file "*later_unc.m*". It includes also the effectors mixing matrix and actuators. The roll and yaw acceleration controls are converted to 7 aero-surface deflections. The inputs (Uni) and outputs (Uno) are theoretically connecting with the normalized uncertainty block Δ. The SSV is calculated across those input and output vectors. They are labeled to show which uncertainty they represent and also the percentage of each variation.

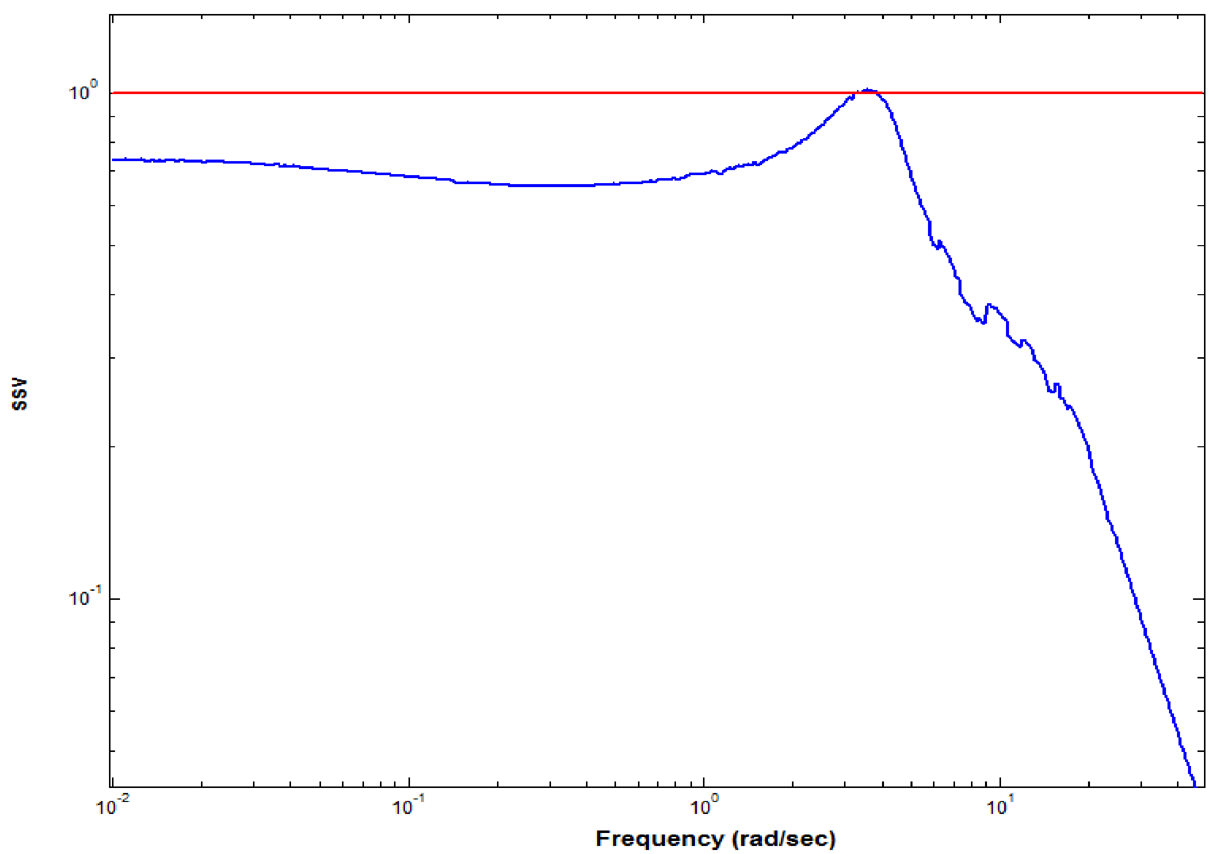
```
% Uses Mu-Analysis to Calculate System Robustness to Structured Uncertainties
d2r=pi/180; r2d=180/pi;
Npv=28; Nlv=32;                                    % Number of Param Variations
[Apu,Bpu,Cpu,Dpu]= pitch_unc;                      % Pitch Vehicle Model with 28 Uncertaint
[Alu,Blu,Clu,Dlu]= later_unc;                      % Later Vehicle Model with 32 Uncertaint
w=logspace(-2,2,500);                              % and Frequ domain analysis

[Acp,Bcp,Ccp,Dcp]=linmod('Pitch_Robust_Anal');
sys=ss(Acp,Bcp,Ccp,Dcp);
sysf= FRD(sys,w);
blk=[-ones(Npv,1), zeros(Npv,1)];
[bnd,muinfo]= mussv(sysf,blk);
ff= get(muinfo.bnds, 'frequency');
muu=get(muinfo.bnds, 'responsedata');
muu=squeeze(muu);
muu=muu(1,:);
figure (1)
loglog(ff,muu, 'LineWidth',1.5)
xlabel('Frequency (rad/sec)')
ylabel('ssv')
Title('Pitch Mu Analysis')
```

The above script file "robust.m" calculates the SSV frequency response of the pitch M(s) system with the control loops closed, as shown in the pitch μ-analysis model "*Pitch_Robust_Anal.Mdl*". A similar script calculates the SSV frequency response for the lateral M(s) system using the lateral μ-analysis model "*Lateral_Robust_Anal.Mdl*". The μ-analysis results shown in the next two figures indicate that the control system is robust to the structured uncertainties defined because $\mu<1$ at all frequencies in both the longitudinal and in the lateral directions. It means that there is no combination of uncertainties within the specified limits that will be able to destabilize the systems.

Pitch Mu Analysis



Lateral Mu Analysis



Alternate Longitudinal Design

The longitudinal control design for the approach and landing phase, described above in Figure (1.4.6), has an implementation problem and it was replaced with an alternate design in the simulation. Although it is technically superior because it includes the phugoid states in the longitudinal LQR design plant consisting of velocity and altitude and, therefore, they are directly attenuated by the state-feedback. In addition, it allows the altitude and velocity states to be controlled by altitude and velocity commands directly from guidance. However, the structure of this control design is considerably different from the previous three control modes that do not include altitude and velocity feedback and the transition to this control law from the previous control mode is not easy to achieve without exciting transients in the state-vector. An alternate design that controls altitude by pitching the aircraft via an Nz-command was implemented in the simulation instead, see Figure (1.4.11). A second loop controls the aircraft speed by modulating the speed-brake opening about its partially opened position as a function of velocity error. This alternate controller is analyzed in directory "*C:\Flixan\Trim\Examples\Lifting-Body Aircraft\Reentry from Space\Mat_Anal\Mch_0.4_nz*". It maintains the original state-feedback structure of the Nz-control mode which makes it easier to transition from this mode. The Nz-command, however, is obtained by combining altitude error and altitude rate signals. A lead-lag filter is also included to improve stability and to attenuate the phugoid oscillation. From the linear analysis point of view the previous design was superior because the controller was designed based on a plant model that includes the phugoid states. However, this design also works, and it was easier to implement in the simulation which is described in detail in the next section (1.5).

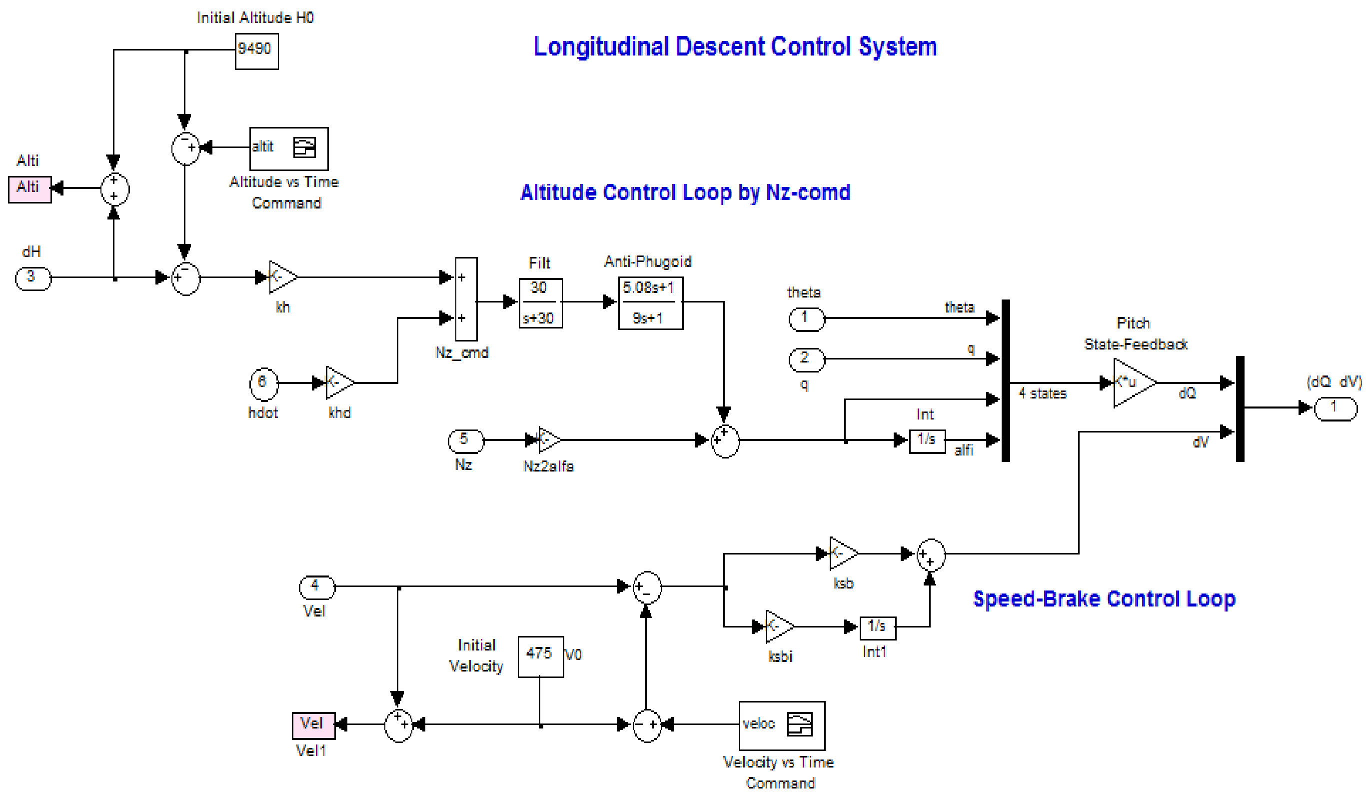
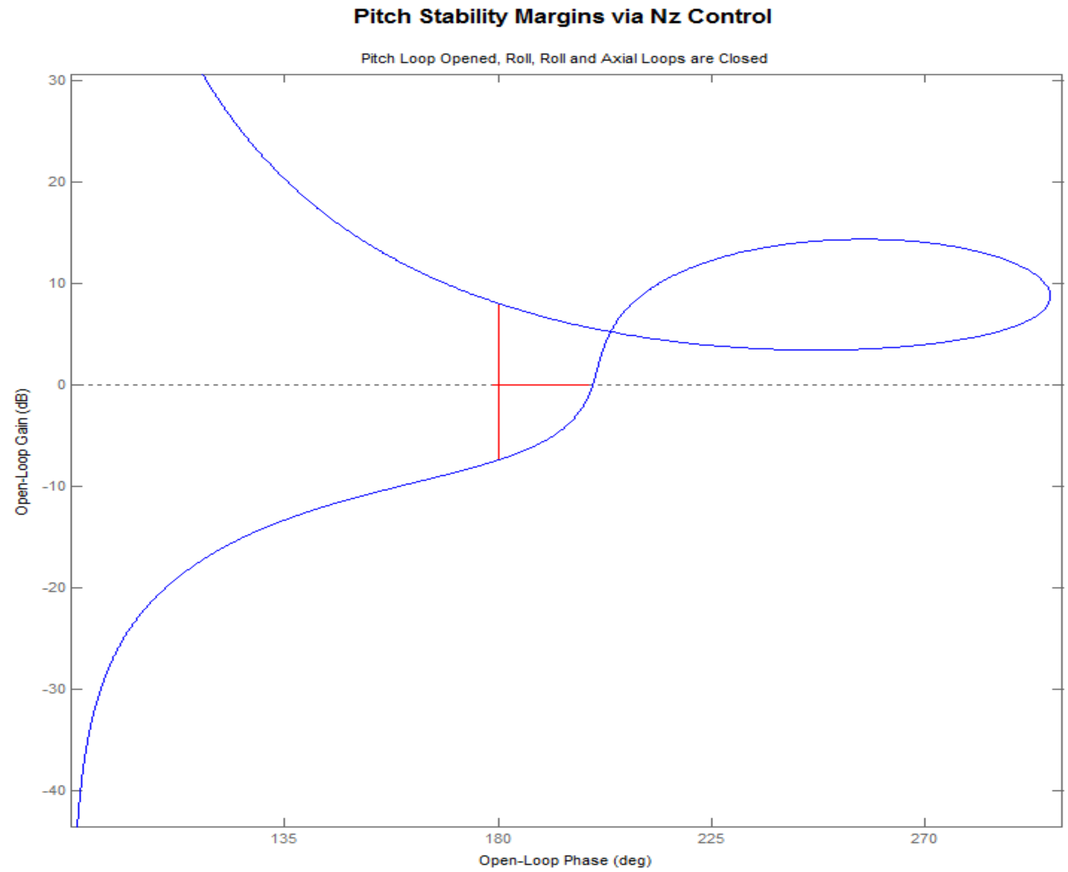
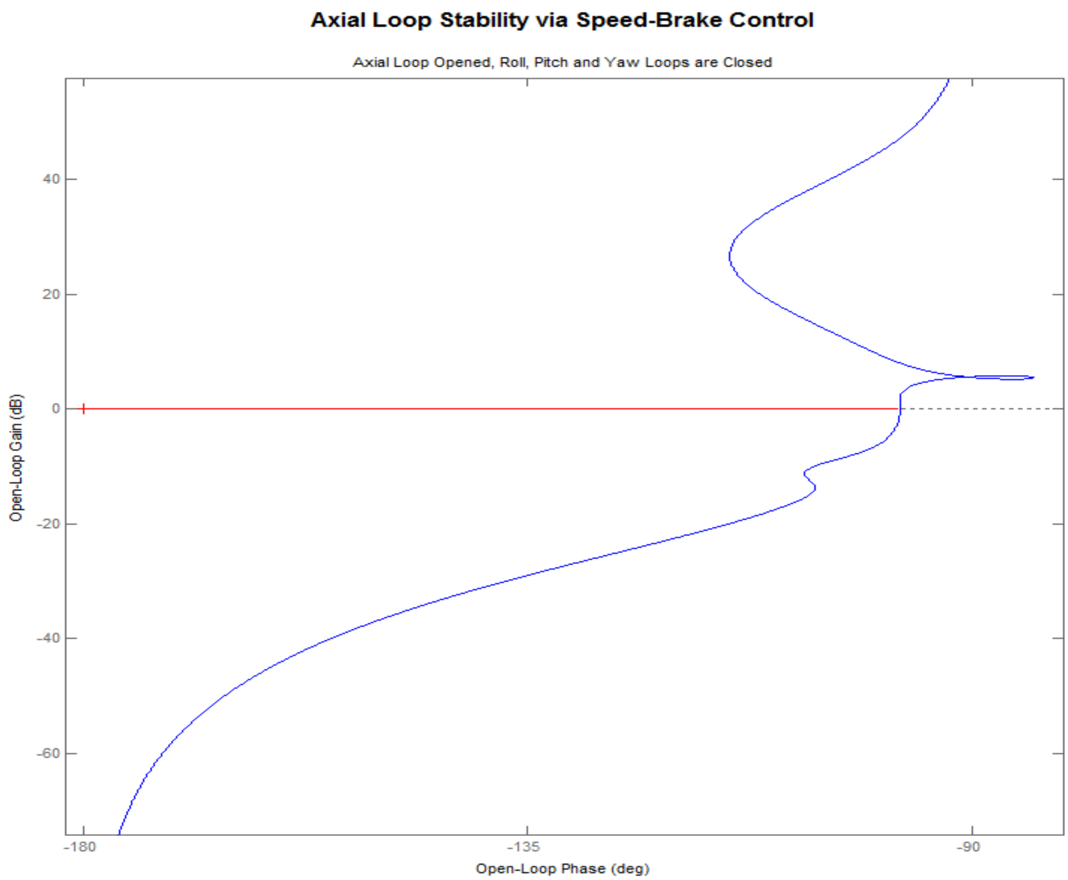


Figure 1.4.11 Alternate Longitudinal Controller for the Approach and Landing Mode Used in the 6-dof Simulation



Pitch Stability Margins via Nz Control
Pitch Loop Opened, Roll, Roll and Axial Loops are Closed
30
20
10
0
-10
-20
-30
-40
135
180
225
270
Open-Loop Phase (deg)
Open-Loop Gain (dB)



Axial Loop Stability via Speed-Brake Control
Axial Loop Opened, Roll, Pitch and Yaw Loops are Closed
40
20
0
-20
-40
-60
-180
-135
-90
Open-Loop Phase (deg)
Open-Loop Gain (dB)

1.5 Six-dof Non-Linear Simulation

The entire re-entry design will now be demonstrated by means of a six-degrees-of-freedom (6-dof) simulation in Matlab/ Simulink. The simulation begins shortly after the de-orbit maneuver when the vehicle is oriented at an α=30°, and it completes 1900 seconds later when the vehicle successfully lands on the runway. The guidance and control system maneuver the aircraft through various phases by employing four types of control modes that achieve different performance goals during each phase. The simulation is located in folder "*C:\Flixan\ Trim\Examples\ Lifting-Body Aircraft\Reentry from Space\ Simulations 6-dof\Re-Entry Simulation (6-dof) -HV Track*" and the Simulink model is "*Reentry-6dof-Sim.Mdl*", shown in Figure (1.5.1). The environment subsystem block is shown in detail in Figure (1.5.2). The block in Figure (1.5.3) calculates the angles of attack, sideslip, dynamic pressure, and Mach number from the velocity vector (x, y, z). The blocks in Figure (1.5.4 through 1.5.7) calculate the aerodynamic forces and moments on the vehicle as a function of the aerodynamic coefficients, Mach number, the angles of attack and sideslip, and the aero-surface deflections.

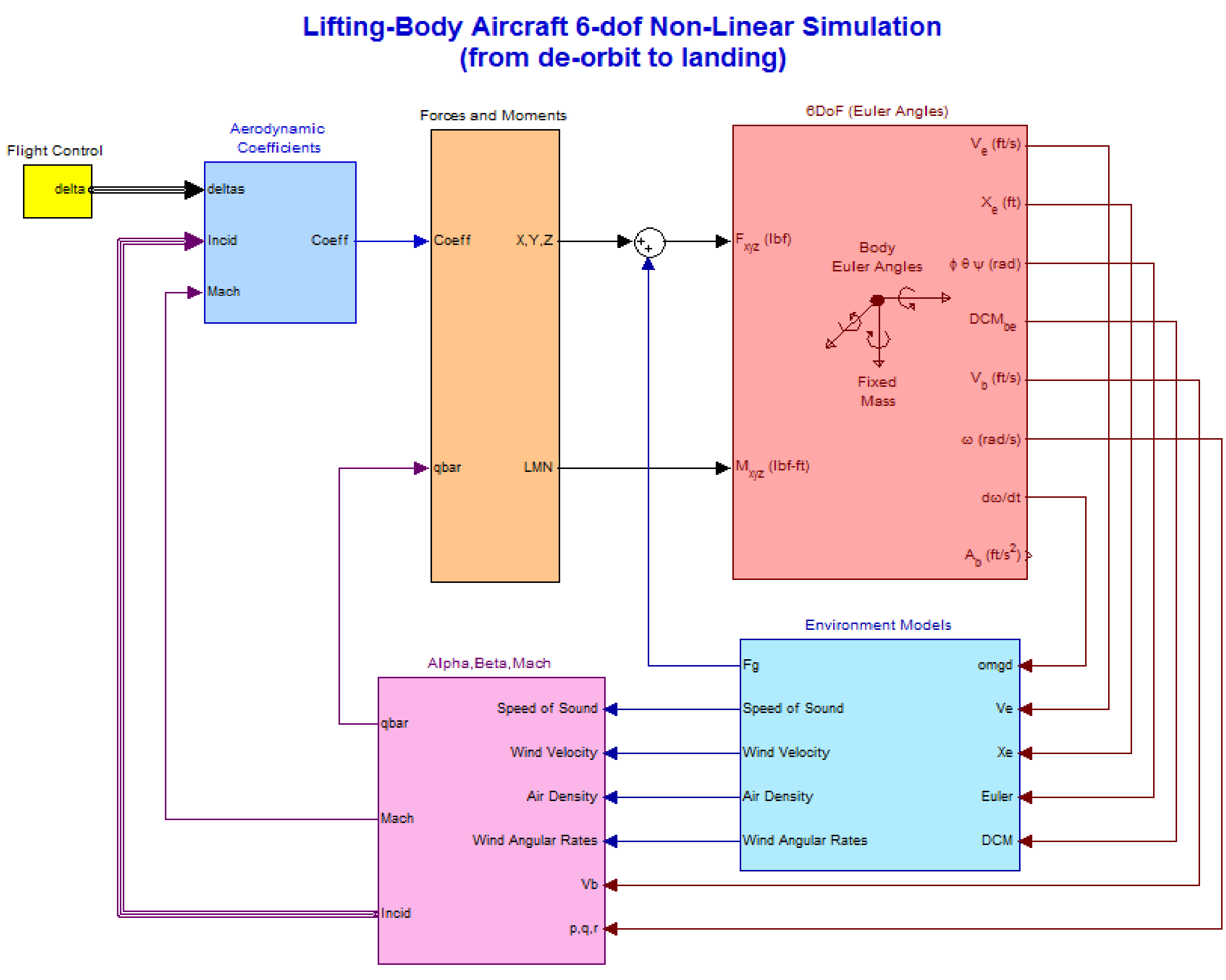


Figure 4.5.1 Simulation Model "*Reentry_6dof_Sim.Mdl*"

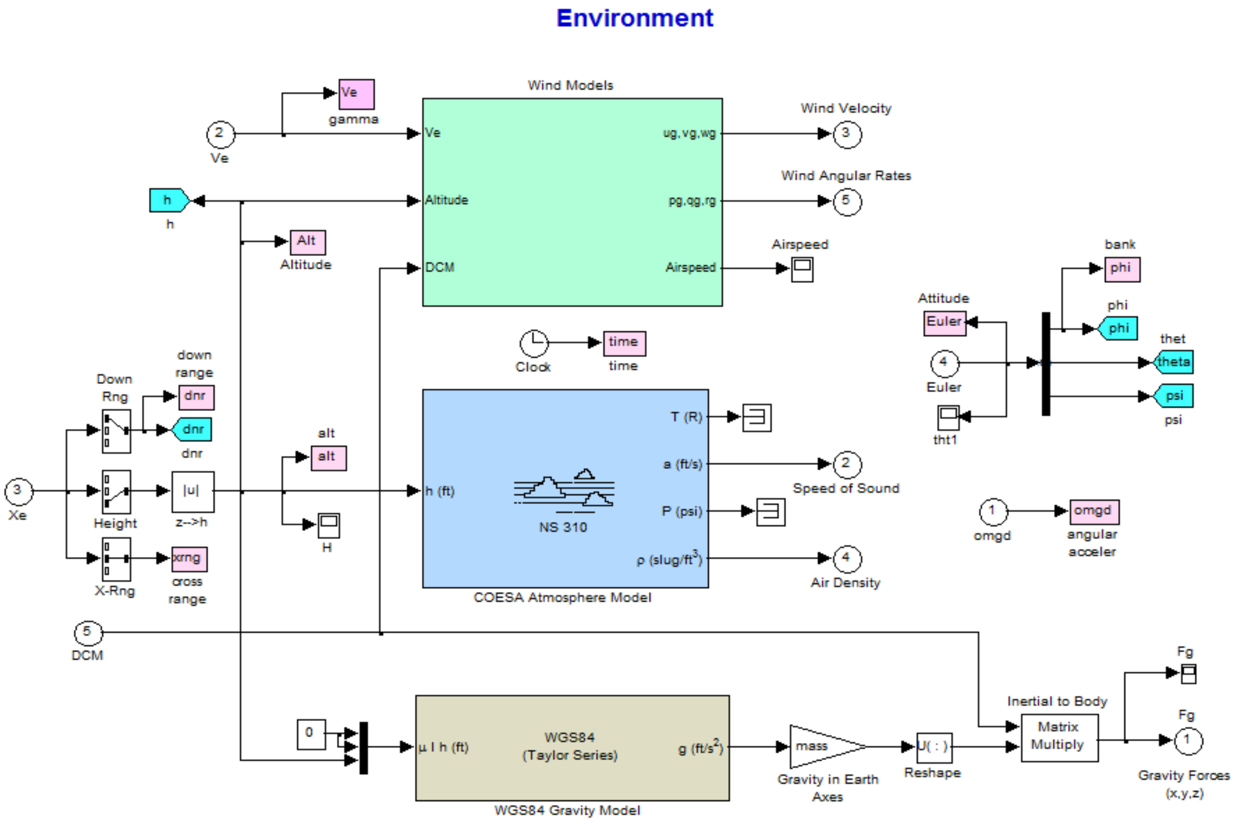


Figure 1.5.2 Environment Subsystem

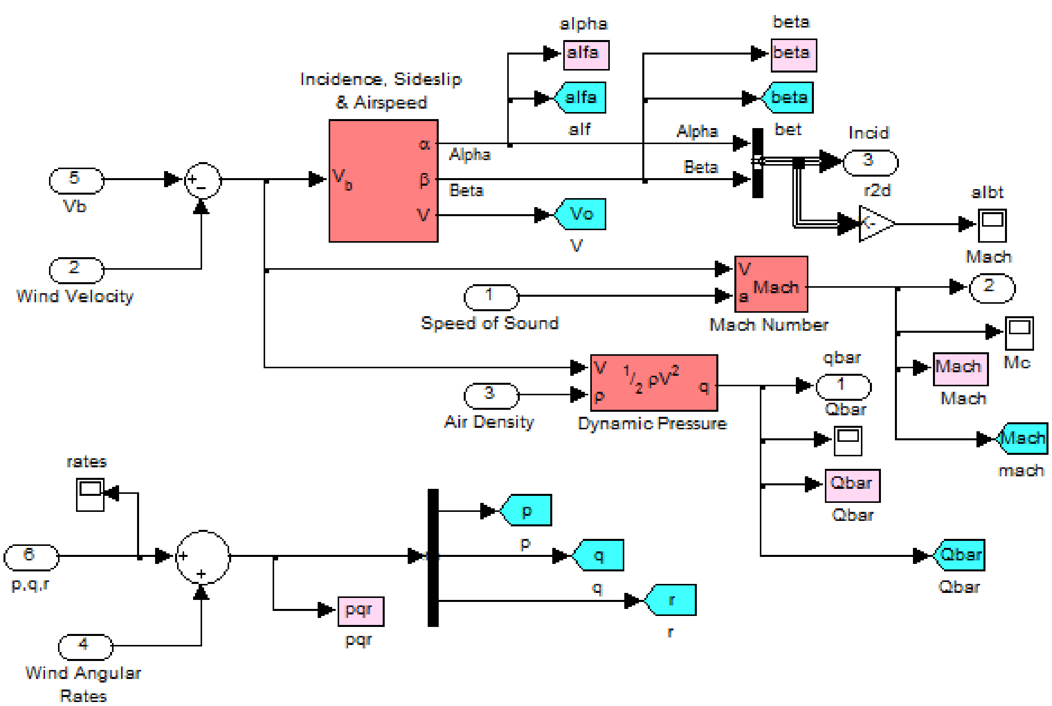


Figure 1.5.3 Angles of Attack, Sideslip and Mach Number calculations

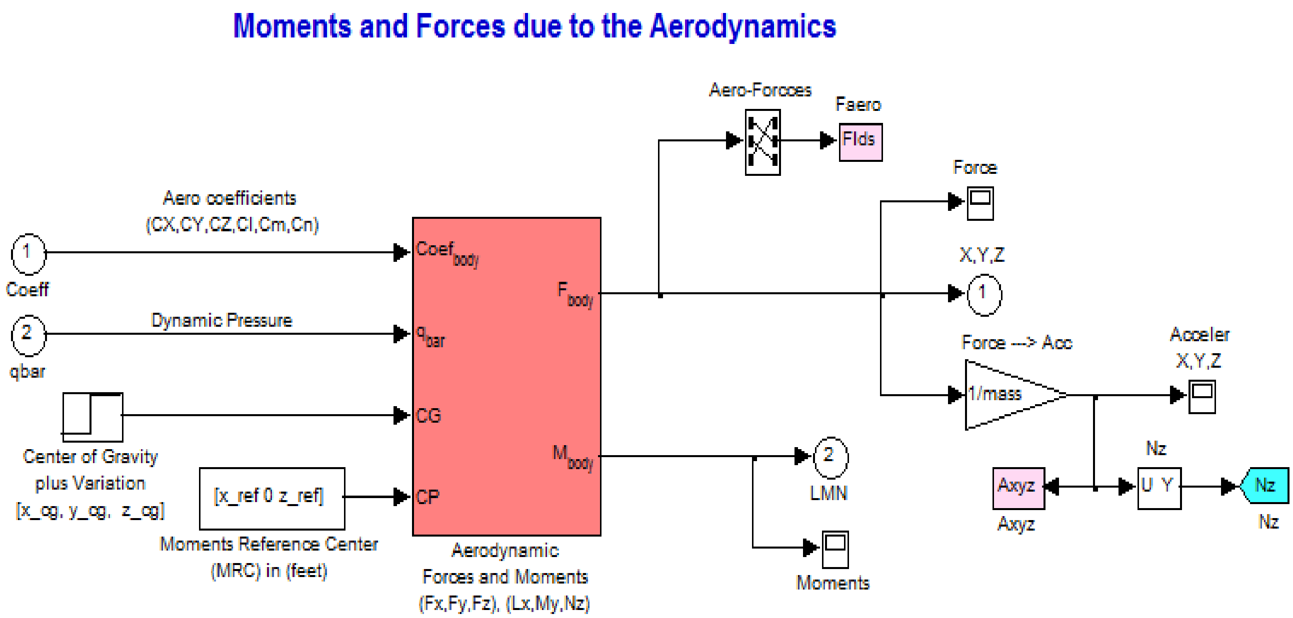


Figure 1.5.4 The Aerodynamic Forces and Moments are functions of the Dynamic Pressure, the Aero-Coefficients, and the CG location relative to the Moments Reference Center.

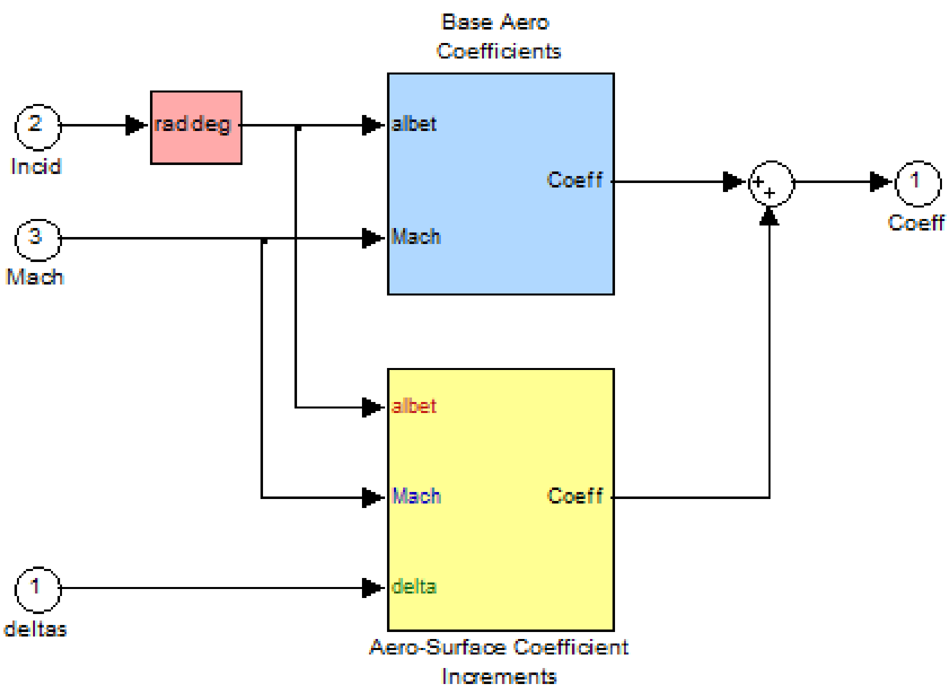


Figure 1.5.5 The Aerodynamic Coefficients consist of Base Body coefficients plus Increments due to Surface Deflections, and they are functions of the Angles of Attack and Sideslip (deg), Mach number, and Surface Deflections (deg).

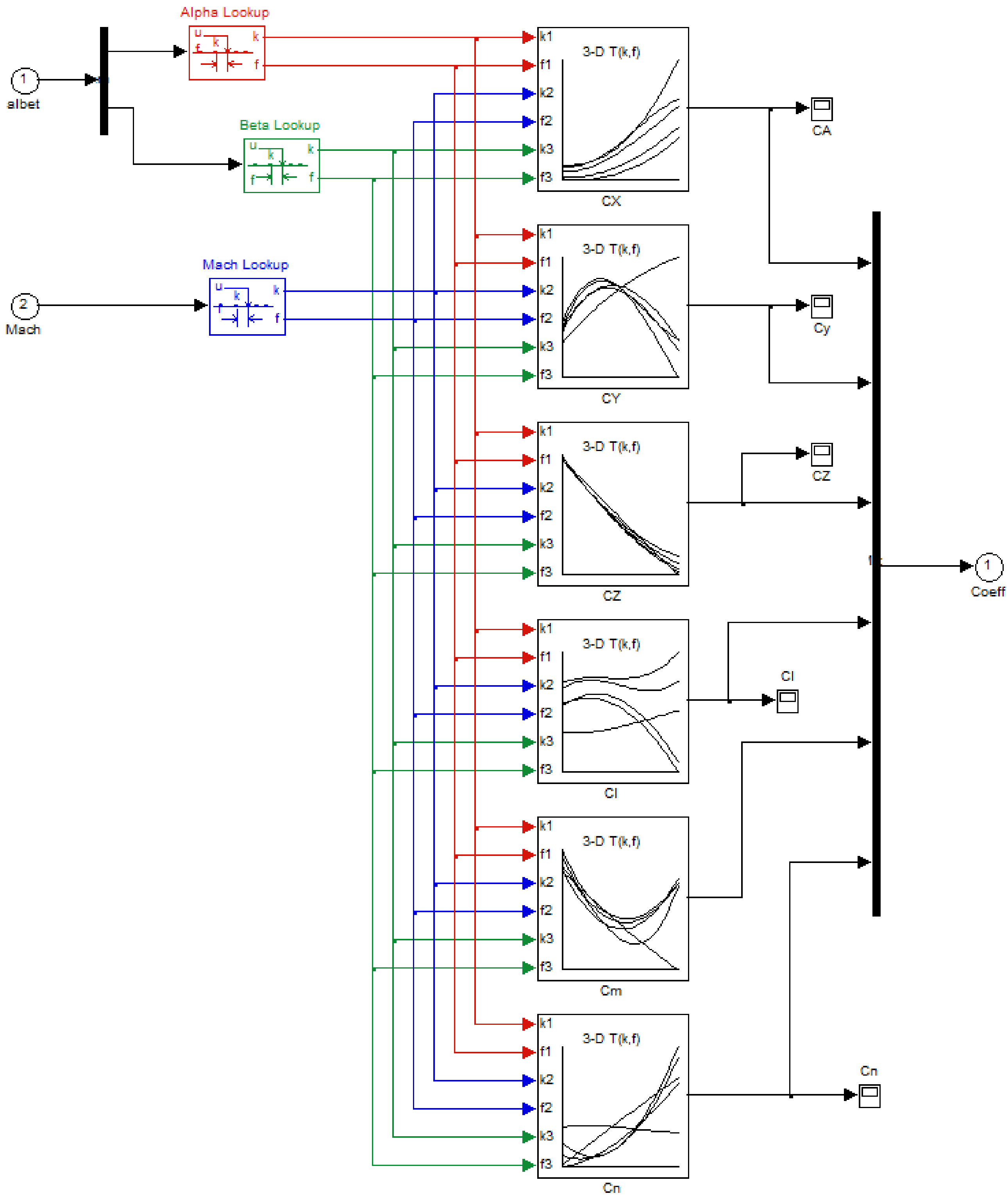


Figure 1.5.6 Base Aero Coefficients {CA, CY, CZ, Cl, Cm, Cn} are functions of: Alpha, Beta, and Mach Number

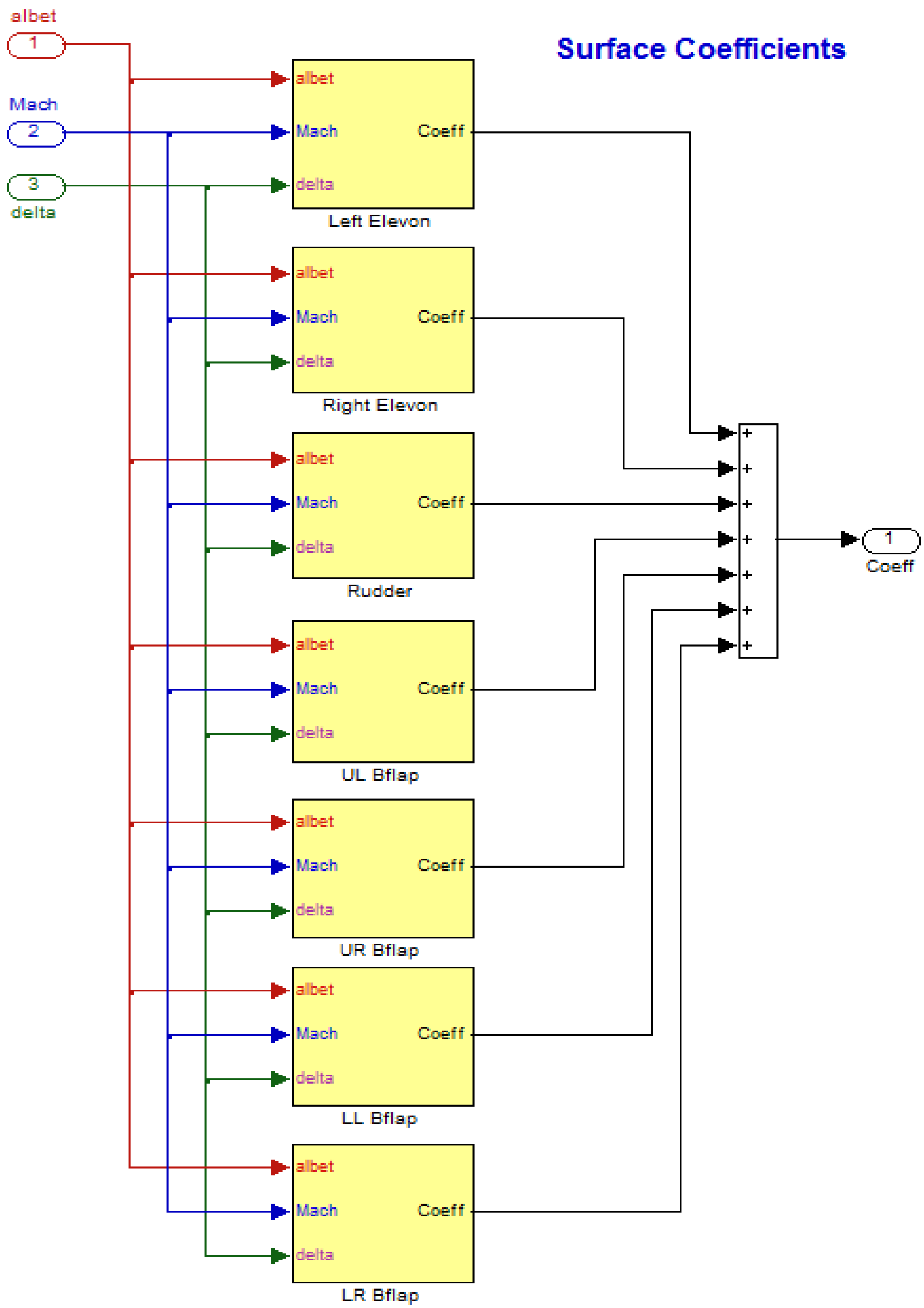
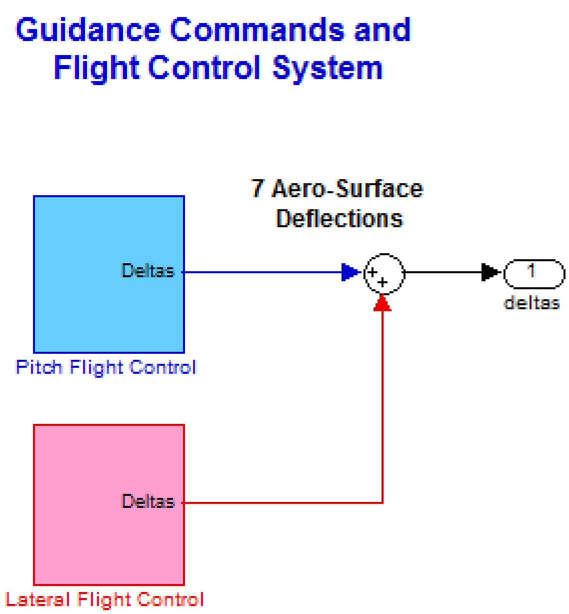


Figure 1.5.7 Aero-Surface Increment Coefficients are functions of: Alpha, Beta, Mach Number, and Deflection

Flight Control System

Figure 1.5.8 shows the flight control system in top-level form. The longitudinal and the lateral control laws are two separate blocks generating the deflection commands to the control surfaces. They are state-feedback designs operating in different modes, as already described in the control design sections. Control gain designs and linear analysis were performed at specific Mach numbers and the gains are interpolated in between Mach. The analysis files are located in separate folders under "*C:\Flixan\Trim\Examples\Lifting-Body Aircraft\Reentry from Space\Mat_Anal*", as shown below. The 7 aero-surfaces are shared by both controllers and the deflection command signals from the longitudinal and lateral blocks are combined before being applied to the surface actuators. For simplicity the sensor feedback signals are not shown in the simulation blocks.



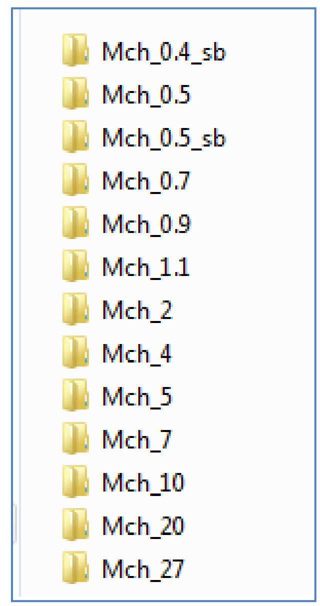


Figure 1.5.8 Flight Control System

Pitch Flight Control System

The longitudinal control law is shown in more detail in Figure 1.5.9. It consists of a state-feedback gain matrix Kq converting {γ, γ-integral, q, α, α-integral, Nz, and Nz-integral} error signals to pitch commands. The pitch flight control law is implemented in Matlab function "*Pitch_FCS.m*", see Figure 1.5.10, which converts the pitch state-feedback to surface deflections and also interpolates the gains between the design cases which are at different Mach numbers. It includes also and interpolates the mixing-logic matrix Kmix that is also calculated at different Mach numbers. Notice that not all of the state variables are feeding-back simultaneously but some of the gains in the state-feedback matrix Kq are set to zero depending on which mode the pitch flight control system is operating. This type of implementation allows an easier transitioning between the four control modes, which are: α-control, Nz-control, γ-control, and altitude/ velocity control.

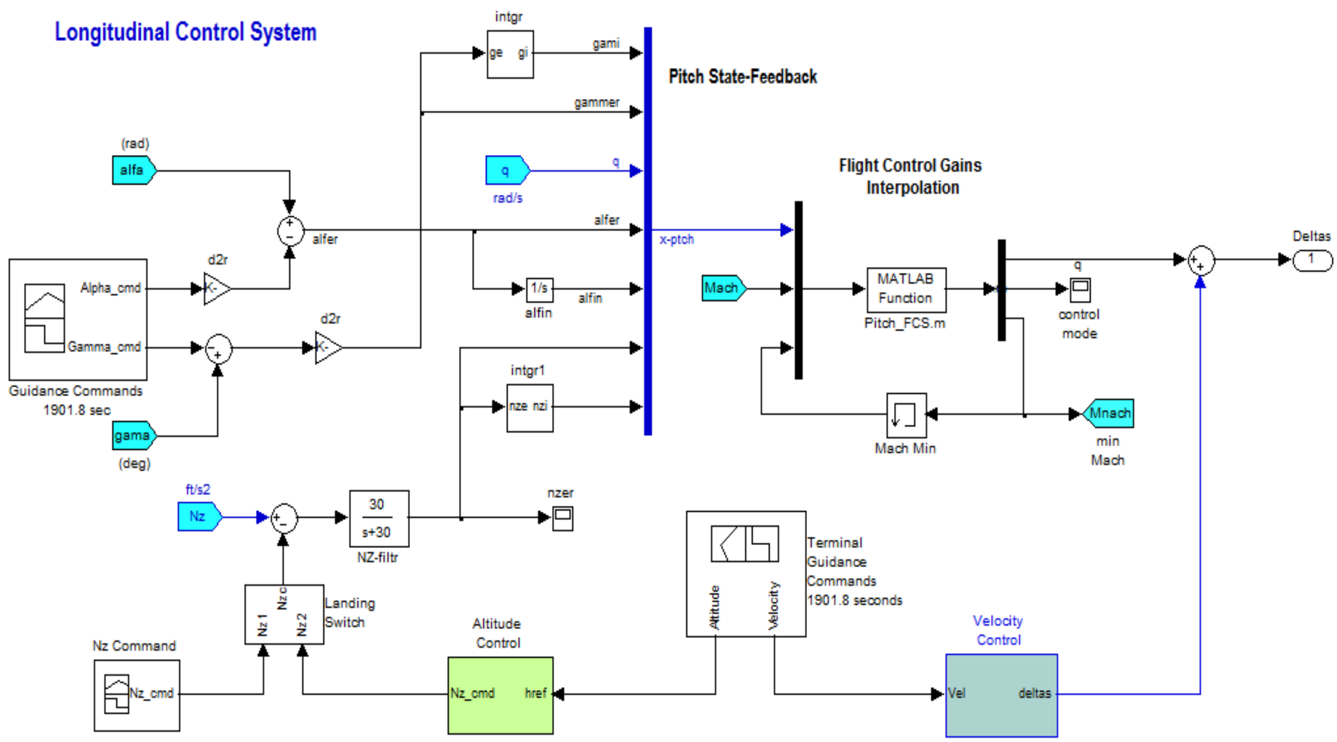


Figure 1.5.9 Longitudinal Control Law consists of State-Feedback and Open-Loop Guidance Commands

Guidance in the simulation is implemented by means of open-loop commands which attempt to control the angle of attack, flight-path angle, normal acceleration, altitude and speed, in different time periods along the descent flight depending on the operating mode. Initially, the first pitch control mode regulates alpha by commanding it at 30°. This angle is gradually reduced as it transitions to the second mode which controls the normal acceleration (Nz) to a pre-scheduled value. Later on it transitions to the gamma-control mode which controls the vehicle flight-path angle. Finally the flight-control system transitions to the approach and landing mode that controls altitude indirectly by applying Nz commands as a function of altitude error. It controls also velocity by modulating the speed-brake opening. This indirect altitude control law (via Nz-command) in the approach and landing mode was preferred, over the direct altitude and velocity state-feedback law described earlier, because it is easier to transition from the previous gamma-control mode. Figure (1.5.11) shows the altitude and velocity control systems in detail. It produces an Nz-command as a function of altitude error and altitude rate. A lead-lag filter was added to attenuate the phugoid mode resonance. A final-flare open-loop command is introduced to maximize the vehicle angle of attack during the final 50 (ft) of altitude before landing. Velocity control operates for a brief period of

65 sec during the shallow glide by modulating the opening and closing of the speed-brake. It occurs at approximately 110 to 45 sec before landing.

```
function Dqpr= Pitch_FCS(u1, mach, mni)
% Implements the Pitch State-Feedback Control Laws
% u1 are the pitch state-feedback variables [gamma,gamma_int,q,alfa,alfa-int,Nz,Nz_in
global Kq Kmix r2d

Ia=int8(2); Ia2=int8(3); da=0;
mnch=min(mach,mni);

% Design Machs: [25, 20, 15, 10, 5, 4, 3, 2, 1.1, 0.9, 0.7, 0.4]
if      (mnch>=25),                 Im=int8(1);  Im2=Im;       q=1;  dm=0;
elseif  (mnch>=20) & (mnch<25),     Im=int8(2);  Im2=int8(1);  q=2;  dm=(mnch-20)/5;
elseif  (mnch>=18) & (mnch<20),     Im=int8(3);  Im2=int8(2);  q=3;  dm=(mnch-18)/2;
elseif  (mnch>=17) & (mnch<18),     Im=int8(4);  Im2=int8(3);  q=4;  dm=(mnch-17)/1;
elseif  (mnch>=16) & (mnch<17),     Im=int8(5);  Im2=int8(4);  q=5;  dm=(mnch-16)/1;
elseif  (mnch>=15) & (mnch<16),     Im=int8(6);  Im2=int8(5);  q=6;  dm=(mnch-15)/1;
elseif  (mnch>=14) & (mnch<15),     Im=int8(7);  Im2=int8(6);  q=7;  dm=(mnch-14)/1;
elseif  (mnch>=13) & (mnch<14),     Im=int8(8);  Im2=int8(7);  q=8;  dm=(mnch-13)/1;
elseif  (mnch>=12) & (mnch<13),     Im=int8(9);  Im2=int8(8);  q=9;  dm=(mnch-12)/1;
elseif  (mnch>=11) & (mnch<12),     Im=int8(10); Im2=int8(9);  q=10; dm=(mnch-11)/1;
elseif  (mnch>=10) & (mnch<11),     Im=int8(11); Im2=int8(10);q=11; dm=(mnch-10)/1;
elseif  (mnch>= 9) & (mnch<10),     Im=int8(12); Im2=int8(11);q=12; dm=(mnch- 9)/1;
elseif  (mnch>= 8) & (mnch< 9),     Im=int8(13); Im2=int8(12);q=13; dm=(mnch- 8)/1;
elseif  (mnch>= 7) & (mnch< 8),     Im=int8(14); Im2=int8(13);q=14; dm=(mnch- 7)/1;
elseif  (mnch>= 6) & (mnch< 7),     Im=int8(15); Im2=int8(14);q=15; dm=(mnch- 6)/1;
elseif  (mnch>= 5) & (mnch< 6),     Im=int8(16); Im2=int8(15);q=16; dm=(mnch- 5)/1;
elseif  (mnch>= 4) & (mnch< 5),     Im=int8(17); Im2=int8(16);q=17; dm=(mnch- 4)/1;
elseif  (mnch>= 3) & (mnch< 4),     Im=int8(18); Im2=int8(17);q=18; dm=(mnch- 3)/1;
elseif  (mnch>=2.5)& (mnch< 3),     Im=int8(19); Im2=int8(18);q=19; dm=(mnch-2.5)/0.5;
elseif  (mnch>=2.0)& (mnch<2.5),    Im=int8(20); Im2=int8(19);q=20; dm=(mnch-2.0)/0.5;
elseif  (mnch>=1.5)& (mnch<2.0),    Im=int8(21); Im2=int8(20);q=21; dm=(mnch-1.5)/0.5;
elseif  (mnch>=1.0)& (mnch<1.5),    Im=int8(22); Im2=int8(21);q=22; dm=(mnch-1.0)/0.5;
elseif  (mnch>=0.71)&(mnch<1.0),    Im=int8(23); Im2=int8(22);q=23; dm=(mnch-0.71)/0.29;
elseif  (mnch>=0.59)&(mnch<0.71),Im=int8(24); Im2=int8(23);q=24; dm=(mnch-0.59)/0.12;
elseif  (mnch>=0.49)&(mnch<0.59),Im=int8(25); Im2=int8(24);q=25; dm=(mnch-0.49)/0.10;
elseif  (mnch< 0.49),                Im=int8(26); Im2=Im;       q=26; dm=0;
end

% Calculate Surface Deflections due to pitch state-feedback u1
dq1=  -Kmix(:,2,Im) *(Kq(:,:,Ia, Im) *u1);         %.. deflects at nominal (Ia,Im)
dq2=  -Kmix(:,2,Im) *(Kq(:,:,Ia2,Im) *u1);         %.. deflects at next (Ia2,Im)
dq3=  -Kmix(:,2,Im2)*(Kq(:,:,Ia, Im2)*u1);         %.. deflects at prev (Ia,Im2)
dq= dq1  + (dq2 - dq1)*da  + (dq3 - dq1)*dm;       %.. Interpolate deflects

delta= dq*r2d;                                      %.. deflects in (deg)
Dqpr=[delta; q;mnch];
```

Figure 1.5.10 Pitch Flight Control Law converts the longitudinal state-vector to surface deflection commands. It also interpolates between the design cases

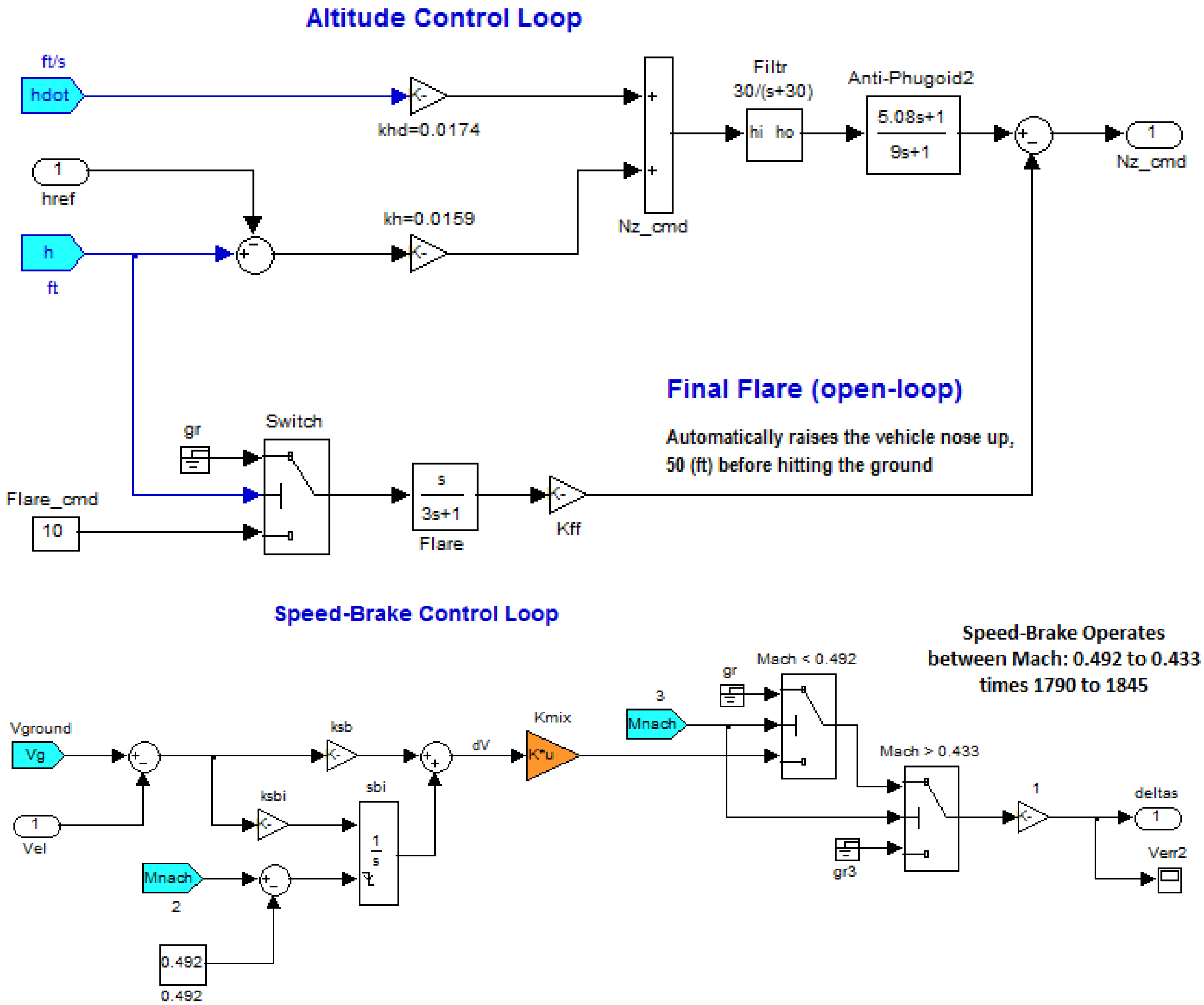


Figure 1.5.11 Altitude and Velocity Control Systems

Lateral Flight Control System

The lateral flight control system is shown in detail in Figure 1.5.12. This is also a state-feedback law converting the states which are: {roll and yaw stability axis rates (about the velocity vector), β, ϕ, β-integral} to deflections for the 7 aero-surfaces. It also has two operating modes. During the first mode the bank angle (ϕ) is directly commanded open-loop, and in the second mode which is applicable prior to landing the heading direction is indirectly controlled by roll commands. The direction errors become roll commands. Notice that the rates are measured in the body axes and they are converted to stability axes as a function of the angle of attack. This reduces the sideslip angle and lateral loads when the vehicle performs roll maneuvers. A turn-coordination block is also included prior to the state-feedback. It commands a yaw rate as a function of the bank angle (ϕ) according to the equation: $\boldsymbol{R_{ff}} = \frac{g}{V_0}\,\mathbf{sin}\,\boldsymbol{\varphi}$. It uses a gravity component to counteract the centripetal side-force due to turning. Notice also that the lateral state-feedback gains were designed using lateral plant models that have their output rates defined in the stability axis, and the turn-coordination logic included in the vehicle dynamic model (by means of flags set in the vehicle input data). It means that the gains know that the rates are in stability axis and the turn-coordination logic is included.

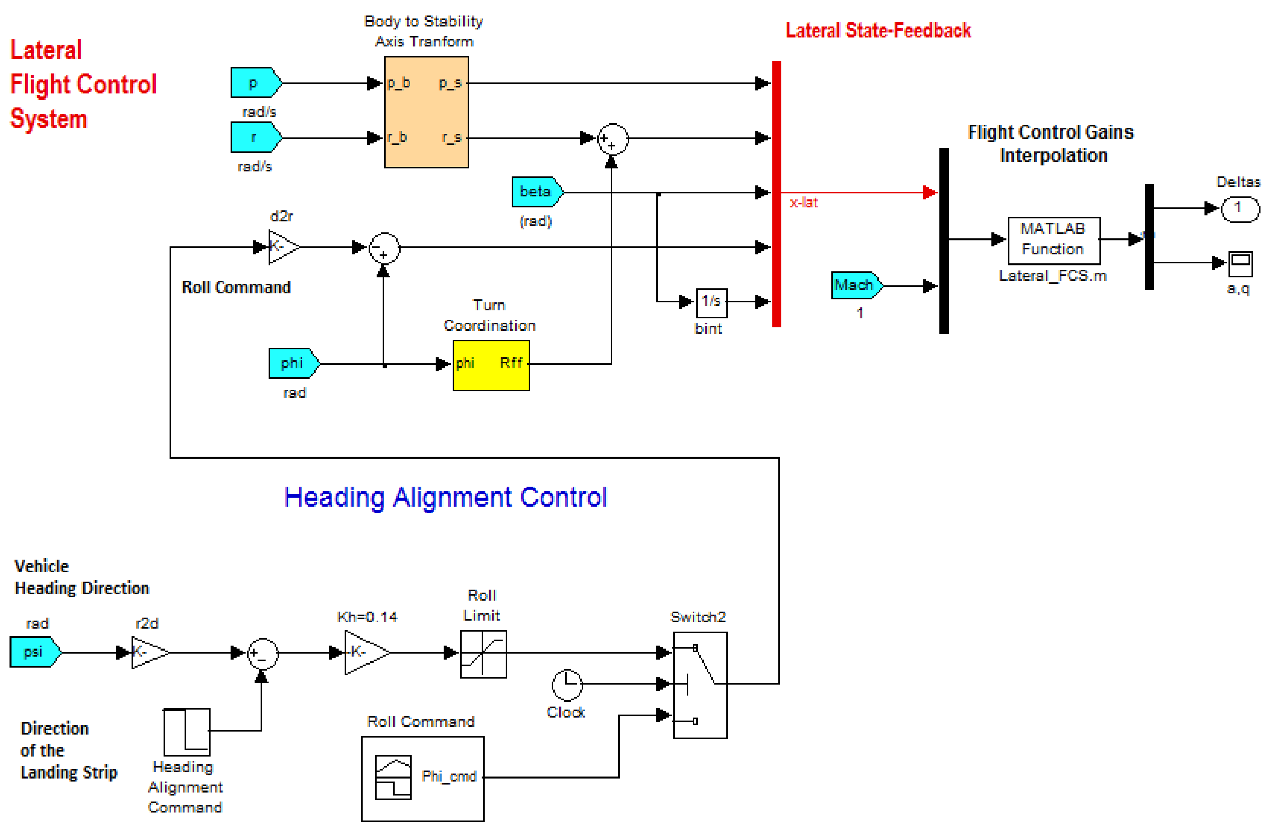


Figure 1.5.12 Lateral Flight Control System

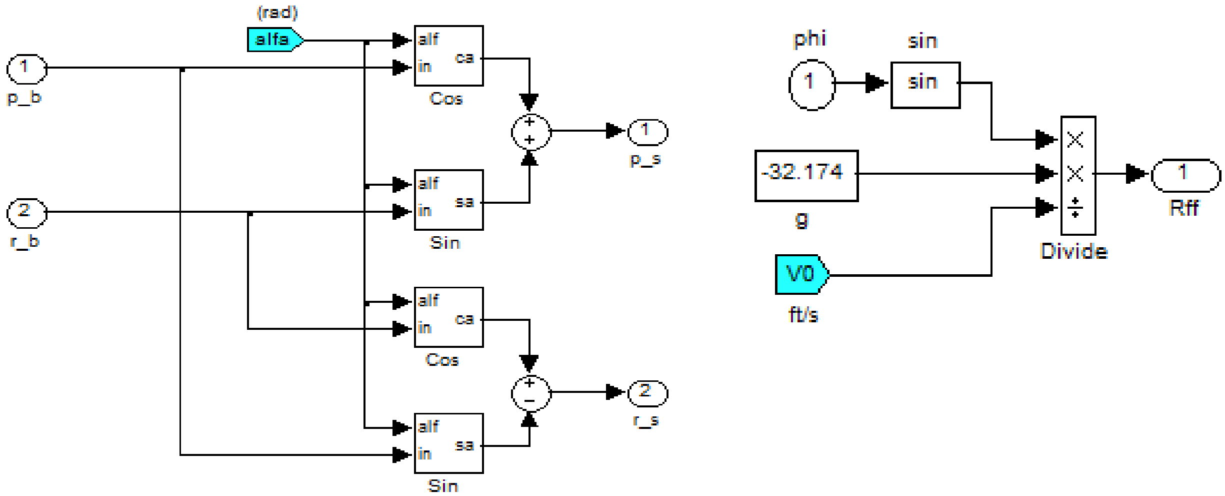
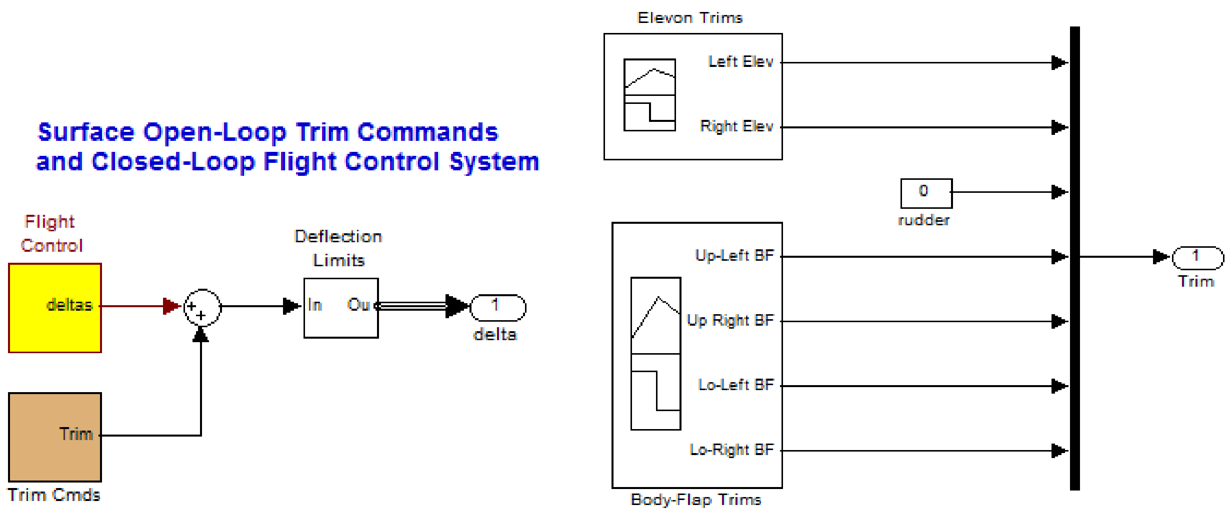


Figure 1.5.13 Body to Stability Axes Transformation and Turn-Coordination Logic

```
function Dqpr= Lateral_FCS(u2, mach)
% Implements Lateral State-Feedback Control Laws
% u2 is the lateral state-feedback variables [phi,p,r,beta,phi-integr]
global Kpr Klmix r2d
Ia=int8(2); Ia2=int8(3); da=0;

% Design Machs: [25, 20, 15, 10, 5, 4, 2, 1.1, 0.7, 0.56, 0.48]
if      (mach>=25),                    Im=int8(1);  Im2=Im;       q=1;  dm=0;
elseif (mach>=20)   & (mach<25),   Im=int8(2);  Im2=int8(1); q=2;  dm=(mach-20)/5;
elseif (mach>=15)   & (mach<20),   Im=int8(3);  Im2=int8(2); q=3;  dm=(mach-15)/5;
elseif (mach>=10)   & (mach<15),   Im=int8(4);  Im2=int8(3); q=4;  dm=(mach-10)/5;
elseif (mach>= 5)   & (mach<10),   Im=int8(5);  Im2=int8(4); q=5;  dm=(mach-05)/5;
elseif (mach>= 4)   & (mach< 5),   Im=int8(6);  Im2=int8(5); q=6;  dm=(mach-04)/1;
elseif (mach>= 2)   & (mach< 4),   Im=int8(7);  Im2=int8(6); q=7;  dm=(mach-02)/2;
elseif (mach>= 1)   & (mach< 2),   Im=int8(8);  Im2=int8(7); q=8;  dm=(mach-01)/1;
elseif (mach>=0.72) & (mach<1.0),  Im=int8(9);  Im2=int8(8); q=9;  dm=(mach-0.72)/0.28;
elseif (mach>=0.56) & (mach<0.72),Im=int8(10); Im2=int8(9); q=10; dm=(mach-0.56)/0.16;
elseif (mach>=0.48) & (mach<0.56),Im=int8(11); Im2=int8(10);q=11; dm=(mach-0.48)/0.08;
elseif (mach< 0.48),                Im=int8(12); Im2=Im;       q=12; dm=0;
end

% Calculate Surface Deflections due to lateral state-feedback u2
dpr1= -Klmix(:,:,Im)*Kpr(:,:,Ia,Im)*u2;        %.. deflects at nominal (Ia,Im)
dpr2= -Klmix(:,:,Im)*Kpr(:,:,Ia2,Im)*u2;       %.. deflects at (Ia2,Im)
dpr3= -Klmix(:,:,Im2)*Kpr(:,:,Ia,Im2)*u2;      %.. deflects at (Ia,Im2)
dpr=dpr1 + (dpr2-dpr1)*da  + (dpr3-dpr1)*dm;   %.. Interpolate deflects

delta= dpr*r2d;
Dqpr=[delta; q;q];
```

Figure 1.5.14 Lateral Flight Control Law converts the lateral state-vector to surface deflection commands. It also interpolates between the design cases which are fewer than the longitudinal cases

The aero-surface actuators do not only receive deflection commands from the flight control system but the surface positions are pre-scheduled open-loop as shown in Figure (1.5.15). The aero-surface trim positions were obtained from the trim analysis performed earlier along the preliminary trajectory as already described in previous sections.



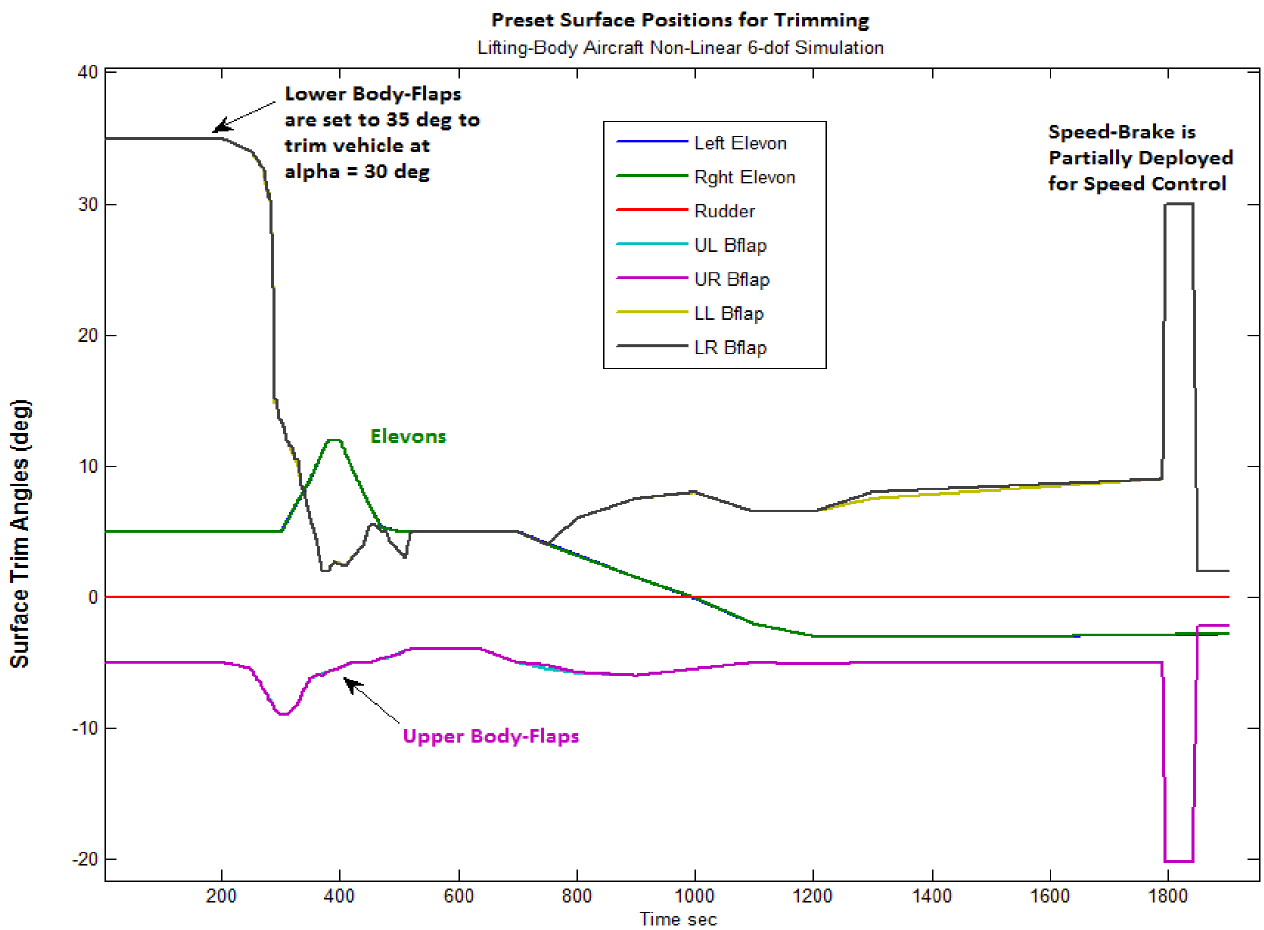
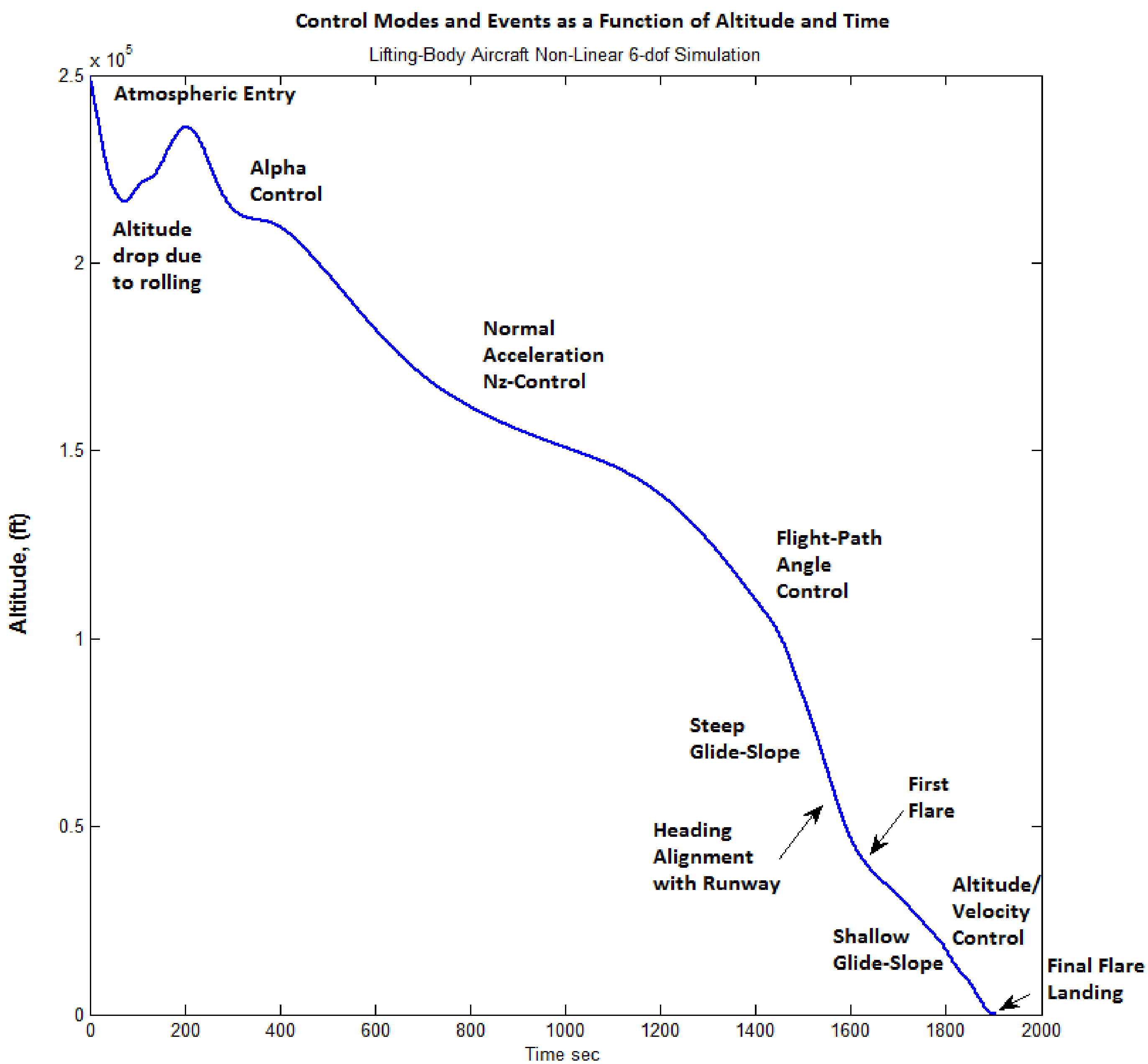


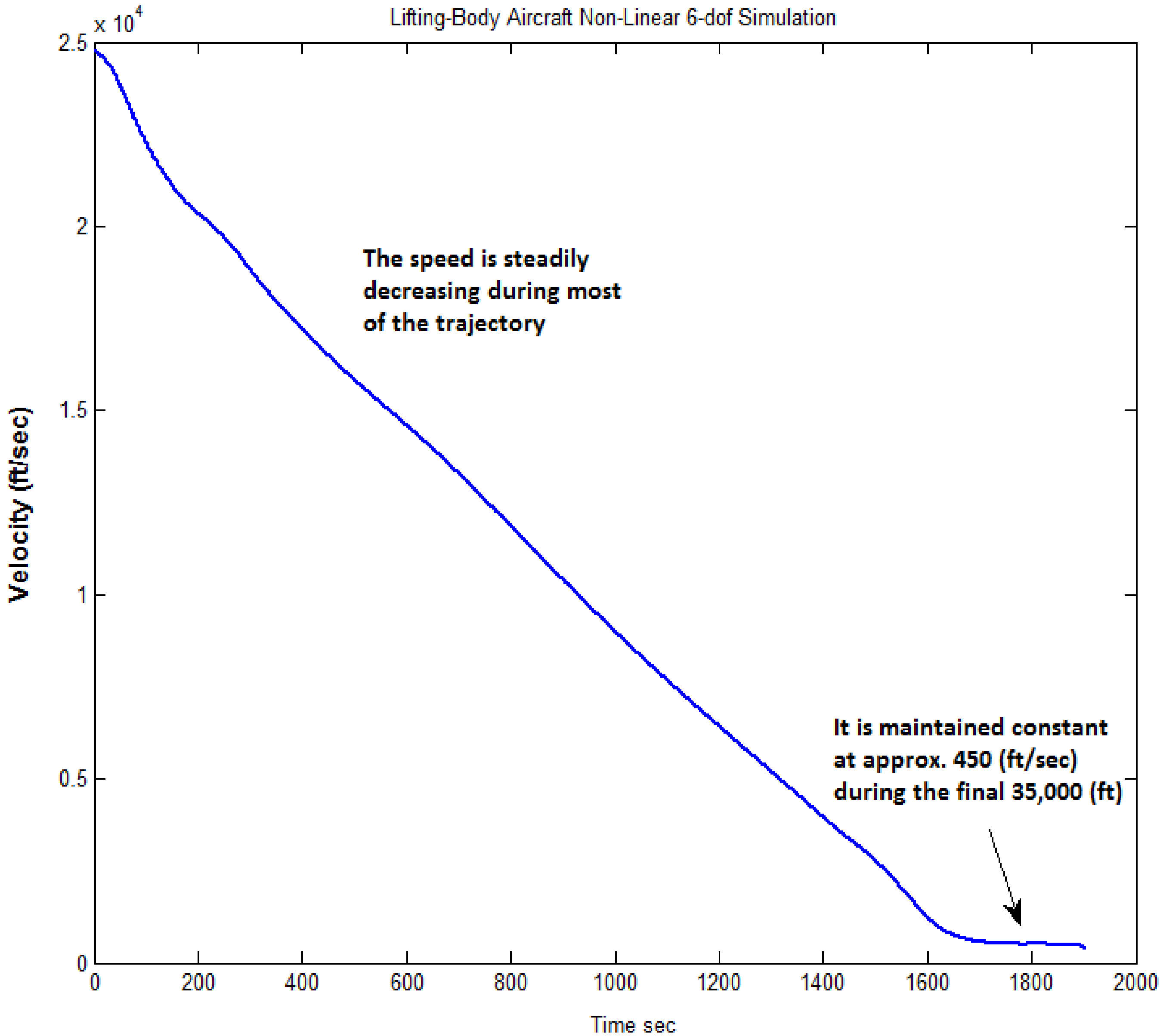
Figure 1.5.15 Aero-Surface Scheduling is based on previous Trim Analysis

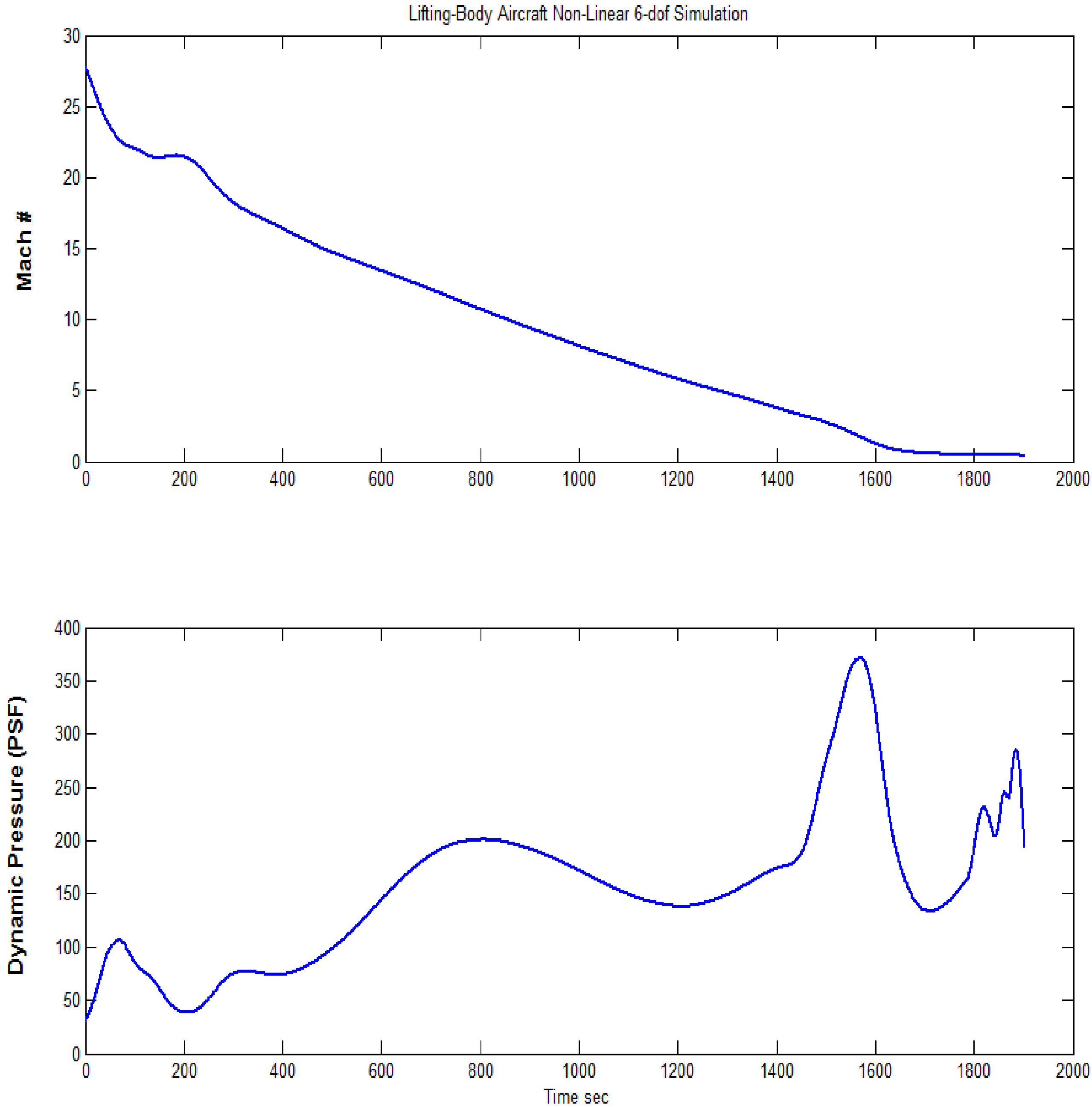
Simulation Analysis

Major Events: The following figure shows the altitude variation versus time and highlights the control modes and major events. The simulation begins at an altitude of 250,000 (feet) above ground where it enters the atmosphere with a shallow negative (γ) and it rolls a couple of times to drop altitude and avoid skipping back up into space. The flight control system operation begins in the alpha-control mode where the aircraft is trimmed to maintain a 29.5° angle of attack which optimizes heat protection during this period. Alpha is reduced further down and the control mode transitions to Nz-control where it maintains a comfortable and almost constant Nz acceleration for a long period.



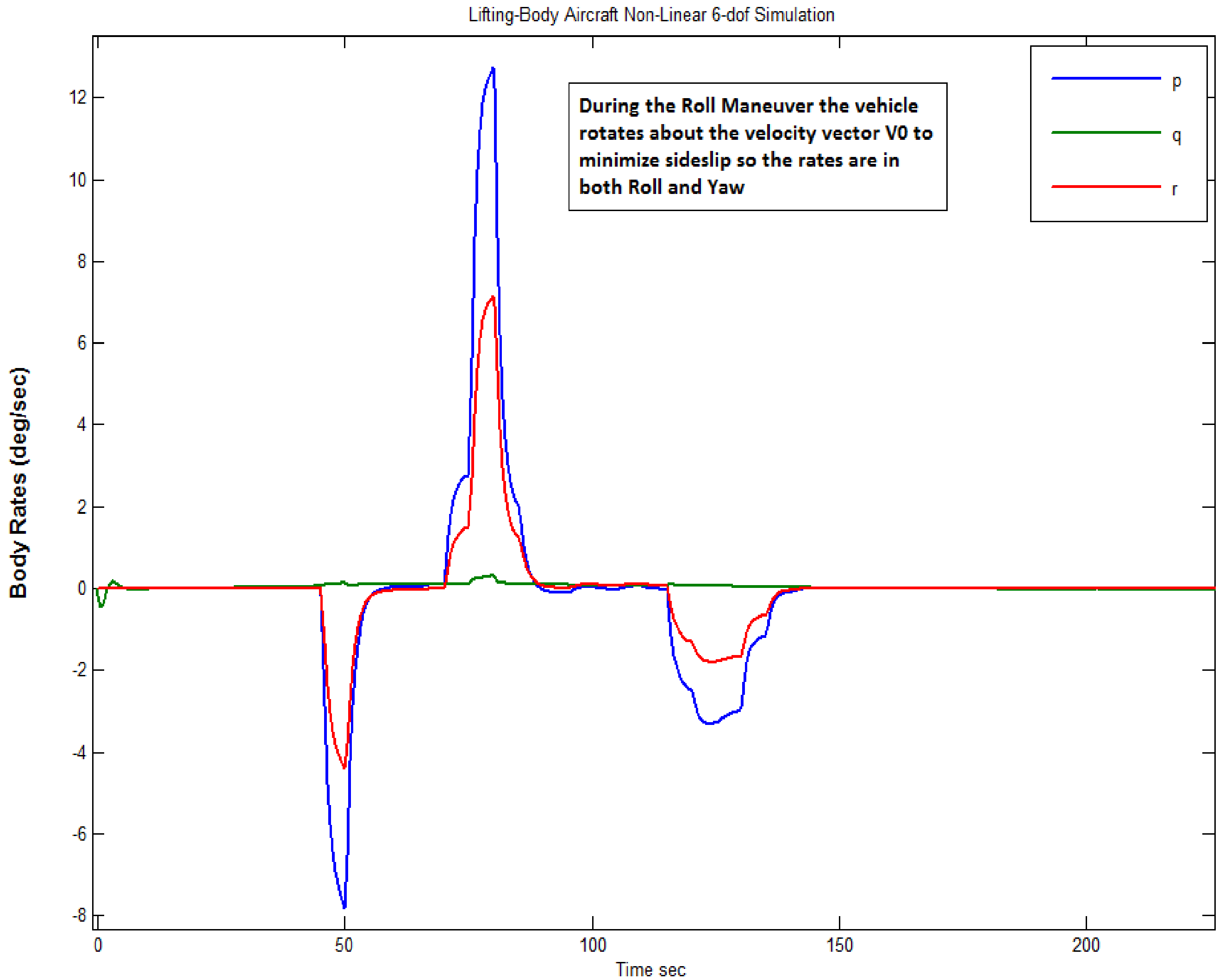
The flight-path guidance is then turned on at about t=1400 sec to regulate the vehicle rate of descent towards the landing site by controlling γ. In the simulation guidance is implemented with an open-loop γ-command. The γ angle is then further reduced in order to maintain sufficient speed for landing. At approximately 50,000 (feet) it rolls again in order to correct its heading and to align its direction with the runway. This figure shows the speed versus time. The speed is steadily decreasing throughout descent and it is maintained constant at around 450 (feet/sec) during the final 35,000 (feet) of altitude by diving to reduce the glide slope. This high speed is required in order to perform the final flare before touch-down. In the final 1000 (feet) of altitude gamma begins to come up and at approximately 50 (feet) before touch down it performs the final-flare and lands with α=13°.



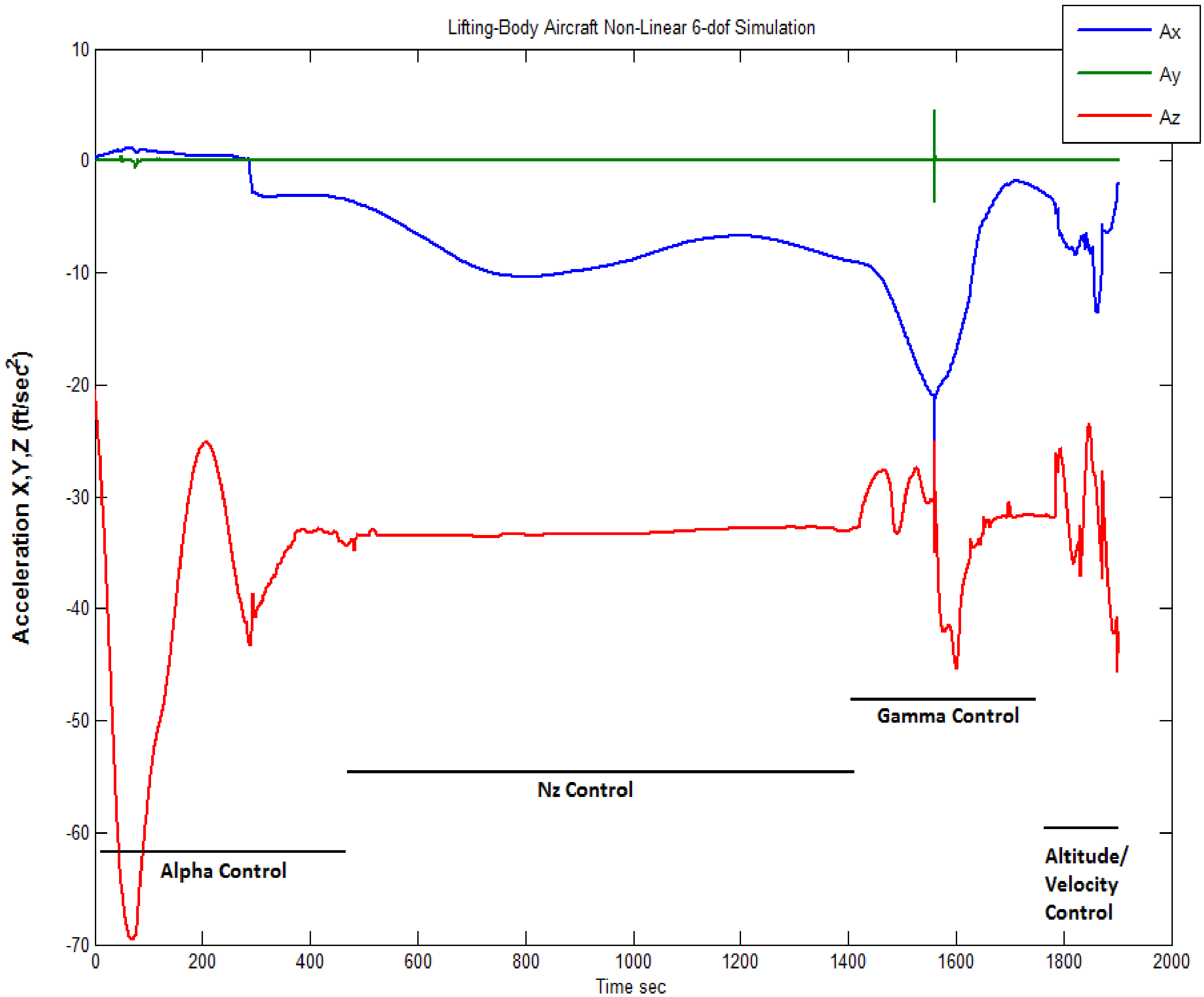


The figure above shows the variation of the Mach number and dynamic pressure as a function of time. It begins at Mach 27.5 and lands at Mach 0.4. The maximum dynamic pressure is 370 (psf) and it occurs during the heading alignment turn.

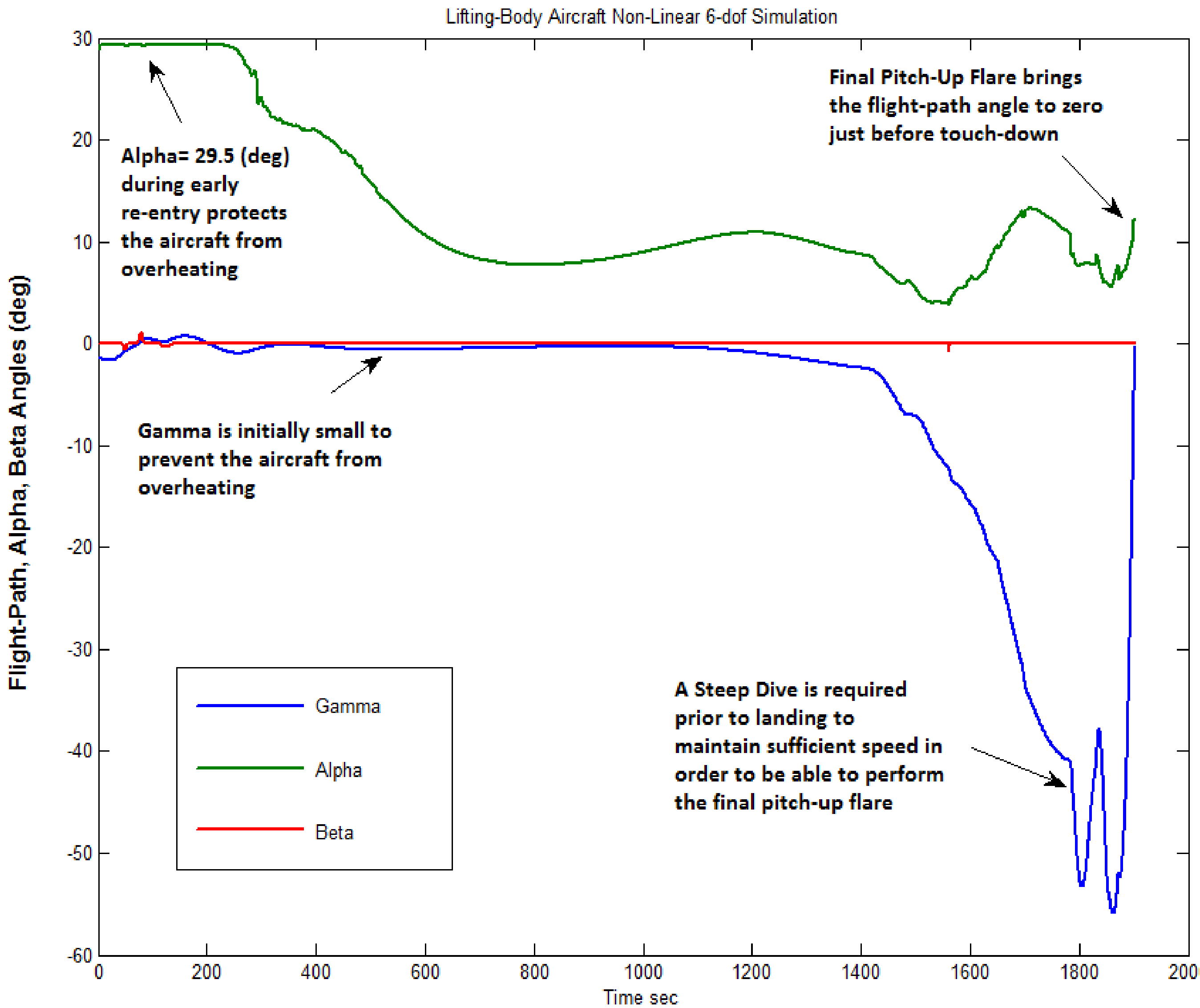
Roll Maneuver: The following figure shows the body rates during the early re-entry roll maneuver where the vehicle rolls about the velocity vector in order to reduce sideslip and lateral loads. The rotation produces similar and proportional rates in both roll and yaw.



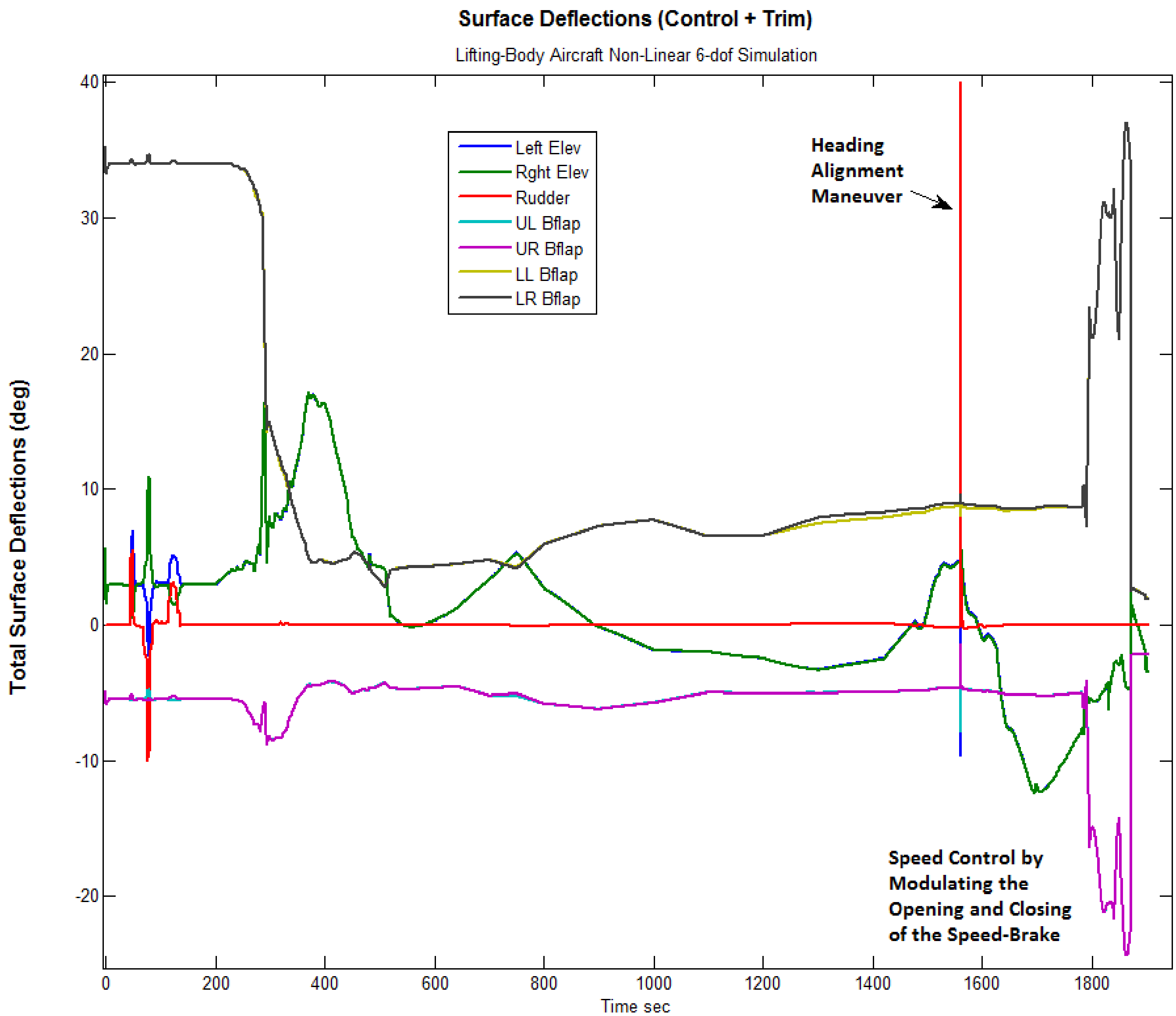
Control Modes: This figure shows the vehicle accelerations versus time along x, y, and z and highlights the four control modes. The normal acceleration reaches a maximum value of little above 2 g in the beginning of atmospheric entry during the period of alpha-control and it stabilizes at approximately 1 g during the Nz-control mode. The large surface deflections occurring at t=1550 sec during heading alignment maneuver cause a short transient in the accelerations. The normal acceleration (red line) briefly increases during the heading alignment turn. The magnitude of the axial deceleration (blue line) increases due to drag during the steep glide-slope dive. The normal acceleration finally peaks again before landing during the final flare.



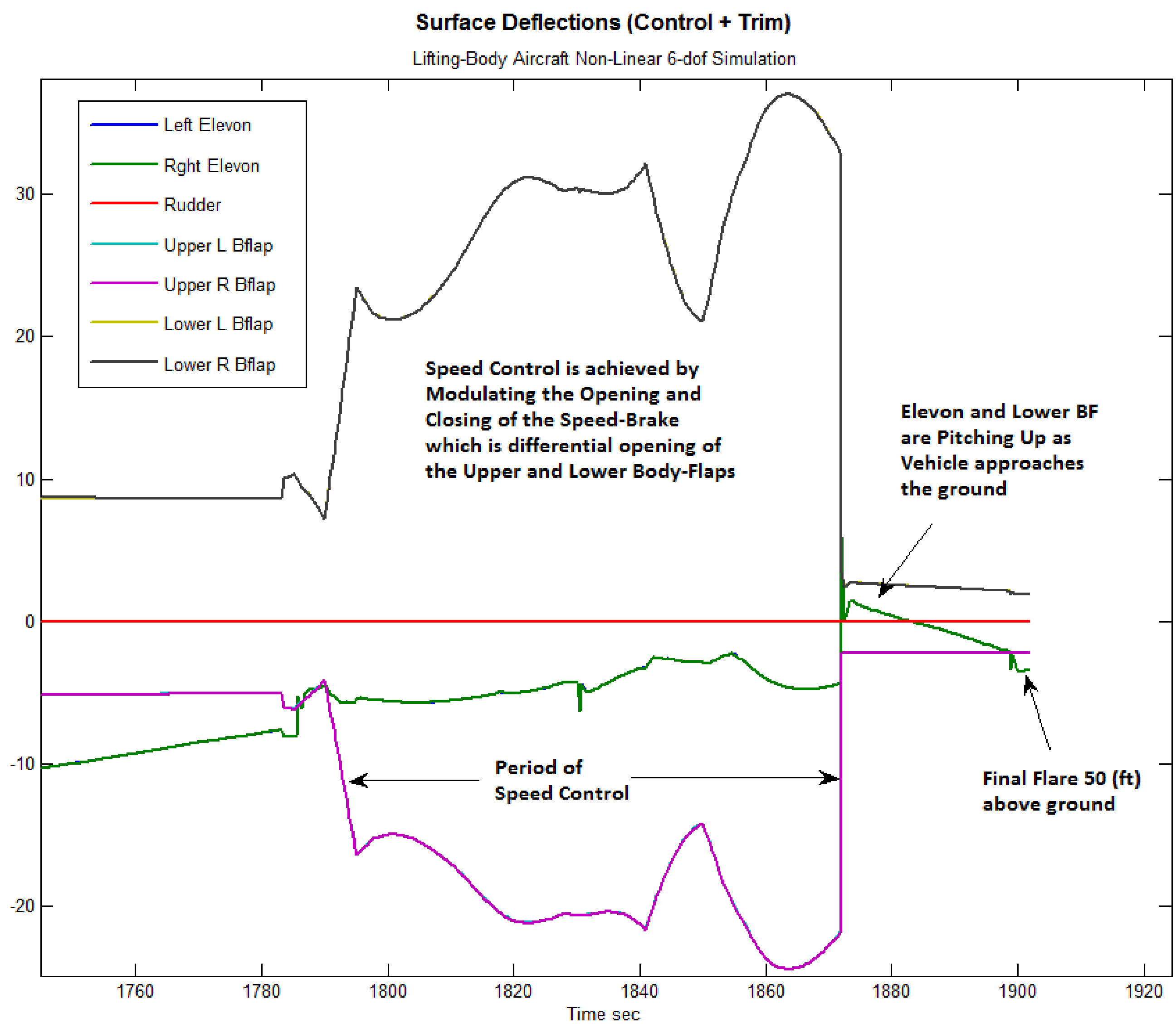
Angles of Attack, Sideslip, and Flight-Path: This figure shows the angles of attack, sideslip, and flight-path as a function of time. The angle of attack begins at 29.5 (deg) in the alpha-control mode and it is gradually reduced to smaller values during the Nz-control period and further. It is approximately 13° at landing, after the final flare where gamma becomes to zero. The flight-path angle γ is initially slightly negative to optimize the atmospheric friction and heating on the vehicle. Then it comes down steeper and briefly exceeds -50° in order to maintain high velocity for the landing flare that brings gamma to zero just before landing. There is a low frequency phugoid oscillation for about 1 minute during the steep glide which is attenuated further down and it does not affect landing. The sideslip angle is close to zero throughout. The small β-transients occur during the roll maneuvers



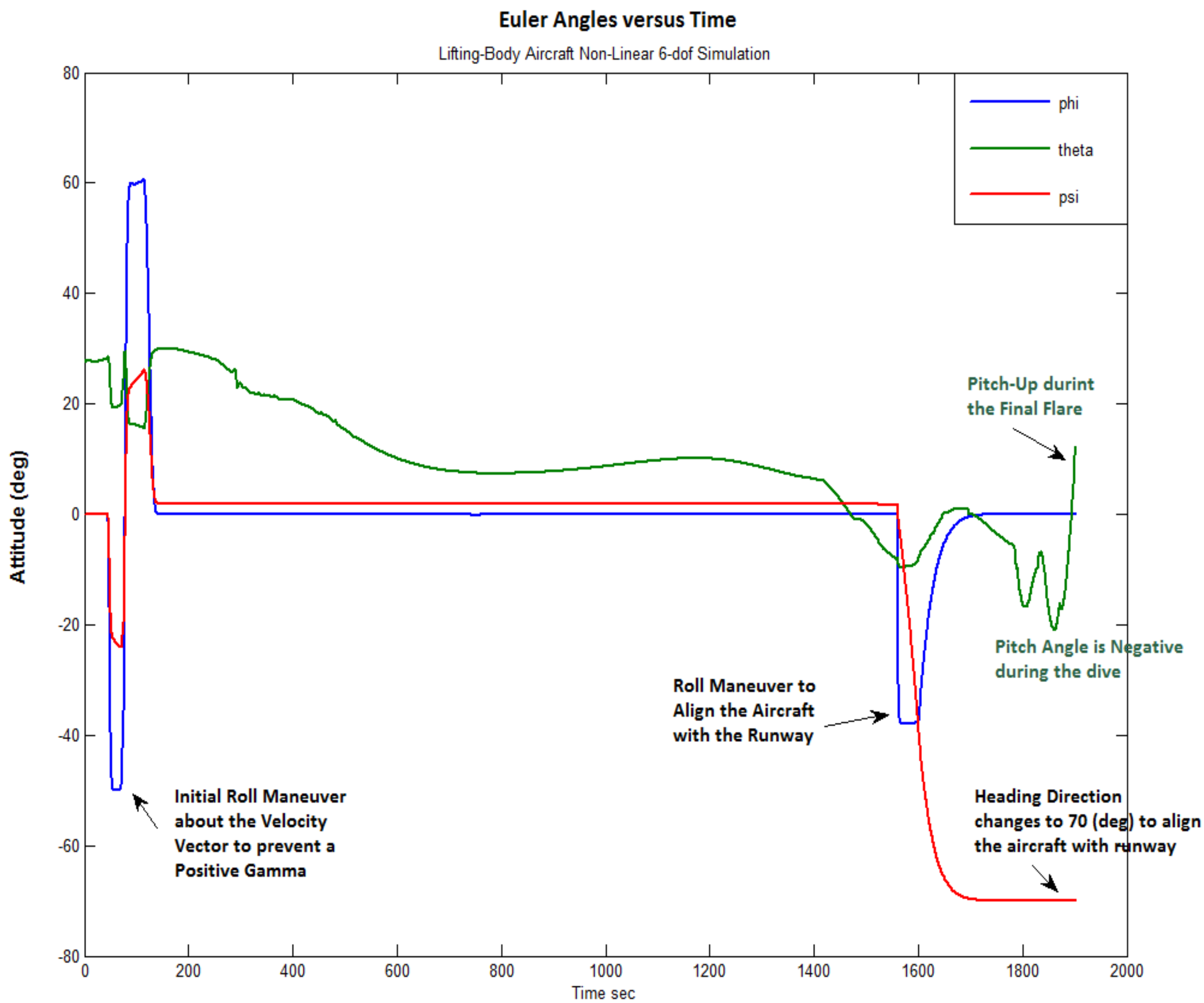
Aerosurface Deflections: This figure shows the aero-surface deflections as a function of time. They consist of two components: scheduled trim commands based on previous trim analysis shown in shown in Figure 1.5.15, and deflection commands generated by the flight control system. It shows the Rudder and the differential Elevon deflections performing the two roll maneuvers. The upper body-flaps are also used in the roll heading alignment maneuver. Notice that the body-flaps are not only used for trimming but they also assist the elevons and rudder in controlling the vehicle.



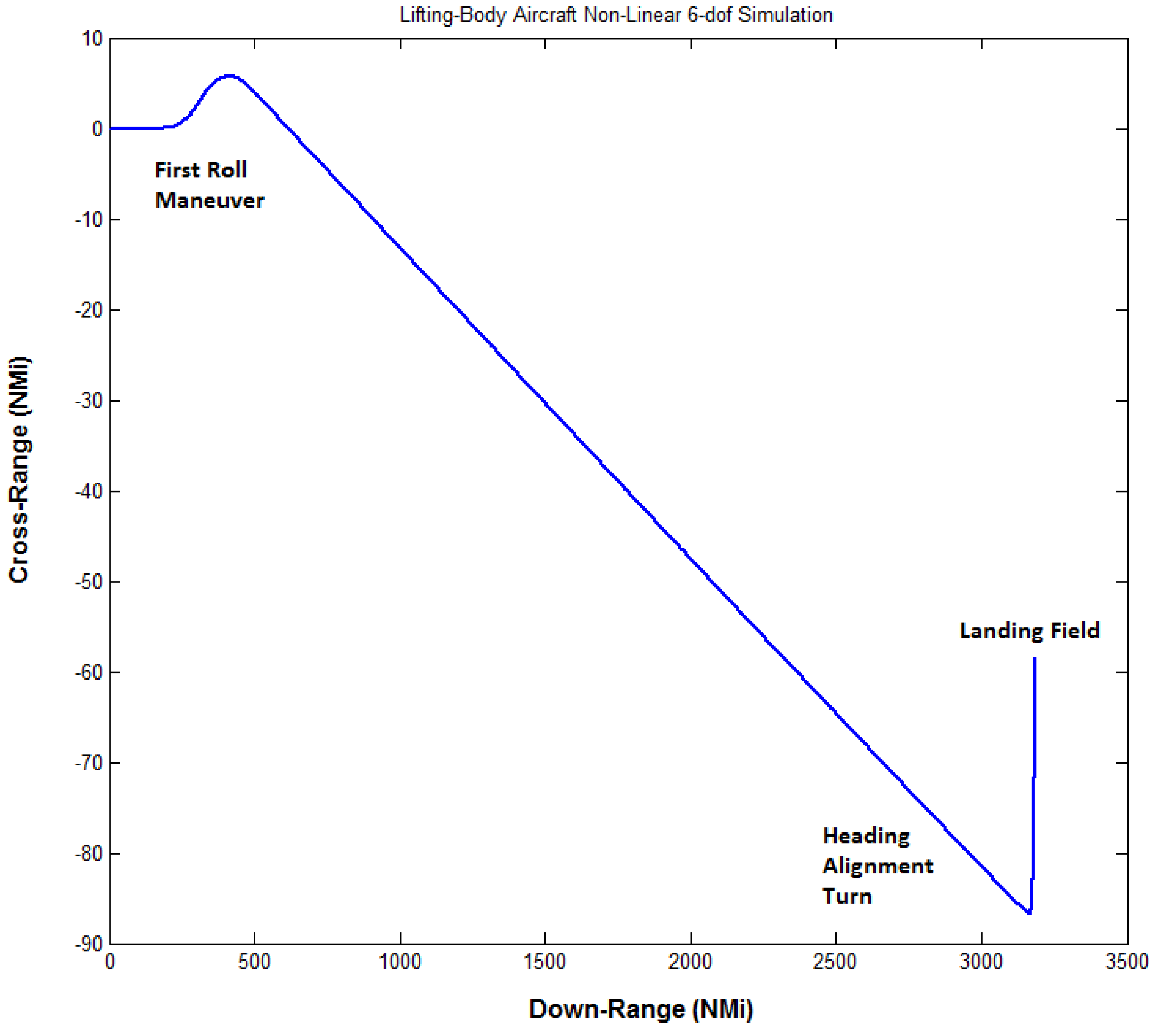
Speed-Brake: This figure shows the velocity control function by means of modulating the speed-brake, which takes place a couple of minutes before landing and it lasts approximately 70 seconds. The speed-brake operates by differentially deflecting the upper and lower body-flaps. During this period the speed-brake is partially opened (trimmed) at approximately 30° for the lower flaps and -20° for the upper flaps. The additional opening and closing of the upper and lower flaps is adjusted as shown by the velocity control system that attempts to control the vehicle speed by adjusting the deceleration. The ratio of upper to lower body-flap deflections is determined by the surface mixing-logic. The velocity command in this simulation is scheduled from a look-up table. The speed-brake is given enough time to regulate the landing speed and it closes about a minute before landing in order to maximize the accuracy and performance of the altitude control system.



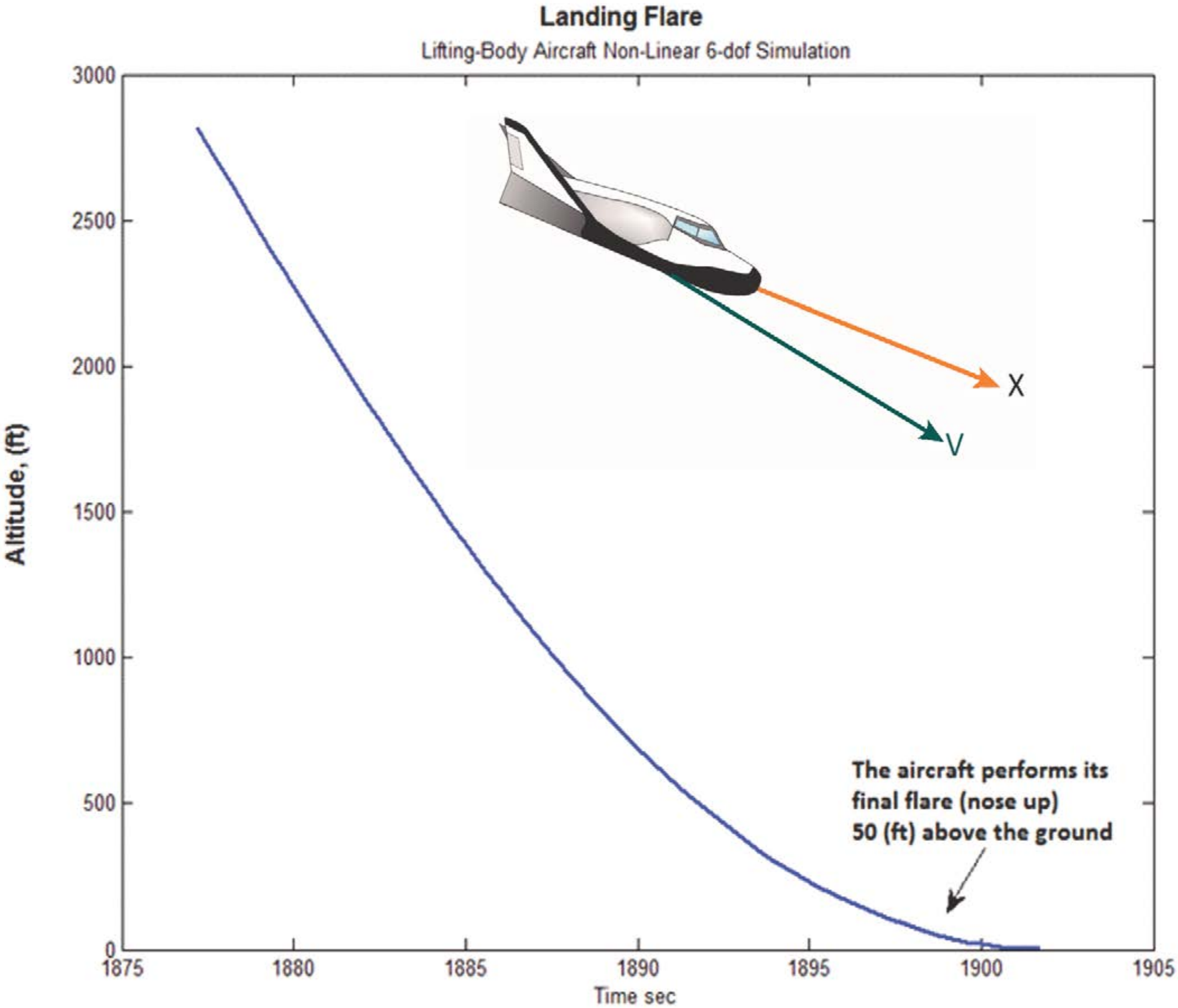
Heading Alignment Maneuver: This figure shows the Euler angles as a function of time. It demonstrates mainly the second roll maneuver that aligns the direction of the vehicle with the runway. The maneuver is performed by the heading alignment control system, shown in Figure (1.5.12), which applies a roll command proportional to the alignment error. The red line is the heading angle which is approximately 1.9° after the first roll maneuver. It is modified to -70° after the second roll maneuver to align the heading of the aircraft with the runway. The blue line shows the roll angle ϕ which reaches a peak value of -40° during the maneuver. The green curve is the pitch attitude θ that comes down to -20° during the steep dive, but it goes up after the flare and reaches 13° before touch down.



Downrange versus Crossrange: This figure shows the downrange versus crossrange vehicle positions beginning from atmospheric reentry all the way to landing. The first roll maneuver which occurs during early reentry points the aircraft heading direction towards the landing site. The second maneuver which occurs near the end of flight further adjusts the heading and aligns the aircraft with the runway before landing.

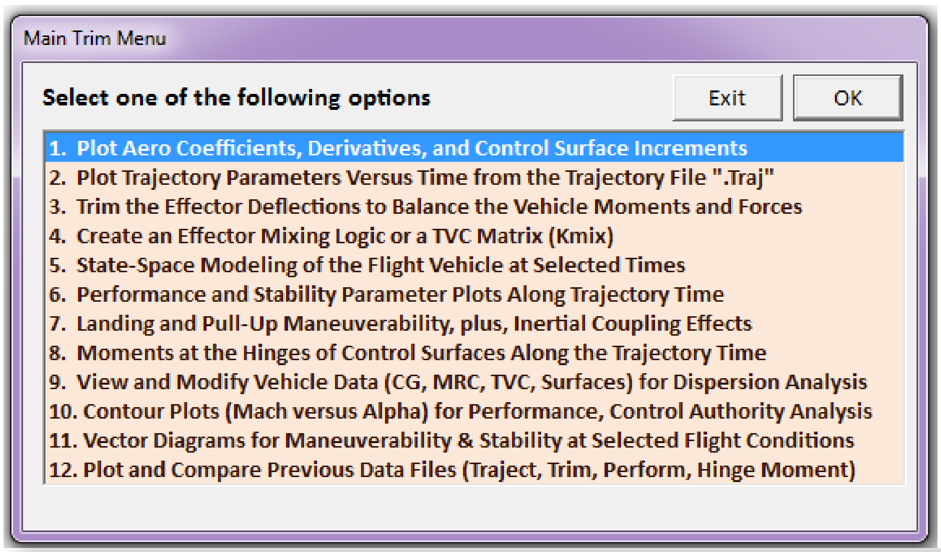


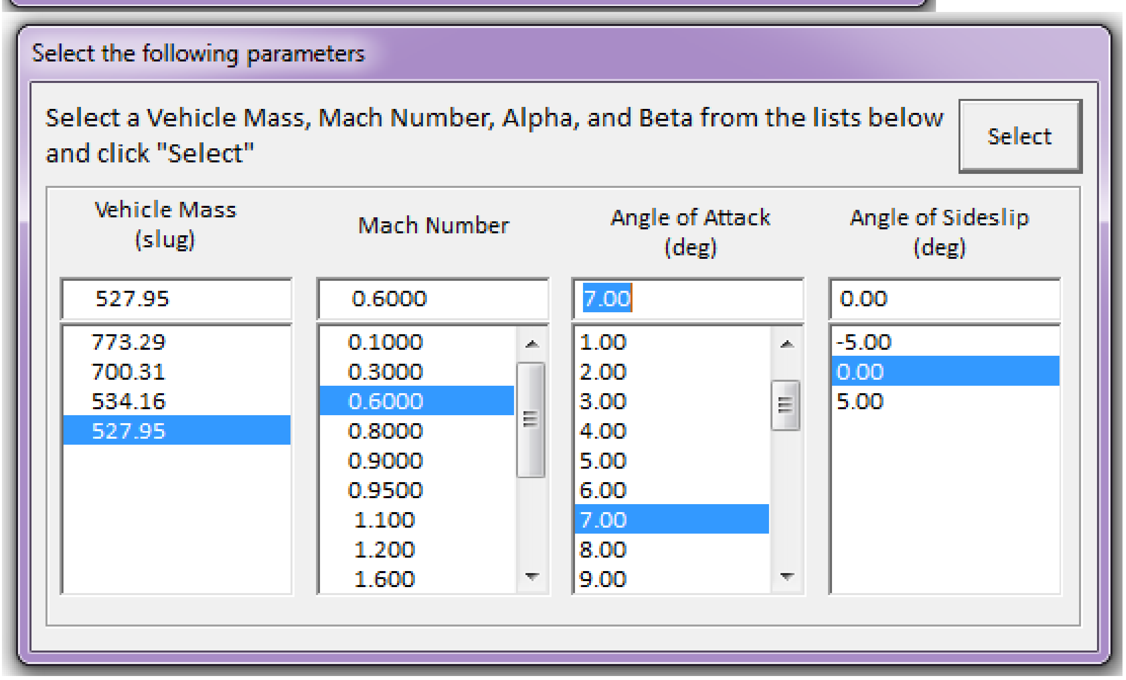
Final Flare and Landing: This figure shows the altitude versus time during the final 25 seconds of flight where the vehicle performs its pitch up flare and lands. It shows that the direction of the velocity becomes horizontal (γ=0°) after the flare which occurs approximately 50 (feet) above the ground. The success of the flare depends on the landing speed which should be maintained higher than 350 (feet/sec) before pitching up. Ground effects were not included in the simulation.

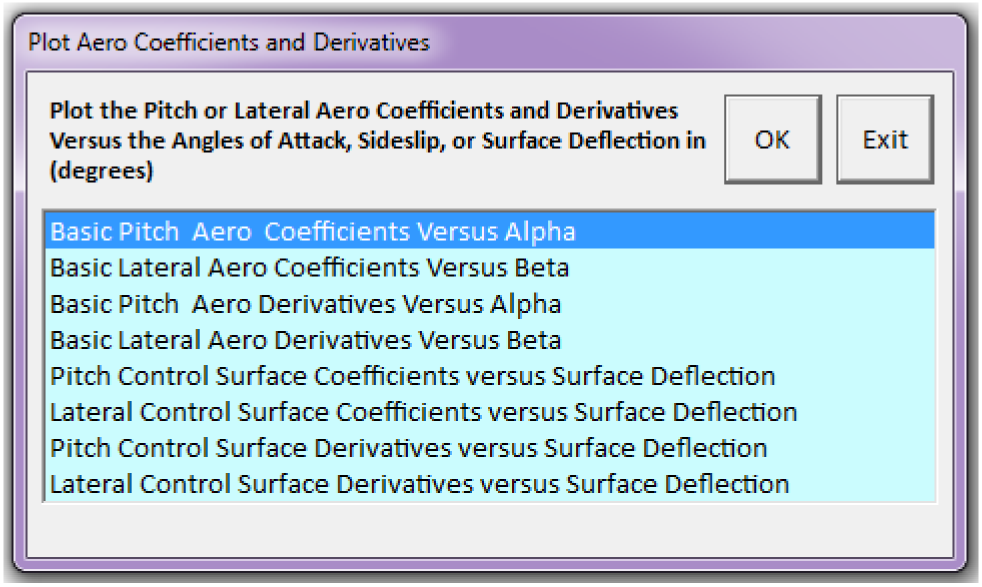


Aero Data

The aero-data plotting utility is very useful for viewing the aero coefficients as a function of Mach number, alpha, and surface deflection. It is the first option that can be selected from the Trim main menu, as shown below. The following dialog selects the vehicle mass, a Mach number, an angle of attack, and an angle of sideslip (typically zero β). The mass is used for transferring the aero moments from the MRC to the corresponding CG. The next menu is used for selecting the type of aero-data to plot, which is, basic aero coefficients and derivatives, and the aero-surface coefficients plus derivatives.







The figures in the next few pages provide the following information regarding the basic vehicle aerodynamic properties as a function of Mach number, alpha, and beta, and also the effectiveness of its aero-surfaces.

- Figures (5.1) and (5.2) show the longitudinal and lateral basic aero coefficients and their derivatives with respect to alpha and beta respectively. They are shown at five different Mach numbers.
- Figures (5.3) and (5.4) show the longitudinal and lateral aero-surface increments and their derivatives for the left elevon. The right elevon is identical in pitch and anti-symmetric in lateral, see Figure (5.5).
- Figures (5.6) and (5.7) show similar longitudinal results for the upper-left and the lower right body-flaps. The body-flaps on the other side are identical in pitch, and anti-symmetric in lateral as shown in figures (5.10) and (5.11).
- Figure (5.8) shows the lateral increments and derivatives for the vertical rudder. It has perfect symmetry about zero. Notice how the rolling moment changes with Mach number. It completely reverses direction in the transonic region.
- Figures (5.9) and (5.10) show the lateral increments and derivatives for the upper-left and the upper-right body-flaps. They seem to be complementing each other in roll and yaw. The body-flaps on the right-hand side are anti-symmetrically similar.

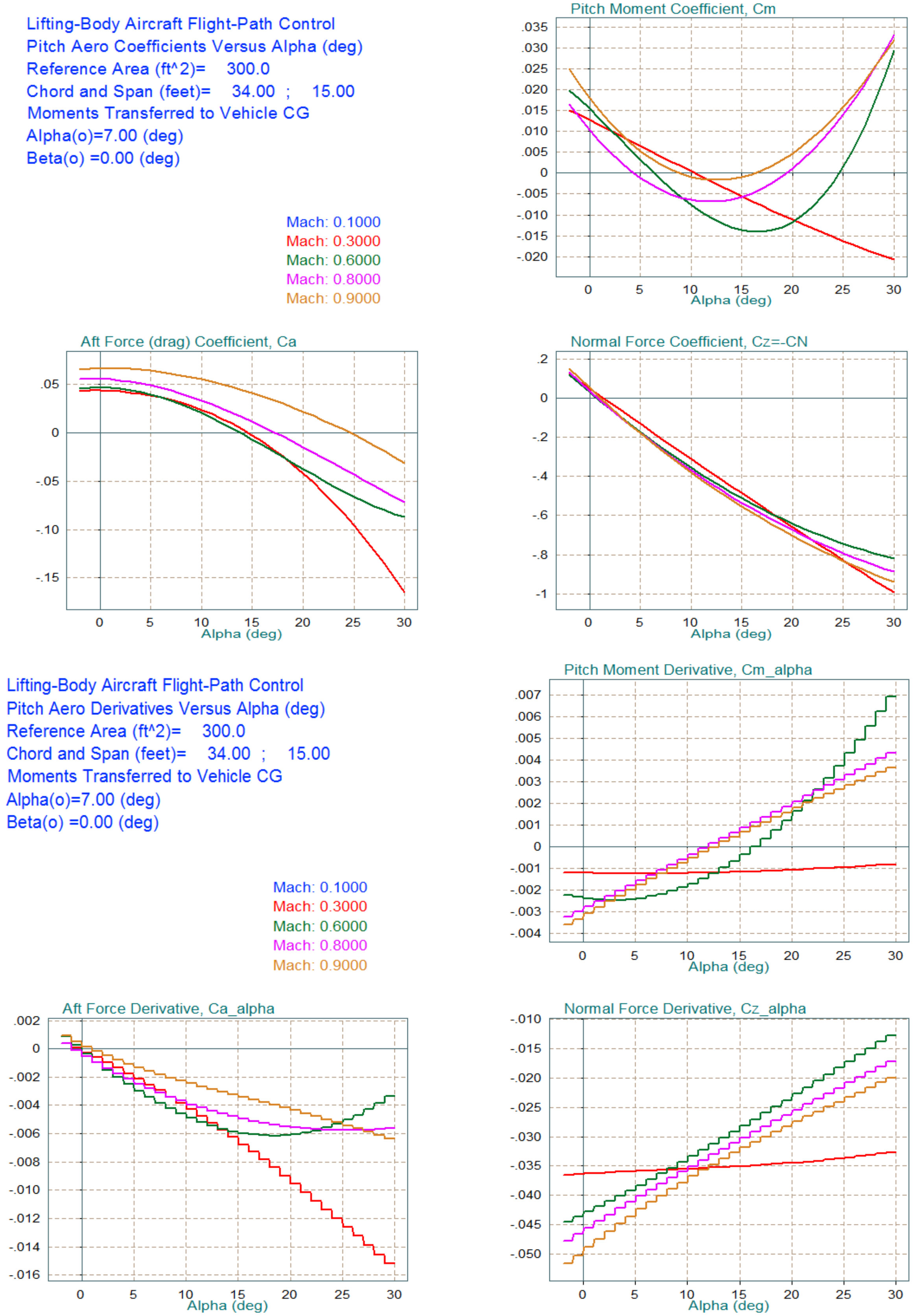


Figure 5.1 Longitudinal Basic Aero Coefficients and their Derivatives with respect to Alpha

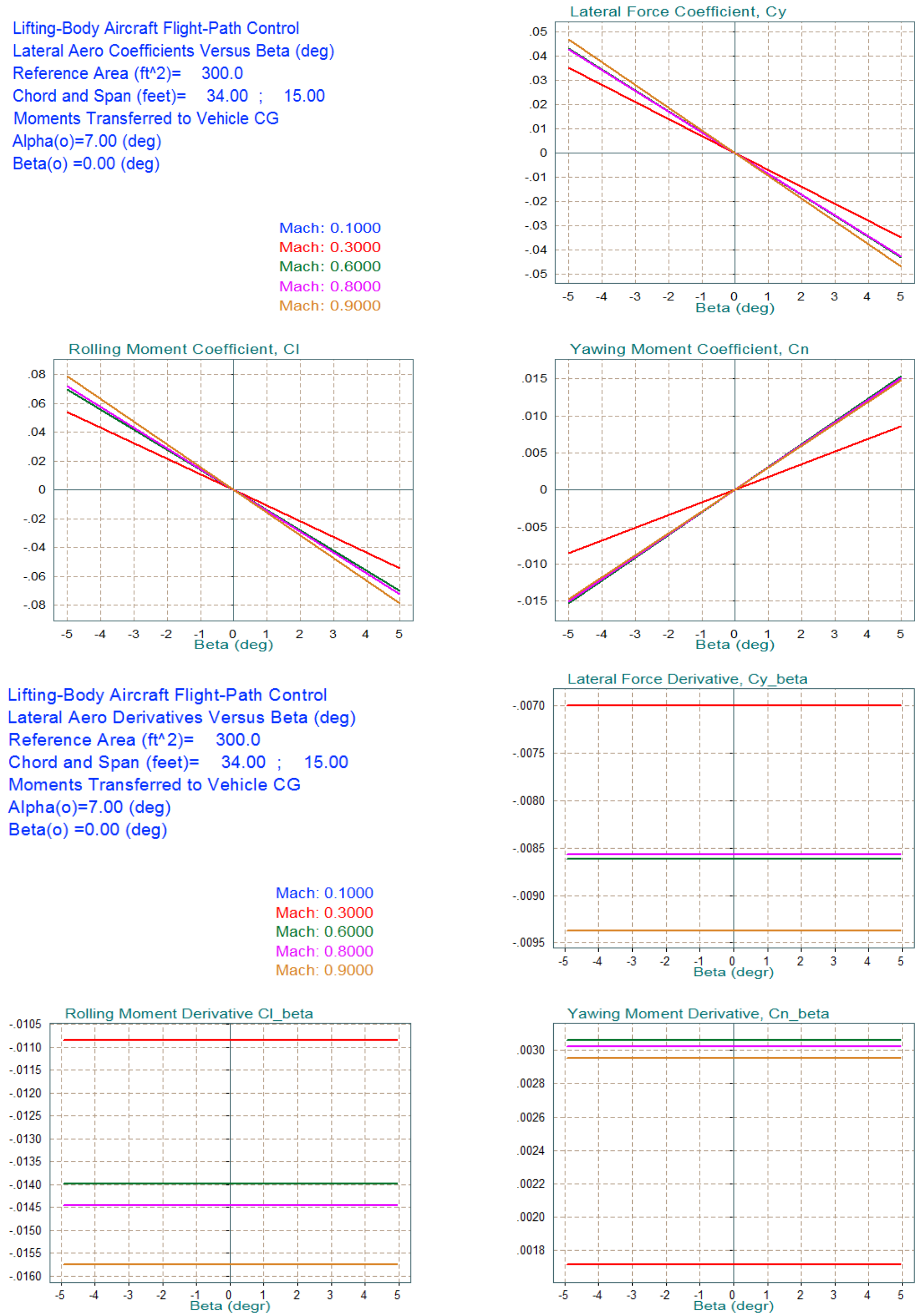


Figure 5.2 Lateral Basic Aero Coefficients and their Derivatives with respect to Beta

Figure 5.3 Left Elevon Aero-Surface Pitch Increments and Derivatives

Figure 5.4 Left Elevon Aero-Surface Lateral Increments and Derivatives

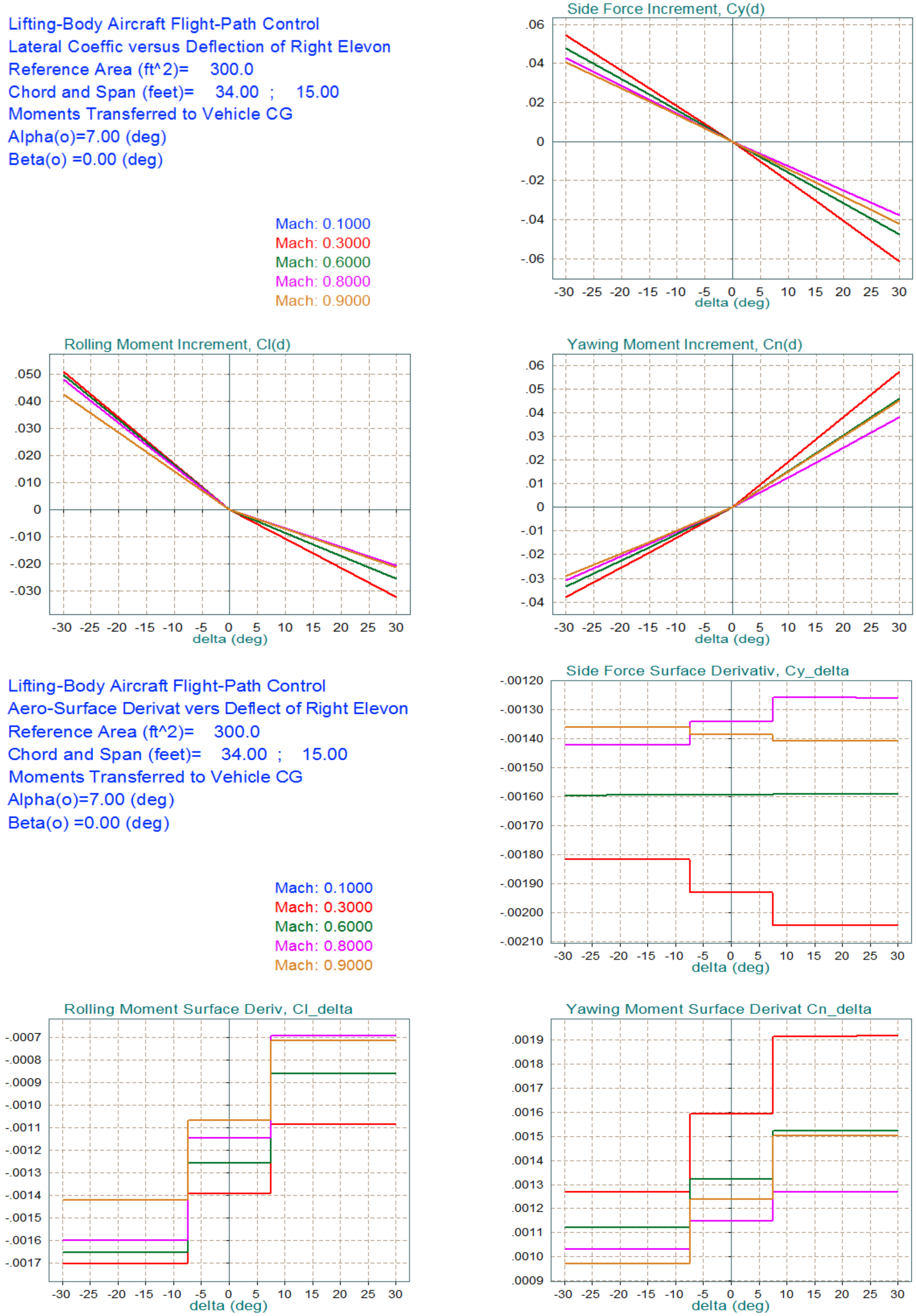


Figure 5.5 Right Elevon Aero-Surface Lateral Increments and Derivatives

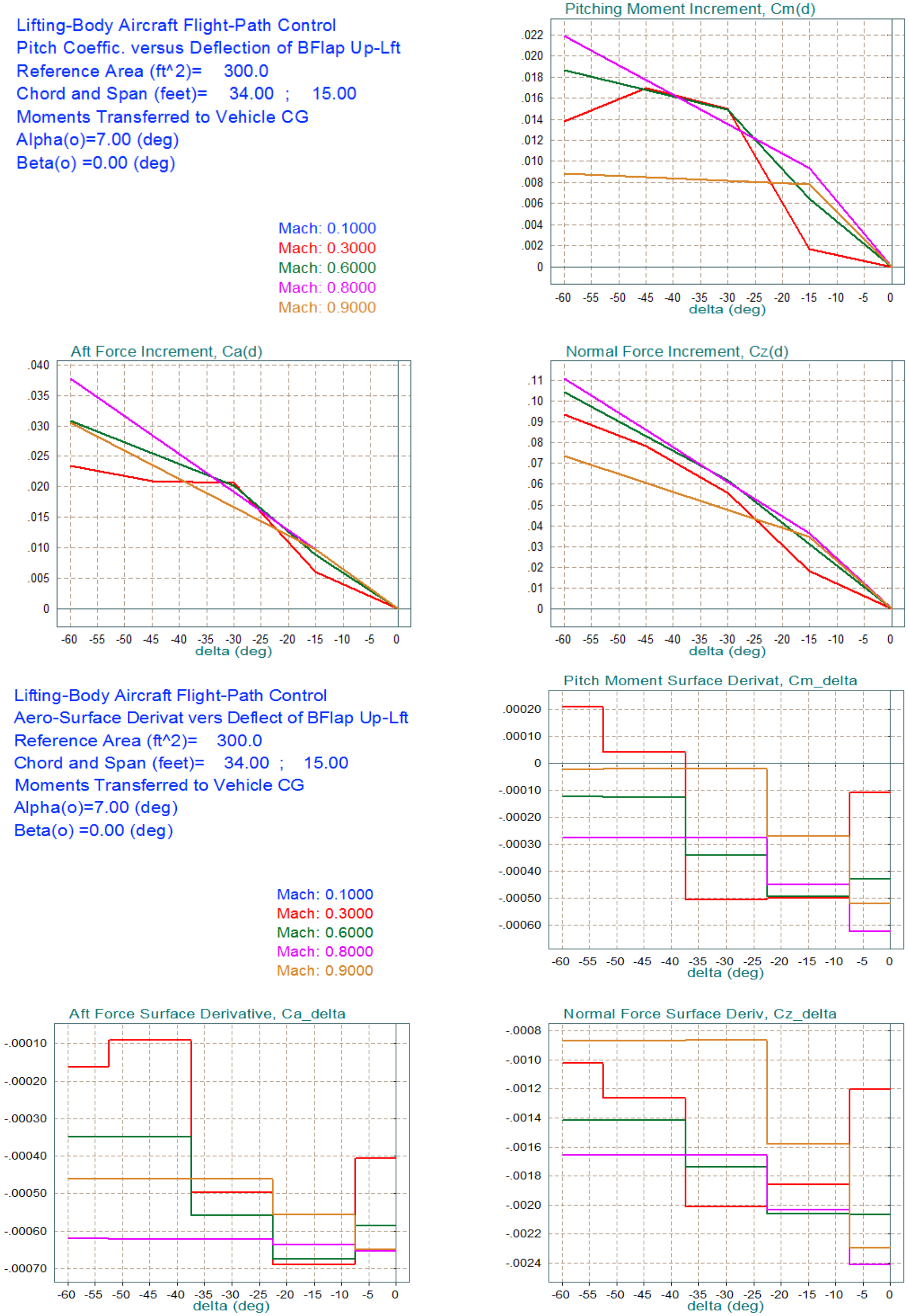
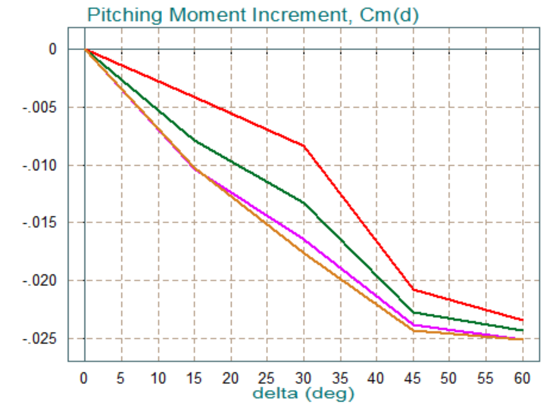
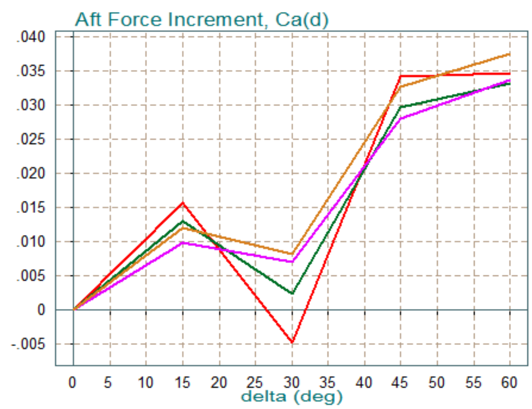


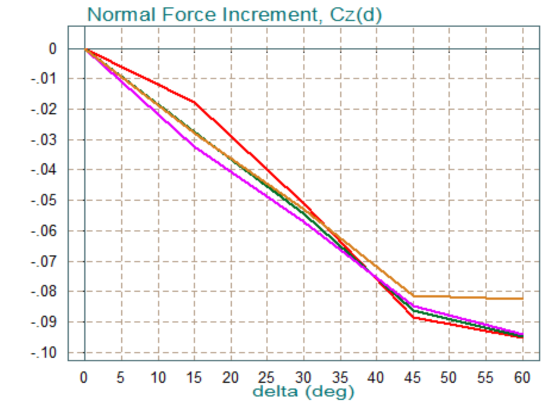
Figure 5.6 Upper Left Body-Flap Pitch Increments and Derivatives

Lifting-Body Aircraft Flight-Path Control
Pitch Coeffic. versus Deflection of BFlap Lo-Rht
Reference Area (ft^2)= 300.0
Chord and Span (feet)= 34.00 ; 15.00
Moments Transferred to Vehicle CG
Alpha(o)=7.00 (deg)
Beta(o) =0.00 (deg)

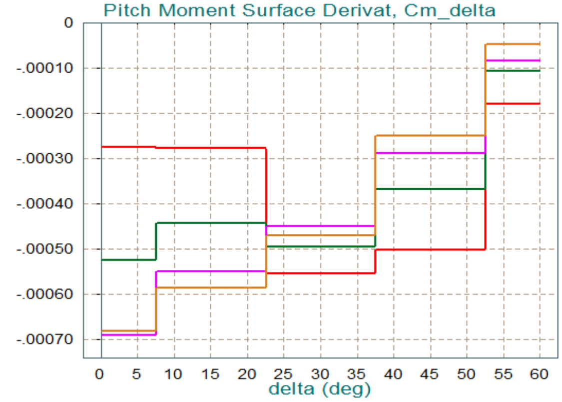


Mach: 0.1000
Mach: 0.3000
Mach: 0.6000
Mach: 0.8000
Mach: 0.9000

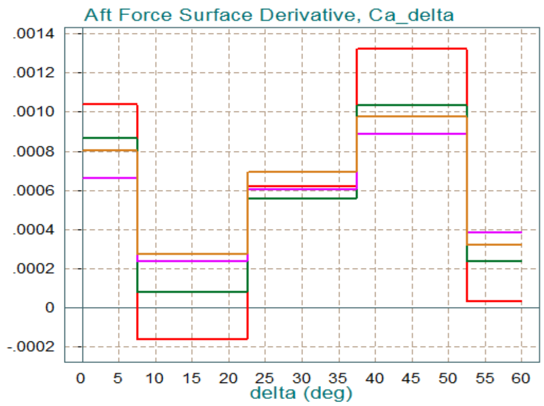




Lifting-Body Aircraft Flight-Path Control
Aero-Surface Derivat vers Deflect of BFlap Lo-Rht
Reference Area (ft^2)= 300.0
Chord and Span (feet)= 34.00 ; 15.00
Moments Transferred to Vehicle CG
Alpha(o)=7.00 (deg)
Beta(o) =0.00 (deg)



Mach: 0.1000
Mach: 0.3000
Mach: 0.6000
Mach: 0.8000
Mach: 0.9000



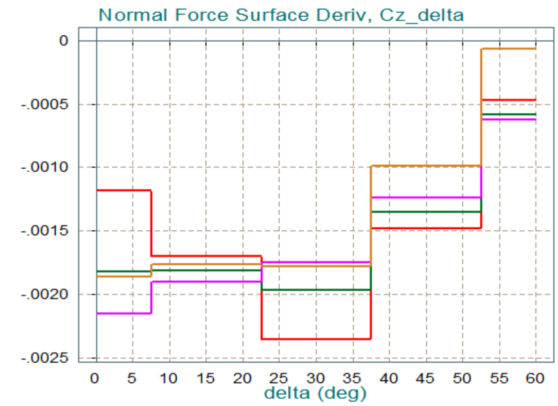


Figure 5.7 Lower Right Body-Flap Pitch Increments and Derivatives

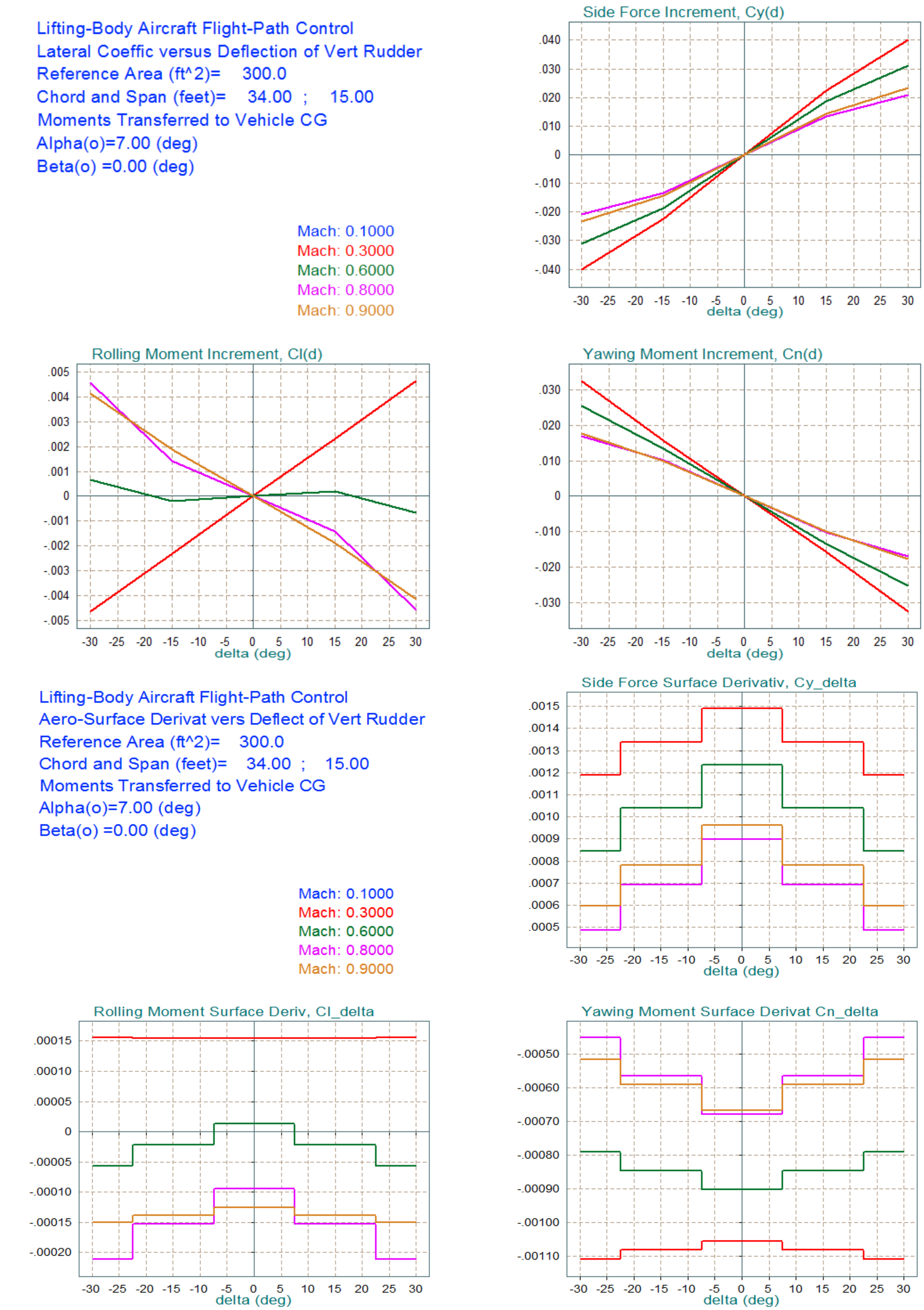


Figure 5.8 Lateral Increments and Derivatives for the Vertical Rudder

Figure 5.9 Lateral Increments and Derivatives for the Upper-Left Body-Flap

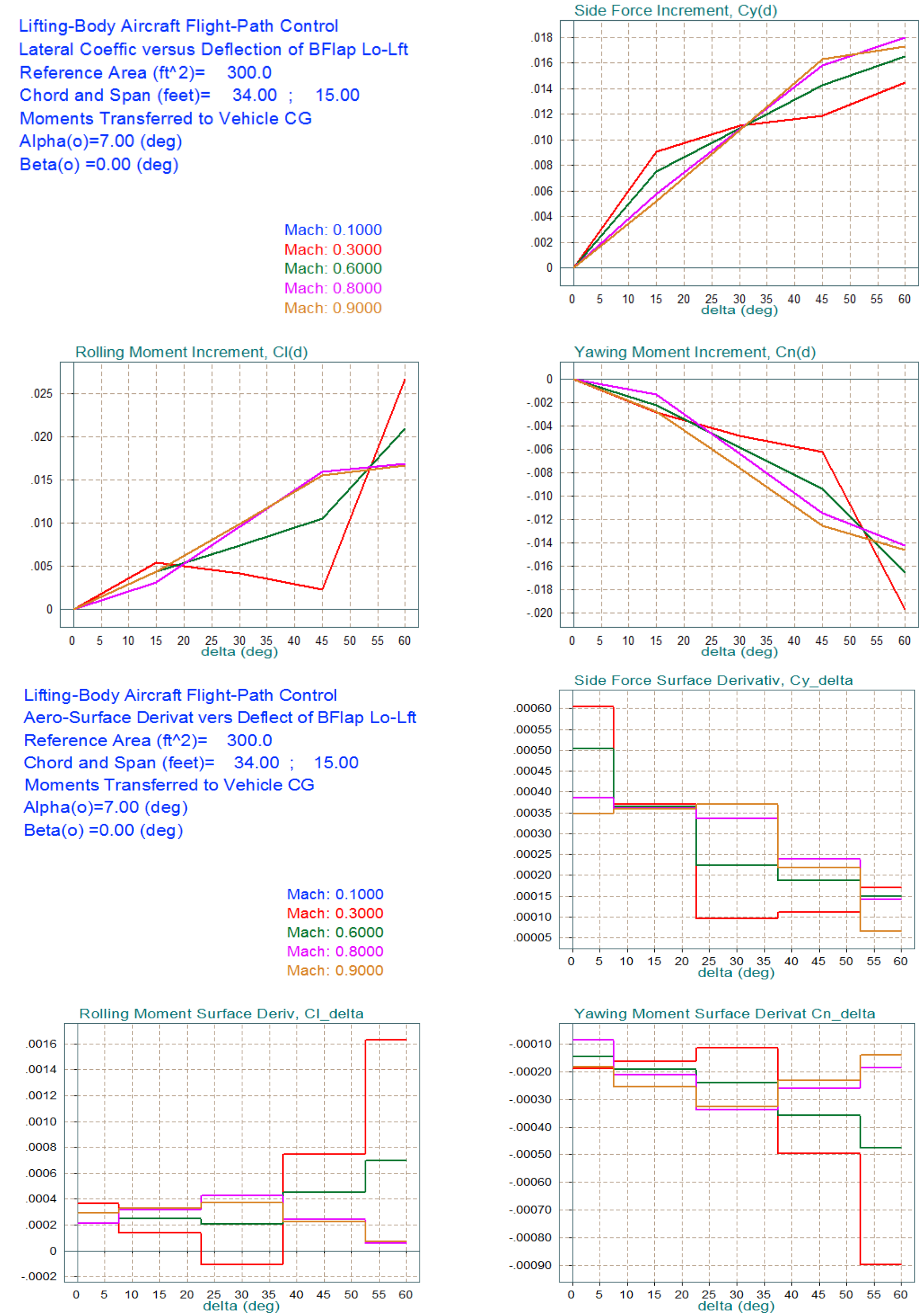


Figure 5.10 Lateral Increments and Derivatives for the Lower-Left Body-Flap

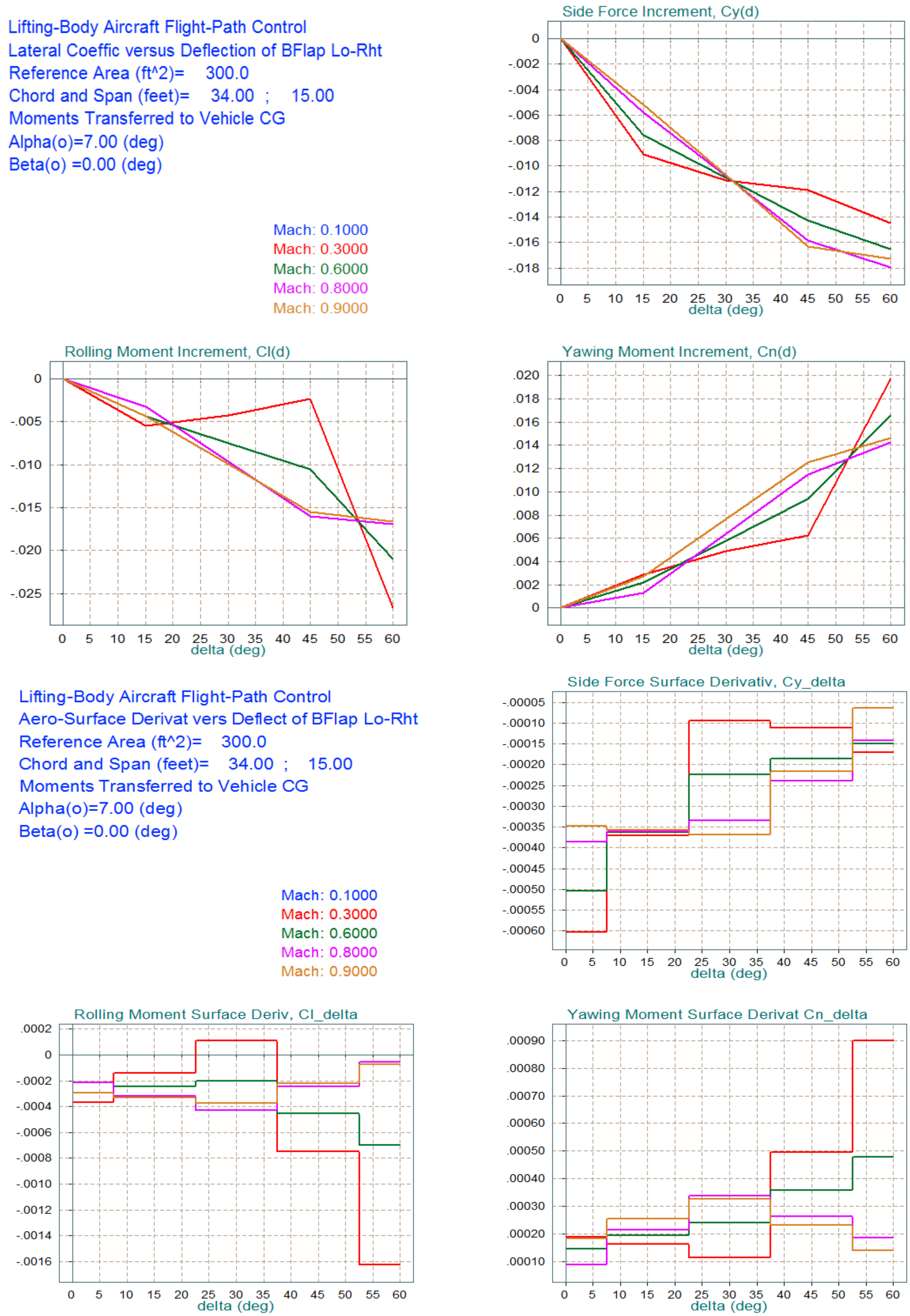


Figure 5.11 Lateral Increments and Derivatives for the Lower-Right Body-Flap

2.0 Vertical Launch

This vehicle is also capable of taking off vertically like a launch vehicle by using its two 18,000 (lb) TVC engines which are also capable of varying their thrusts and regulating the vehicle speed by a closed-loop throttle control system. During boosting all vehicle effectors: engines and aerosurfaces, are used for trimming as well as flight control. This is a good example for demonstrating how aero-surfaces, TVC, and throttling are combined together to control the vehicle in multiple directions. The trajectory used in this analysis is separated in two sections, the boost phase where the engines are active, and the descent phase where the unpowered vehicle glides back to land on the runway. Similar to the reentry trajectory we will analyze both phases separately by trimming the effectors, analyzing static performance and controllability using contour plots and vector diagrams. We will also use Flixan to generate dynamic models at selected flight conditions, perform flight control designs, simulate and analyze stability in Matlab.

2.1 Ascent/ Boost Phase

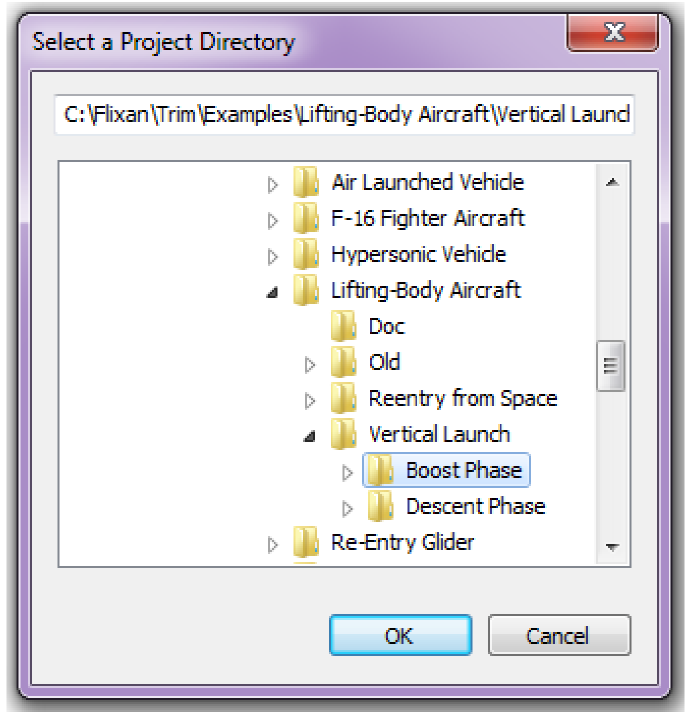
The analysis during the boost phase is performed in folder "*C:\Flixan\Trim\Examples\Lifting-Body Aircraft\Vertical Launch\Boost Phase*". The first part of the trajectory which includes the engines thrust is in file "*LiftBo_Ascent.Traj*". The thrust in the trajectory file is the total thrust from both engines. The engine information is included in the engines file "*Lift_Body.Engn*" which specifies the number of engines, their nominal thrust, the gimbal locations, their mounting angles (relative to the vehicle -x direction), max deflections, and max throttling capability. The nominal thrust direction is along the vehicle x axis. The maximum deflections from mounting are ±5° in pitch and yaw, and the max throttling capability is ±40% relative to nominal thrust. The engines mass, inertia, and the moment arms between the engine CG and gimbal are not used in this analysis.

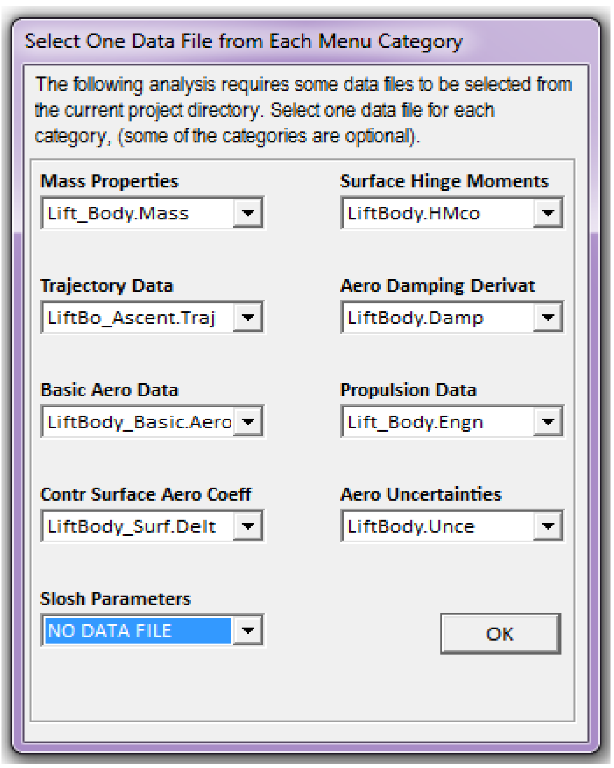
```
Lifting Body Aircraft Rocket Engines
Engine Description, Thrust     Mass      Ieng        Mom Arm     Location (x,y,z)      Mounting Angles (Dy, Dz)  Max Deflection       Max Throttl
                    (lb)       (slug)    (slug-ft2)  (ft)        (feet)                Elevat, Azimuth (degr)    Dym,Dzm (deg)        (0-1)
Left TVC Eng#1      18000.0    60.0      8.0         0.7         -33.5 -6.0  -2.2      0.0     0.0               5.0  5.0             0.4
Rght TVC Eng#2      18000.0    60.0      8.0         0.7         -33.5 +6.0  -2.2      0.0     0.0               5.0  5.0             0.4
```

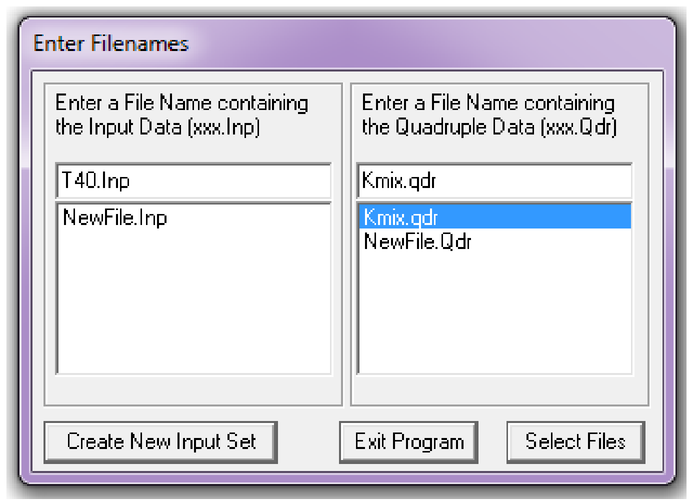
The vehicle mass properties are not constant during ascent but they vary as a function of mass. The mass properties file is the same as before "*Lift_Body.Mass*", and it contains the vehicle moments of inertia and CG location as a function of its mass. The aero coefficients for the basic body and the aero-surfaces, files "*LiftBody_Basic.Aero*" and "*LiftBody_Surf.Delt*", are the same as during re-entry. The aero-surface bias positions and deflection range where modified, however, to better affect the trimming conditions. The hinge moment coefficient file, the damping derivatives, and the uncertainties file: "*LiftBody.HMco*", "*LiftBody.Damp*", and "*LiftBody.Unce*", are the same as before.

Trajectory

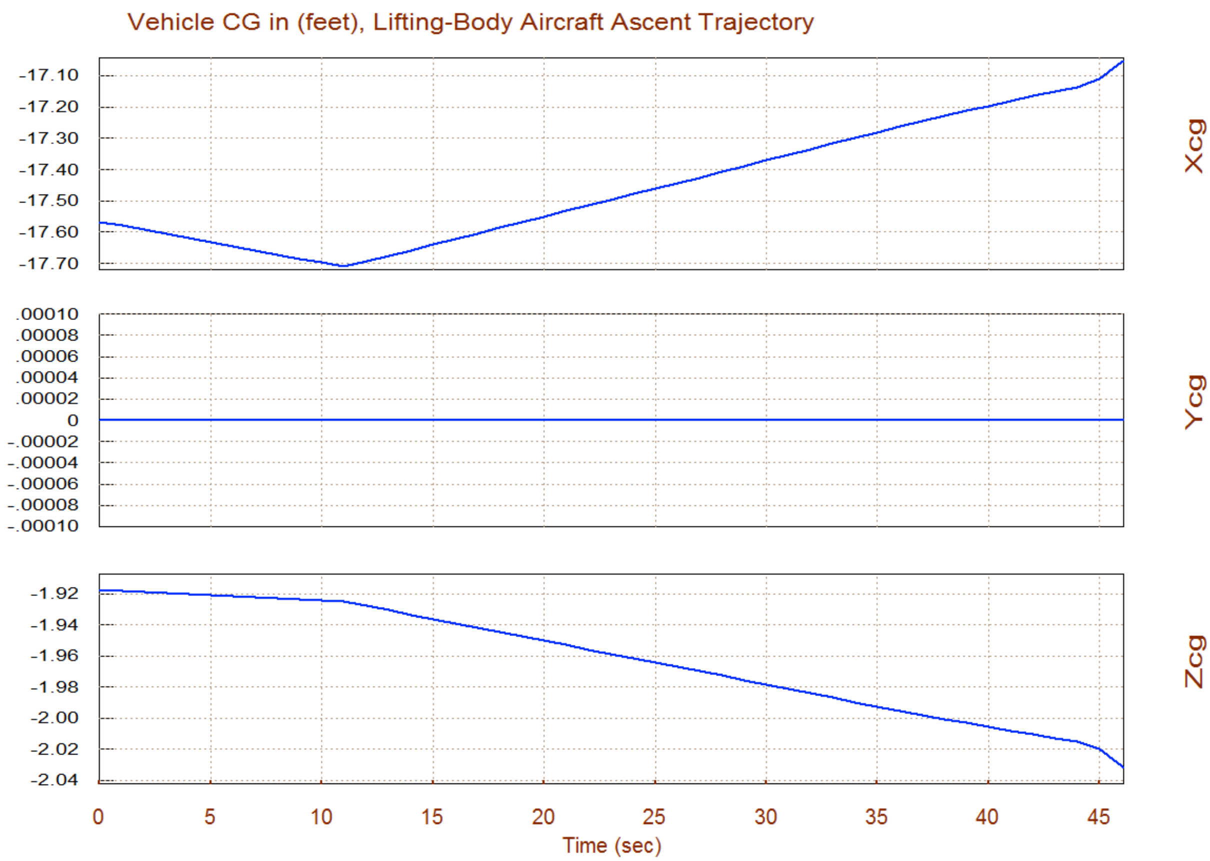
Let us first take a look at the trajectory file. Start the Flixan/Trim program, select the boost phase folder and from the filename selection menu select the vehicle data files. In the following filename selection menu you may keep the default filenames "NewFile" for now or you may select "Kmix.Qdr" that will later on be used in performance analysis. You may also enter an input filename "T40.Inp" to later on create a dynamic model.

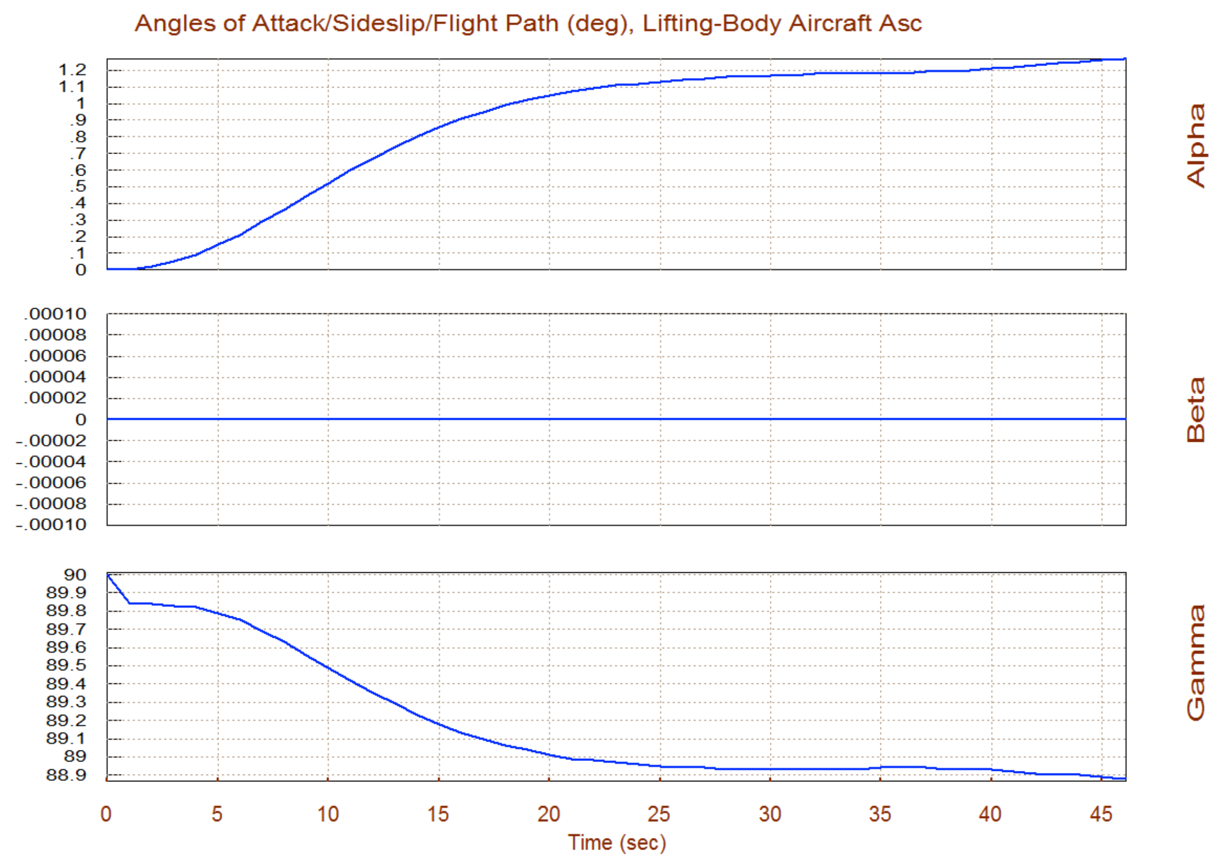


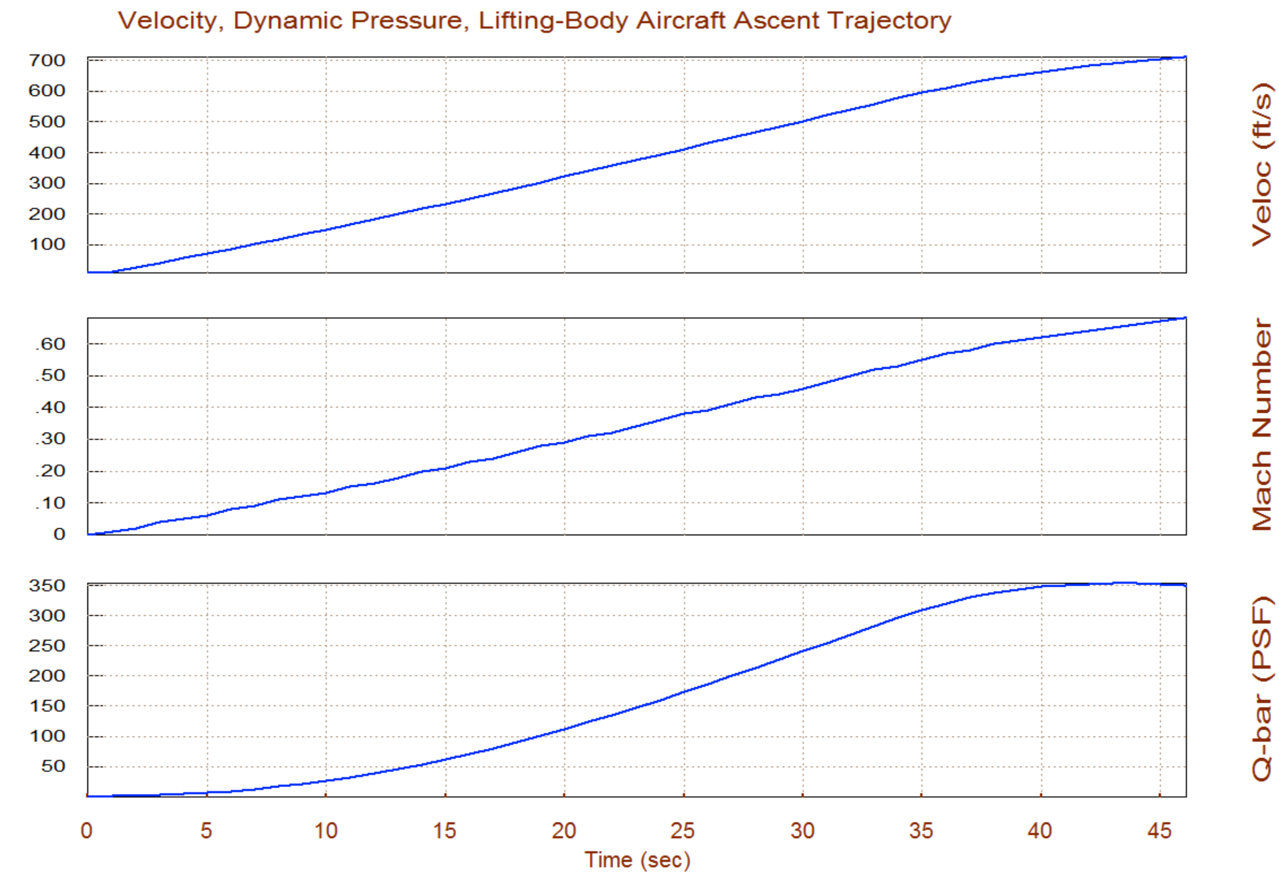


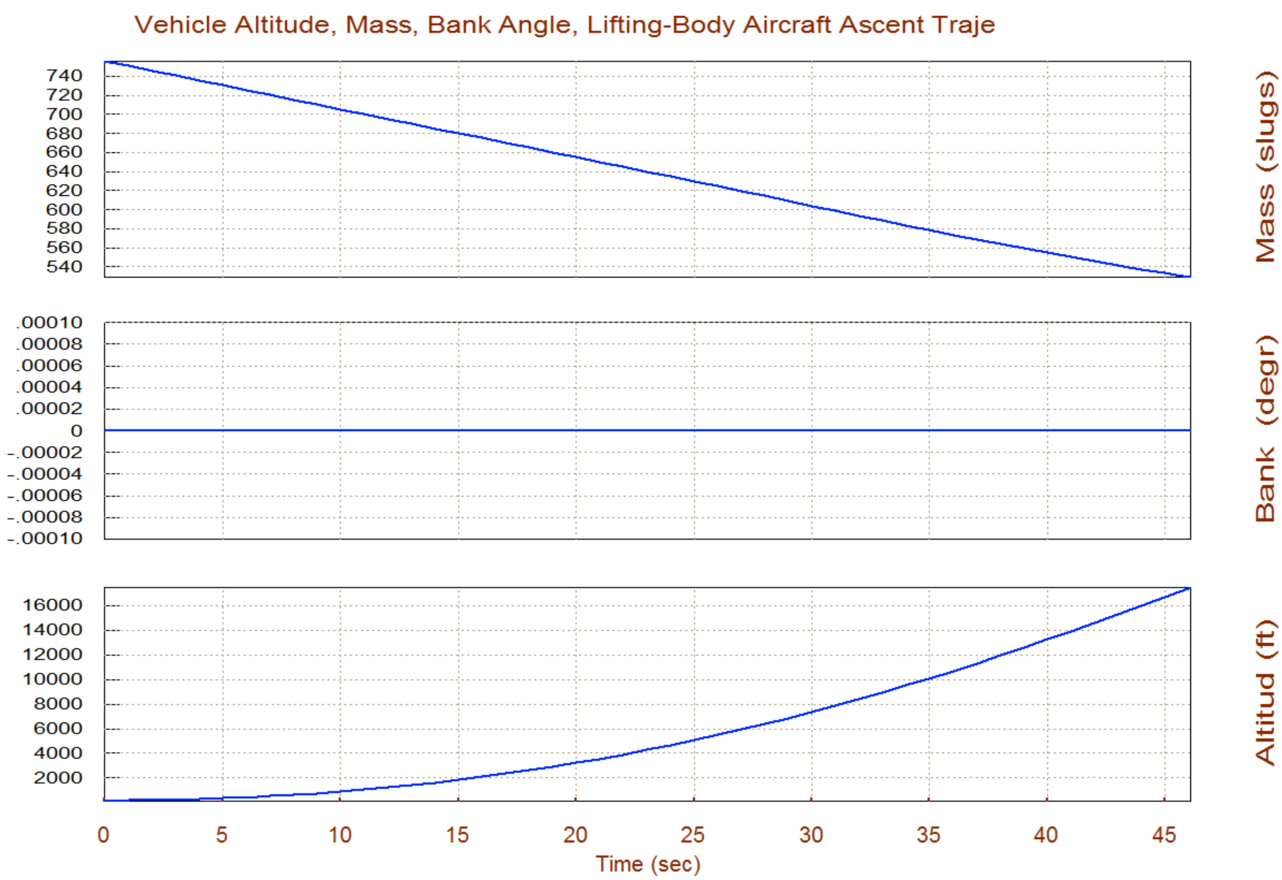


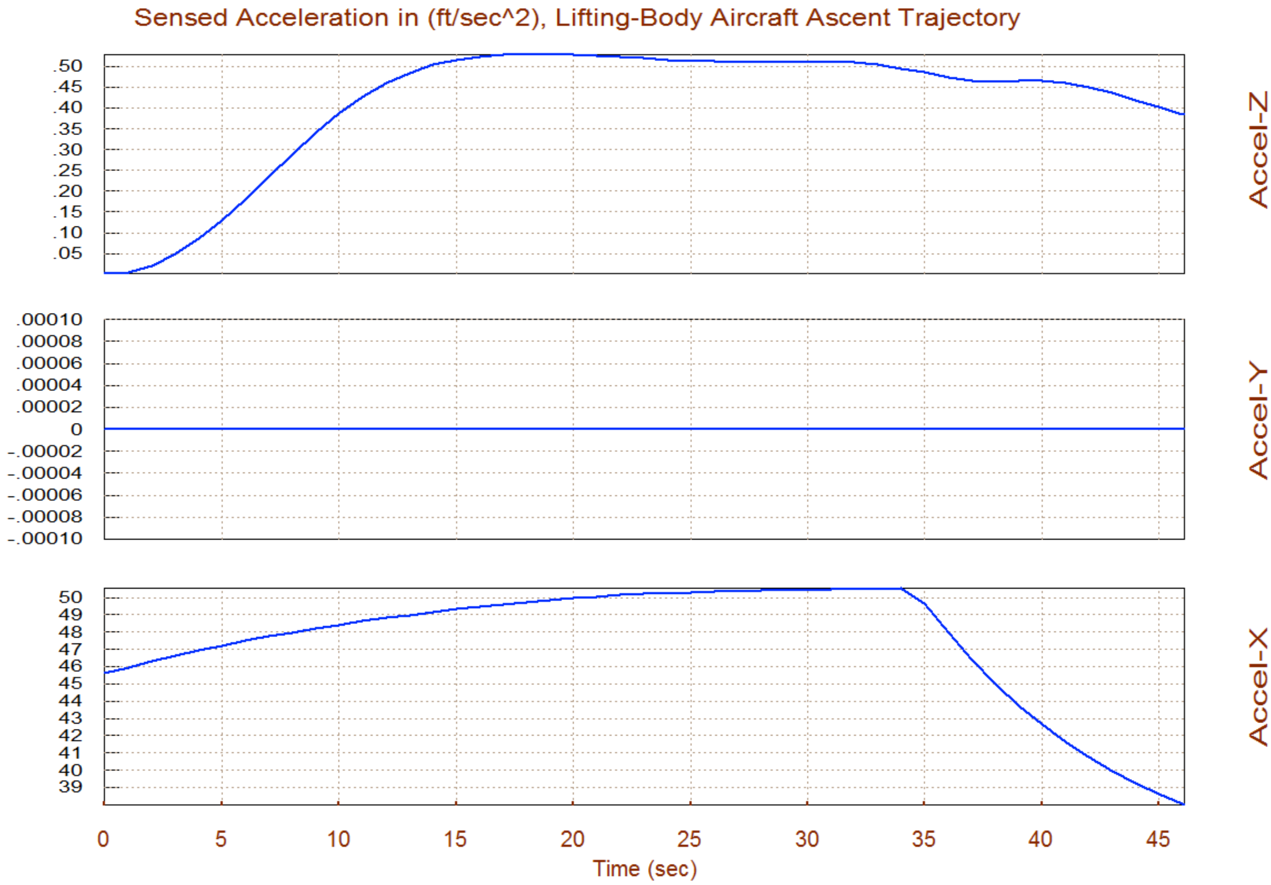
From the Trim main menu select the second option to plot the trajectory data, as shown below. Notice how the CG is now varying with time because the vehicle mass is depleted by the engines firing. The direction of the flight path angle begins at γ=90° and it remains almost vertical during the entire boost changing to γ=88.9° towards the end of boost. The dynamic pressure reaches 350 (psf) when the engines cut-off, the altitude reaches 17,000 (ft) above sea level, and the velocity 700 (ft/sec). The angle of attach begins at zero and it gradually changes to 1.2° as the vehicle prepares for its glide back to the ground. The thrust is not constant but it throttles back towards the end of boost.


Vehicle CG in (feet), Lifting-Body Aircraft Ascent Trajectory
-17.10
-17.20
-17.30
-17.40
-17.50
-17.60
-17.70
Xcg
.00010
.00008
.00006
.00004
.00002
0
-.00002
-.00004
-.00006
-.00008
-.00010
Ycg
-1.92
-1.94
-1.96
-1.98
-2.00
-2.02
-2.04
Zcg
0
5
10
15
20
25
30
35
40
45
Time (sec)

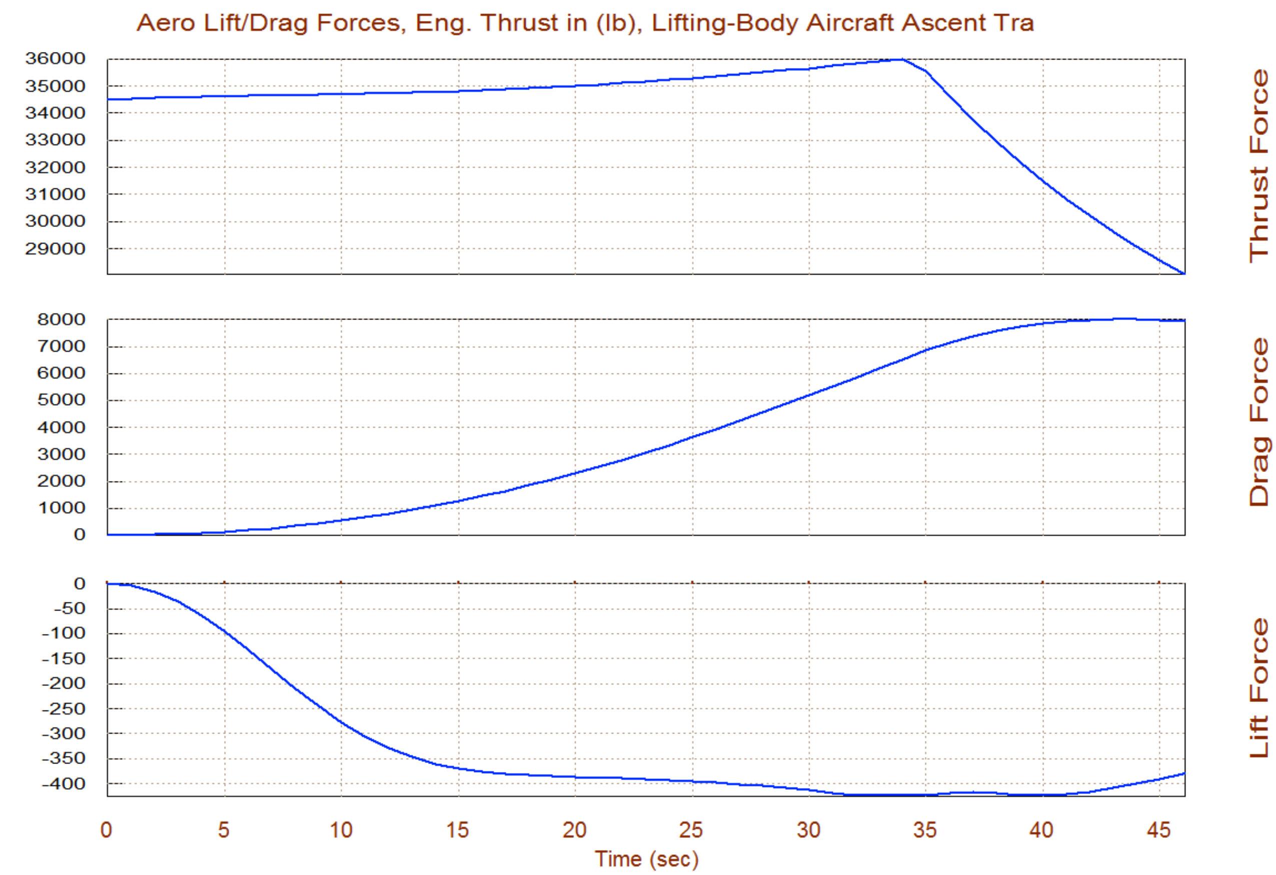

Angles of Attack/Sideslip/Flight Path (deg), Lifting-Body Aircraft Asc
1.2
1.1
1
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
Alpha
.00010
.00008
.00006
.00004
.00002
0
-.00002
-.00004
-.00006
-.00008
-.00010
Beta
90
89.9
89.8
89.7
89.6
89.5
89.4
89.3
89.2
89.1
89
88.9
Gamma
0
5
10
15
20
25
30
35
40
45
Time (sec)


Velocity, Dynamic Pressure, Lifting-Body Aircraft Ascent Trajectory
Veloc (ft/s)
Mach Number
Q-bar (PSF)
Time (sec)


Vehicle Altitude, Mass, Bank Angle, Lifting-Body Aircraft Ascent Traje
Mass (slugs)
Bank (degr)
Altitud (ft)
Time (sec)



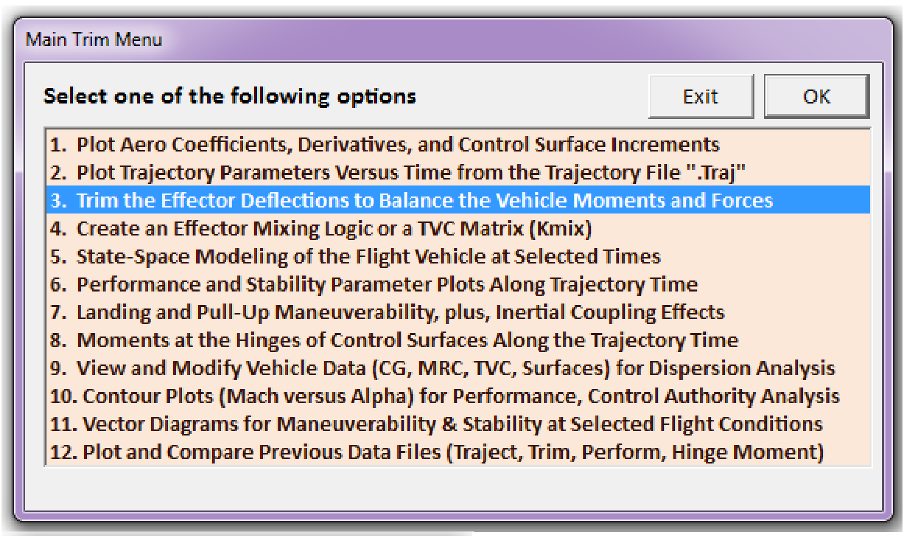
Sensed Acceleration in (ft/sec^2), Lifting-Body Aircraft Ascent Trajectory
Accel-Z
Accel-Y
Accel-X
Time (sec)

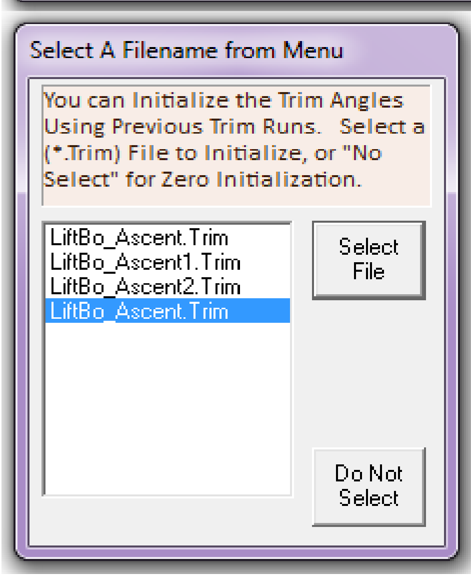


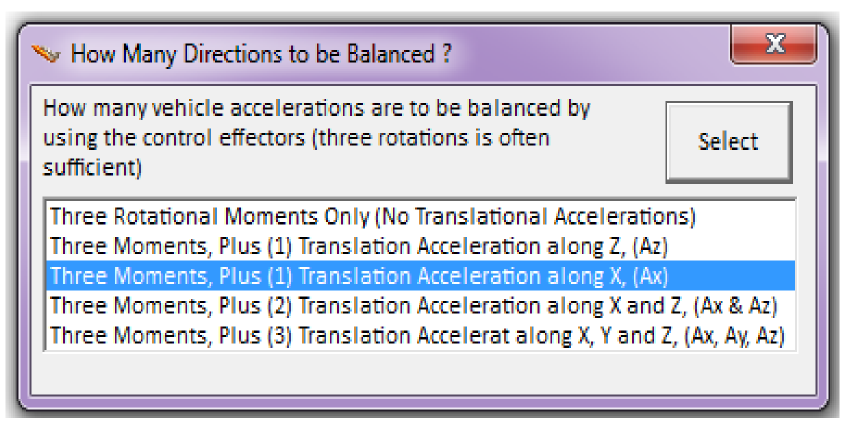
Aero Lift/Drag Forces, Eng. Thrust in (lb), Lifting-Body Aircraft Ascent Tra
Thrust Force
Drag Force
Lift Force
Time (sec)

Trimming

We will now trim the effectors and determine their positions required to balance the vehicle moments and axial acceleration along the ascent trajectory. This time we have 13 effectors for trimming, because in addition to the 7 aero-surfaces we have 4 TVC effectors (2 pitch & 2 yaw) and 2 engine throttles, a total of 13 effectors. Return to the Trim main menu and choose option (3) for trimming. Do not select a trim initialization file, if it is the first time you are trimming this configuration, and select to trim along three rotational moments, roll, pitch, yaw, plus axial acceleration (3rd option). The program will determine a combination of effector positions for balancing the moments and acceleration based on the individual capabilities of each effector along those directions. The trim deflections are saved in file "*LiftBo_Ascent.Trim*".

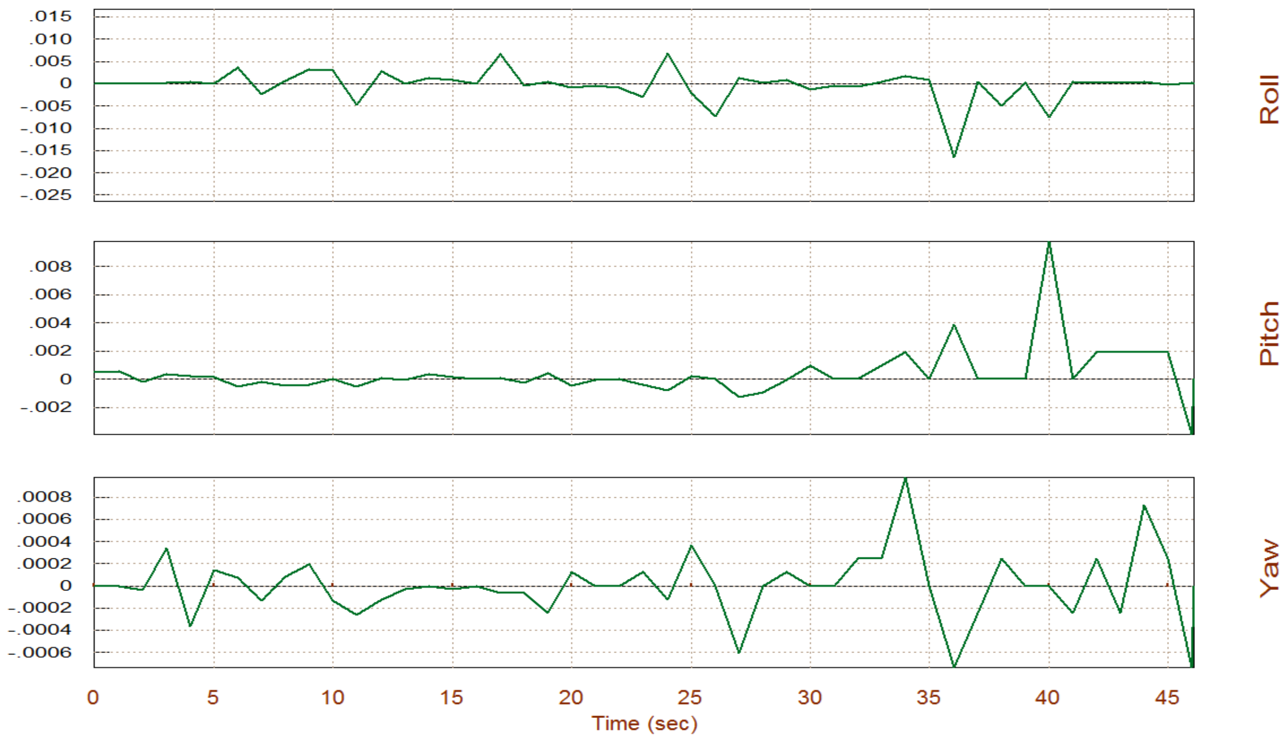




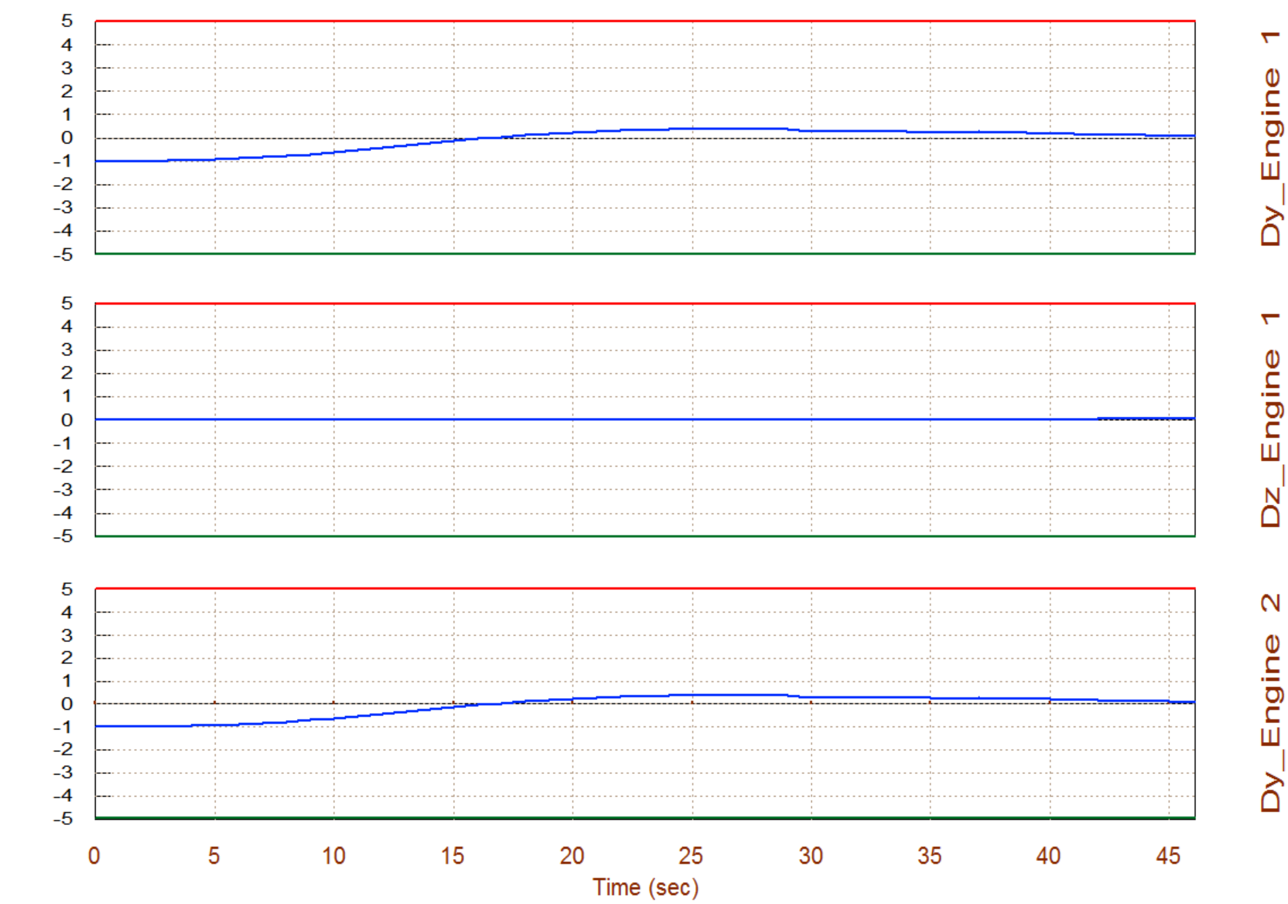


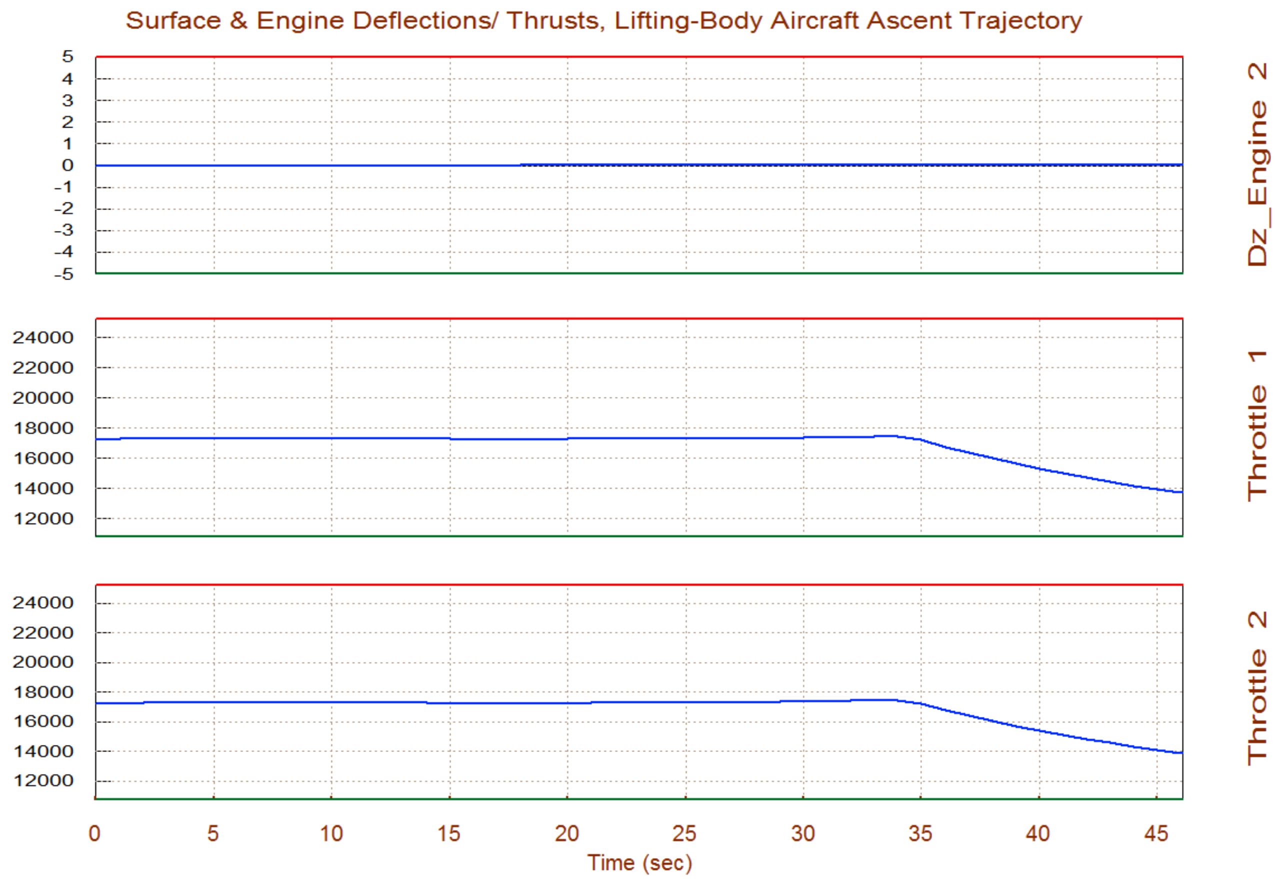
Notice that the residual moments are zero indicating that the trim was successful. The two pitch engine deflections are varying during boost in order to balance the pitch moment. The two elevons are also varying in a similar fashion assisting the engines. In the yaw direction the activity of the TVC engines and rudder are very small.

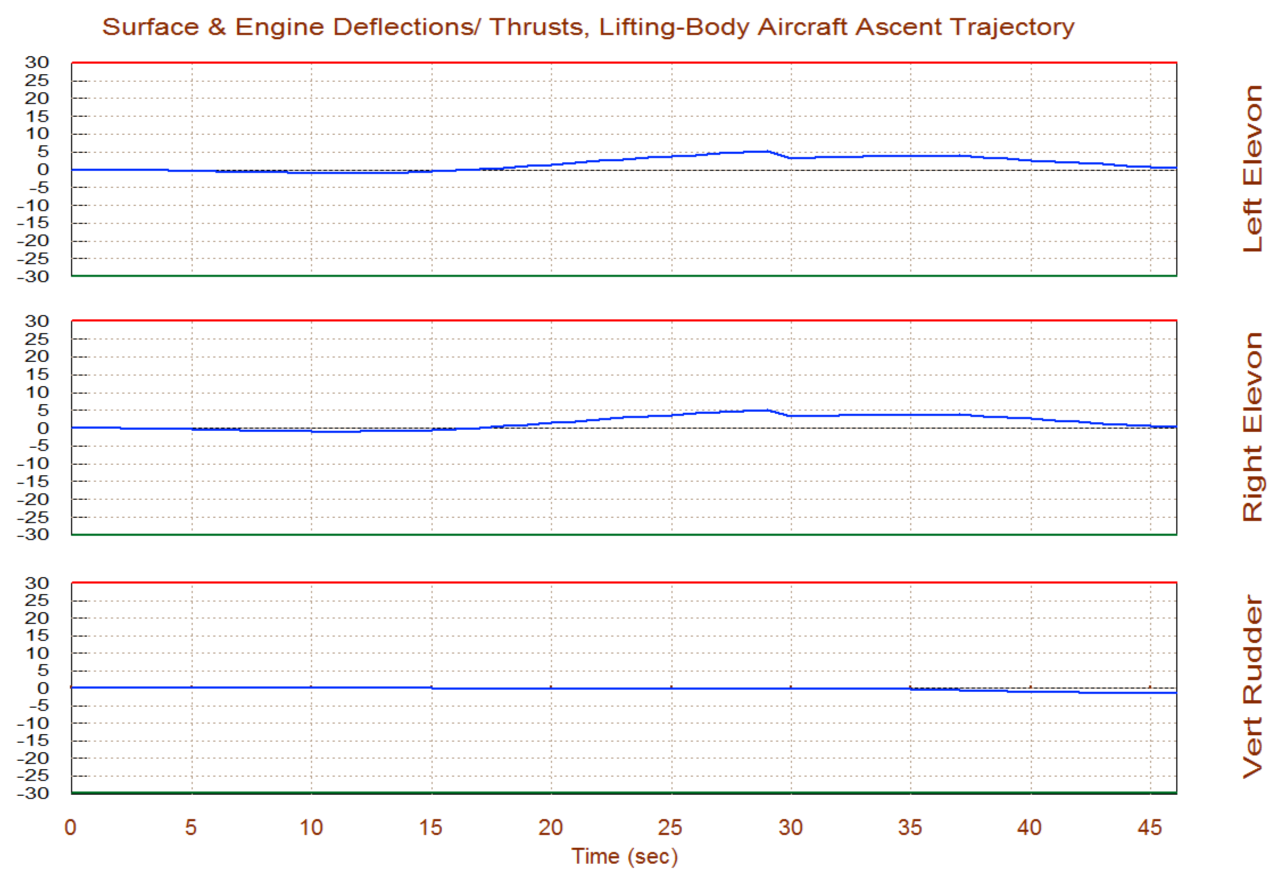
Residual Moments After Trimming (ft-lb) Lifting-Body Aircraft Ascent Trajectory

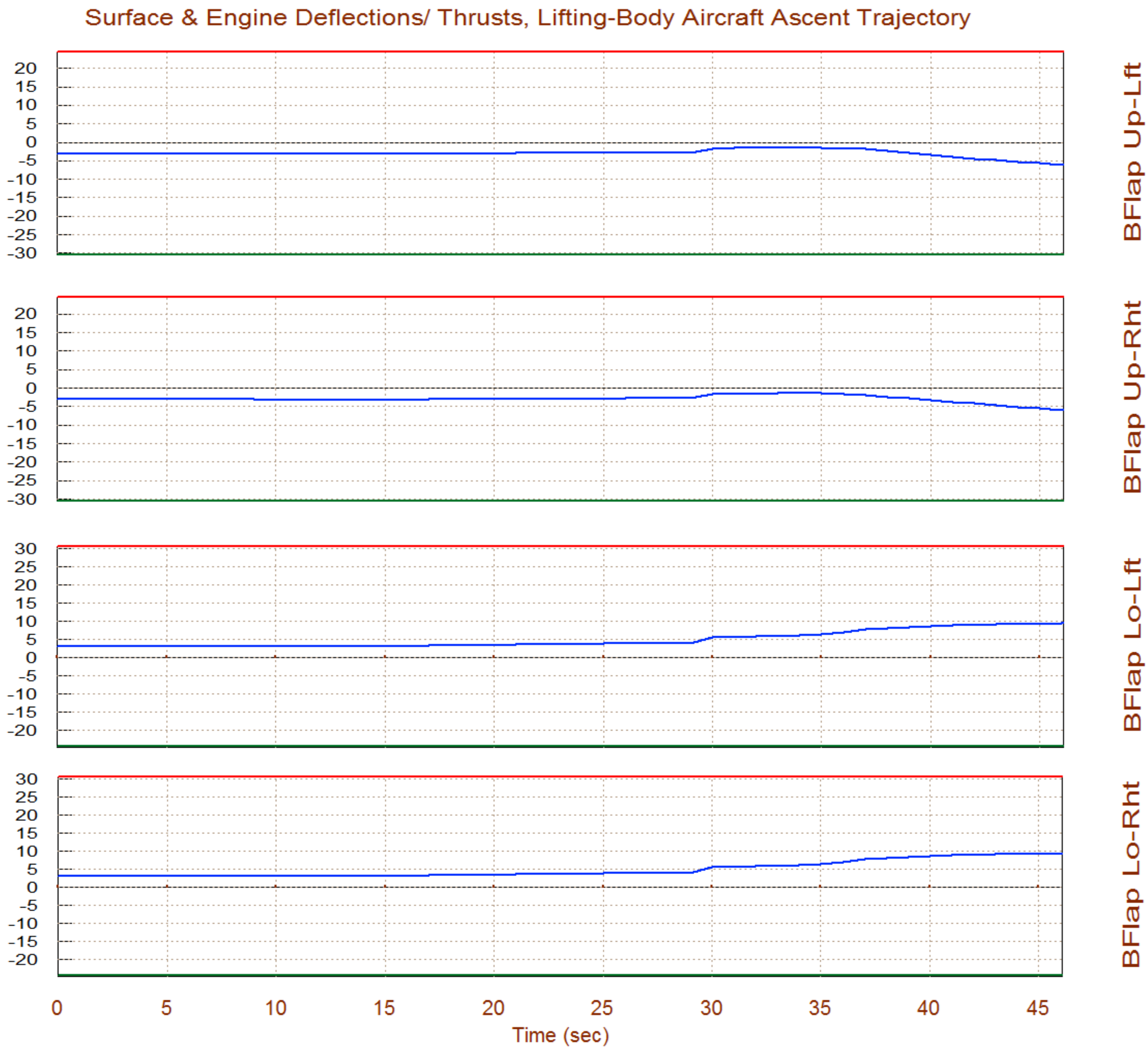


Surface & Engine Deflections/ Thrusts, Lifting-Body Aircraft Ascent Trajectory




Surface & Engine Deflections/ Thrusts, Lifting-Body Aircraft Ascent Trajectory
Dz_Engine 2
Throttle 1
Throttle 2
Time (sec)

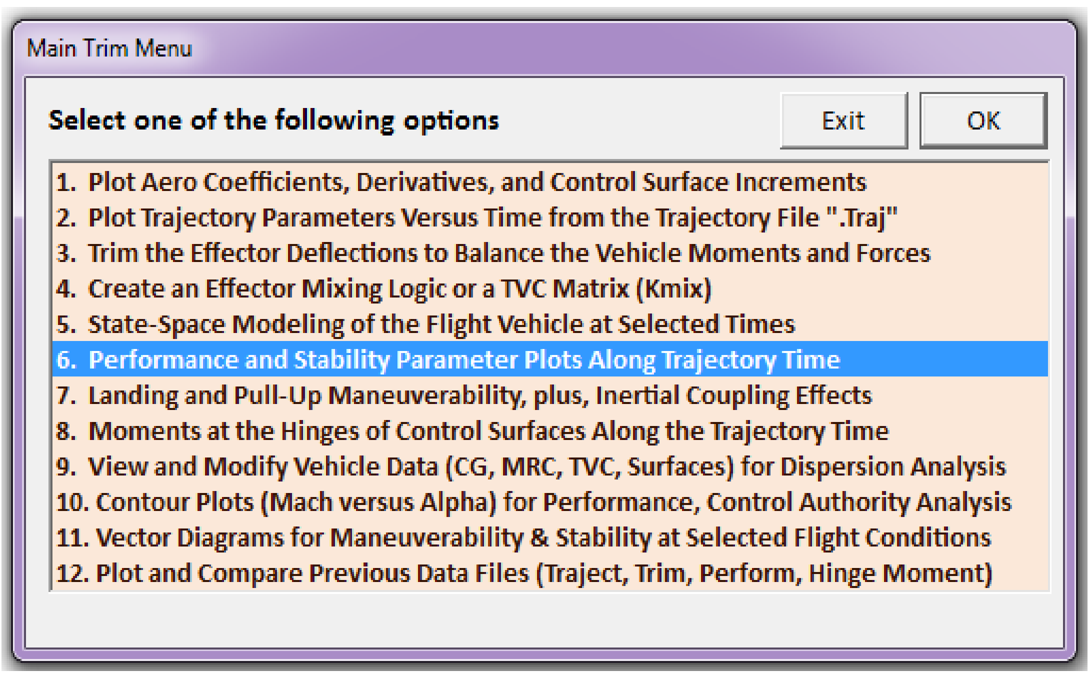

Surface & Engine Deflections/ Thrusts, Lifting-Body Aircraft Ascent Trajectory
Left Elevon
Right Elevon
Vert Rudder
Time (sec)

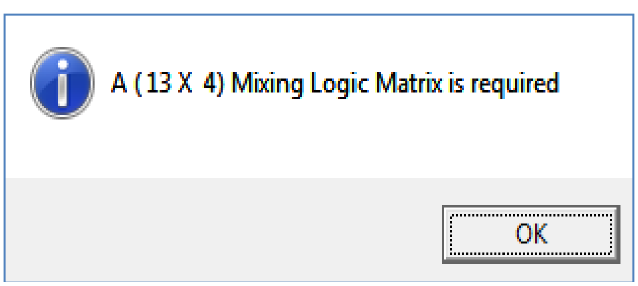


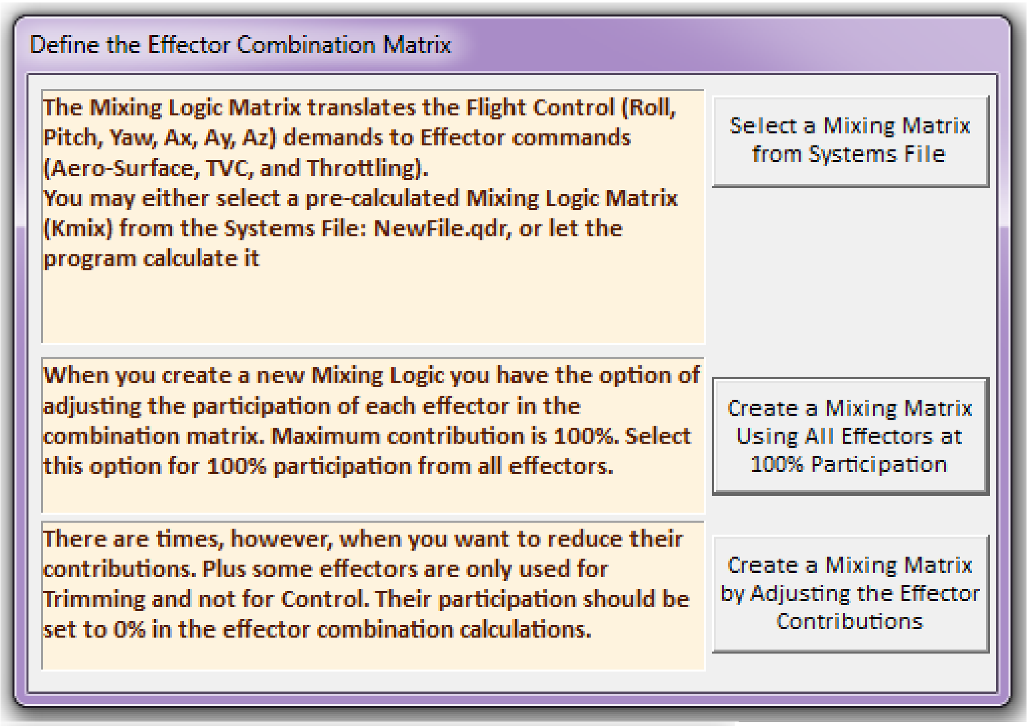
Notice also how the thrust of the two engines vary in order to match the vehicle acceleration in the x direction. The deflections of the four body-flaps also vary, as shown above. They initially trim at ±3° and their deflections increase slightly in magnitude as alpha increases and the engine thrusts are reduced. Because of physical limitations the upper body-flap deflections are always negative, and the lower body-flap deflections are always positive.

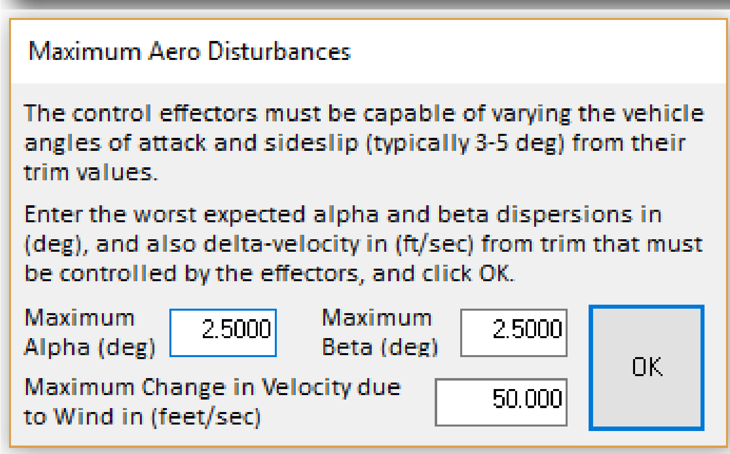
Performance Parameters along the Trajectory

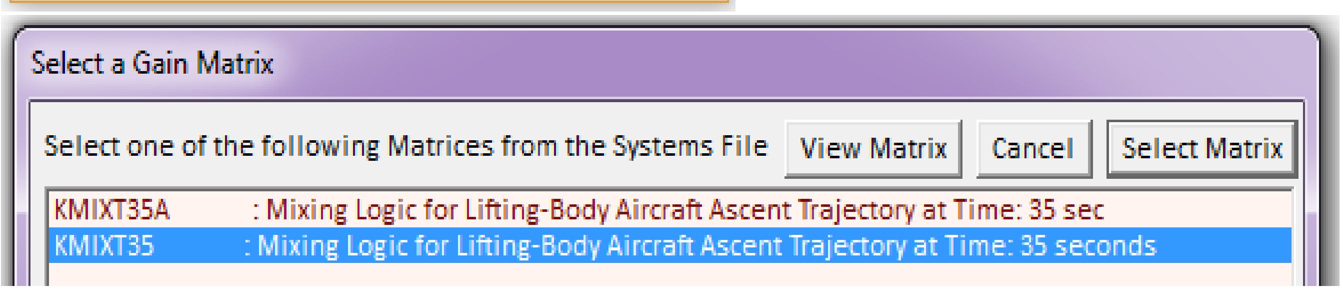
From the Trim main menu we select option (6) to analyze the static stability and performance parameters along the ascent trajectory. Those parameters provide a preliminary evaluation of the overall performance and they are described in detail in Section 3. This analysis, however, requires a (13x4) mixing-logic matrix to define how the 13 effectors are to be combined together to control roll, pitch, yaw, plus axial acceleration directions, and the control authority of the effector system strongly depends upon this matrix. The Flixan mixing-logic algorithm was used to create an effector combination matrix but it was modified to allow more rudder and yaw TVC deflections in order to improve the LCDP ratio at the expense of roll controllability. The matrix KmixT35 from file "Kmix.Qdr" is selected to combine the engines and aero-surfaces together, as shown. In the aero disturbances dialog you must enter the maximum variation of the velocity vector incidence angle relative to trim and also the maximum variation of the air-speed. These parameters define the magnitude of the wind disturbances and are required for the control authority calculations. The α_{max} and β_{max} dispersion angles are both set to 2.5° in this case and the air-speed variation due to wind is set to 50 (feet/sec).

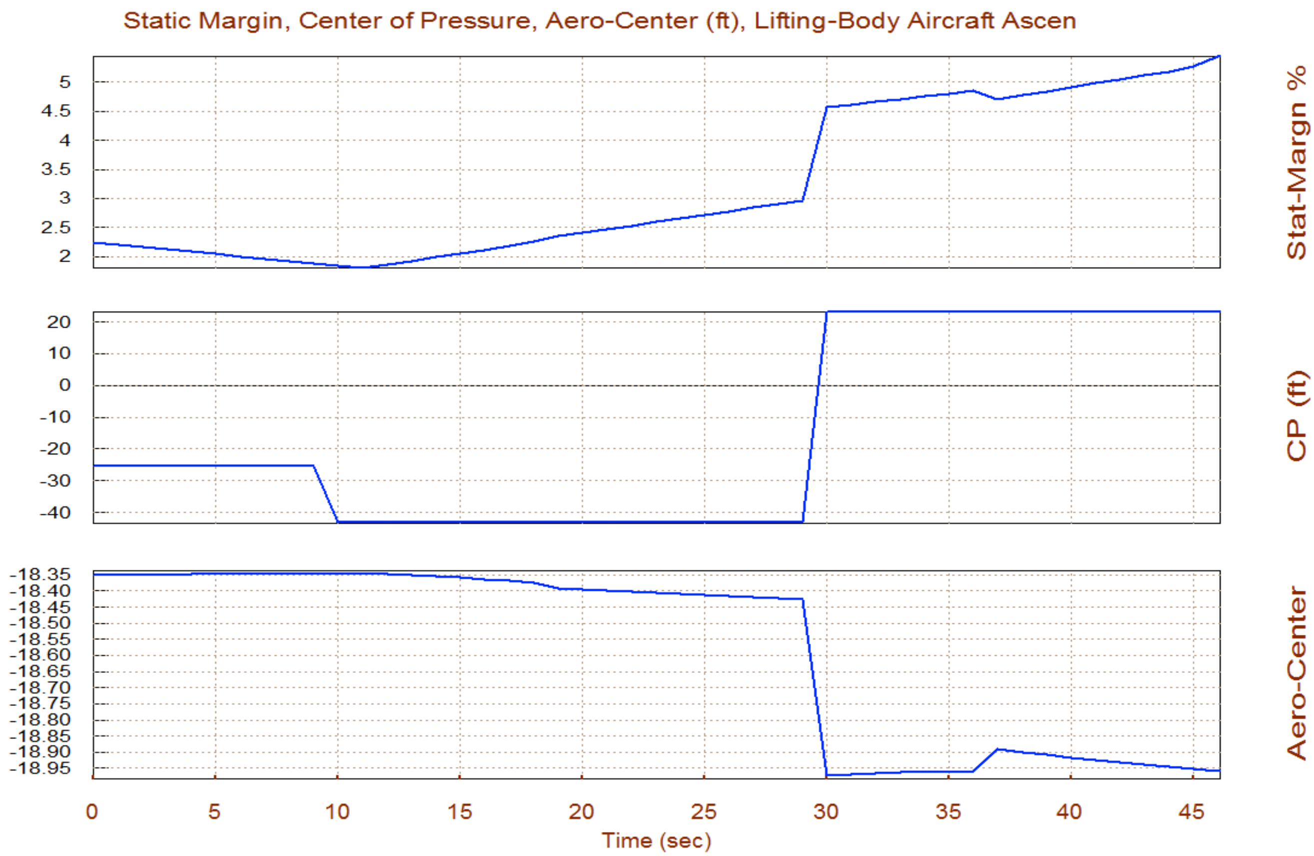


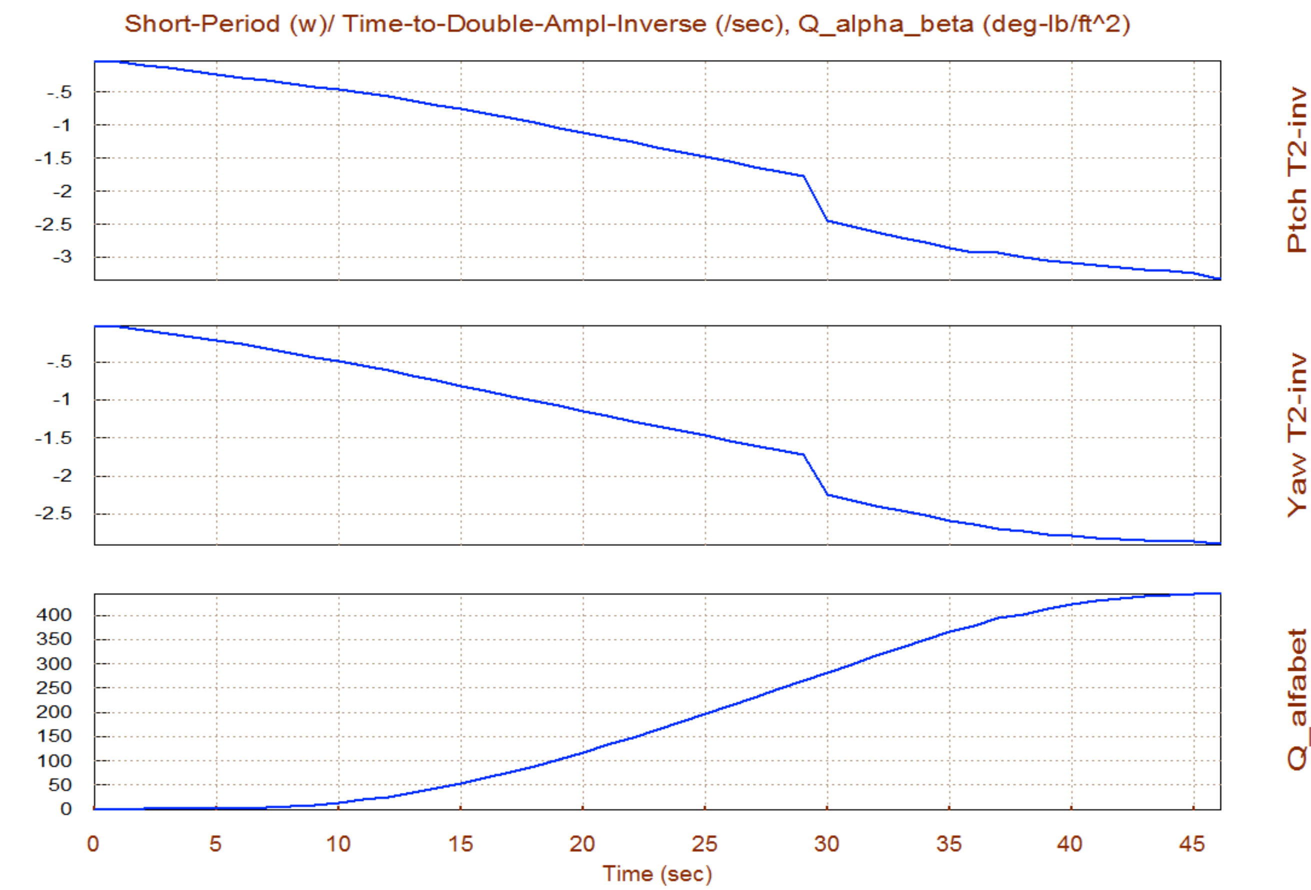


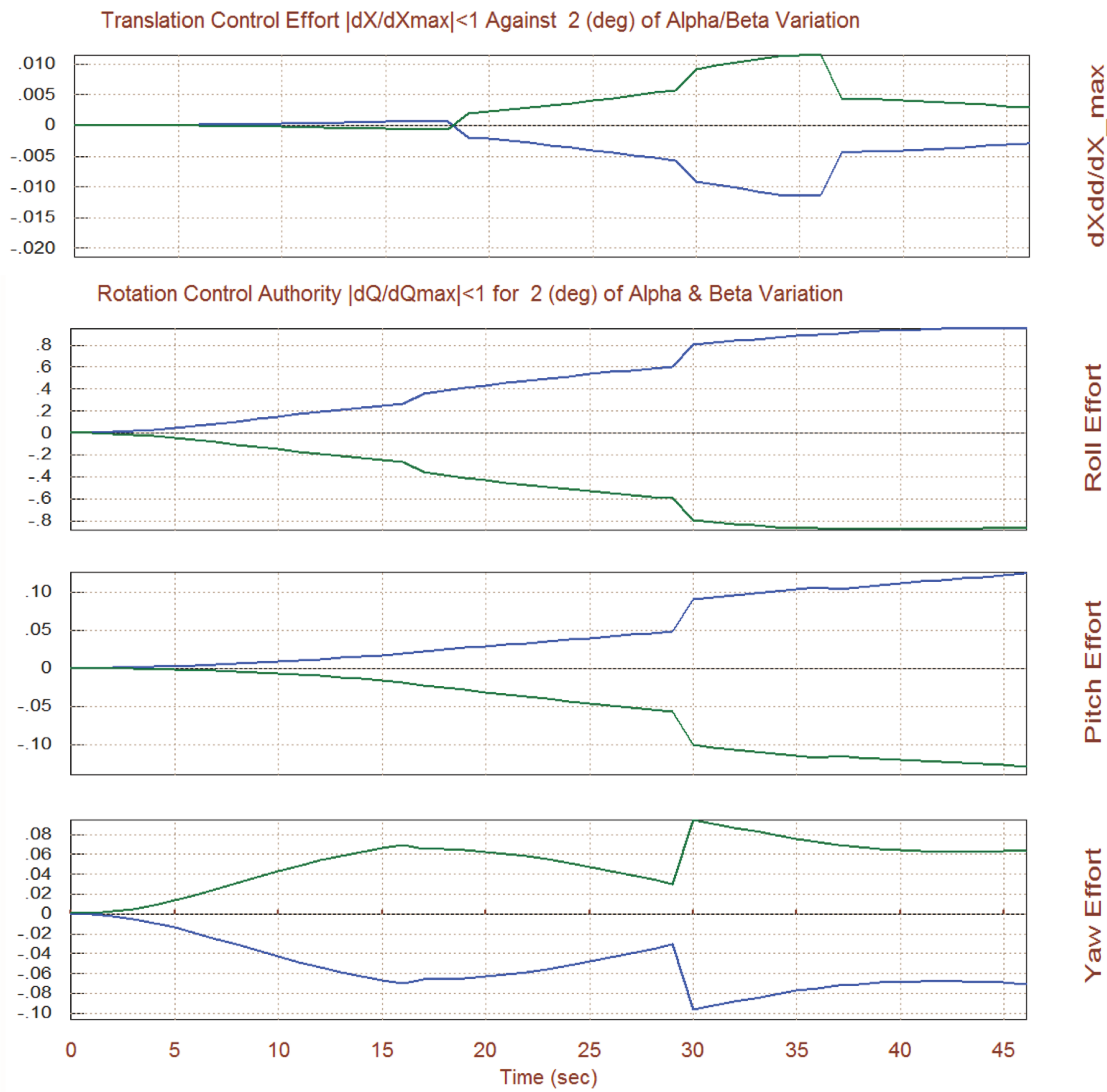

Define the Effector Combination Matrix
The Mixing Logic Matrix translates the Flight Control (Roll, Pitch, Yaw, Ax, Ay, Az) demands to Effector commands (Aero-Surface, TVC, and Throttling).
You may either select a pre-calculated Mixing Logic Matrix (Kmix) from the Systems File: NewFile.qdr, or let the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


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)
2.5000
Maximum Beta (deg)
2.5000
OK
Maximum Change in Velocity due to Wind in (feet/sec)
50.000

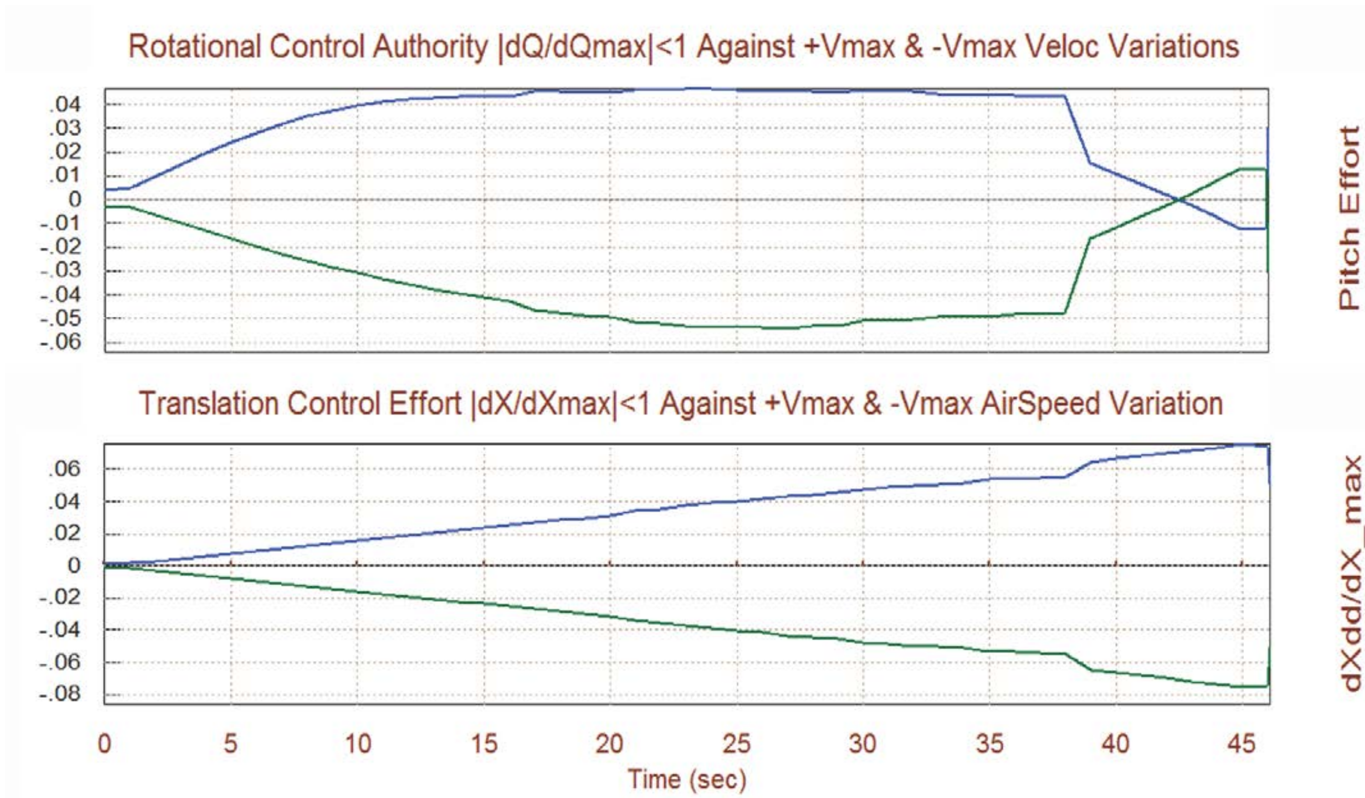

Select a Gain Matrix
Select one of the following Matrices from the Systems File
View Matrix
Cancel
Select Matrix
KMIXT35A : Mixing Logic for Lifting-Body Aircraft Ascent Trajectory at Time: 35 sec
KMIXT35 : Mixing Logic for Lifting-Body Aircraft Ascent Trajectory at Time: 35 seconds

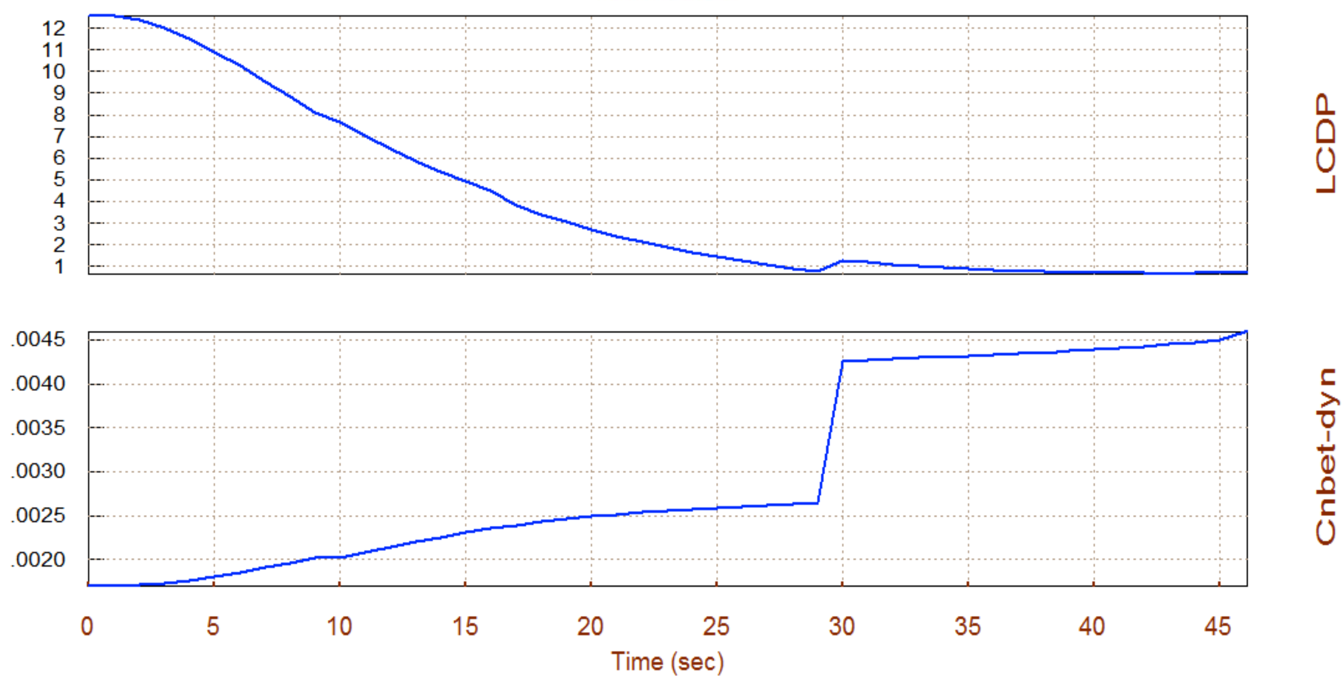

Static Margin, Center of Pressure, Aero-Center (ft), Lifting-Body Aircraft Ascen
Stat-Margn %
CP (ft)
Aero-Center
Time (sec)


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)

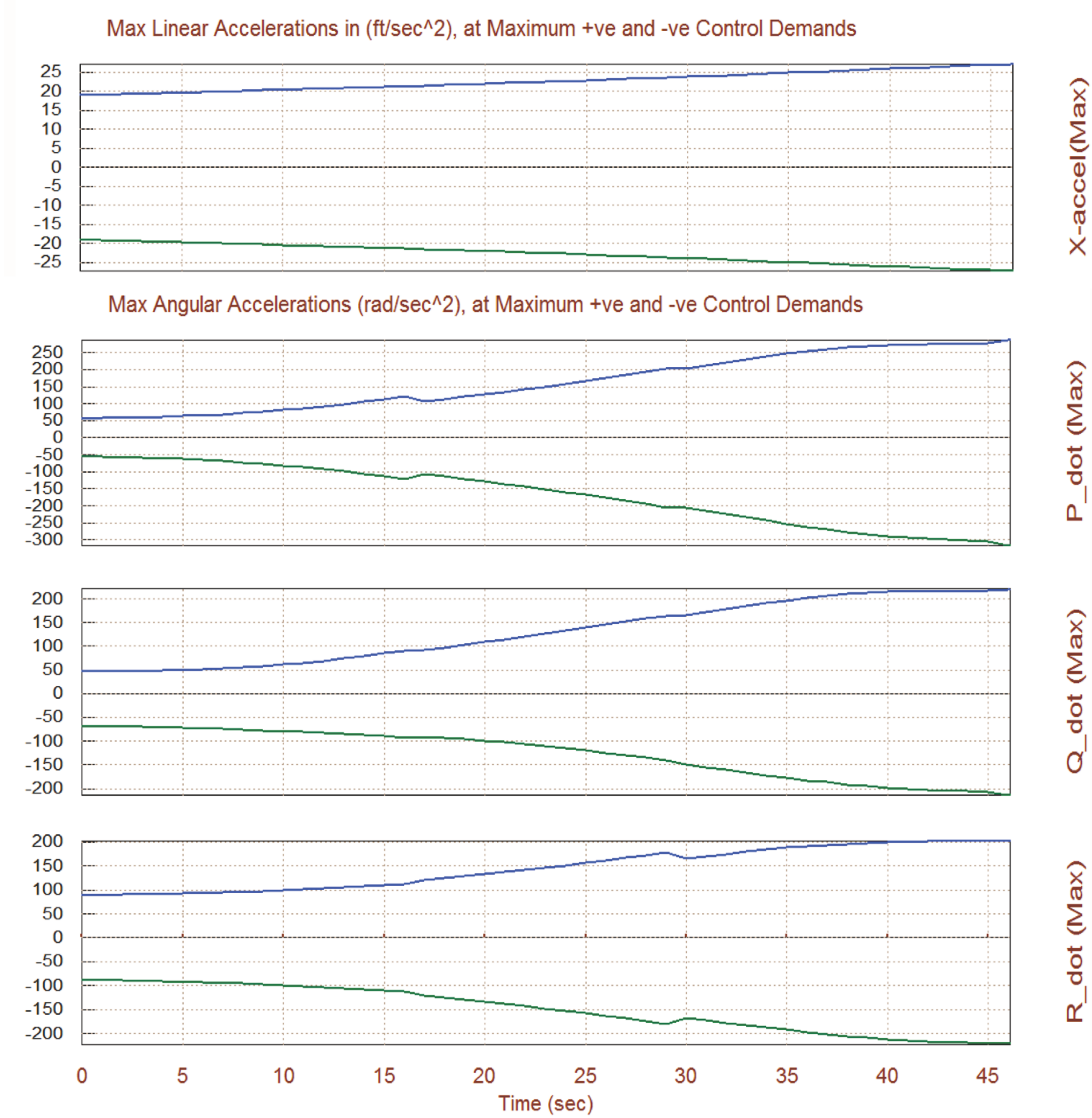


The stability results show that the vehicle is statically stable in both pitch and lateral directions with a static margin between 2% and 5.5%. The T2-inverse parameters are negative indicating that the short period resonances begin from zero at lift-off and reach 3.5 (rad/sec) in pitch and lateral. The Q-alpha, Q-beta loading reaches only 400 (psf-deg) because alpha is small during ascent. The control effort is very good in all directions except roll. Roll control authority becomes marginal towards the end of boost because the dynamic pressure and angle of attack increase enabling the dihedral to affect roll controllability. It means that the vehicle has plenty of control authority to counteract wind disturbances due to α_{max} and β_{max} angles in all directions except roll. This is not a problem, however, because during ascent the vehicle is not expected to maneuver in roll. There is also plenty of pitch and throttle control authority to counteract against air-speed variations.





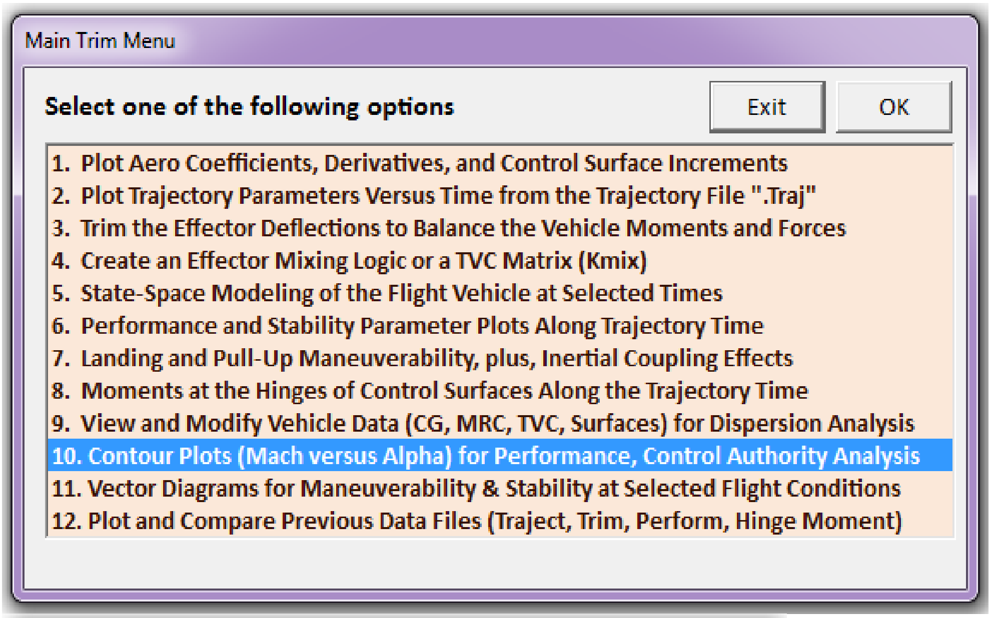
The Cnβ-dynamic is positive which means that the vehicle is directionally stable. The LCDP ratio was adjusted to vary between 12.5 at lift-off to 0.9 towards the end of boost. The adjustment was made in the mixing-logic matrix by allowing bigger rudder and yaw TVC contributions in roll to avoid very small LCDP magnitudes and sign reversals. The bank angle parameter (ϕ) is ignored because it is only applicable near landing.

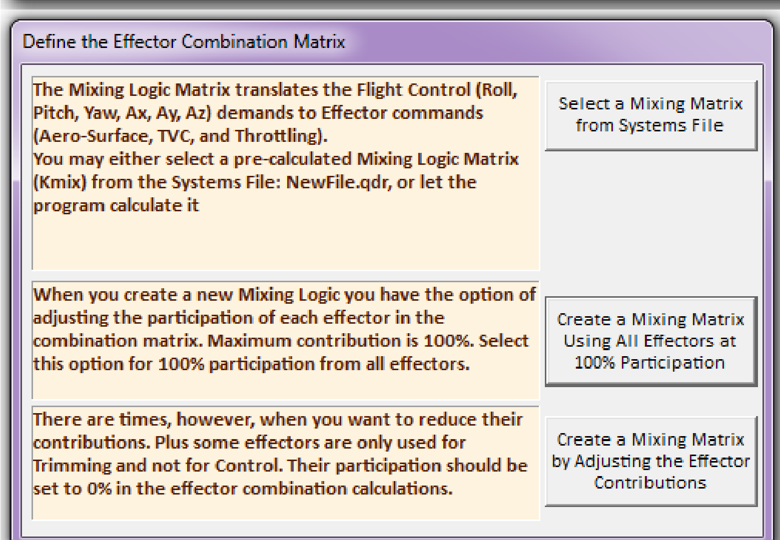


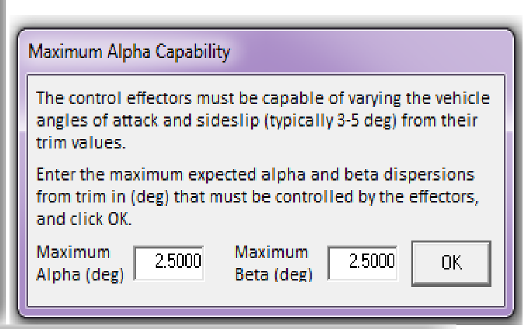
The last figure shows that the effectors system provides sufficient control acceleration in all four directions. The first one is translational x-acceleration in (feet/sec^2), and the last three are rotational in (deg/sec^2). The maximum acceleration capability increases with the dynamic pressure and also because the vehicle becomes lighter and more maneuverable, such as the x-acceleration by varying the thrust.

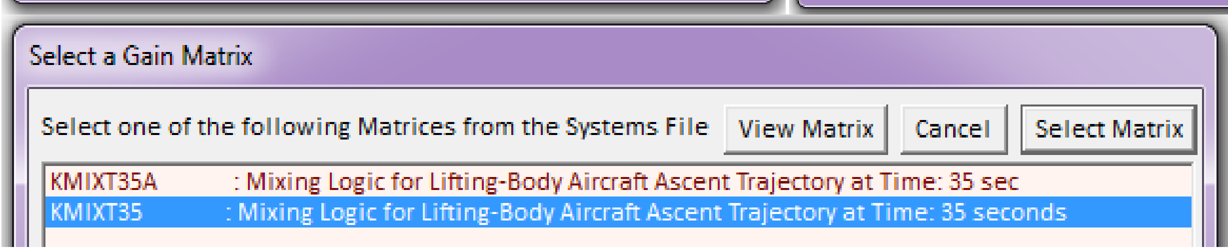
Contour Plots Analysis

Contour plots allow us to observe the state of some of the most important vehicle performance parameters over the entire Mach versus Alpha range. These parameters depend on the effector mixing-logic matrix so we must select again matrix KmixT35 from file "Kmix.Qdr". Contour plots are the 10th option that can be selected from the Trim main menu, as shown.

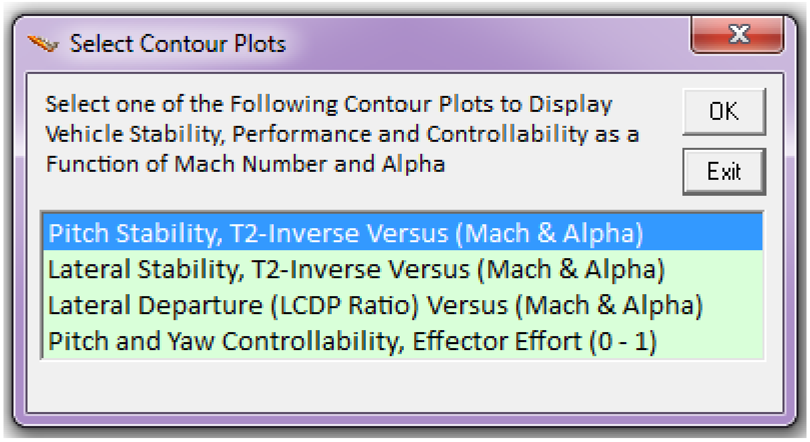








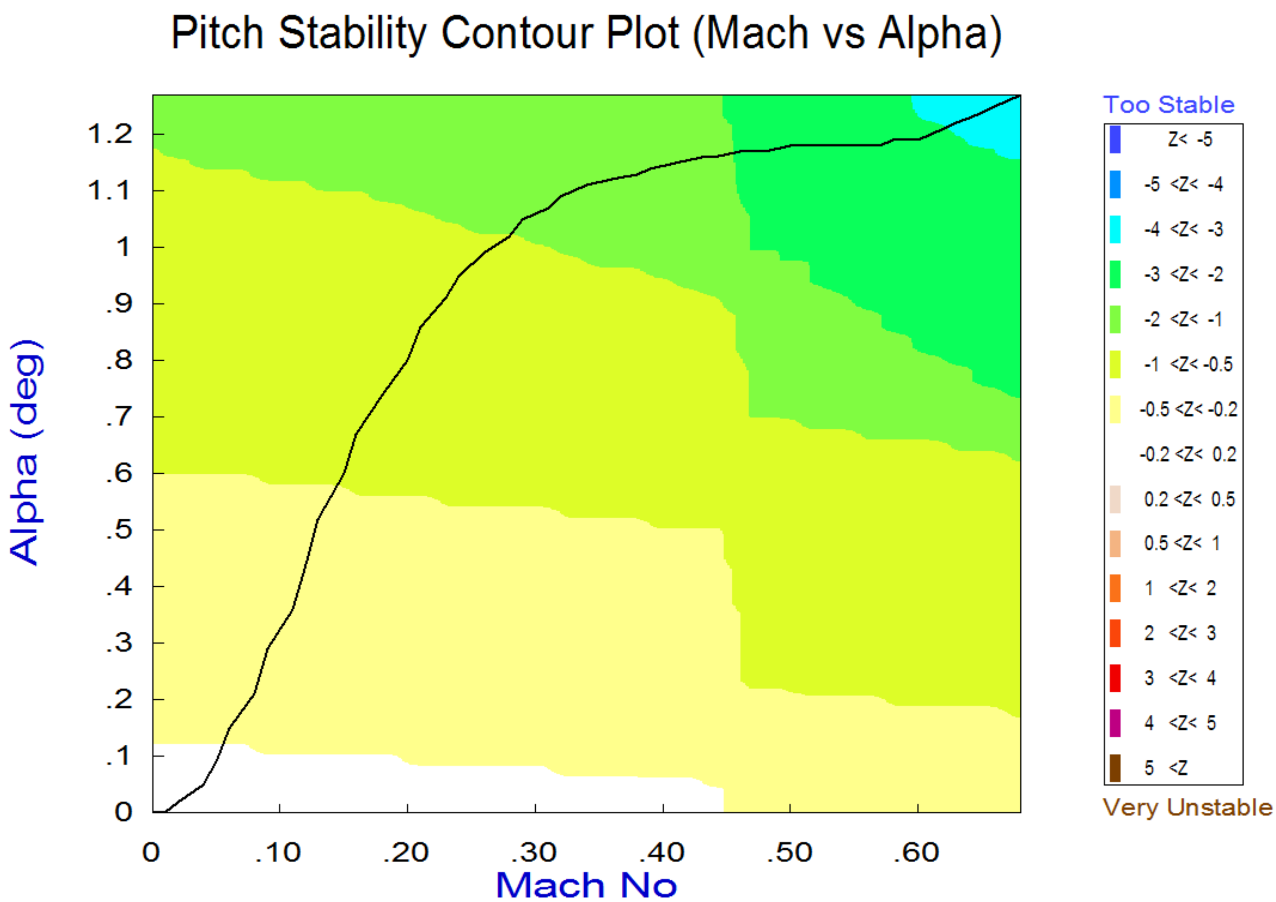
The following menu is used to select some of the performance parameters to be shown in contour plots.



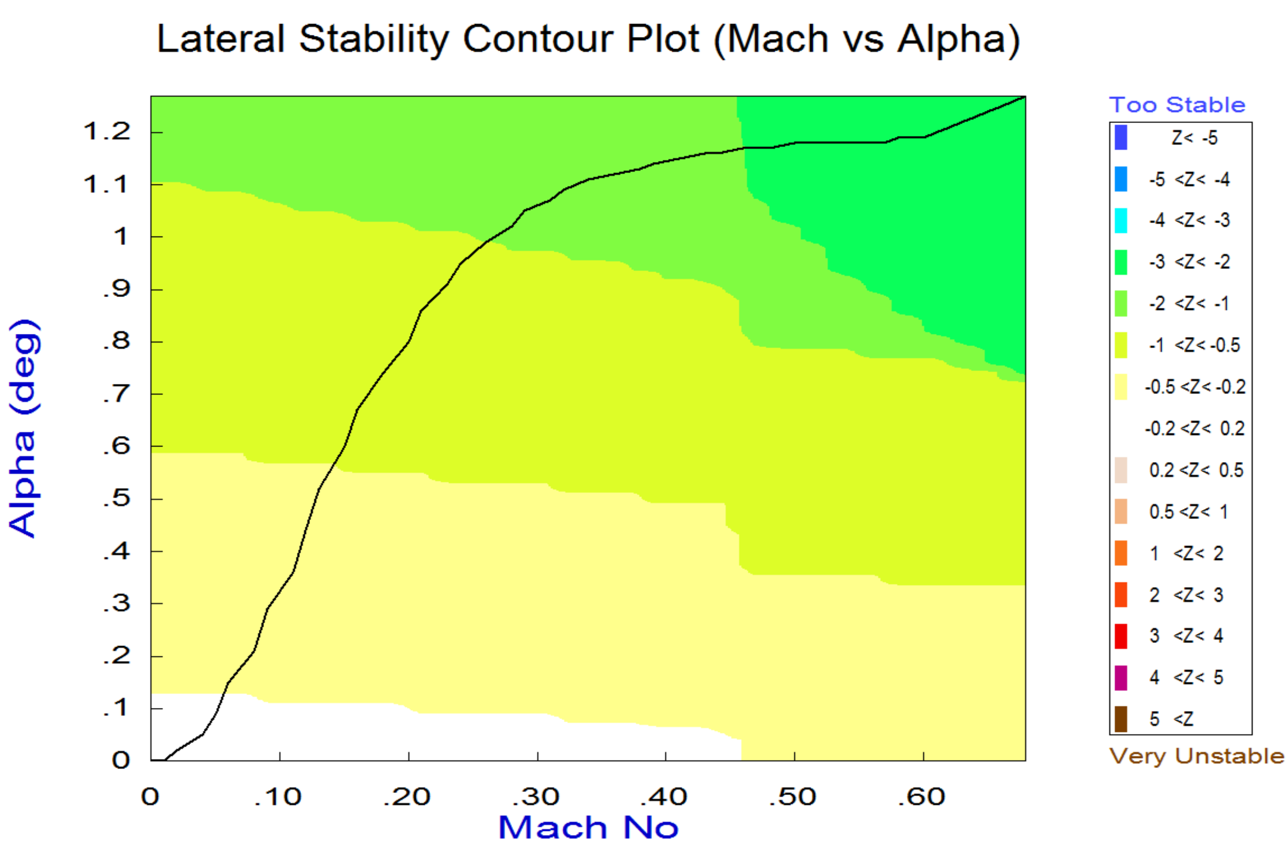
The first two contour plots are showing the pitch and lateral stability parameter in the entire Mach versus alpha range, and they are very similar. The trajectory is shown by the dark line beginning in the lower left-hand corner where both alpha and Mach are zero and ending up in the upper right-hand corner, where α=1.2° and Mach= 0.67. The vehicle is neutrally stable at lift-off and its stability progressively increases in both pitch and lateral as the dynamic pressure increases.

The LCDP ratio which is a measure of dynamic roll controllability was adjusted in the mixing-logic matrix to remain positive throughout the boost phase. In fact its value is close to 1 near the end of boost. This was achieved by trading-off some of the roll control authority which becomes marginal near the end of boost.

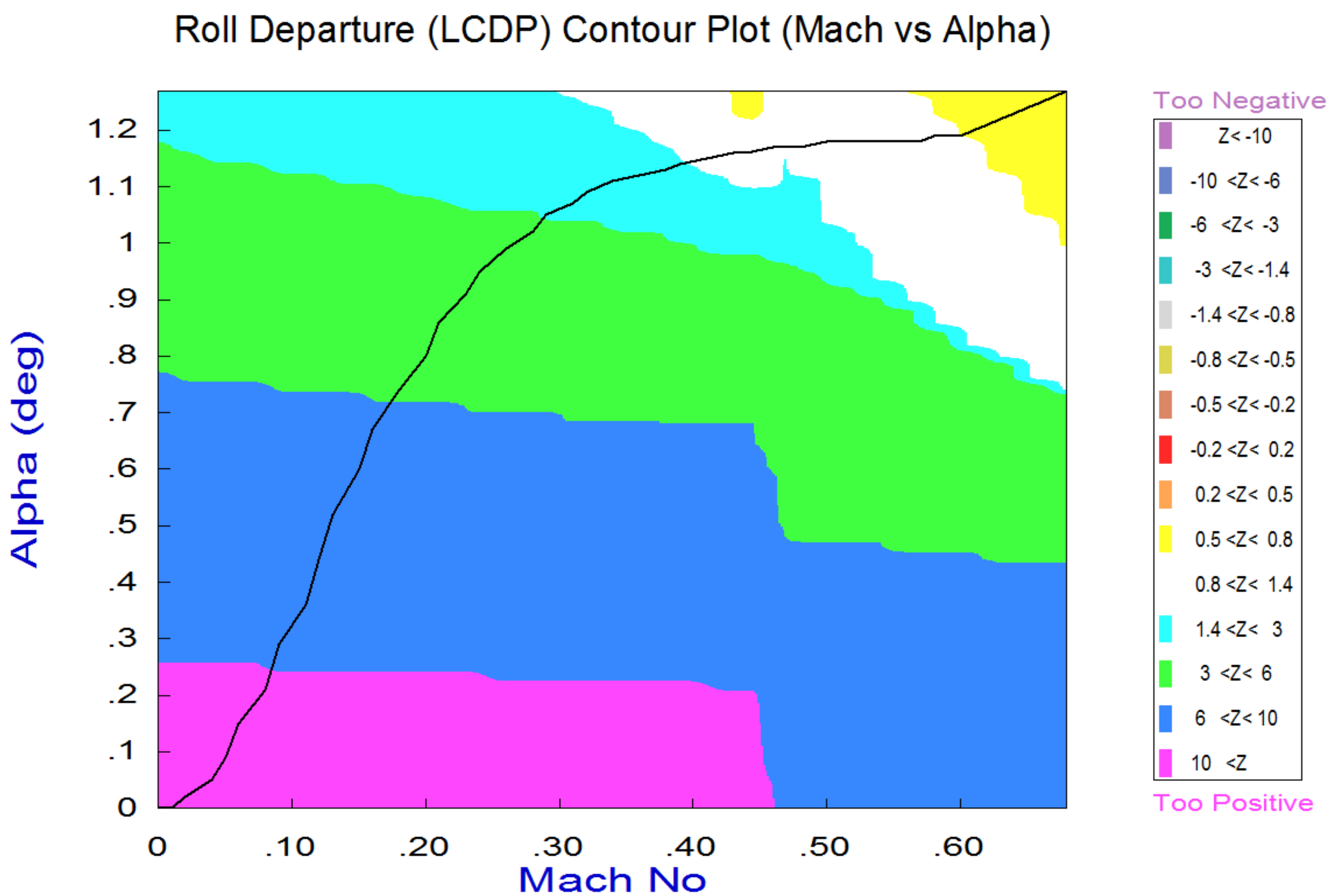
The control authority in pitch and yaw is very good in both directions because the magnitude of the control effort is much less than one. In this case the control effort is measured against 2.5° of (α_{max} and β_{max}) dispersions from nominal.

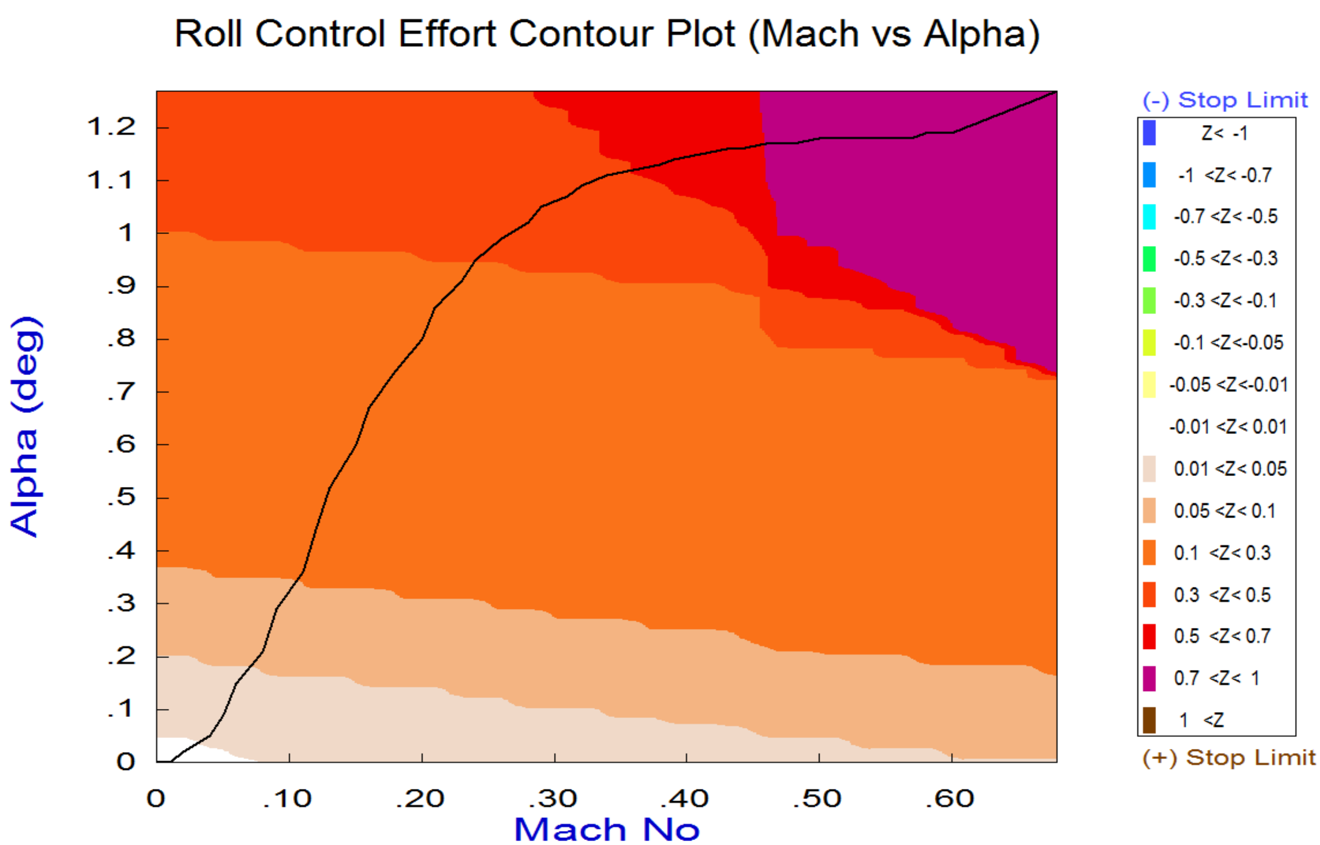


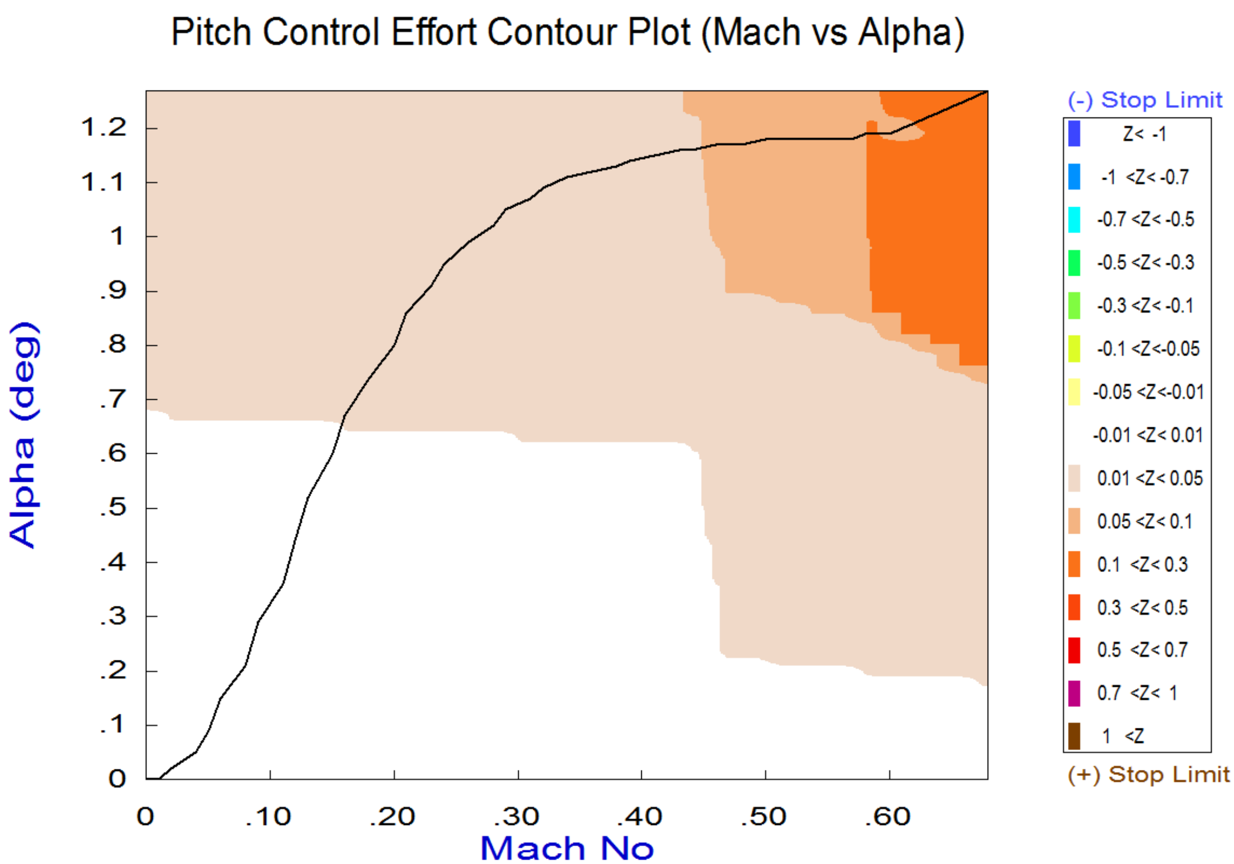
Pitch Stability Contour Plot (Mach vs Alpha)
Alpha (deg)
1.2
1.1
1
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
0
.10
.20
.30
.40
.50
.60
Mach No
Too Stable
Z< -5
-5 <Z< -4
-4 <Z< -3
-3 <Z< -2
-2 <Z< -1
-1 <Z< -0.5
-0.5 <Z< -0.2
-0.2 <Z< 0.2
0.2 <Z< 0.5
0.5 <Z< 1
1 <Z< 2
2 <Z< 3
3 <Z< 4
4 <Z< 5
5 <Z
Very Unstable

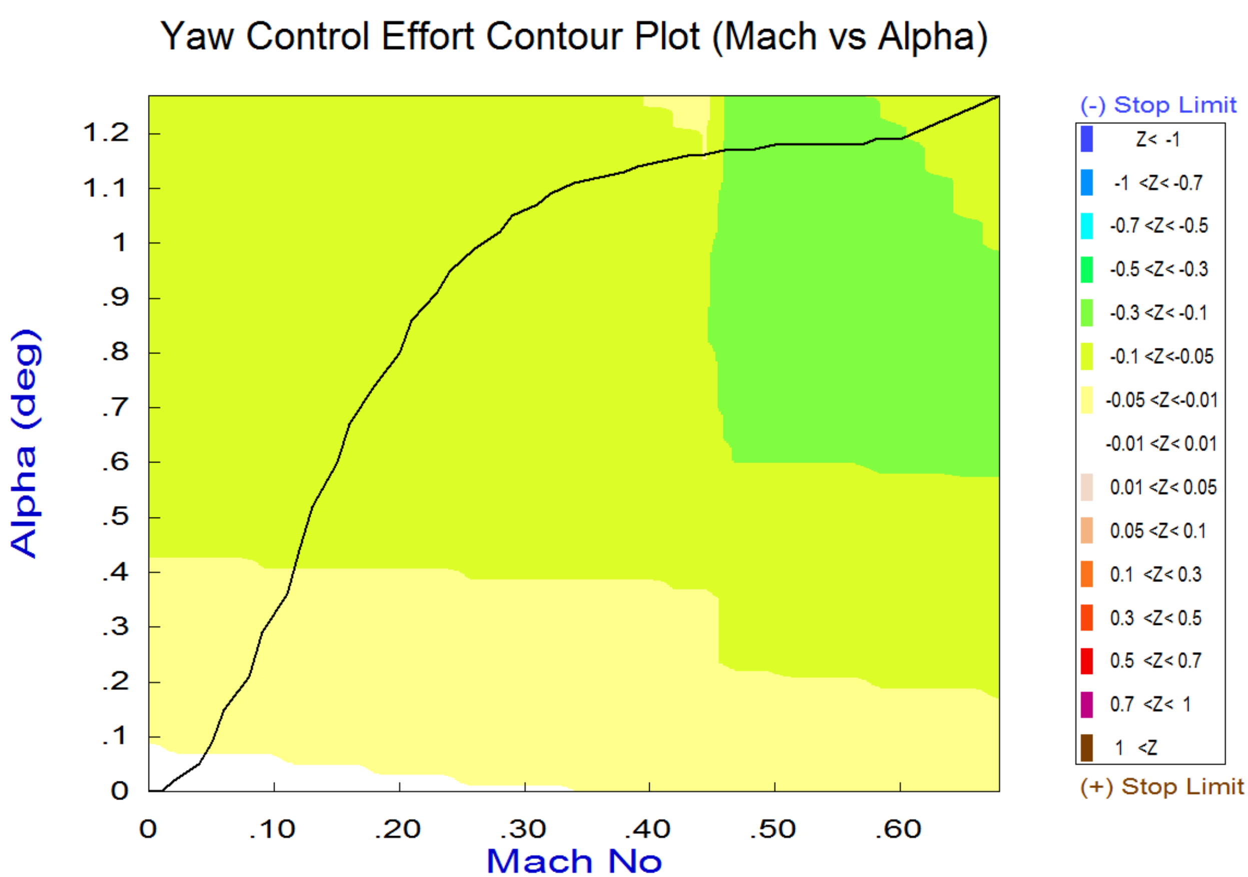


Lateral Stability Contour Plot (Mach vs Alpha)
Alpha (deg)
1.2
1.1
1
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
0
.10
.20
.30
.40
.50
.60
Mach No
Too Stable
Z< -5
-5 <Z< -4
-4 <Z< -3
-3 <Z< -2
-2 <Z< -1
-1 <Z< -0.5
-0.5 <Z< -0.2
-0.2 <Z< 0.2
0.2 <Z< 0.5
0.5 <Z< 1
1 <Z< 2
2 <Z< 3
3 <Z< 4
4 <Z< 5
5 <Z
Very Unstable


Roll Departure (LCDP) Contour Plot (Mach vs Alpha)
Alpha (deg)
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1
1.1
1.2
Mach No
0
.10
.20
.30
.40
.50
.60
Too Negative
Z< -10
-10 <Z< -6
-6 <Z< -3
-3 <Z< -1.4
-1.4 <Z< -0.8
-0.8 <Z< -0.5
-0.5 <Z< -0.2
-0.2 <Z< 0.2
0.2 <Z< 0.5
0.5 <Z< 0.8
0.8 <Z< 1.4
1.4 <Z< 3
3 <Z< 6
6 <Z< 10
10 <Z
Too Positive

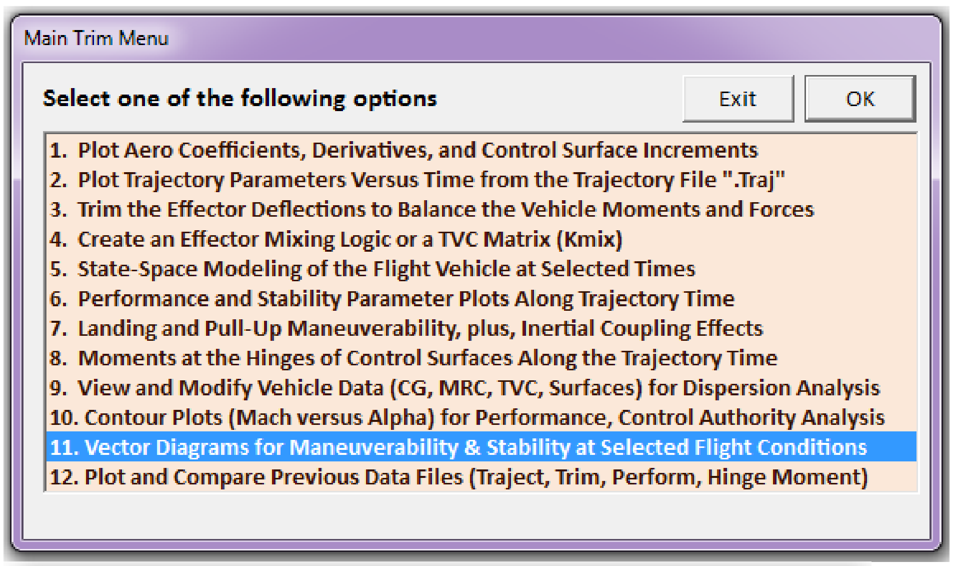

Roll Control Effort Contour Plot (Mach vs Alpha)
Alpha (deg)
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1
1.1
1.2
Mach No
0
.10
.20
.30
.40
.50
.60
(-) Stop Limit
Z< -1
-1 <Z< -0.7
-0.7 <Z< -0.5
-0.5 <Z< -0.3
-0.3 <Z< -0.1
-0.1 <Z<-0.05
-0.05 <Z<-0.01
-0.01 <Z< 0.01
0.01 <Z< 0.05
0.05 <Z< 0.1
0.1 <Z< 0.3
0.3 <Z< 0.5
0.5 <Z< 0.7
0.7 <Z< 1
1 <Z
(+) Stop Limit

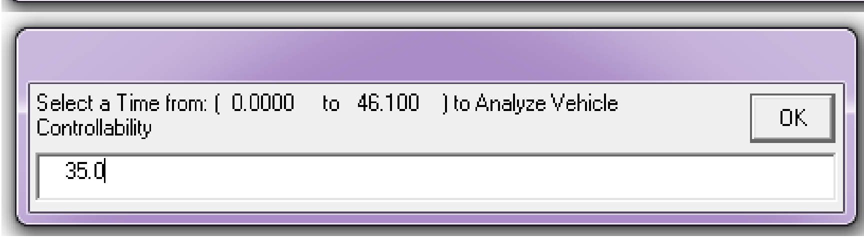

Pitch Control Effort Contour Plot (Mach vs Alpha)
Alpha (deg)
1.2
1.1
1
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
0
.10
.20
.30
.40
.50
.60
Mach No
(-) Stop Limit
Z< -1
-1 <Z< -0.7
-0.7 <Z< -0.5
-0.5 <Z< -0.3
-0.3 <Z< -0.1
-0.1 <Z<-0.05
-0.05 <Z<-0.01
-0.01 <Z< 0.01
0.01 <Z< 0.05
0.05 <Z< 0.1
0.1 <Z< 0.3
0.3 <Z< 0.5
0.5 <Z< 0.7
0.7 <Z< 1
1 <Z
(+) Stop Limit


Yaw Control Effort Contour Plot (Mach vs Alpha)
Alpha (deg)
1.2
1.1
1
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
0
.10
.20
.30
.40
.50
.60
Mach No
(-) Stop Limit
Z< -1
-1 <Z< -0.7
-0.7 <Z< -0.5
-0.5 <Z< -0.3
-0.3 <Z< -0.1
-0.1 <Z<-0.05
-0.05 <Z<-0.01
-0.01 <Z< 0.01
0.01 <Z< 0.05
0.05 <Z< 0.1
0.1 <Z< 0.3
0.3 <Z< 0.5
0.5 <Z< 0.7
0.7 <Z< 1
1 <Z
(+) Stop Limit

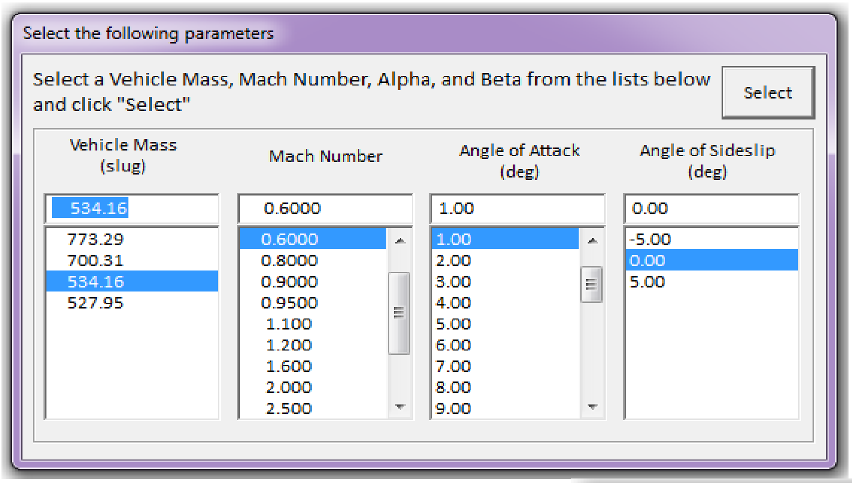
Controllability Analysis Using Vector Diagrams

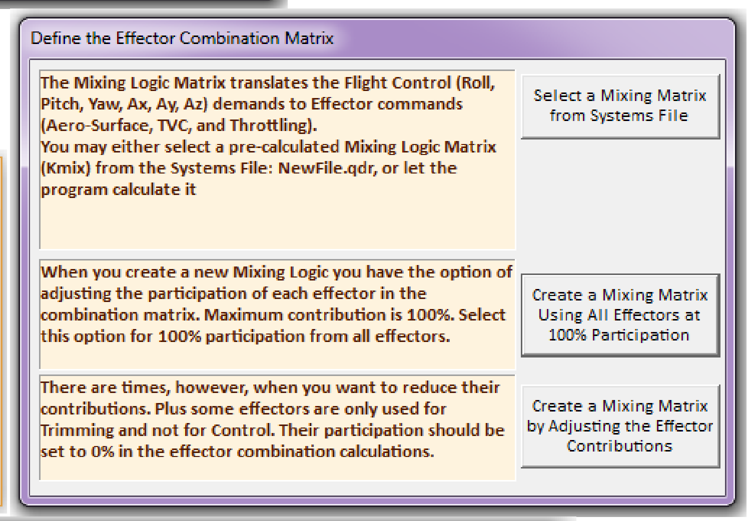
Vector diagrams are 2-dimensional diagrams used for analyzing the vehicle controllability at a steady flight condition. Each vector diagram compares the control capability of the effectors as a system in two directions against the effect of the wind-shear disturbance due to alpha and beta dispersions in the same two directions, and determine if the effectors provides enough control authority to counteract against the disturbance moments and forces. It allows us to examine the directions of the controls against the disturbance directions. It also helps evaluate the orthogonality of the control system, compare the acceleration magnitudes due to controls and winds, and to determine if the controls are more powerful and their corresponding directions capable of counteracting the disturbance effects along the controlled directions, which in this case they are four: roll, pitch, yaw and axial acceleration. From the Trim menu select option (11), and then an arbitrary flight condition within the range of the trajectory, let's say at t=35 sec.

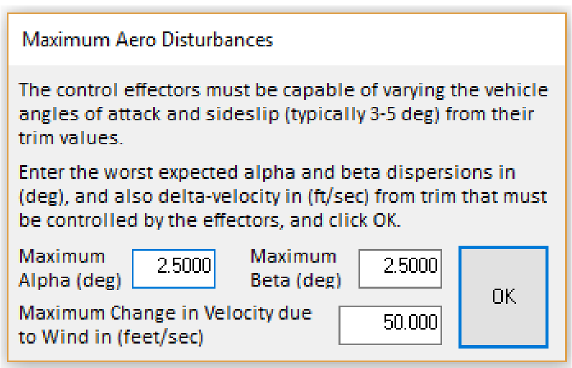


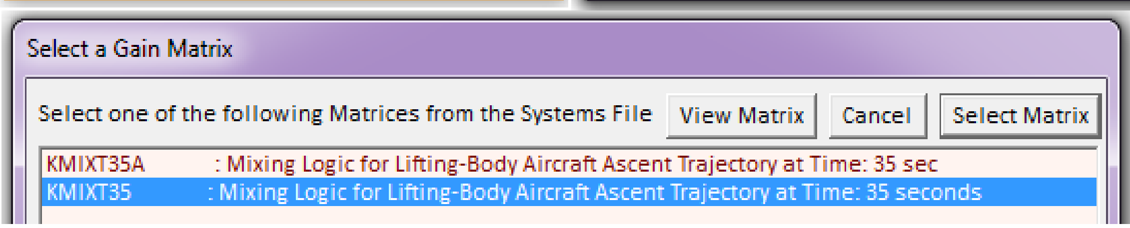


The following dialog consists of menus used for selecting the vehicle mass, Mach number, alpha, and beta. Keep the default values which correspond to the selected flight condition and click "*Select*". Notice that Mass=534, Mach 0.6, and α=1° are the nearest values to the selected time. The disturbances are caused by wind-shear defined by the maximum α_{max} and β_{max} variations from trim. In the following dialog enter the maximum disturbance angles (α_{max} and β_{max})=2.5°, and then select the (13x4) effector combination matrix "KmixT35" from file Kmix.Qdr, as shown.









The vector diagrams in figure 2.1.1 show the roll/ yaw moments and side-force, non-dimensional (C_l, C_n, C_Y), produced when the roll and yaw FCS demands are maximized to the effectors limits. The solid blue vector corresponds to max positive yaw FCS demand $\delta R_{+FCSMax}$ and the dashed blue vector to max negative yaw demand $\delta R_{-FCSMax}$. The effect is mostly in the demanded yaw direction but it also couples into roll. Similarly, the green vectors are due to the maximum roll demands $\delta P\pm_{FCSMax}$ and they are mainly in the intended direction. The green vector below shows the effect that the yaw FCS demand $\delta R\pm_{FCSMax}$ has in yaw and also in side-force. Positive yaw produces negative side-force, as expected. 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. The disturbance in this case is mainly in roll due to β variations, $+\beta_{max}$ generates a negative rolling moment because the vehicle has significant amount of dihedral effect. It also produces a negative side-force. The red rectangles at the tips of the red arrows show the moments and side-force uncertainty in this flight condition. The rectangles at the tips of the control vectors represent the control uncertainties. The uncertainties are obtained from file "*LiftBody.Unce*".

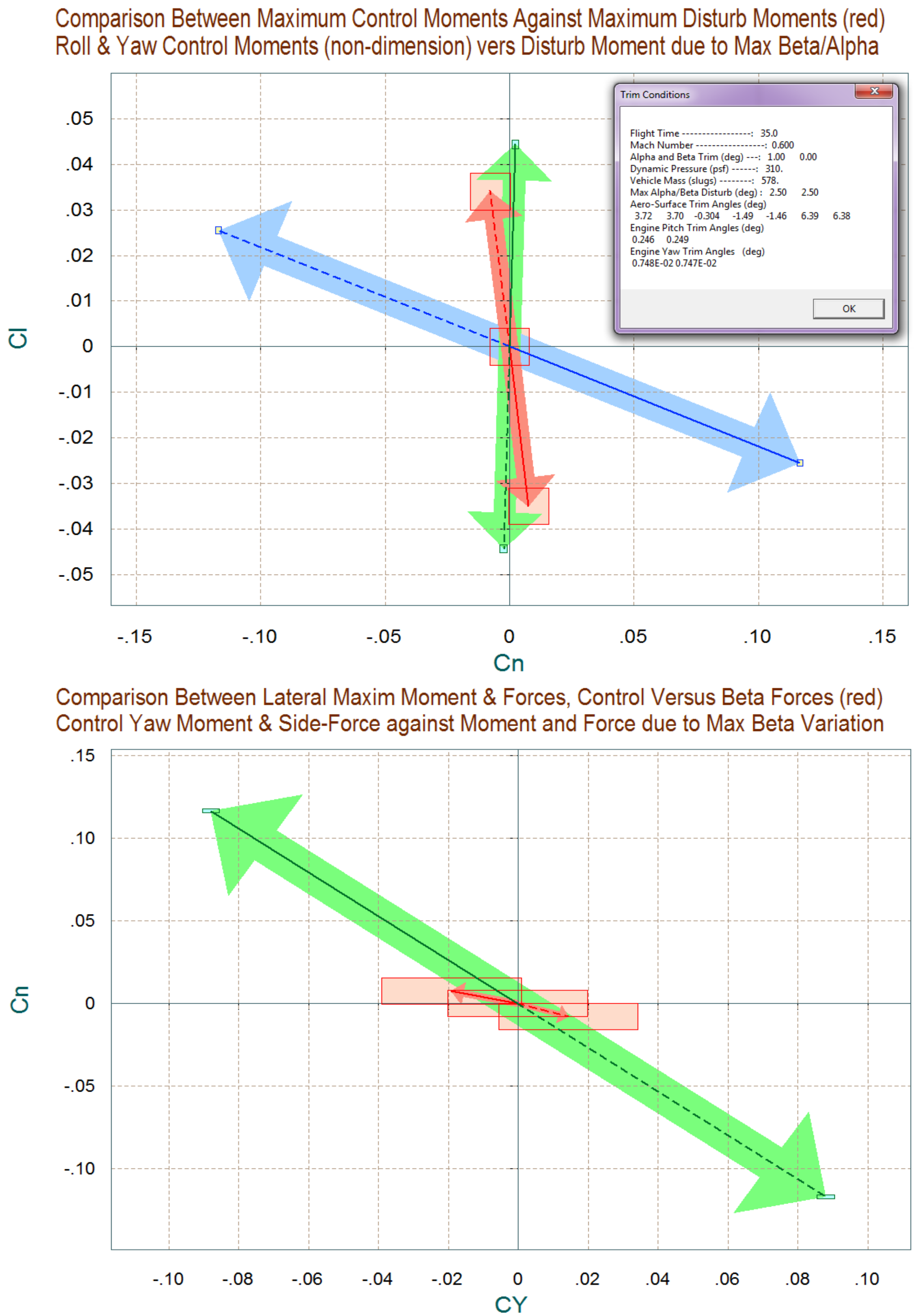
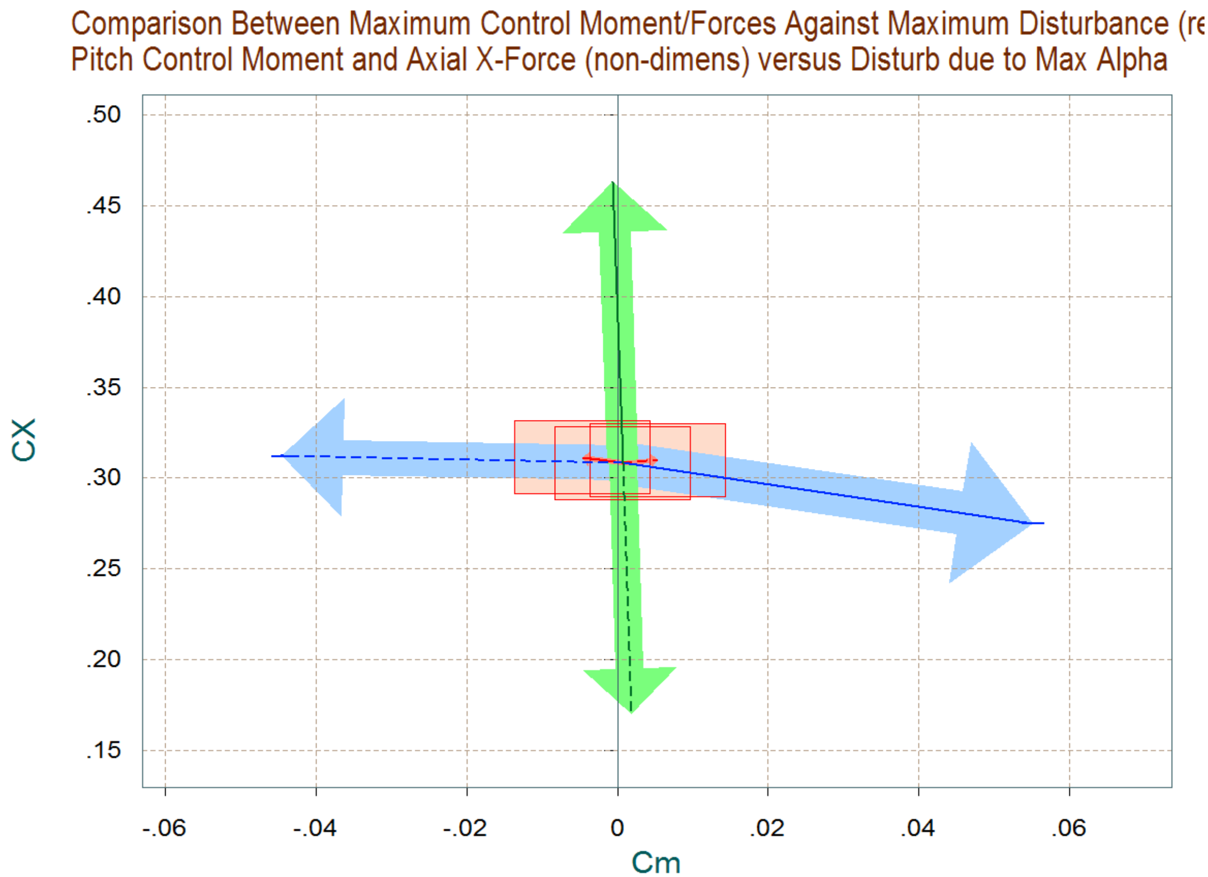


Figure 2.1.1 Maximum Roll and Yaw Moments and Side-Force produced due to $\pm\beta_{max}$ and Controls

The next two plots in figure (2.1.2) analyze controllability in the longitudinal directions when the pitch and axial acceleration control demands are maximized. The control system during ascent in addition to pitch control it can also vary the thrust of the two engines in order to adjust its acceleration. The flight control system produces two longitudinal demands, pitch (δQ_{FCS}) and axial (δX_{FCS}) accelerations. The actual effector deflections and thrust variations are determined by the mixing-logic matrix. The figures show the pitch moment Cm plotted against the forces CZ and CX. The blue vectors show the maximum pitch moment and forces produced when the pitch control demand is maximized. The solid blue vector is due to max positive demand $\delta Q_{+FCSMax}$, and the dashed blue vector is due to max negative demand $\delta Q_{-FCSMax}$. The pitch control, in addition to producing the required pitching moment, it also generates force variations in both x and z directions, mainly due to the TVC deflections. Unlike the lateral directions, the vectors here are not symmetrical because the pitch moment and z-force variation produced by a max positive control demand $\delta Q_{+FCSMax}$ is larger than the moment and force produced by a max negative demand.

The vehicle is trimmed in pitch because Cm=0 when the control $\delta Q_{FCS}=0$. It is, however, accelerating in +x and in -z directions because CX>0 and CZ<0 when $\delta Q_{FCS}=0$. The +x acceleration is due to the engine firing at nominal thrust, and the -z acceleration is because the engines are trimmed with positive deflections $\delta_e=+0.25°$. A +pitch control demand decreases the CX force and increases the CZ force because the gimbal deflections are negative pointing the thrust towards +z. The green vectors show the effects of the axial acceleration control by throttling the engines on the axial force C_X and the pitch moment Cm. The effect is mainly in the x-force direction CX which has a nominal value of 0.31 when the vehicle thrust is nominal. It can be varied between 0.17 and 0.46 by the ±40% thrust variation that is provided by the throttle control system. The red vectors show the pitch moment, axial and z forces generated by the variations in the angles of attack and sideslip (α_{max} and β_{max})=±2.5° from their trim positions. The disturbance in this case is mainly due to the $\pm\alpha_{max}$ variations. A positive α_{max} generates a negative pitching moment because the vehicle is stable in this flight condition. It also produces a negative z-force, because, an increase in α makes the z-force more negative (up). The rectangles show the possible variations of the vectors due to the uncertainties in the aero-coefficients.



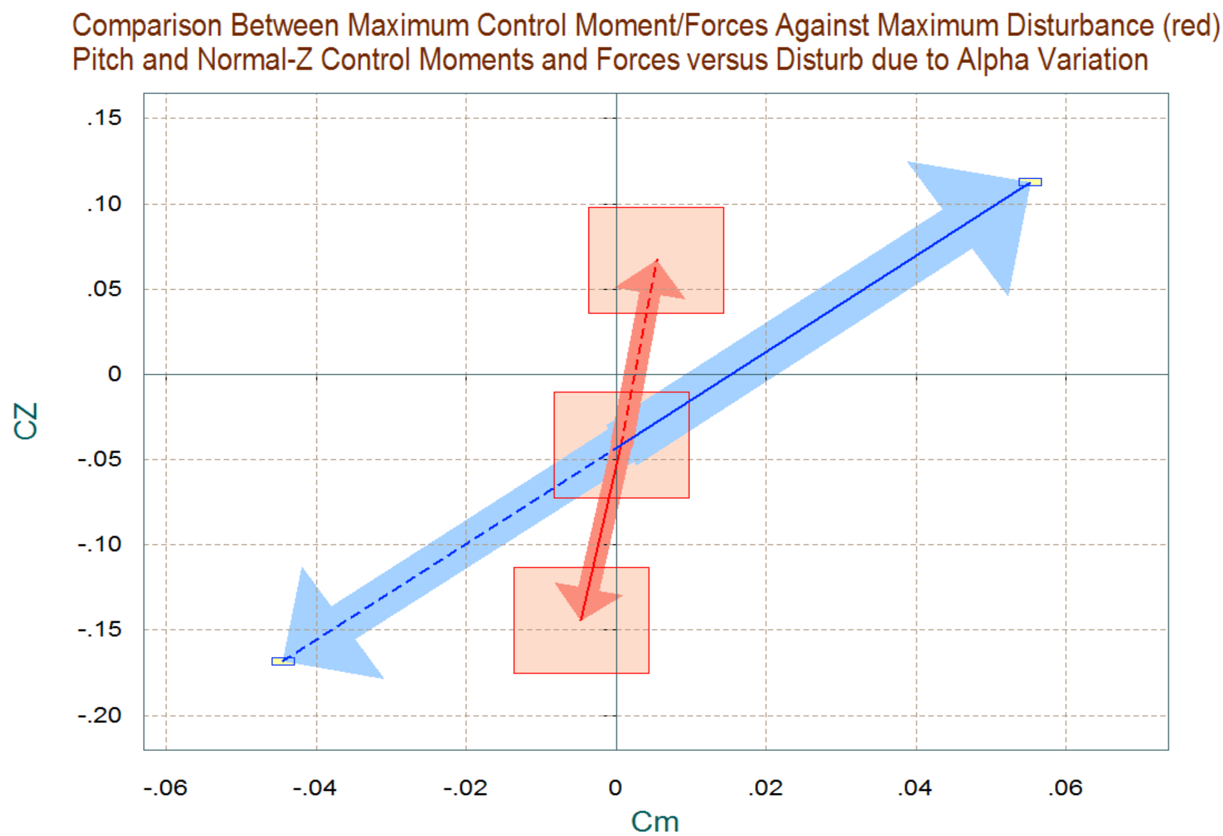
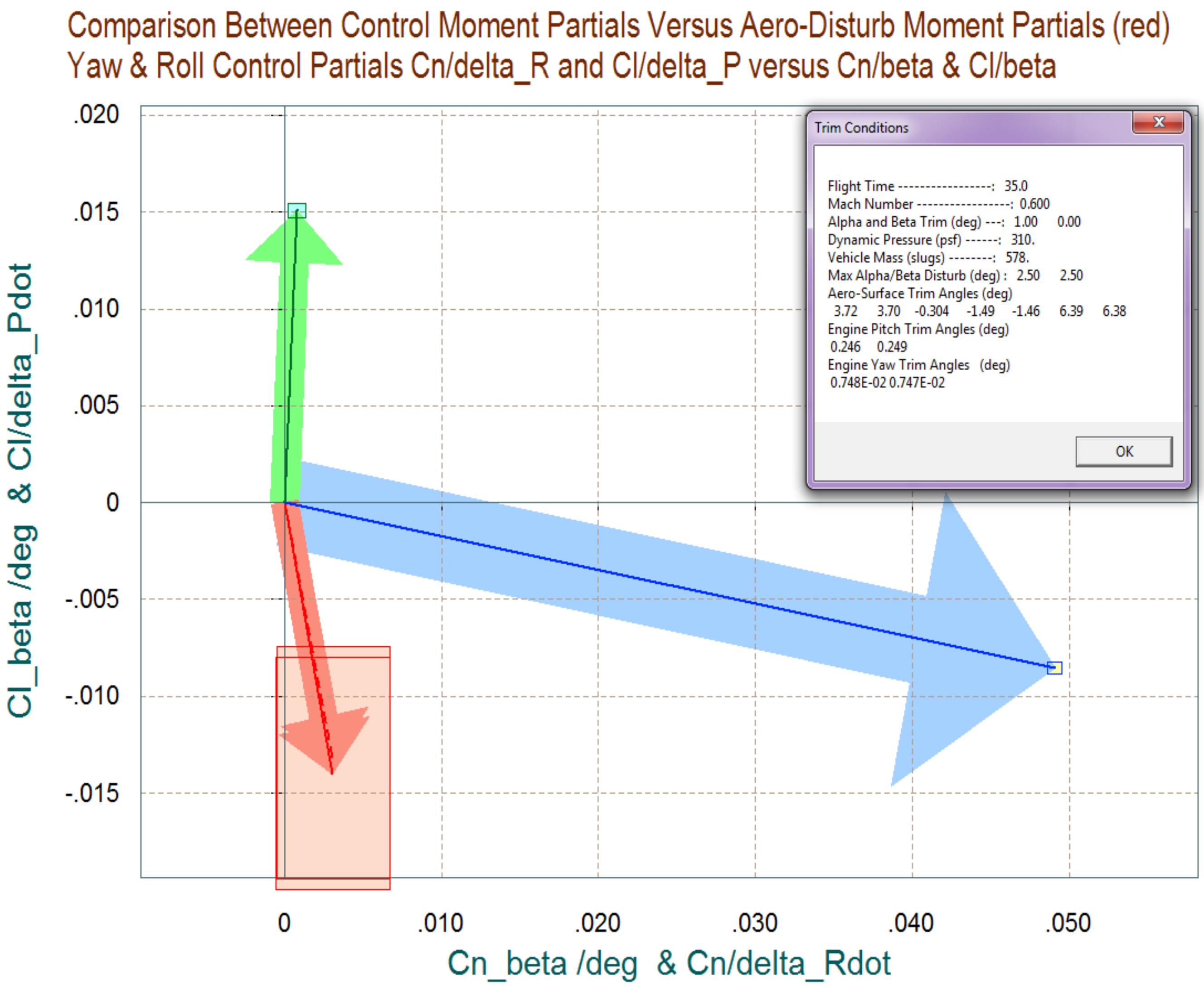
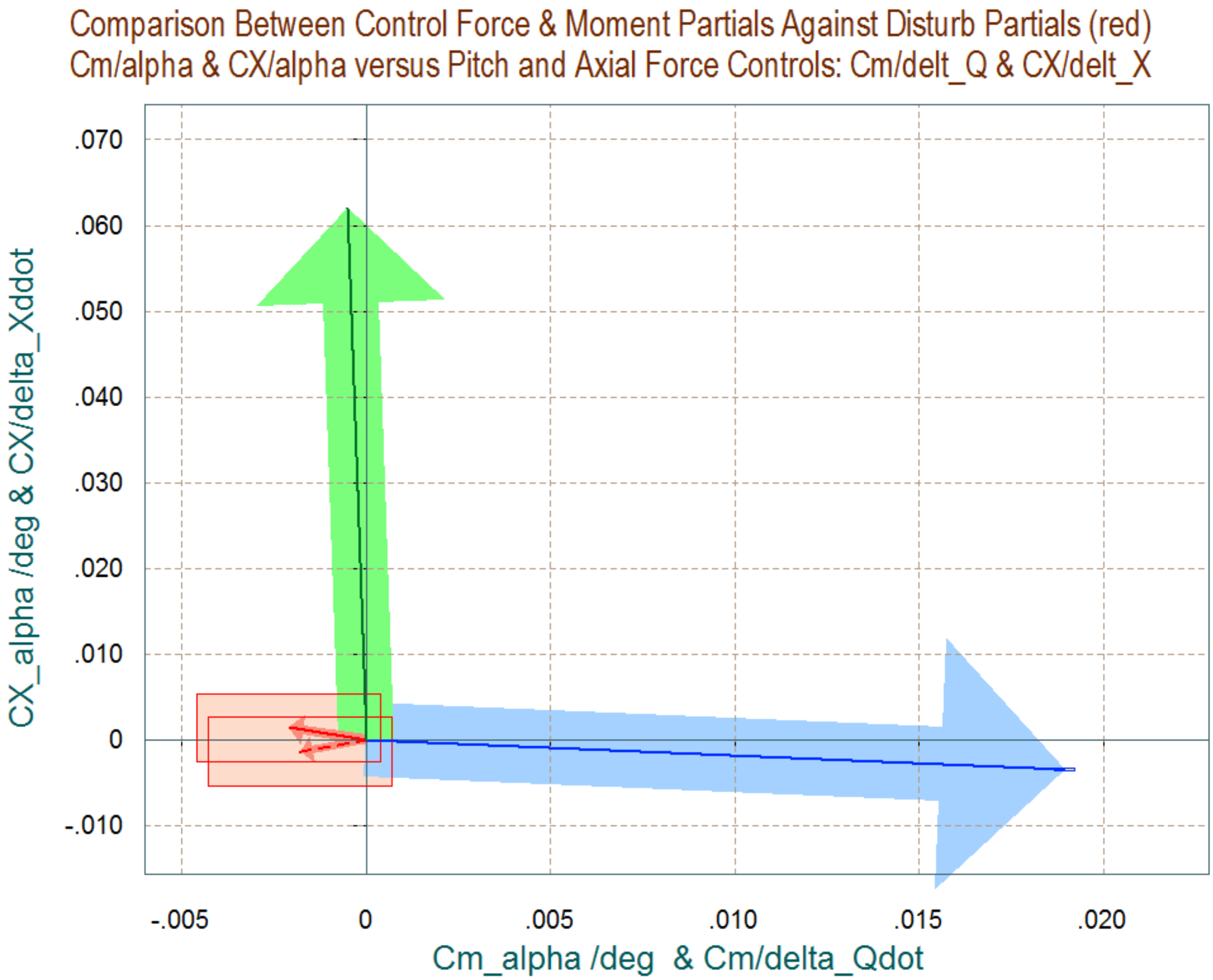


Figure 2.1.2 Pitch Moment, Normal and Axial Forces produced due to $\pm\alpha_{max}$ and Longitudinal Controls



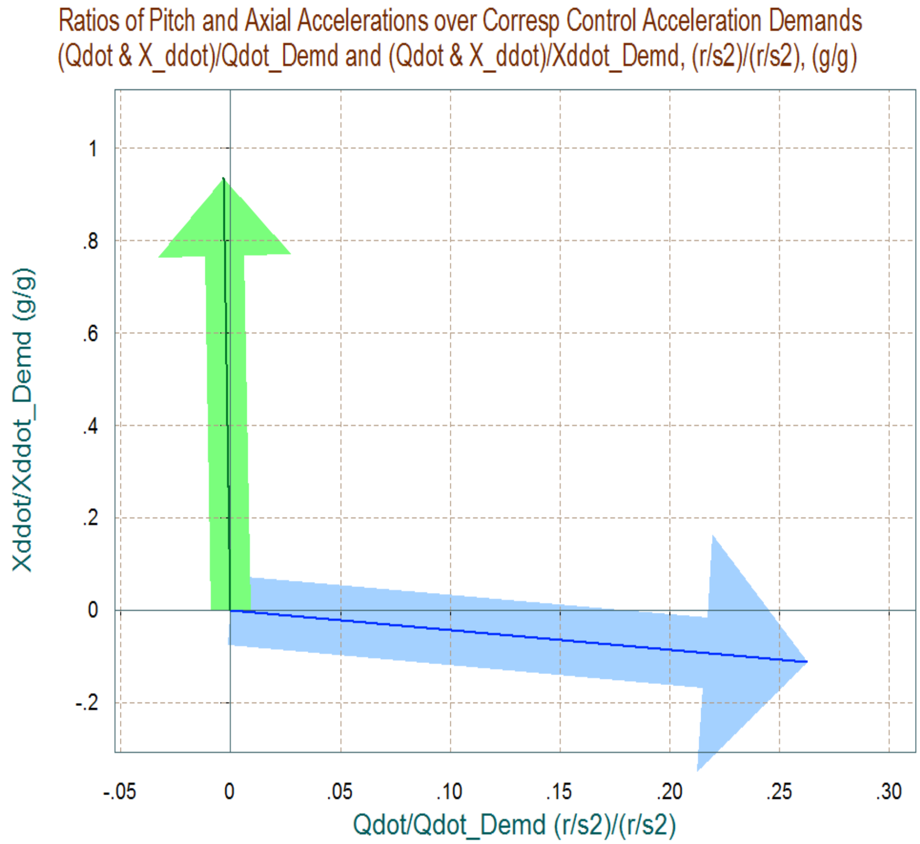
The above figure is a moment partials vector diagram showing the variation in roll and yaw moments per acceleration demands in roll and yaw in (rad/sec^2). The blue vector is the moment partials {$Cn\delta R_{FCS}$, $Cl\delta R_{FCS}$} per yaw control demand and it is mostly in the yaw direction. The green vector is the moment partials {$Cn\delta P_{FCS}$, $Cl\delta P_{FCS}$} per roll demand and it is mainly in roll. They both couple into each other's direction but they are close to being orthogonal to each other, which is a good property for control. The red vectors pointing downward are the scaled {Cnβ, Clβ} partials. Notice that Clβ is negative due to the dihedral and it is bigger in magnitude than Cnβ. The red rectangle centered at the tip of the {Cnβ, Clβ} vector is due to the uncertainties in the two partials. Similarly the yellow rectangle at the tip of the yaw control partial is due to the uncertainties in {CnδR, ClδR}, and the cyan rectangle at the tip of the roll control partial is due to the uncertainties in {CnδP , ClδP}. The uncertainties are obtained from file "*LiftBody.Unce*".



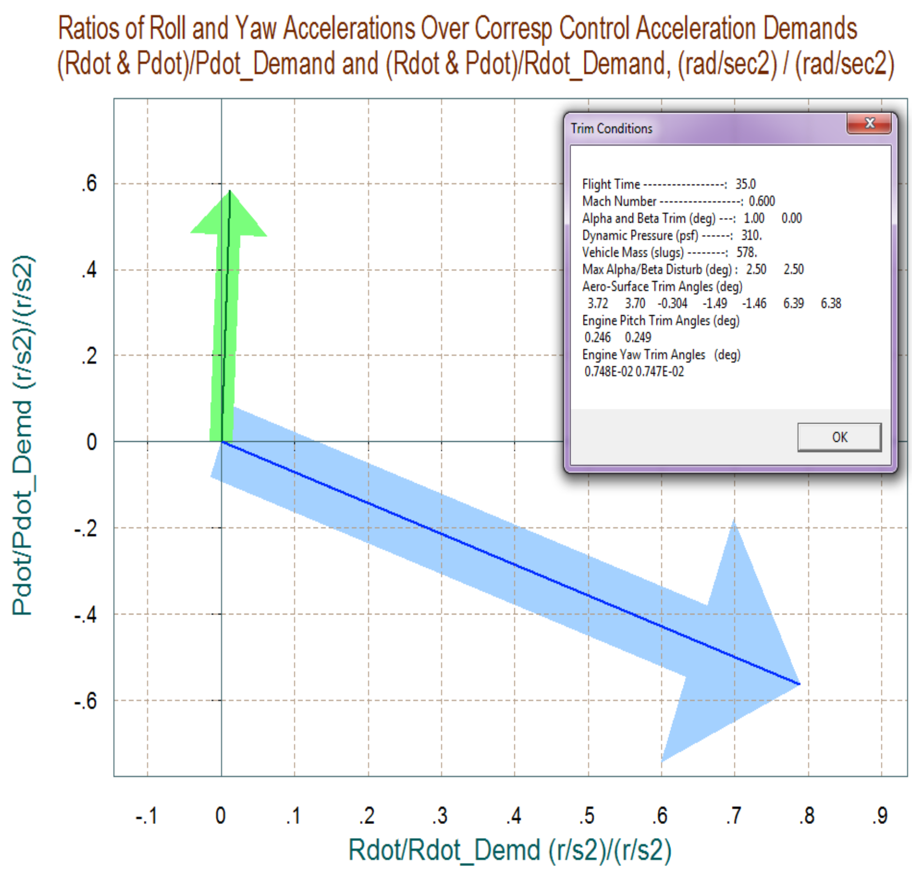
This vector diagram shows partials in the two longitudinal control directions which are variations in pitch moment and axial force per acceleration demands in pitch (rad/sec^2), and in x-direction (ft/sec^2). The blue vector shows the partials $\{CX\delta Q_{FCS}, Cm\delta Q_{FCS}\}$ per pitch control demand and it is mostly in the horizontal pitch direction. The green vector represents the partials $\{CX\delta X_{FCS}, Cm\delta X_{FCS}\}$ per axial acceleration control demand (throttle) and it is mainly in the +vertical axial force direction. They are almost orthogonal to each other and pointing in the demanded directions, which is good.

The red vectors are the scaled $\{C_{X\alpha,} C_{m\alpha}\}$ partials. They are two because they are calculated at the two extreme $\pm\beta_{max}$ positions. Notice that $Cm\alpha$ is negative because the vehicle is stable in this configuration. The red rectangles centered at the tips of the $\{C_{X\alpha,}\ C_{m\alpha}\}$ vectors are due to the uncertainties in the two partials. Similarly the yellow rectangle at the tip of the yaw control partial is due to the uncertainties in $\{Cn\delta R, Cl\delta R\}$, and the cyan rectangle at the tip of the roll control partial is due to the uncertainties in $\{Cn\delta P, Cl\delta P\}$. The uncertainties are obtained from file "*LiftBody.Unce*".

This figure shows the longitudinal partials of accelerations per acceleration demands in pitch and axial directions. The blue vector is {$\dot{Q}/\delta Q_{FCS}$, $\ddot{X}/\delta Q_{FCS}$}, and the green vector is {$\dot{Q}/\delta X_{FCS}$, $\ddot{X}/\delta X_{FCS}$}. It shows that both vectors are pointing mainly in their corresponding and demanded directions indicating that controllability in both directions can be achieved.

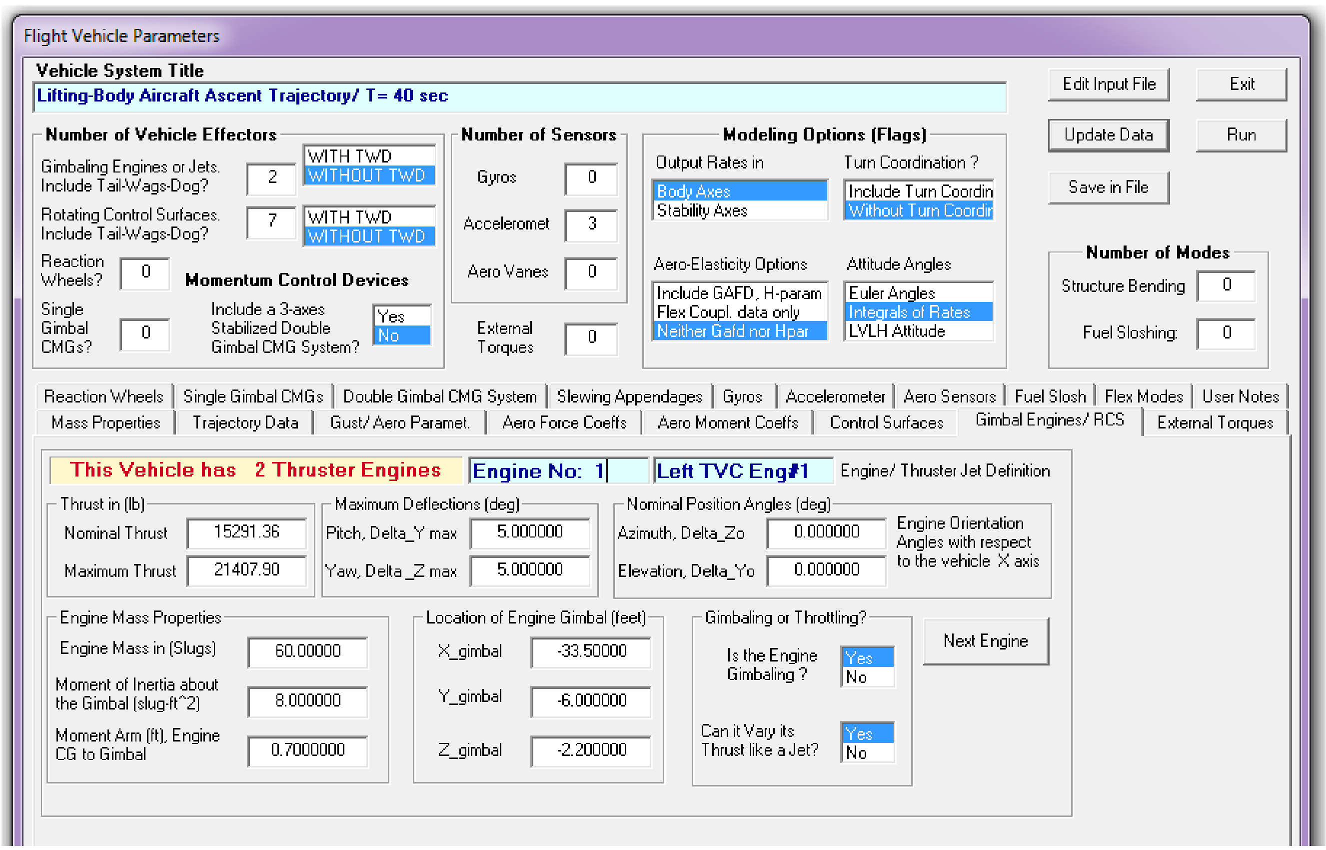


This figure shows the partials of accelerations per acceleration demands in roll and yaw. The green vector is {$\dot{P}/\delta P_{FCS}$, $\dot{R}/\delta P_{FCS}$}, and the blue vector is {$\dot{P}/\delta R_{FCS}$, $\dot{R}/\delta R_{FCS}$}. The axis units are in (rad/sec^2)/ (rad/sec^2). They are close to being orthogonal to each other, which means that control is achievable in both directions.



Modeling, Control Design, and Stability Analysis

We will now create dynamic models for the vehicle at a fixed flight condition during ascent. We will use these models to design control laws, an effector combination logic, and analyze stability in the frequency domain. The effector combination matrix used in the linear analysis is KmixT35 which was also used in the Trim performance analysis. It combines the 7 aero-surfaces, TVC, and throttling to provide accelerations in 4 directions: roll, pitch, yaw, and axial acceleration. The vehicle dynamic model was created using Flixan, as shown below. The flight condition chosen was 40 sec after lift-off. From one of the trajectory plots, go the top menu bar and choose "*Graphic Options*". Then from the vertical pop-up menu click on "*Select Time to Create State-Space System*". Then using the mouse click along the horizontal axis at time t=40 sec, to select the flight condition. The program confirms the flight time and prepares the dynamic model. Using the following dialog you may modify the data, labels, or flags before saving it in file "T40.Inp".



Notice, the attitude angles in this model are not defined to be Euler angles as in the reentry models but they are integrals of the body rates. This has to do with the flight control system structure which is different from the reentry structure. During ascent it is more important to control attitude rather than alpha or normal-acceleration because the thrust needs to be pointed in the right direction. The flight control system is receiving increments of attitude commands from guidance relative to its current attitude, rather than absolute Euler angle commands, so for a short time step the next attitude relative to the previous position can be approximated with the integral of the body rate.

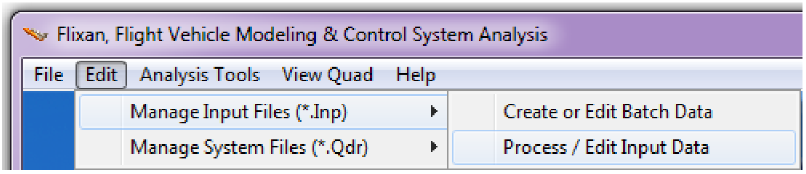
In this case, however, we will skip the preparation details because the input data file corresponding to trajectory time: 40 (sec) after lift-off is already prepared in file "*T40.Inp*". This file also contains data-sets for generating pitch and lateral control design plants and converting them to Matlab format. The Matlab analysis for this flight condition is performed in folder "*C:\Flixan\Trim\Examples\ Lifting-Body Aircraft\Vertical Launch\Boost Phase\T40*".

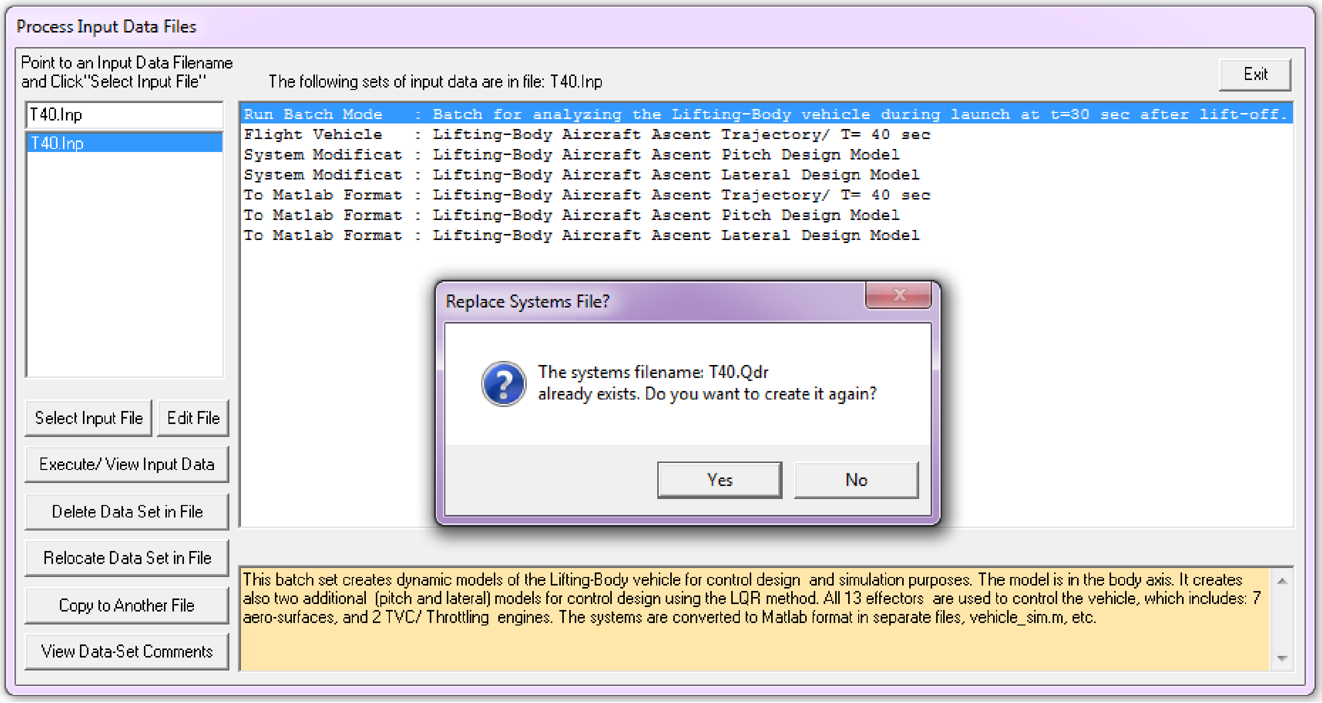
Processing the Input Data

We will now describe the contents of the input data file "*T40.Inp*" and process it using Flixan. It creates the following systems that will be used in control design and analysis:

- A vehicle dynamic model "*Lifting-Body Aircraft Ascent Trajectory/ T= 40 sec*". The rates in this system are body rates and the attitudes are body rate integrals. This model is also saved in file "*vehicle_sim*" for Matlab analysis.
- Two plant models which are used for pitch and lateral flight control designs, "*Lifting-Body Aircraft Ascent Pitch Design Model*" and "*Lifting-Body Aircraft Ascent Lateral Design Model*" which are also saved in files "*pitch_des.m*" and "*later_des.m*" respectively and used in Matlab for LQR control design.

This file can be processed 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 "*T40.Inp*" form 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 titled "*Batch for analyzing the Lifting-Body vehicle during launch at t=40 sec after lift-off*". Flixan will process the input file and save the systems and matrices in file "*T40*.Qdr". It will also create the system functions for Matlab analysis.

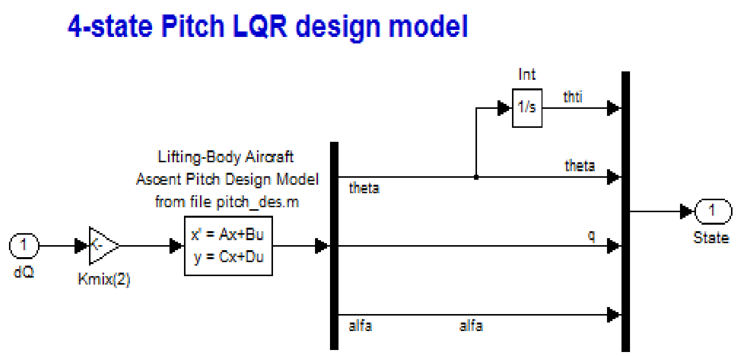
LQR Control Design

The following Matlab file "Init.m" loads the simulation and design systems, and the effectors combination matrix in Matlab, and performs the pitch and lateral LQR designs.

```
% Initialization and LQR design, File Init.m
d2r=pi/180; r2d=180/pi;
[Aps, Bps, Cps, Dps] = pitch_des;                   % Load Pitch Design Model
[Als, Bls, Cls, Dls] = later_des;                   % Load Lateral Design Model
[Ave, Bve, Cve, Dve] = vehicle_sim;                 % Simulation 6-dof Model
load KmixT35.mat -ascii; Kmix=KmixT35;              % Load Surfaces Mix Logic (13 x 4)
Te=15900;                                           % Nominal Engine thrust

% Pitch LQR Design Using the 13 Effectors
[Ap4,Bp4,Cp4,Dp4]= linmod('Pdes4x');                % 4-state des model {thet_int,theta,q,alfa}
R=0.01; Q=[8 5  4 0.05]; Q=diag(Q);                 % LQR Weights for {thet_int,theta,q,alfa}
[Kq,s,e]=lqr(Ap4,Bp4,Q,R)                           % Perform LQR design
save Kq_T35.mat Kq -ascii                           % Pitch State-Feedback Gain Kq

% Lateral LQR Design Using the 13 Effectors
[A14,B14,C14,D14]= linmod('Ldes5x');                % 5-state des model {phi_int,phi,p,r,beta}
R=[1,1]*20; R=diag(R);                              % LQR Weights R=[1,10]*2
Q=[15 8 2 2 0.05]*0.008; Q=diag(Q);                 % LQR Weights Q=[1 1 1 0.04 0.04]*0.4
[Kpr,s,e]=lqr(A14,B14,Q,R)                          % Perform LQR design
save Kpr_T35.mat Kpr -ascii                         % Lateral State-Feedback Gain Kpr
```

Pitch LQR Design

The pitch LQR design plant in file "pitch_des.m" originally consisting of states: {θ, q, and α} is augmented using Simulink file "Pdes4x.Mdl" to include also θ-integral in the state-vector, as shown. The second column of the Kmix matrix is also included in the pitch plant to reduce its inputs to a single pitch acceleration demand input. The pitch attitude is controlled during ascent, instead of α or Nz, because it is important to point the thrust in the proper vertical direction as commanded by guidance.



The following Simulink model "*Sim_Pitch_Simple.Mdl*", shown in figure (2.1.3), is used for evaluating performance of the ascent LQR design. It includes the state-feedback matrix Kq and the mixing-logic matrix. It calculates the system's response to 1° pitch attitude step command. However, instead of alpha, Nz feedback will be implemented in the simulation model.

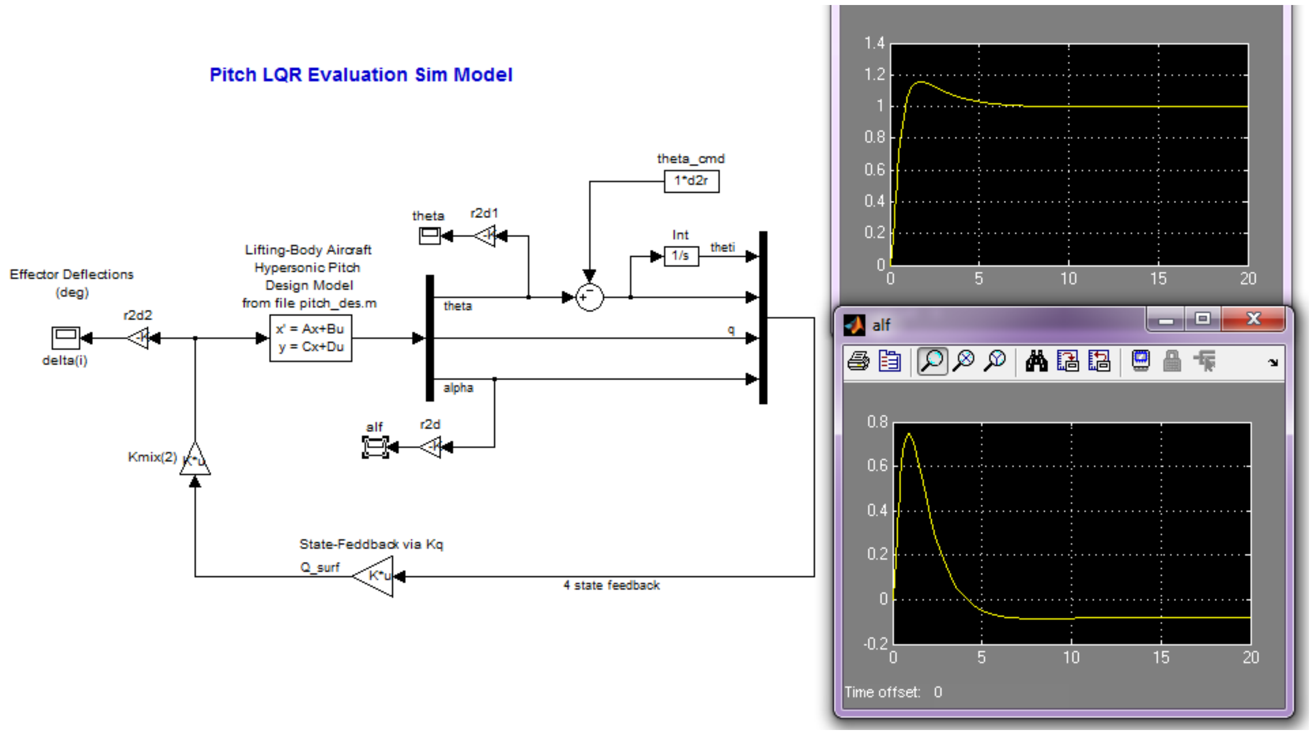
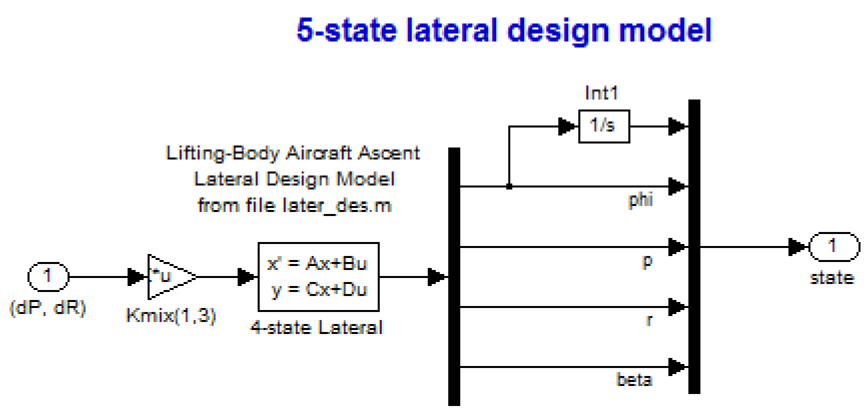


Figure 2.1.3 Simulink Model "*Sim_Pitch_Simple.Mdl*" used for evaluating the Pitch LQR design

Lateral Control Design

The system in file "*later_des.m*" is used in the lateral design plant. It originally consists of states: {ϕ, p, r, and β} and it is augmented using the Simulink file "Ldes5x.Mdl" to include also ϕ-integral in the state-vector, as shown. The rates are in the body axis (rather than stability) because the angle of attack is small during ascent. The first and third columns of the Kmix matrix are also included in the lateral plant to reduce the inputs to two; roll and yaw acceleration demands.



The Simulink model "*Sim_Later_Simple.Mdl*" is used for evaluating the lateral design. It includes the state-feedback matrix Kpr and the mixing-logic matrix KmixT35. However, instead of beta, Ny feedback will be implemented in the simulation model

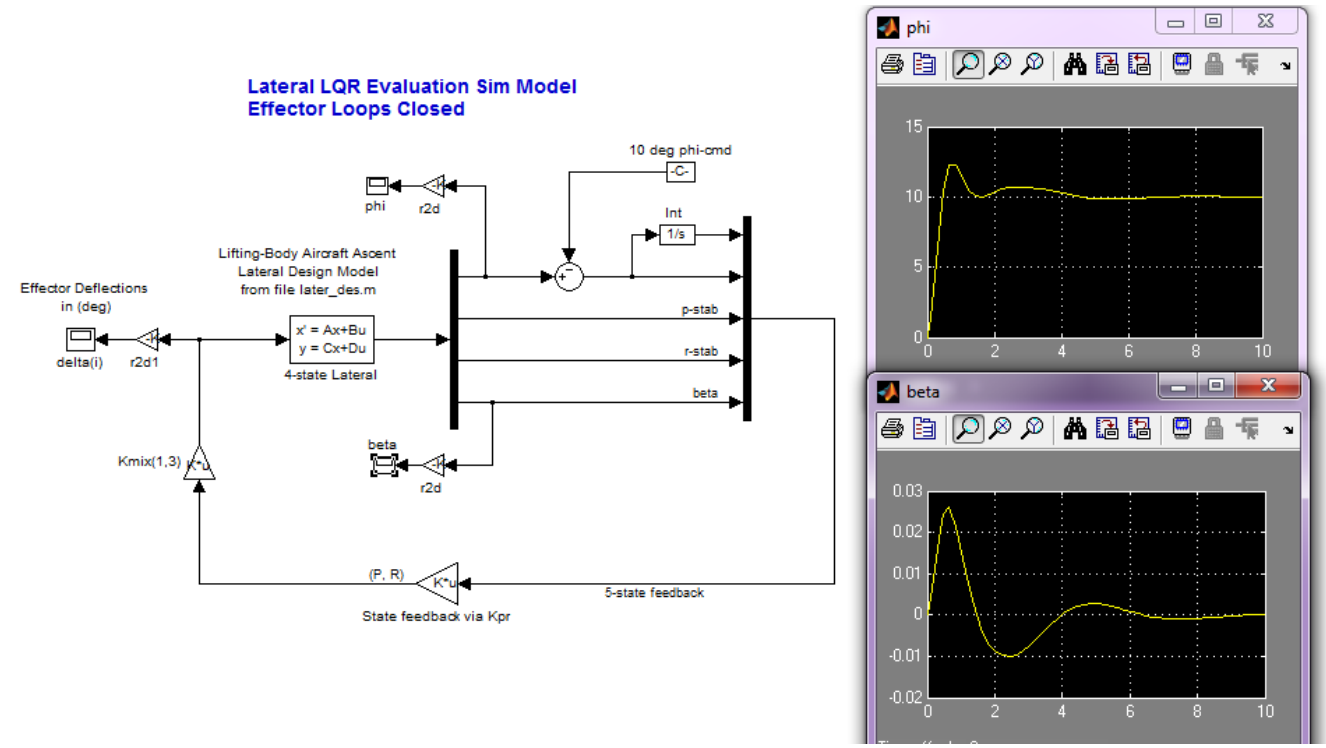


Figure 2.1.4 Simulink Model "*Sim_Later_Simple.Mdl*" used for evaluating the Lateral LQR design

Linear Simulation Model

The Matlab linear simulation model for ascent (at t=40 sec) is in file "*Simul_Ascent.Mdl*", shown in figure (2.1.5). It uses the vehicle state-space system "*Lifting-Body Aircraft Ascent Trajectory/ T= 40 sec*" from file "*vehicle_sim.m*". In the longitudinal directions the pitch attitude is controlled by a combination of TVC and elevon deflections, including some body-flap. Velocity is also controlled by varying the engines thrust. In the lateral directions yaw attitude is not directly controlled, only roll is commanded. The dihedral makes it difficult to independently command both roll and yaw. However, both directions are stable. A combination of TVC, elevon, and rudder deflections are used to control the lateral directions. Notice, that in the simulation model the α-feedback is replaced with Nz feedback and also the β-feedback is replaced with Ny feedback. It is used for evaluating the system's response to ϕ , θ, and δV commands and also to wind-gust disturbances.

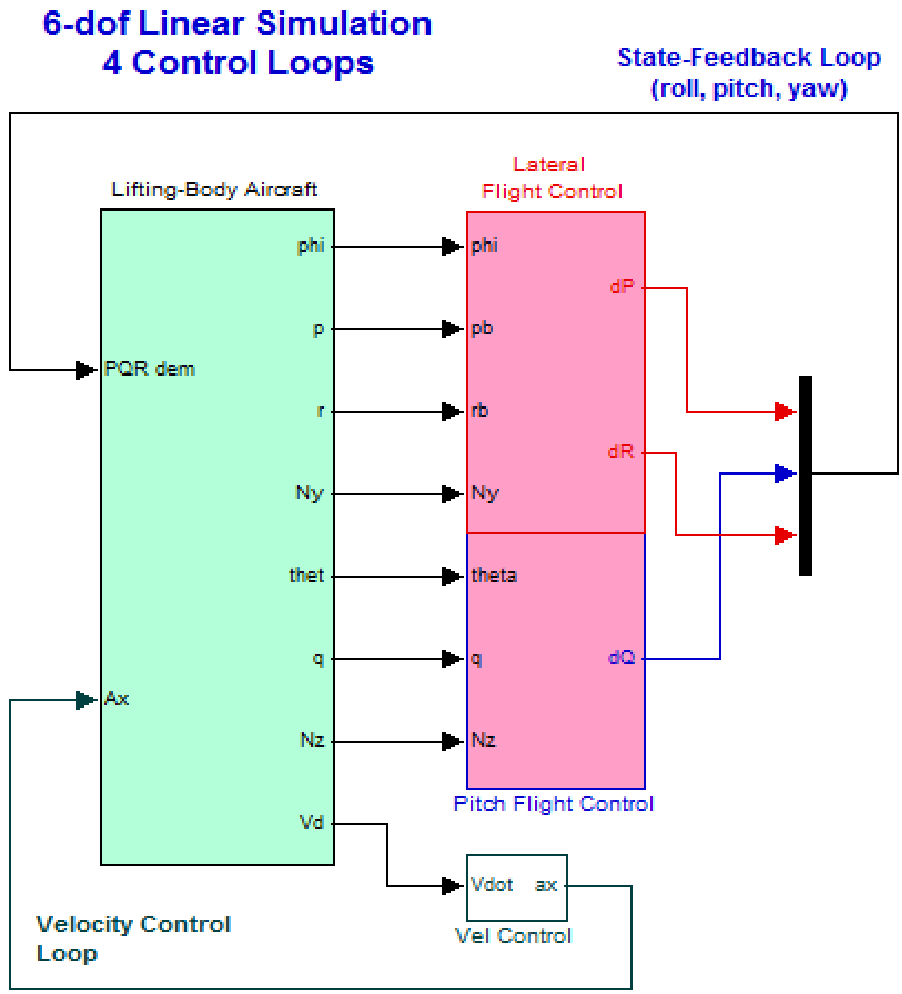
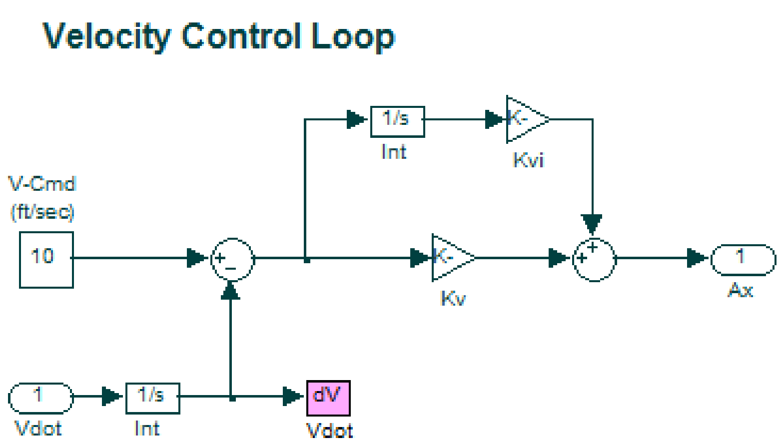
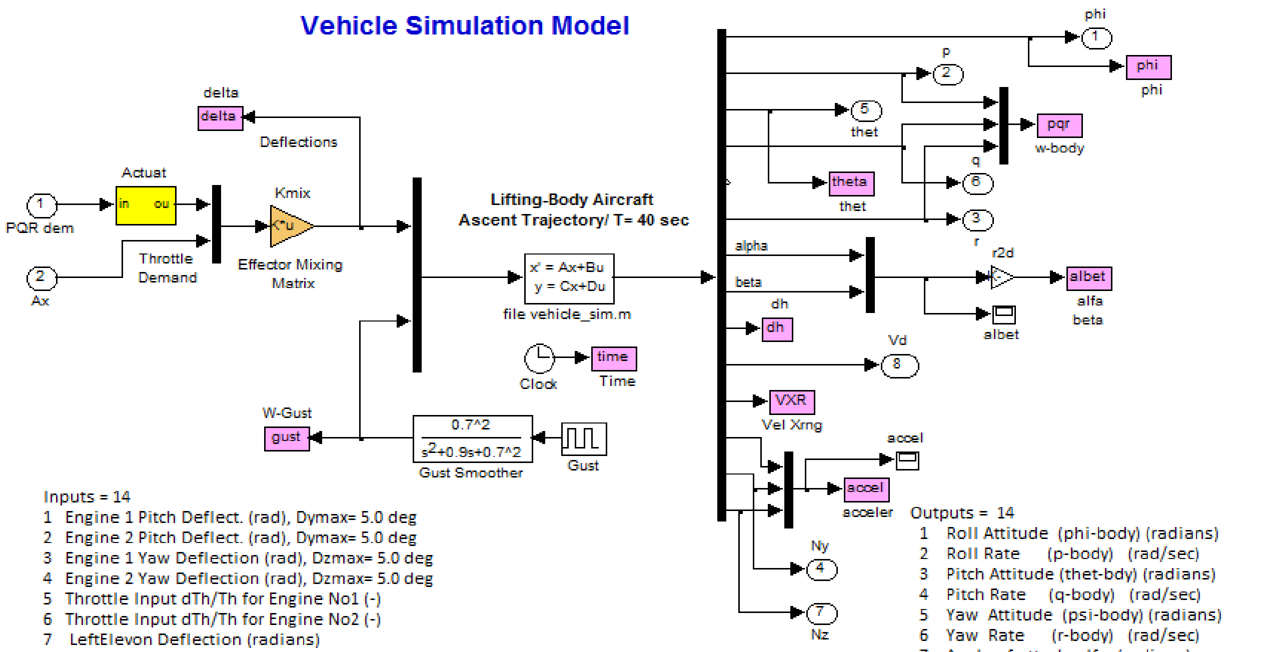


Figure 2.1.5 Ascent Simulation Model in File "*Simul_Ascent.Mdl*"



Vehicle Simulation Model



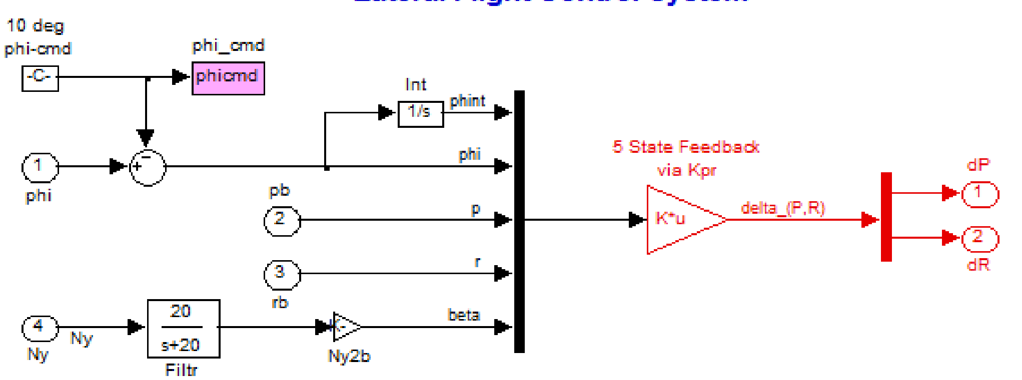
Inputs = 14

1 Engine 1 Pitch Deflect. (rad), Dymax= 5.0 deg
2 Engine 2 Pitch Deflect. (rad), Dymax= 5.0 deg
3 Engine 1 Yaw Deflection (rad), Dzmax= 5.0 deg
4 Engine 2 Yaw Deflection (rad), Dzmax= 5.0 deg
5 Throttle Input dTh/Th for Engine No1 (-)
6 Throttle Input dTh/Th for Engine No2 (-)
7 LeftElevon Deflection (radians)
8 Right Elevon Deflection (radians)
9 Vertical Rudder Deflection (radians)
10 Upper-Left Body-Flap Deflection(radians)
11 Upper-Right Body-Flap Deflection (radians)
12 Lower-Left Body-Flap Deflection(radians)
13 Lower-Right Body-Flap Deflection (radians)
14 Wind Gust Azim, Elev Angles=(45,90) (deg)

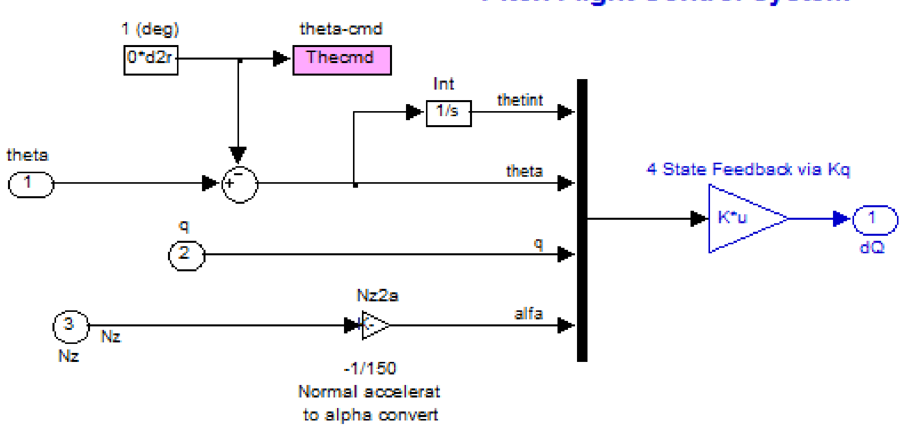
Outputs = 14

1 Roll Attitude (phi-body) (radians)
2 Roll Rate (p-body) (rad/sec)
3 Pitch Attitude (thet-bdy) (radians)
4 Pitch Rate (q-body) (rad/sec)
5 Yaw Attitude (psi-body) (radians)
6 Yaw Rate (r-body) (rad/sec)
7 Angle of attack, alfa, (radians)
8 Angle of sideslip, beta, (radian)
9 Change in Altitude, delta-h, (feet)
10 Forward Acceleration (V-dot) (ft/sec)
11 Cross Range Velocity (Vcr) (ft/sec)
12 CG Acceleration along X axis, (ft/sec^2)
13 CG Acceleration along Y axis, (ft/sec^2)
14 CG Acceleration along Z axis, (ft/sec^2)

Lateral Flight Control System



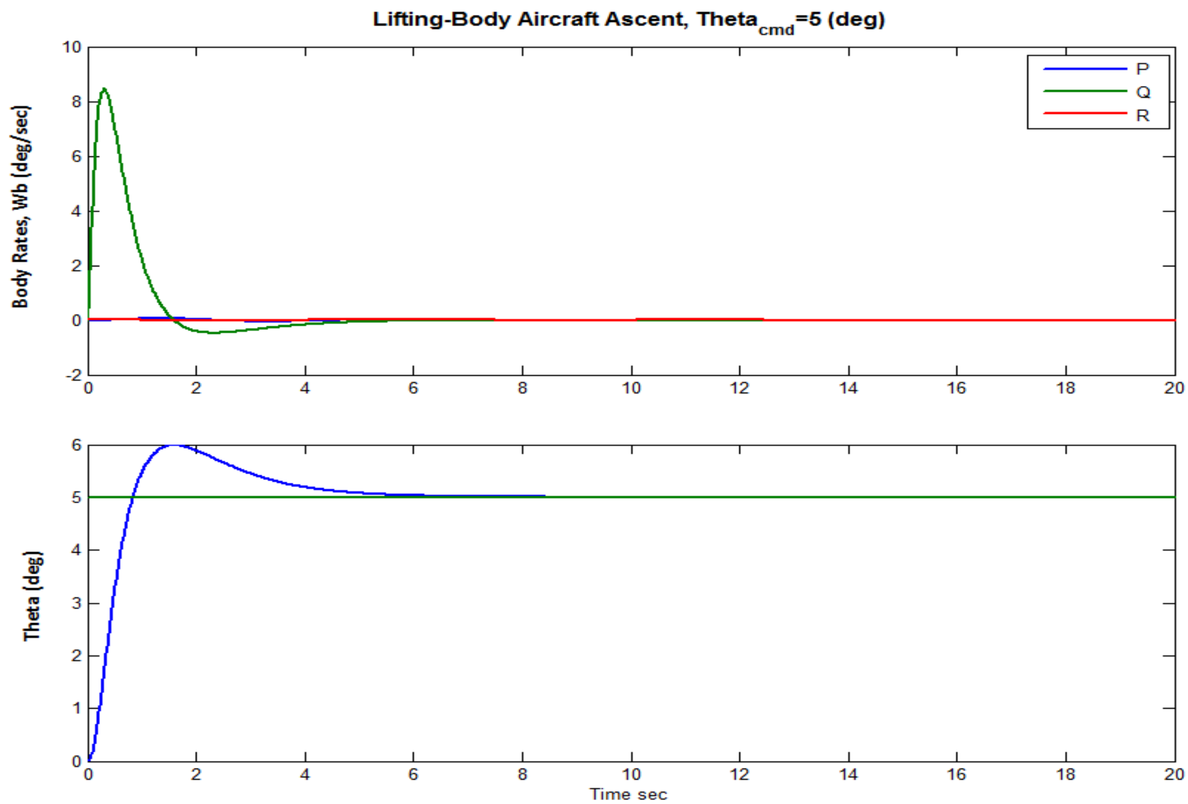
Pitch Flight Control System

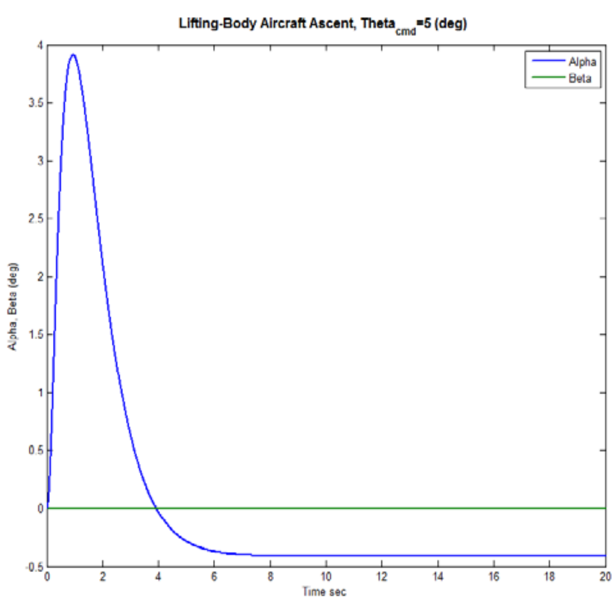


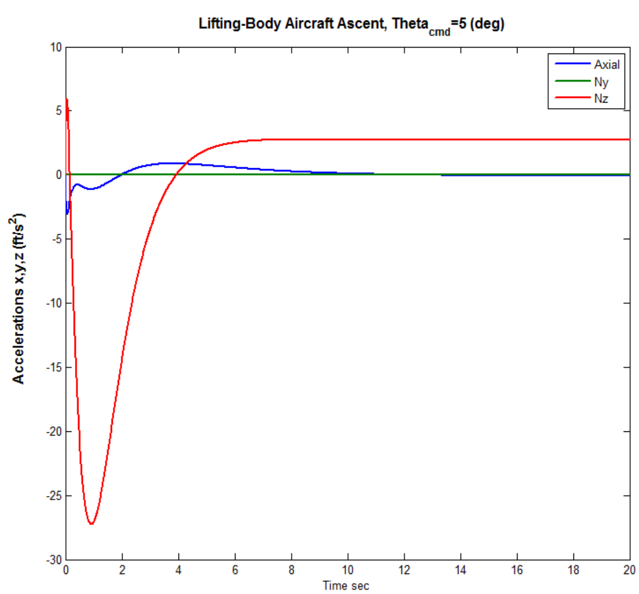
Simulation Results

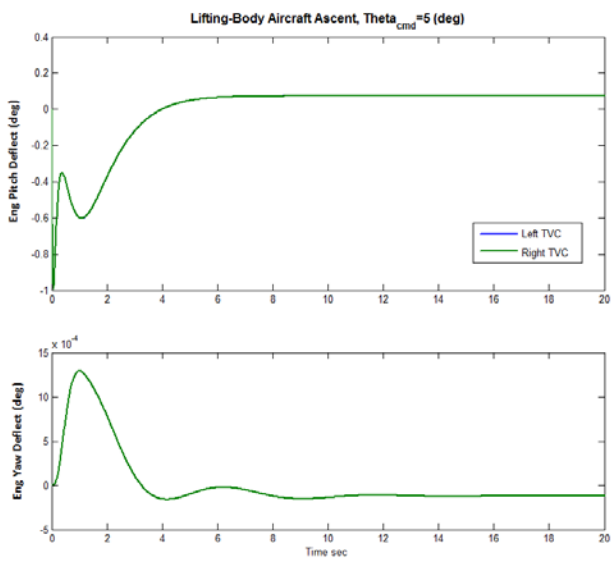
The simulation model "*Simul_Ascent.Mdl*" will now be used to simulate the vehicle response to step commands in pitch and roll attitude and to a change in velocity.

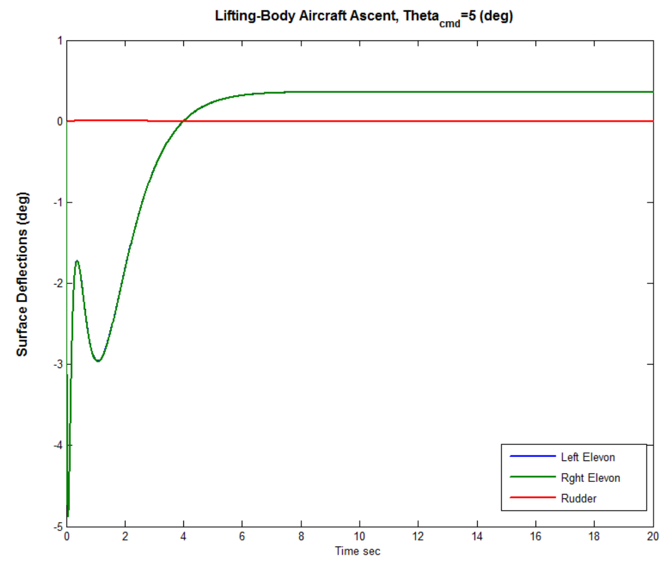
Pitch Step Command: Starting with a 5° θ_command step in pitch attitude. The plots show how the vehicle uses both: pitch TVC and elevon deflections to catch-up to the step attitude command. Notice the similarity between the angle of attack and the normal (Nz) acceleration.



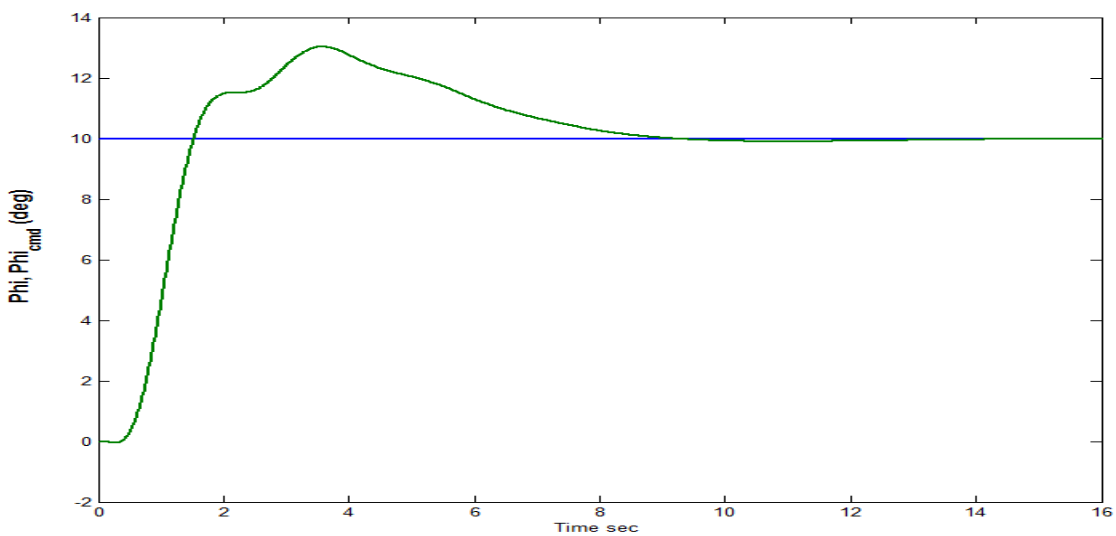


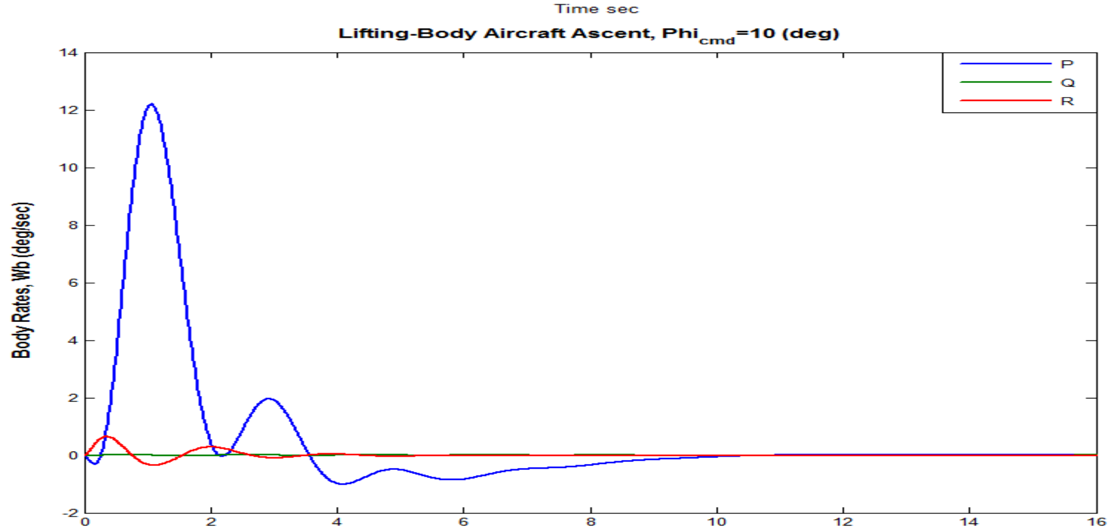


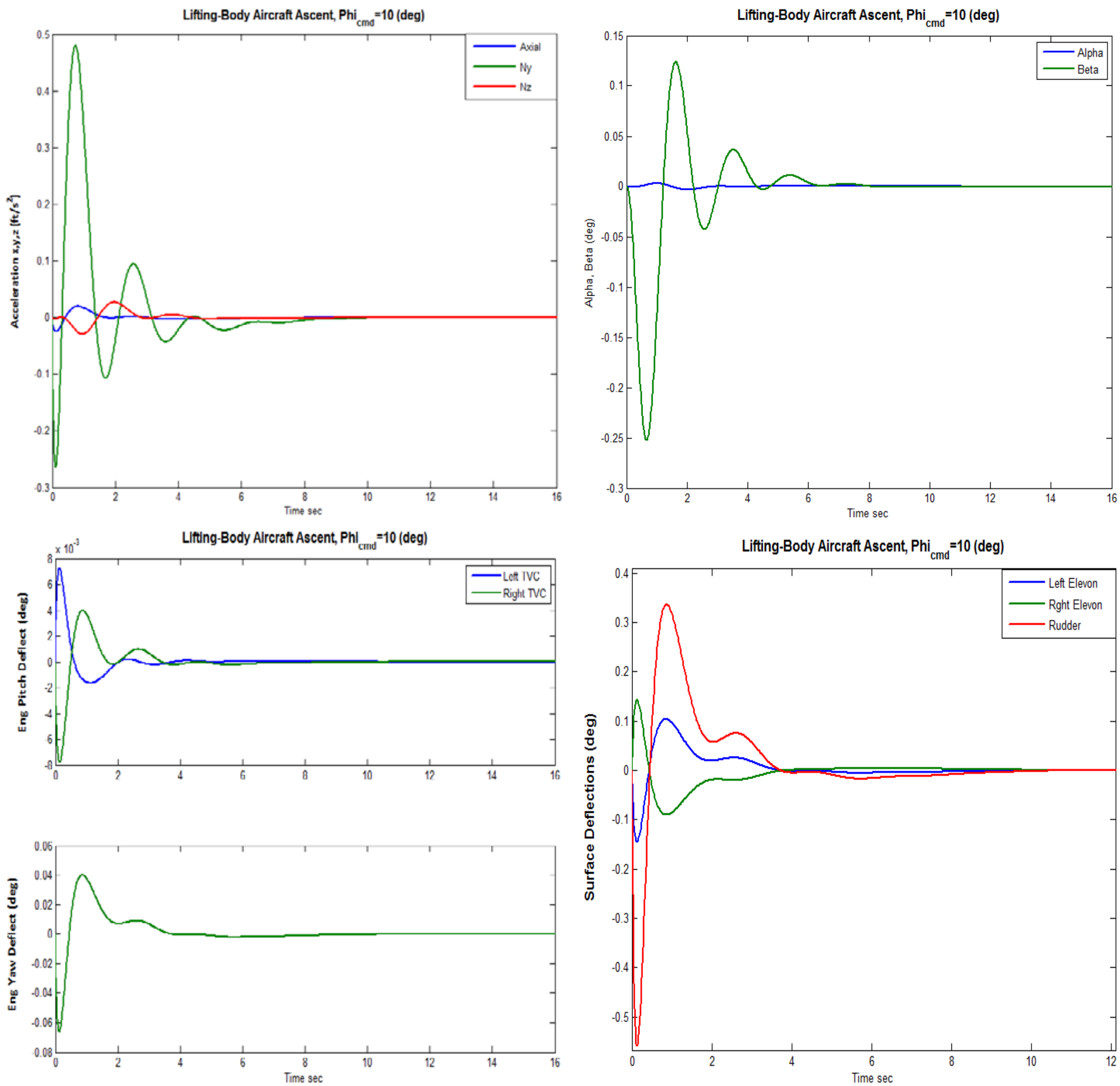




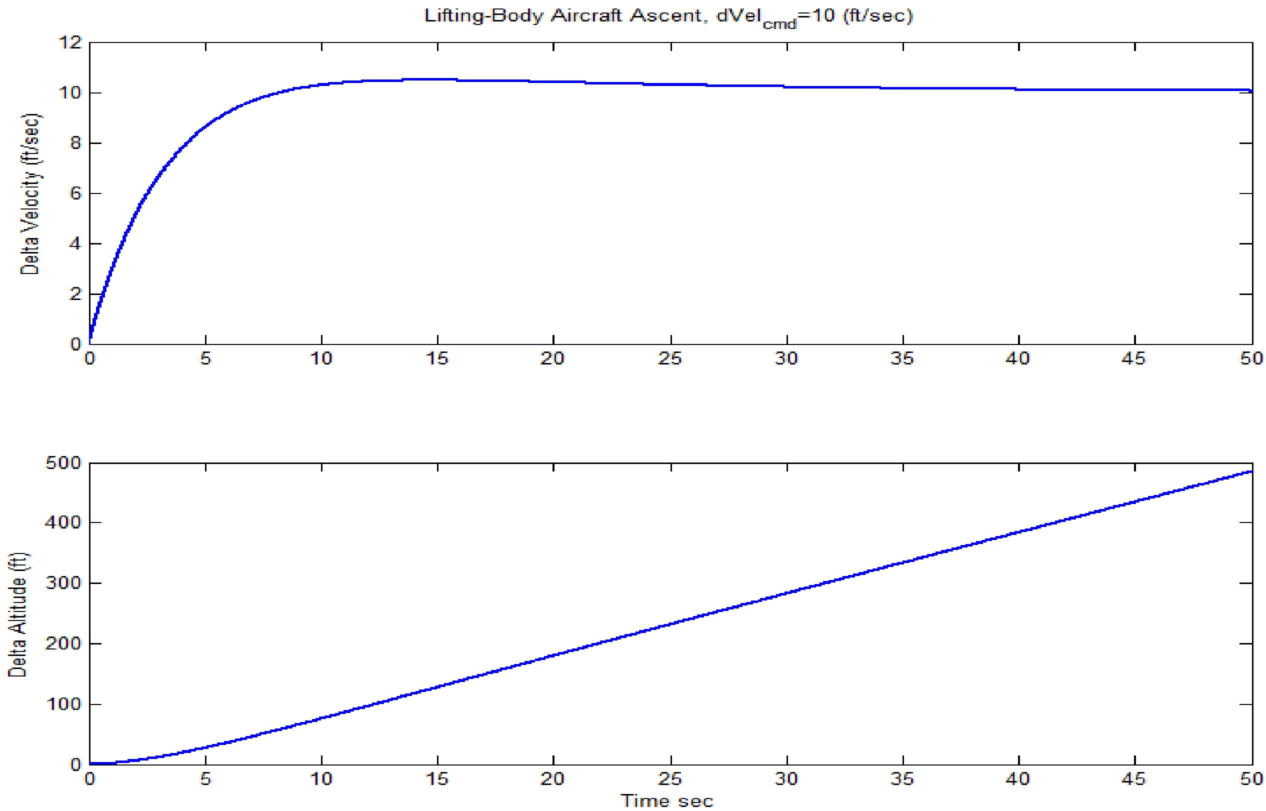
<u>Roll Step Command</u>: The next set of plots show the vehicle response to a 10° step command in roll. The vehicle uses TVC, elevon, and rudder deflections to catch-up with the ϕ_command.

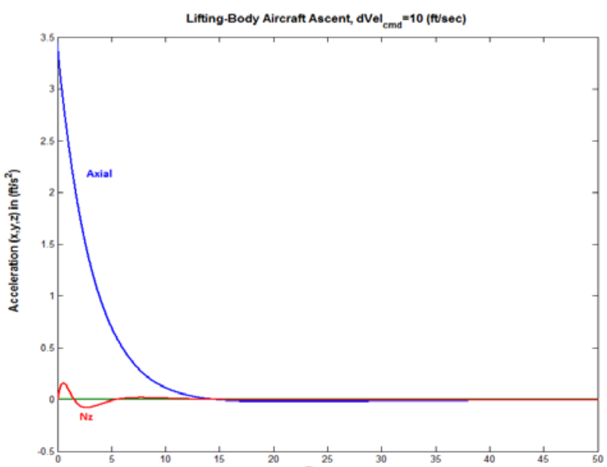


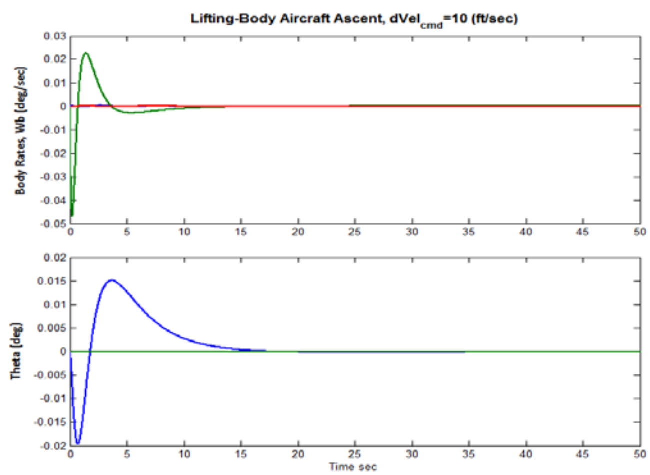


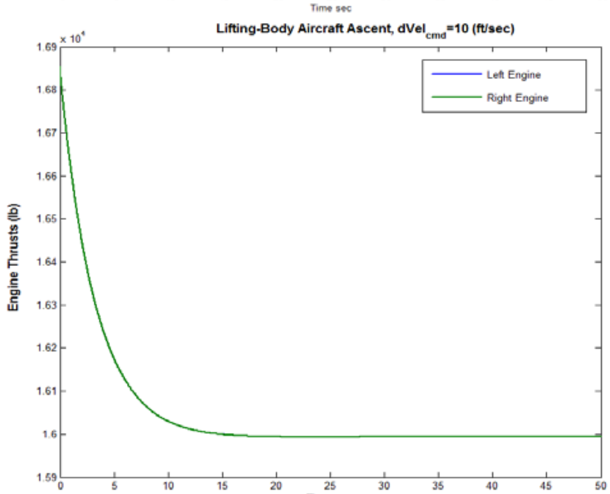


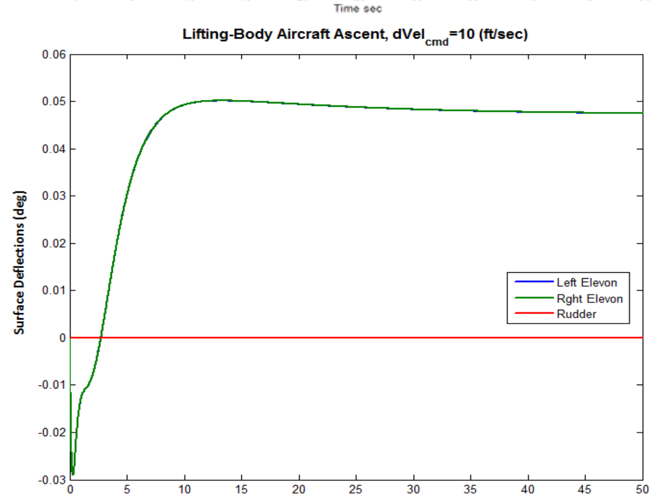
Velocity Step-Command: The last set of plots show the vehicle response to a 10 (ft/sec) step-increase in speed. There is a momentary increase in engine thrust that causes an axial acceleration that eventually decays to zero. The speed catches up to the commanded value in less than 10 sec. The increase in velocity also causes an increase in altitude since the flight-path angle is almost vertical in this flight condition. The elevons also respond to the command as they try to maintain a steady pitch attitude during this maneuver.


Lifting-Body Aircraft Ascent, dVel$_{cmd}$=10 (ft/sec)
Delta Velocity (ft/sec)
Delta Altitude (ft)
Time sec


Lifting-Body Aircraft Ascent, dVel$_{cmd}$=10 (ft/sec)
Acceleration (x,y,z) in (ft/s^2)
Axial
Nz
Time sec


Lifting-Body Aircraft Ascent, dVel$_{cmd}$=10 (ft/sec)
Body Rates, Wb (deg/sec)
Theta (deg)
Time sec


Lifting-Body Aircraft Ascent, dVel$_{cmd}$=10 (ft/sec)
x 10^4
Engine Thrusts (lb)
Left Engine
Right Engine
Time sec


Lifting-Body Aircraft Ascent, dVel$_{cmd}$=10 (ft/sec)
Surface Deflections (deg)
Left Elevon
Rght Elevon
Rudder
Time sec

Stability Analysis

Figure (2.1.6) shows the Simulink model "Stab_Anal.mdl" used for analyzing the stability margins for this ascent t=40 sec case. This model is similar to the simulation model "Simul_Ascent.Mdl" but it is configured for open-loop analysis. Only one loop is opened at a time and the other 3 loops are closed. The Matlab file "Frequ.m" uses this model to calculate the frequency response across the opened loop. The next 3 figures show the Nichols plots in the axial, roll, and pitch directions and the red lines are highlighting the phase margins for this t=40 sec case.

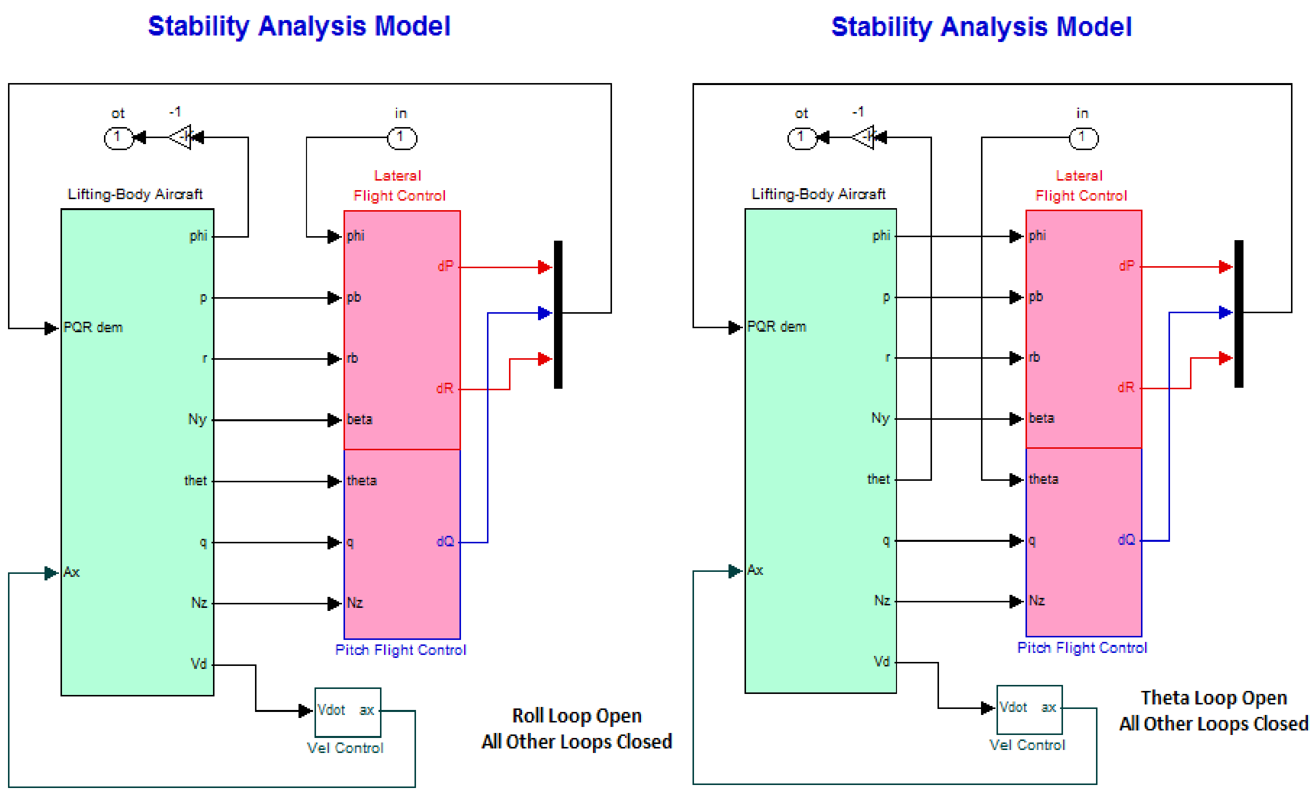
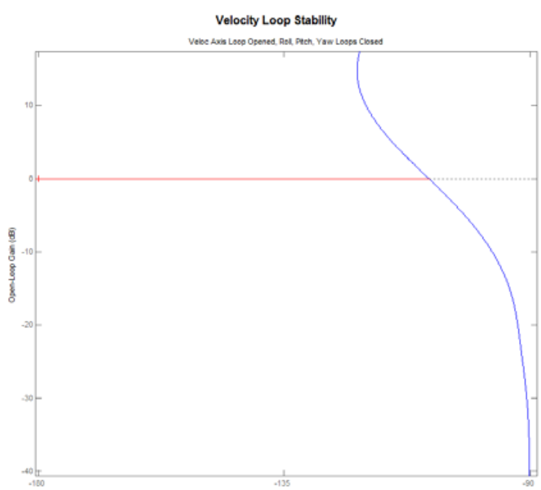
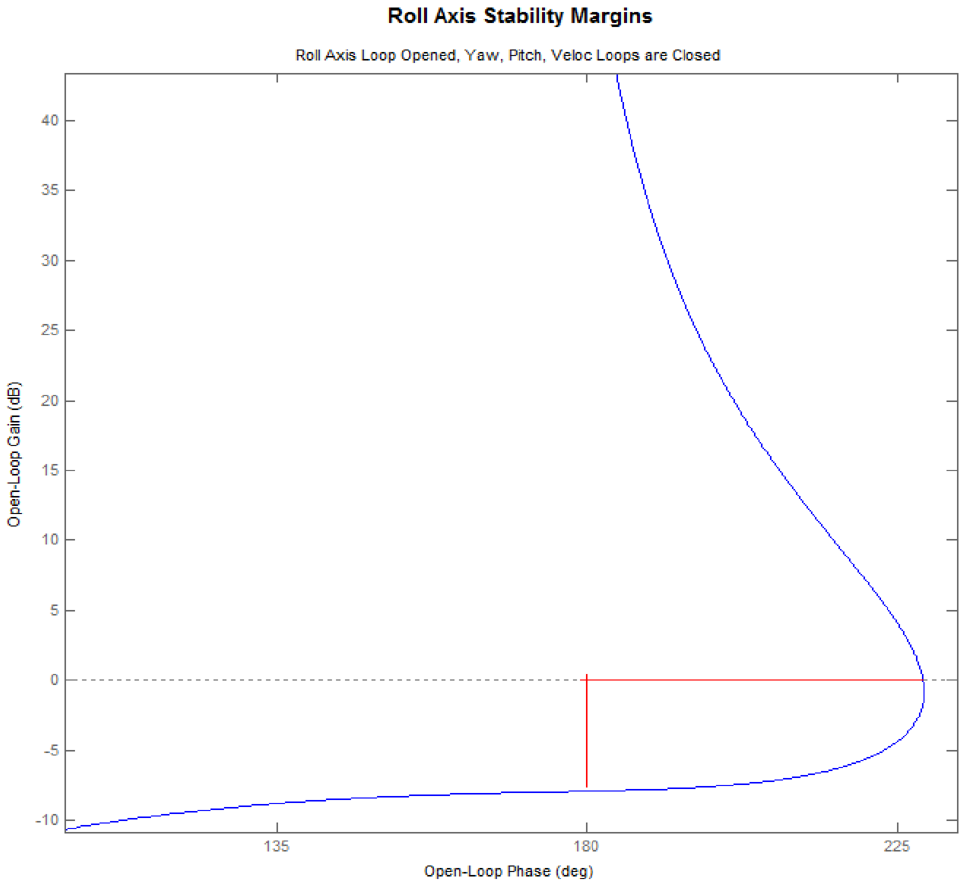
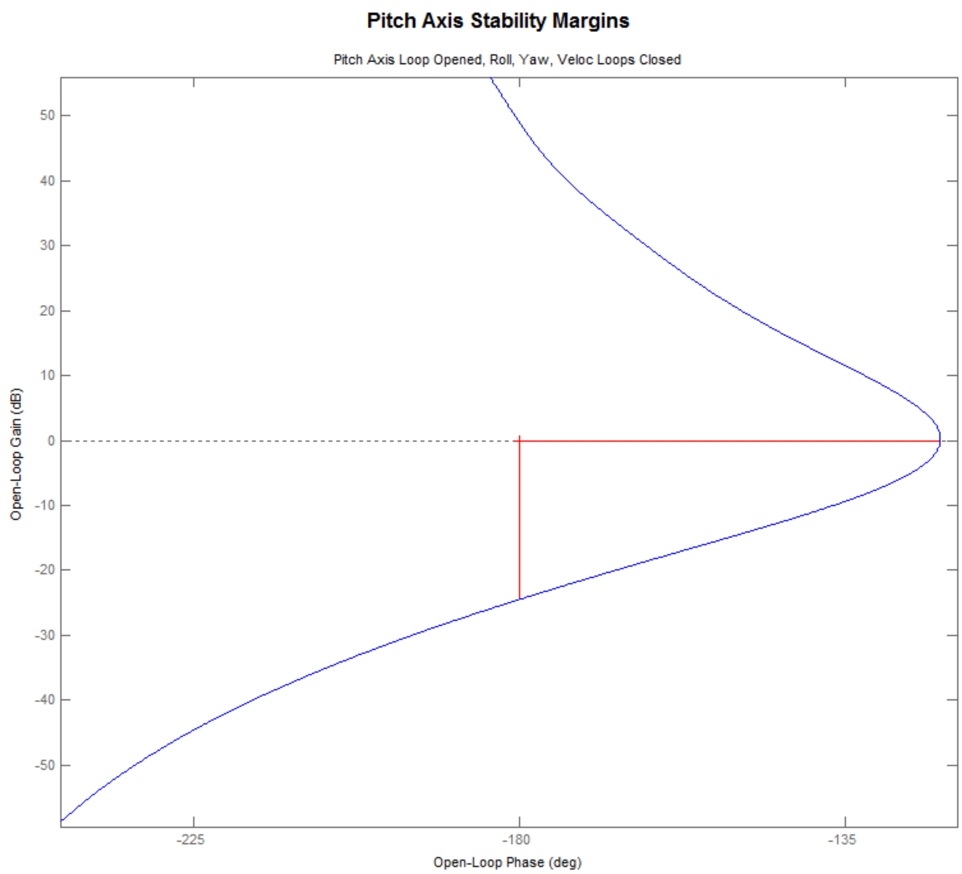


Figure 2.1.6 Simulink model "Stab_Anal.mdl" used for Open-Loop Stability Analysis

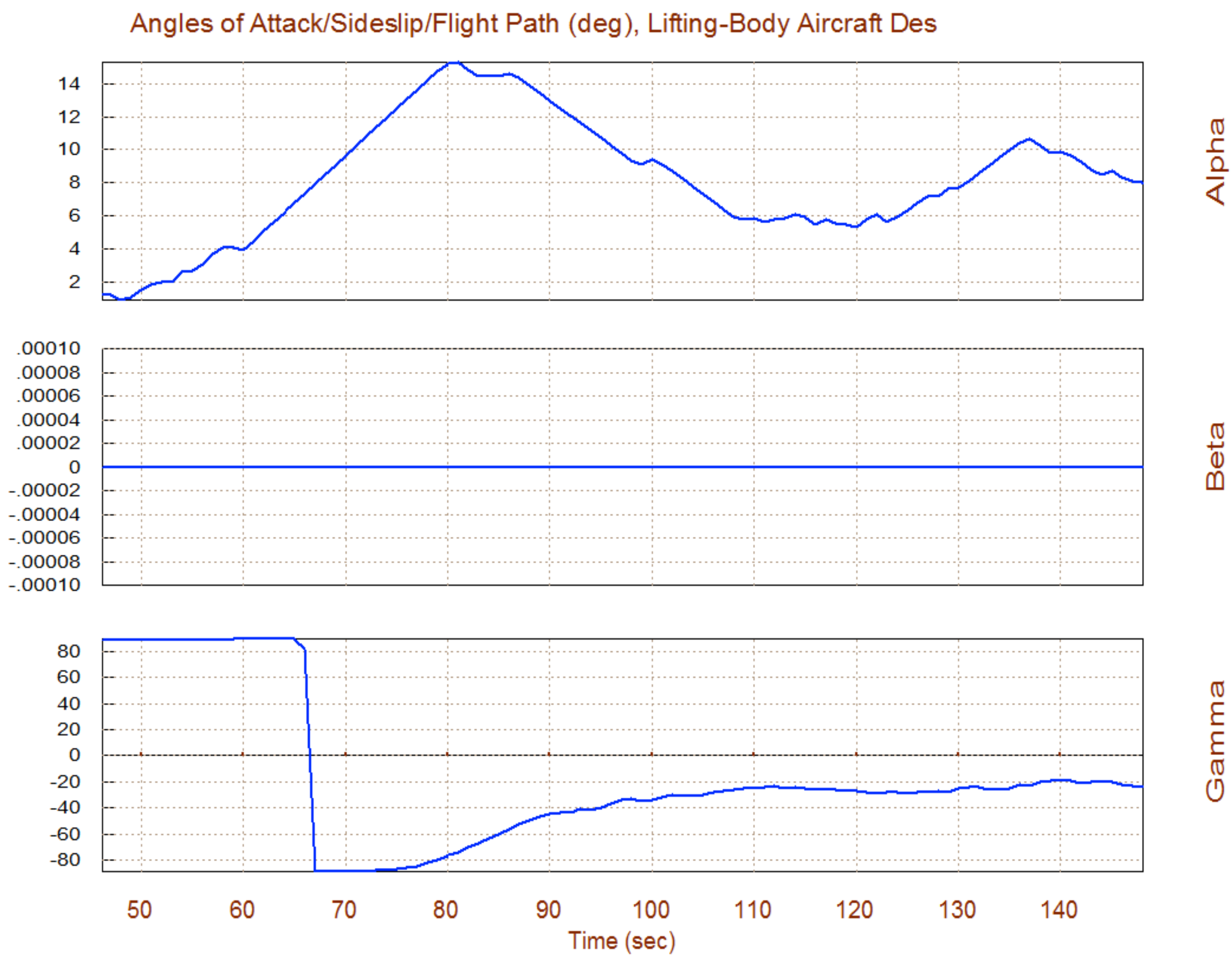


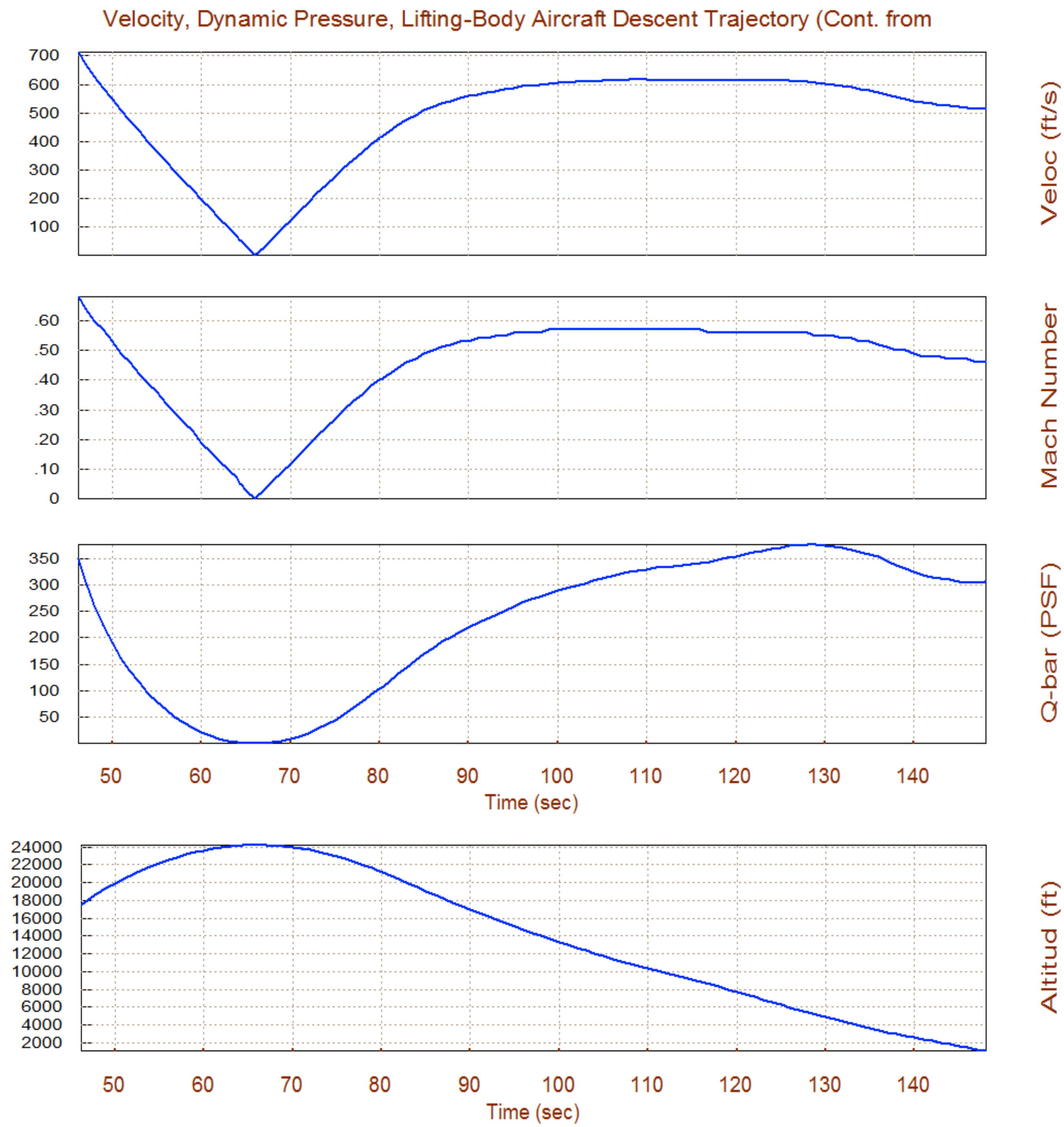

Roll Axis Stability Margins
Roll Axis Loop Opened, Yaw, Pitch, Veloc Loops are Closed
Open-Loop Gain (dB)
Open-Loop Phase (deg)
40
35
30
25
20
15
10
5
0
-5
-10
135
180
225


Pitch Axis Stability Margins
Pitch Axis Loop Opened, Roll, Yaw, Veloc Loops Closed
Open-Loop Gain (dB)
Open-Loop Phase (deg)
50
40
30
20
10
0
-10
-20
-30
-40
-50
-225
-180
-135

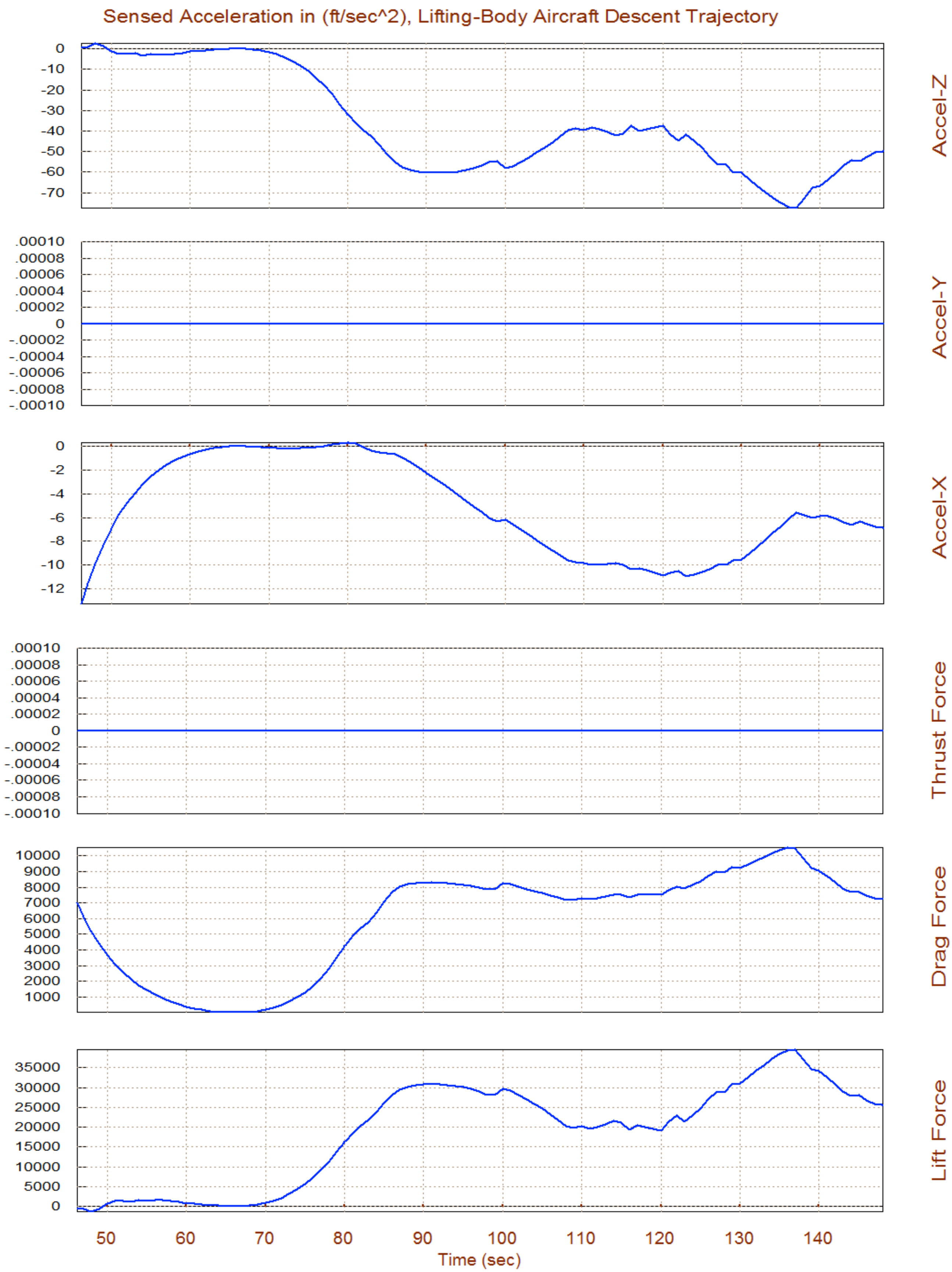
2.2 Descent from Boost

After the main engines thrust cut-off the vehicle continues to rise for another 20 seconds to an altitude of 24,000 (ft) and then it turns its nose towards the ground and begins to fall vertically under gravity with a γ close to $-90°$. The angle of attack continues to rise during this direction reversal but it does not exceed 15°, to prevent stalling, and then it comes down to about 6°. In the mean-time the flight-path angle (γ) increases to less negative values of approximately -25° before the landing flare where it is reduced to zero (not shown). The files for the descent from boost analysis are in: "*C:\Flixan\Trim\ Examples\Lifting-Body Aircraft\Vertical Launch\Descent Phase*".





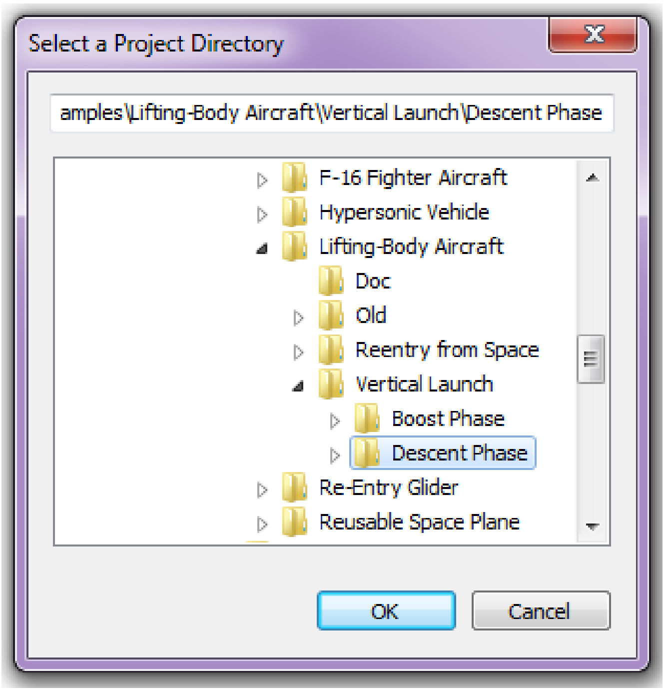
Velocity, Dynamic Pressure, Lifting-Body Aircraft Descent Trajectory (Cont. from
Veloc (ft/s)
Mach Number
Q-bar (PSF)
Time (sec)
Altitud (ft)
Time (sec)

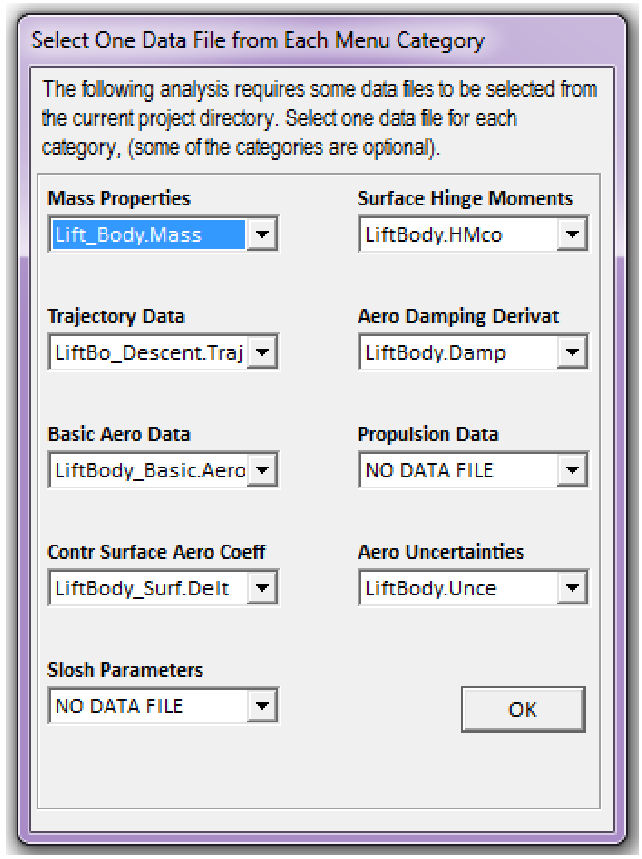


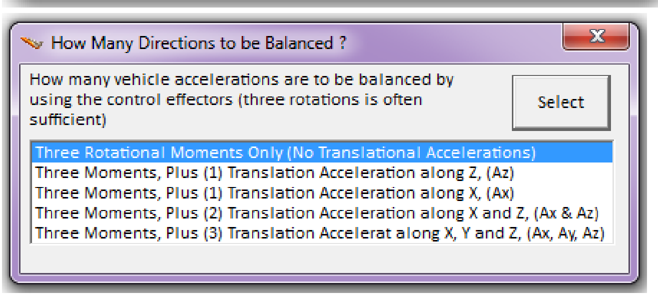
Sensed Acceleration in (ft/sec^2), Lifting-Body Aircraft Descent Trajectory
Accel-Z
Accel-Y
Accel-X
Thrust Force
Drag Force
Lift Force
Time (sec)

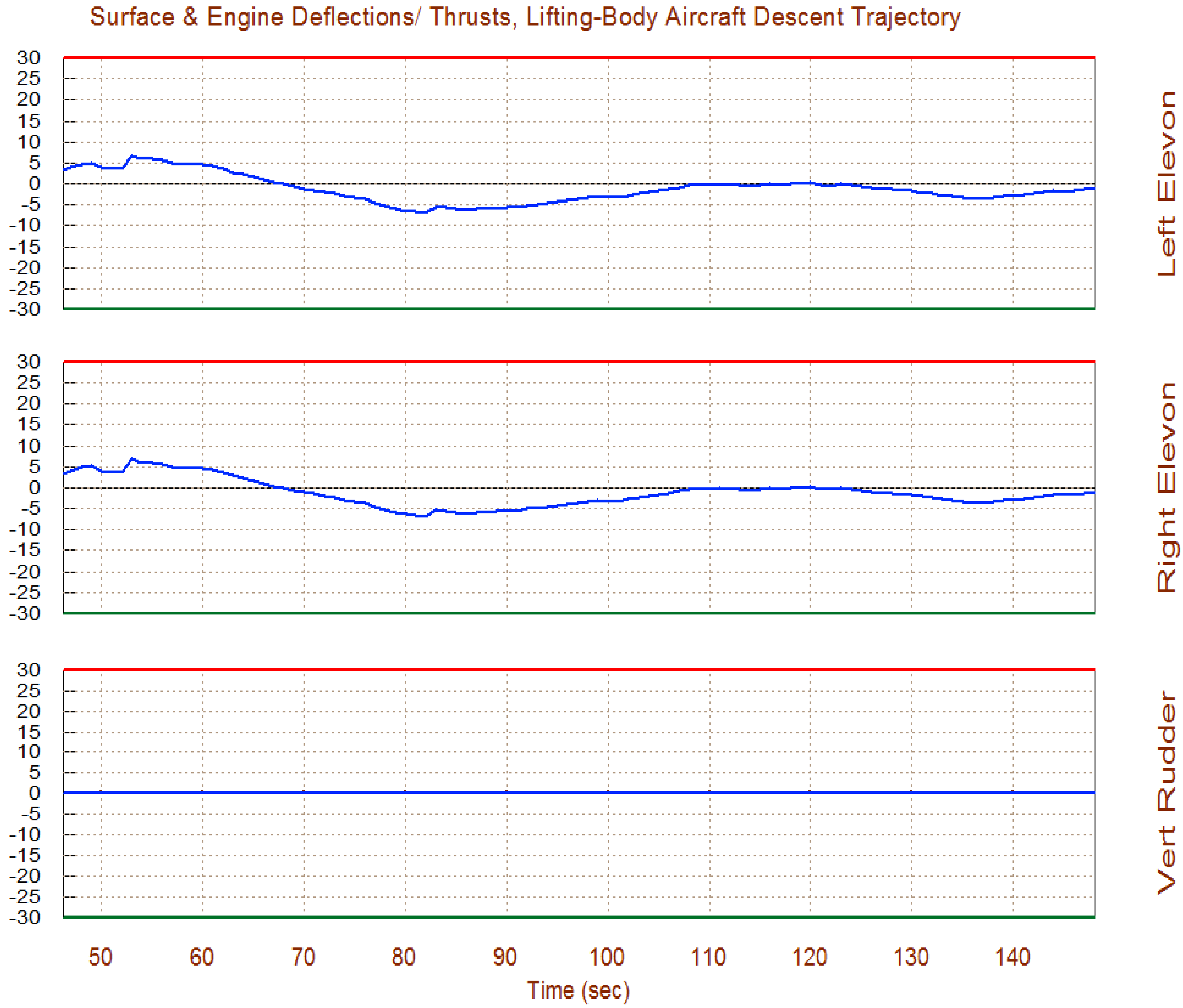
Trimming along the Descent Trajectory

The following plots show trimming positions of the 7 aero-surfaces along the descent part of the boost trajectory. Only the 3 moments are trimmed during this phase which is similar to the reentry phase.

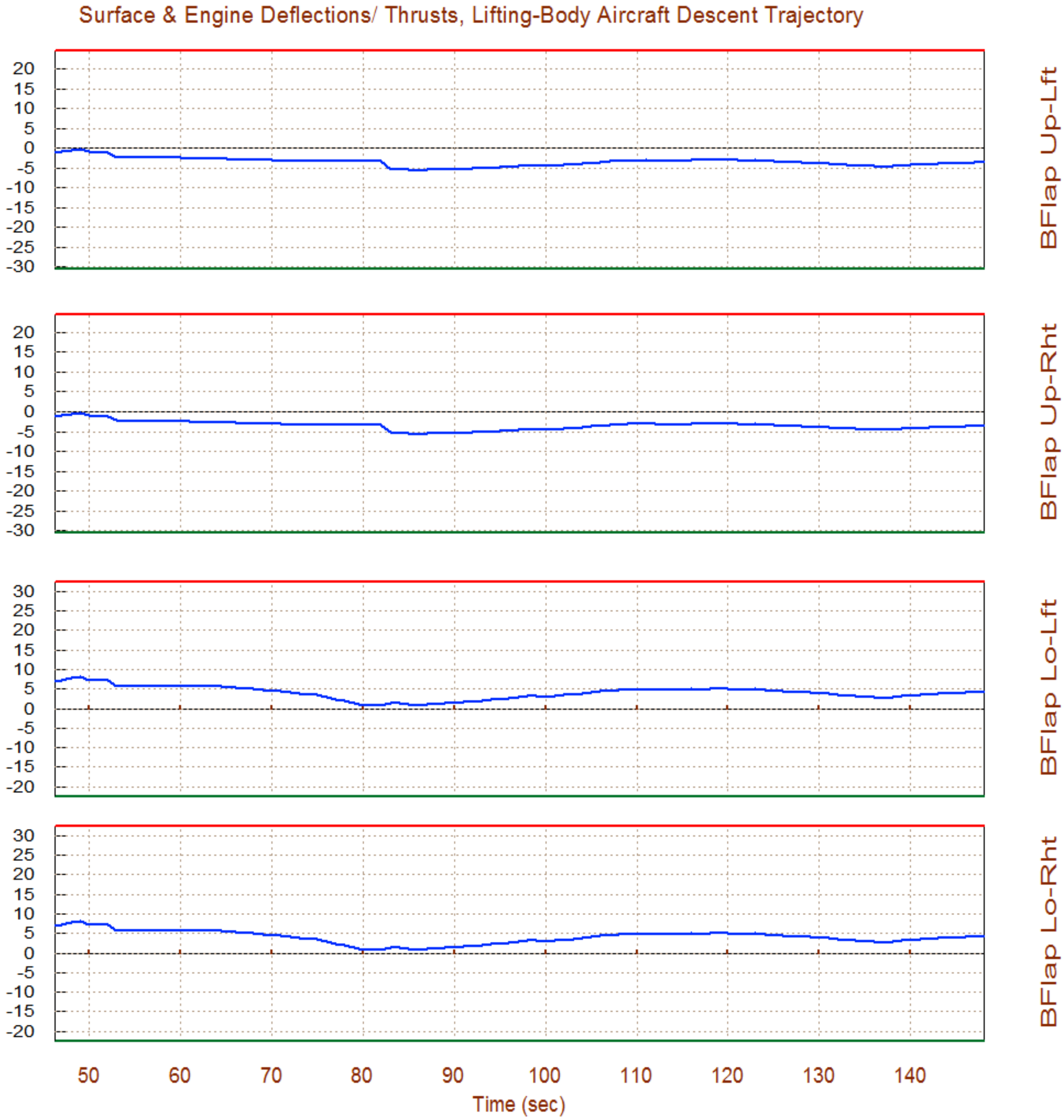






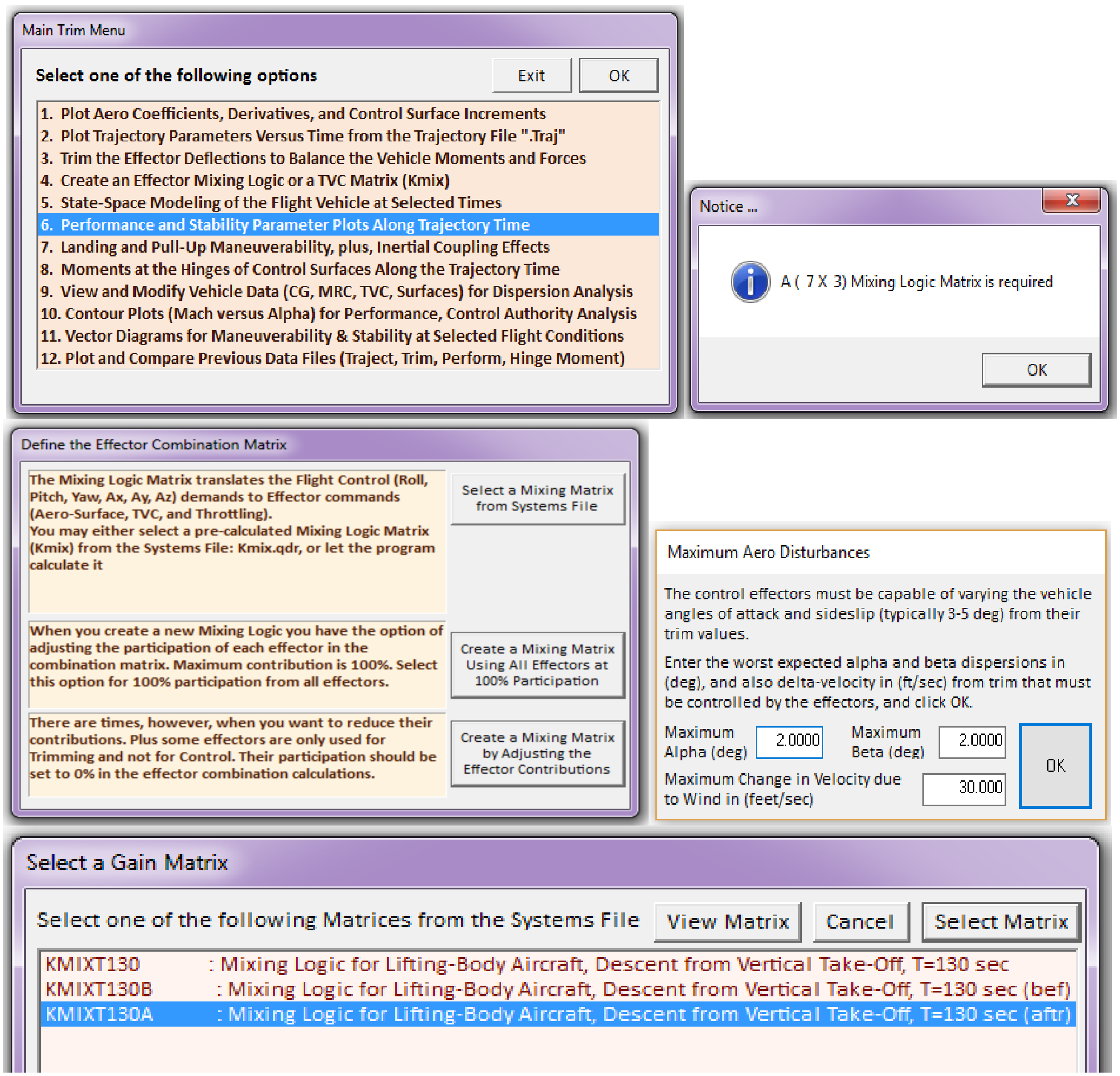


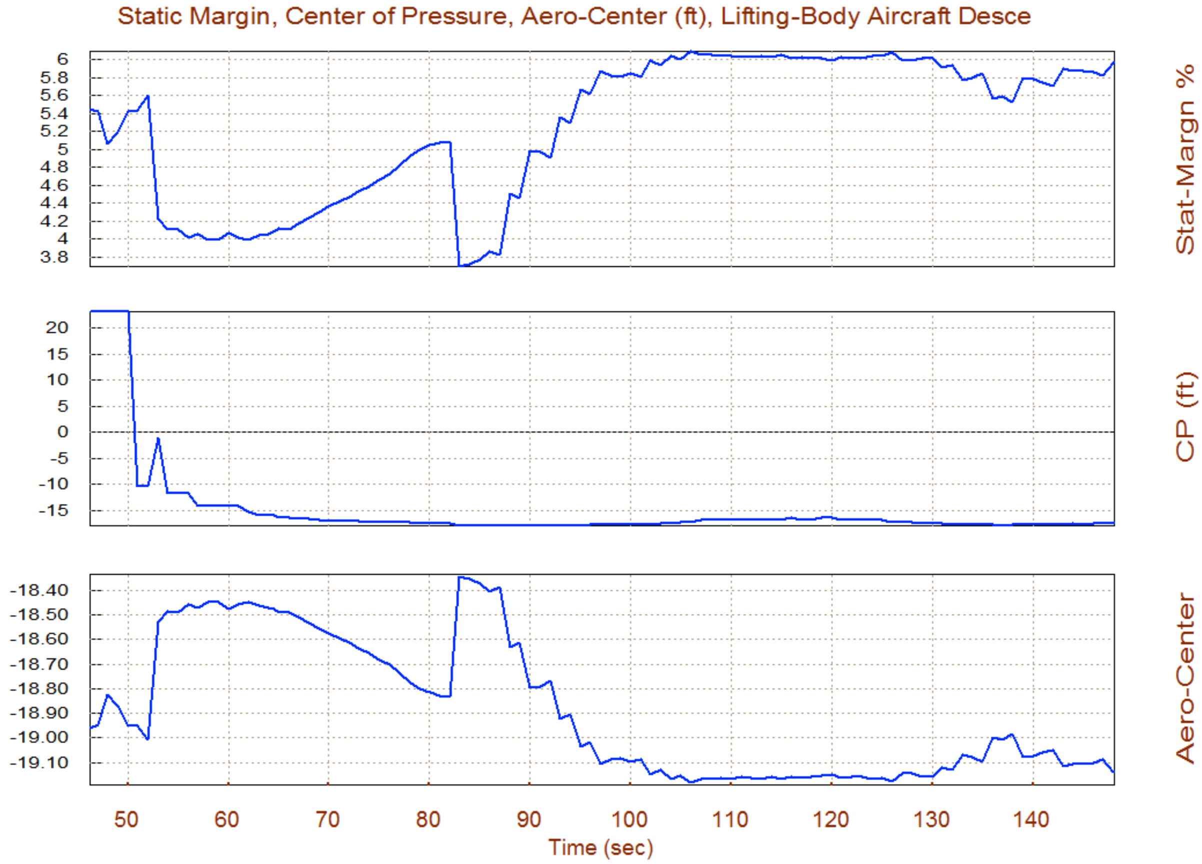
Notice that initially the vehicle base moment at α=2° is positive and, therefore, a negative pitching moment is required by the elevons and the lower body-flaps (positive deflections) in order to trim. As the angle of attack increases towards α=14° the base vehicle moment becomes negative and the elevon deflections become negative to produce a positive pitch moment to trim. The upper body-flaps also deflect negative while the lower body-flaps move closer to zero to help trimming.


Surface & Engine Deflections/ Thrusts, Lifting-Body Aircraft Descent Trajectory
BFlap Up-Lft
BFlap Up-Rht
BFlap Lo-Lft
BFlap Lo-Rht
Time (sec)

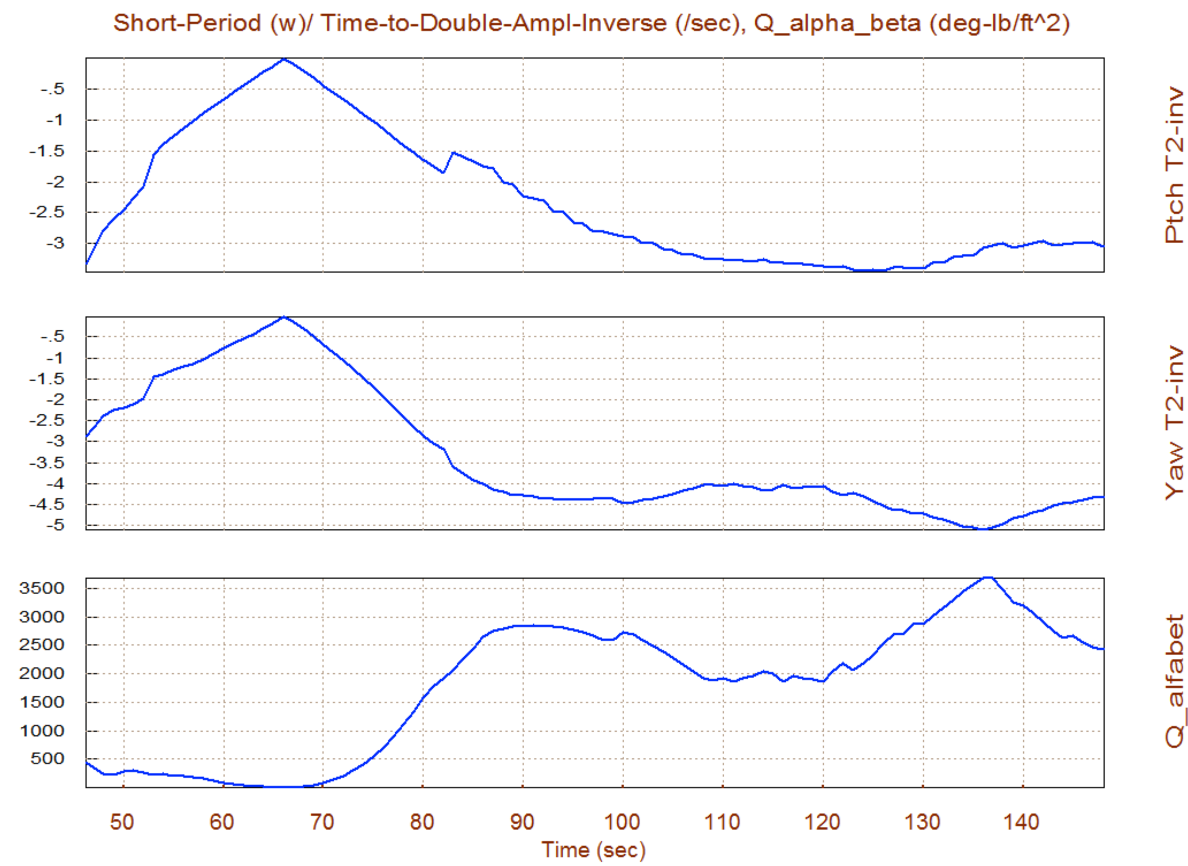
Performance Parameters along the Trajectory

From the Trim main menu select option-6 to analyze the vehicle static stability and performance parameters along the descent trajectory. Before evaluating the vehicle performance, however, the program needs to know the mixing-logic matrix that combines the 7 surfaces together in order to control roll, pitch, and yaw, and the control authority strongly depends on this matrix. The matrix KmixT130a is selected from file "Kmix.Qdr". We must also define the maximum $\pm\alpha_{max}$ and $\pm\beta_{max}$ dispersion angles, which are both set to 2° in this case and the maximum air-speed variation $\pm V_{max}$=30 (feet/sec).

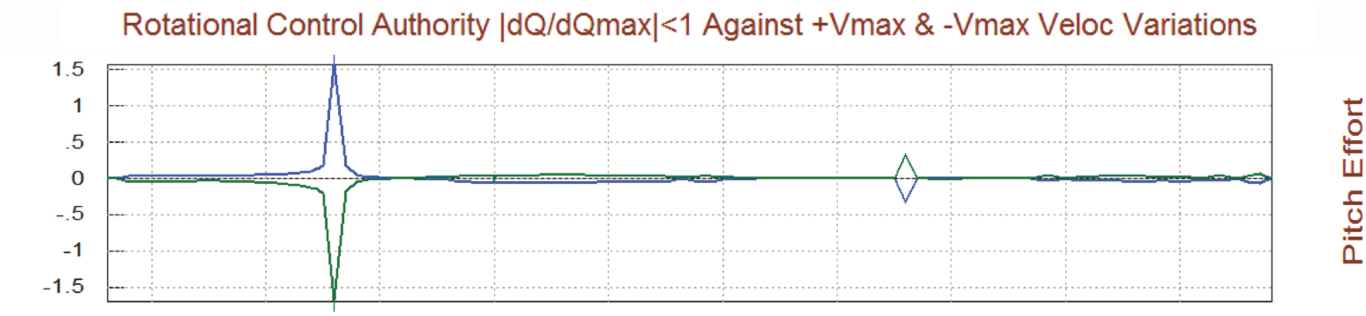


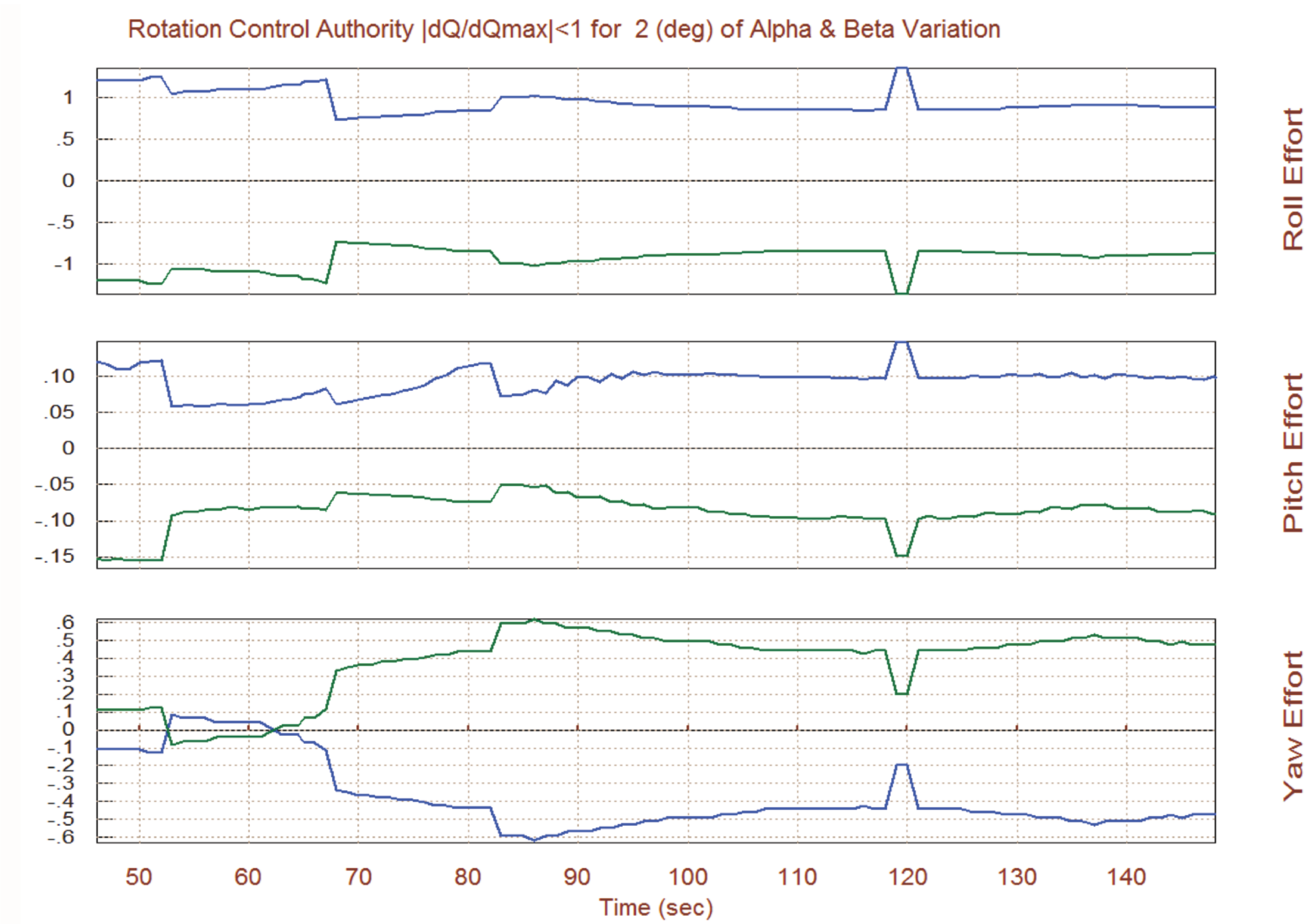


Static Margin, Center of Pressure, Aero-Center (ft), Lifting-Body Aircraft Desce
Stat-Margn %
CP (ft)
Aero-Center
Time (sec)



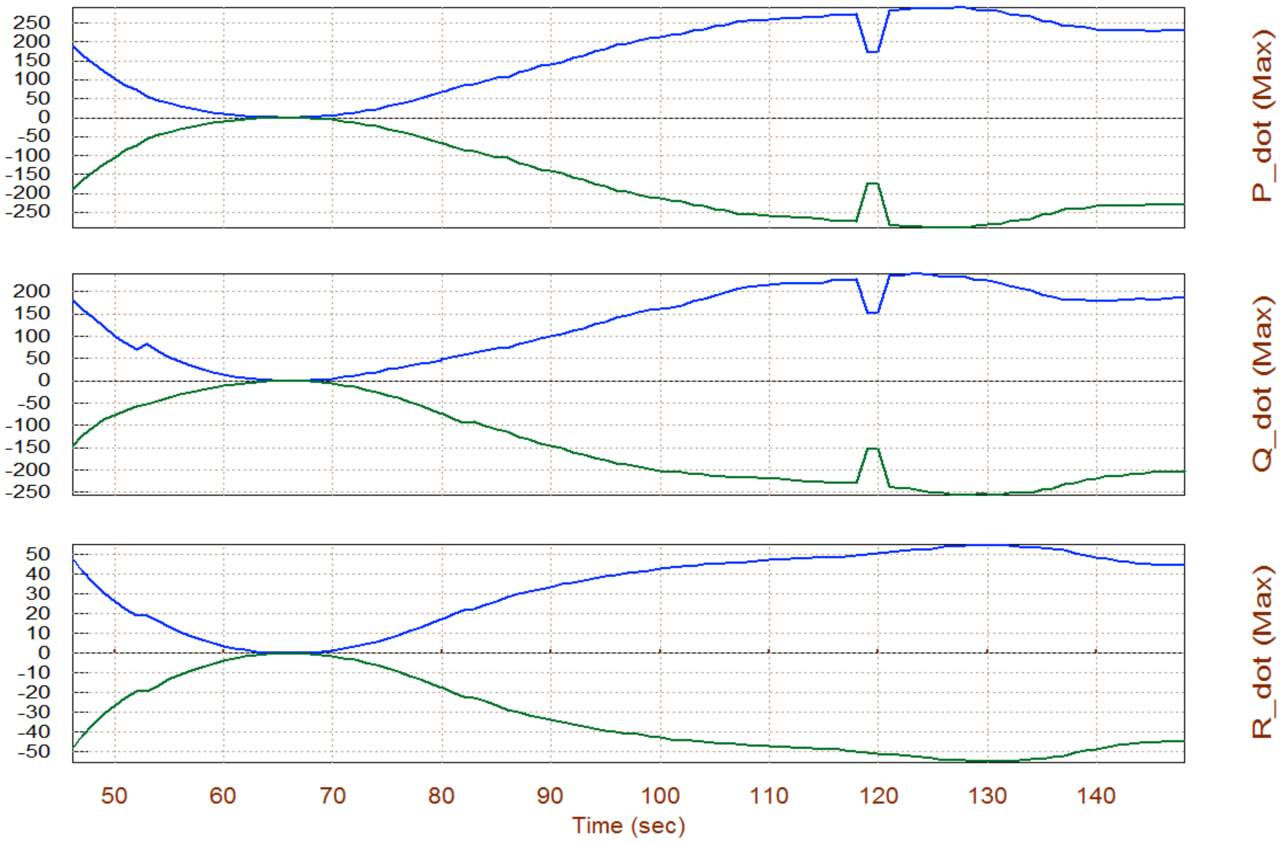
Short-Period (w)/ Time-to-Double-Ampl-Inverse (/sec), Q_alpha_beta (deg-lb/ft^2)
Ptch T2-inv
Yaw T2-inv
Q_alfabet
Time (sec)



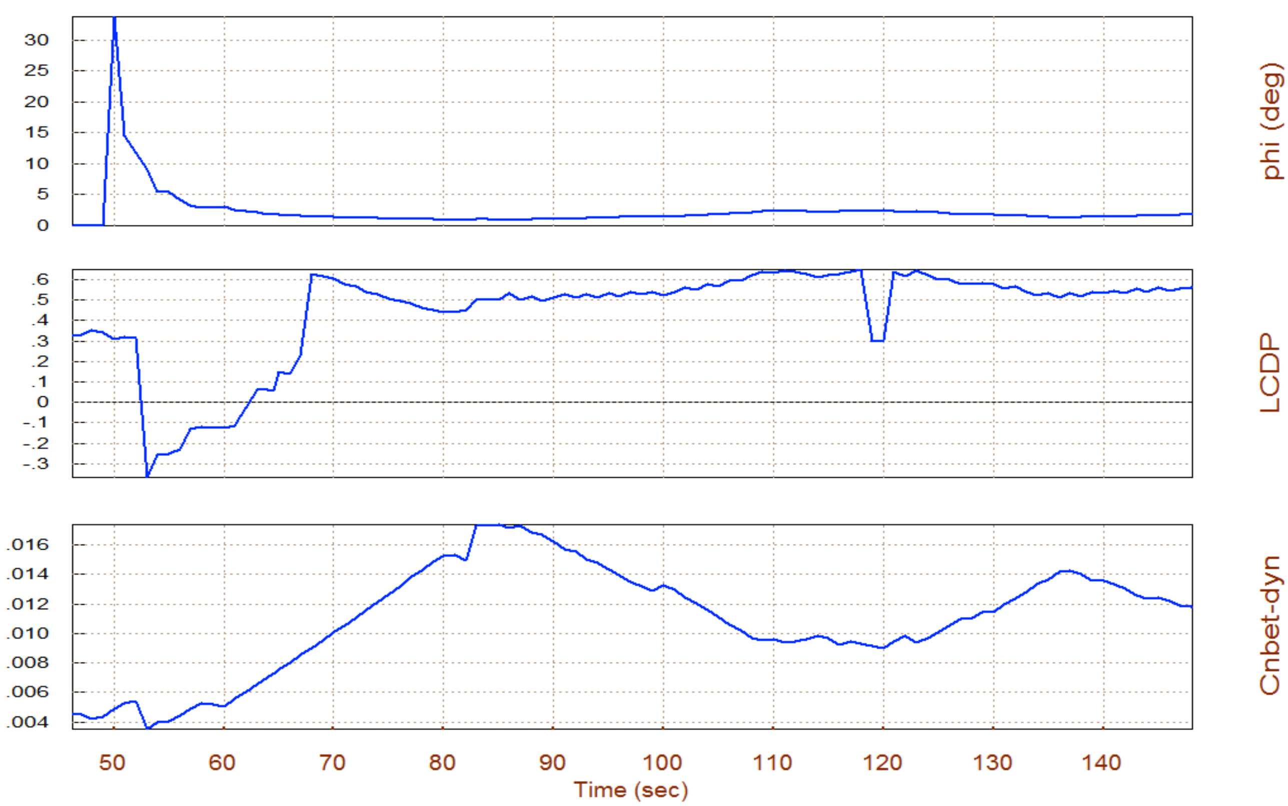


The control authority against α_{max} and β_{max} variations is good in the pitch and yaw axes. In the roll axis, however, it is not that great, but it was expected because of the dihedral lifting-body shape. It means that it will be a little sensitive to winds in roll, but still able to be maneuvered to its destination. At 60 seconds it is also sensitive to airspeed variations because the control effort exceeds 1. This is because the dynamic pressure drops to zero at this point and makes the aerosurfaces ineffective. This is also obvious in the maximum acceleration figures that show the control acceleration dropping to zero. It means that you have to rely on the RCS during this short period, for control and also to perform the 180^o pitch maneuver (from facing up to facing down). The LCDP is good after 70 seconds, but it is transitioning between positive and negative at times between 50 and 68 seconds, which makes it unreliable for roll control. This is another reason having to rely on RCS for roll control during this period. The bank angle (ϕ) for landing with β_{max} cross-wind disturbance is acceptable.

Max Angular Accelerations (rad/sec^2), at Maximum +ve and -ve Control Demands



Bank Angle, LCDP Ratio, Cn_beta_dynam /deg, Lifting-Body Aircraft Descent Trajec

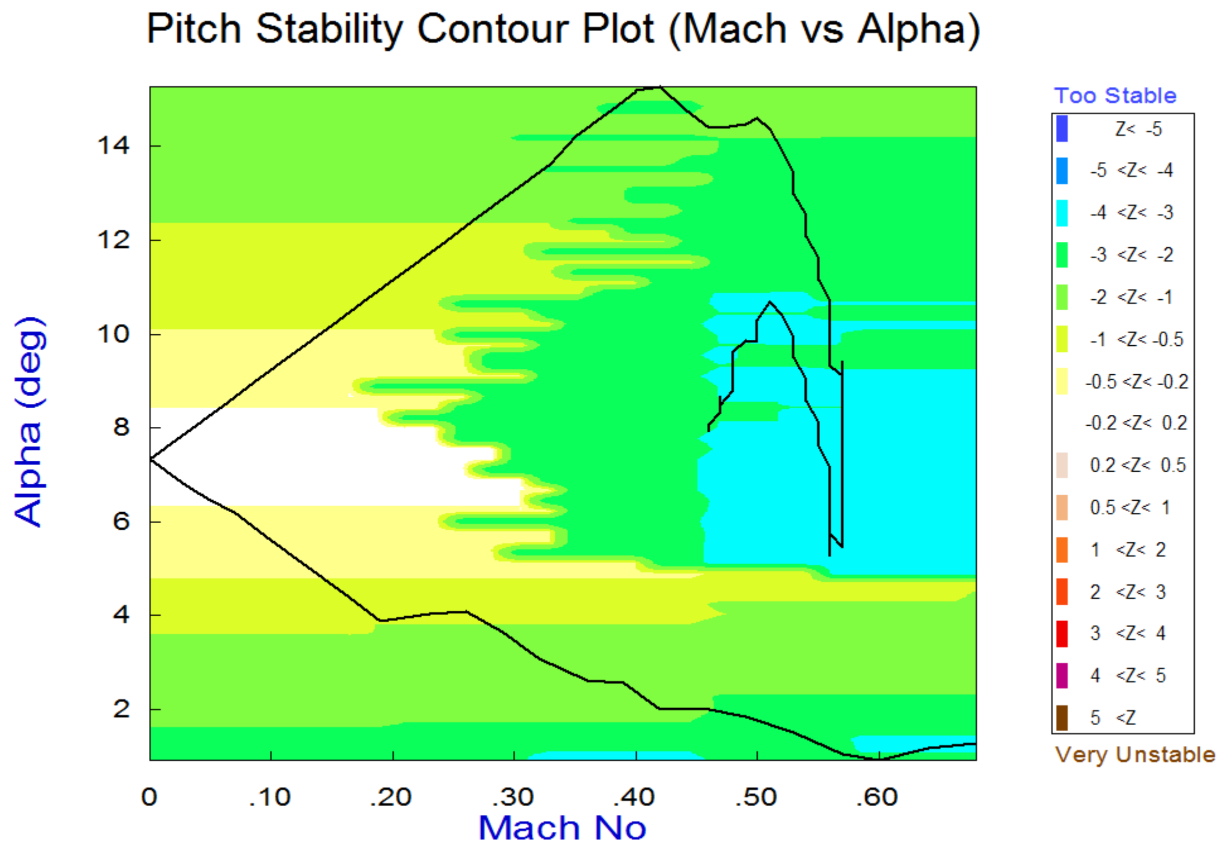


Contour Plots Analysis

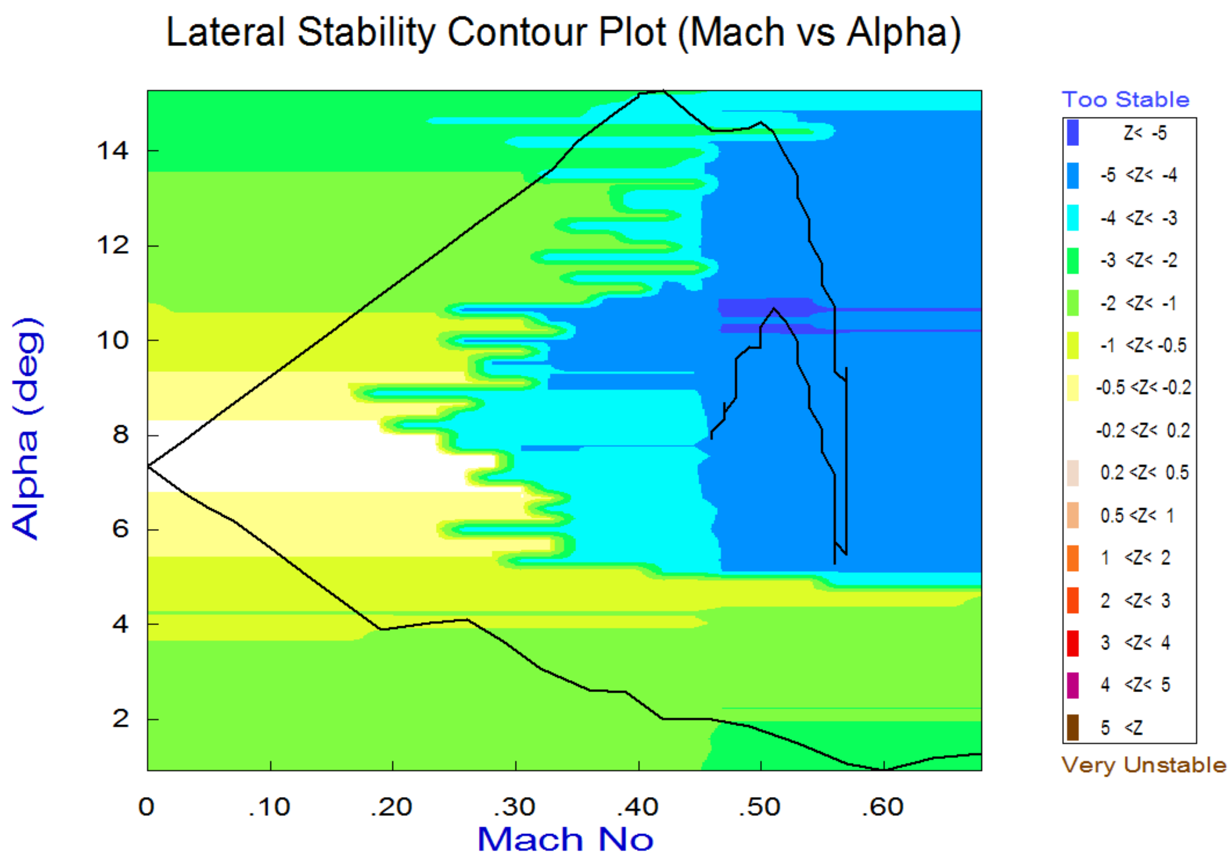
"Contour-plots" is the 10th option in the Trim main menu and it allows us to check some of the most important performance parameters over the entire Mach versus Alpha range. As we already mentioned, these parameters depend on the effector mixing-logic matrix so we must, therefore, select again matrix KmixT130a from file "Kmix.Qdr".

The first two contour plots show the pitch and lateral stability parameter (T2-inverse) in the entire Mach versus alpha range, and they are similar. The trajectory is shown by the dark line beginning in the lower right-hand corner where alpha is 2° and Mach is 0.65. The stability parameter is negative in both pitch and lateral indicating that the vehicle is stable with a short-period and a Dutch-roll resonance beginning at 3 (rad/sec) and temporarily dropping to zero in the white neutrally stable region on the left side. This is where the vehicle reaches its highest altitude and the speed is reduced to zero. The trajectory continues as the vehicle begins to drop and it terminates with an alpha of 8° and a Mach of 0.45. The short-period resonance does not exceed 4 (rad/sec) but the Dutch-roll resonance temporarily exceeds 5 (rad/sec).

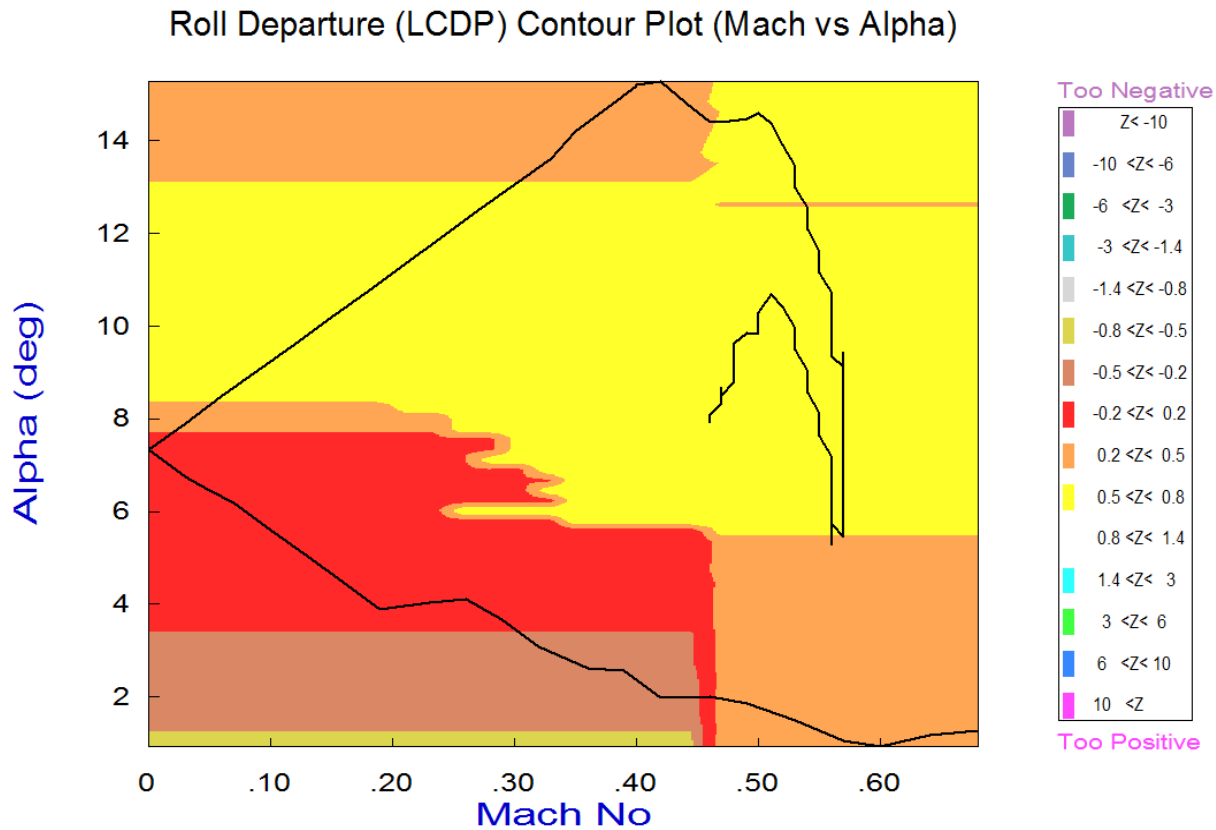
The LCDP ratio which is a measure of dynamic roll controllability was adjusted by the mixing-logic matrix to achieve positive LCDP values when the vehicle is descending, that is, when the γ angle is negative, or at times $t>68$ sec. A different mixing-logic matrix is needed for times $t<68$ sec. The control authority in pitch and yaw is very good in both directions because the magnitude of the control effort is much less than one. The control authority, however, in roll is marginal.

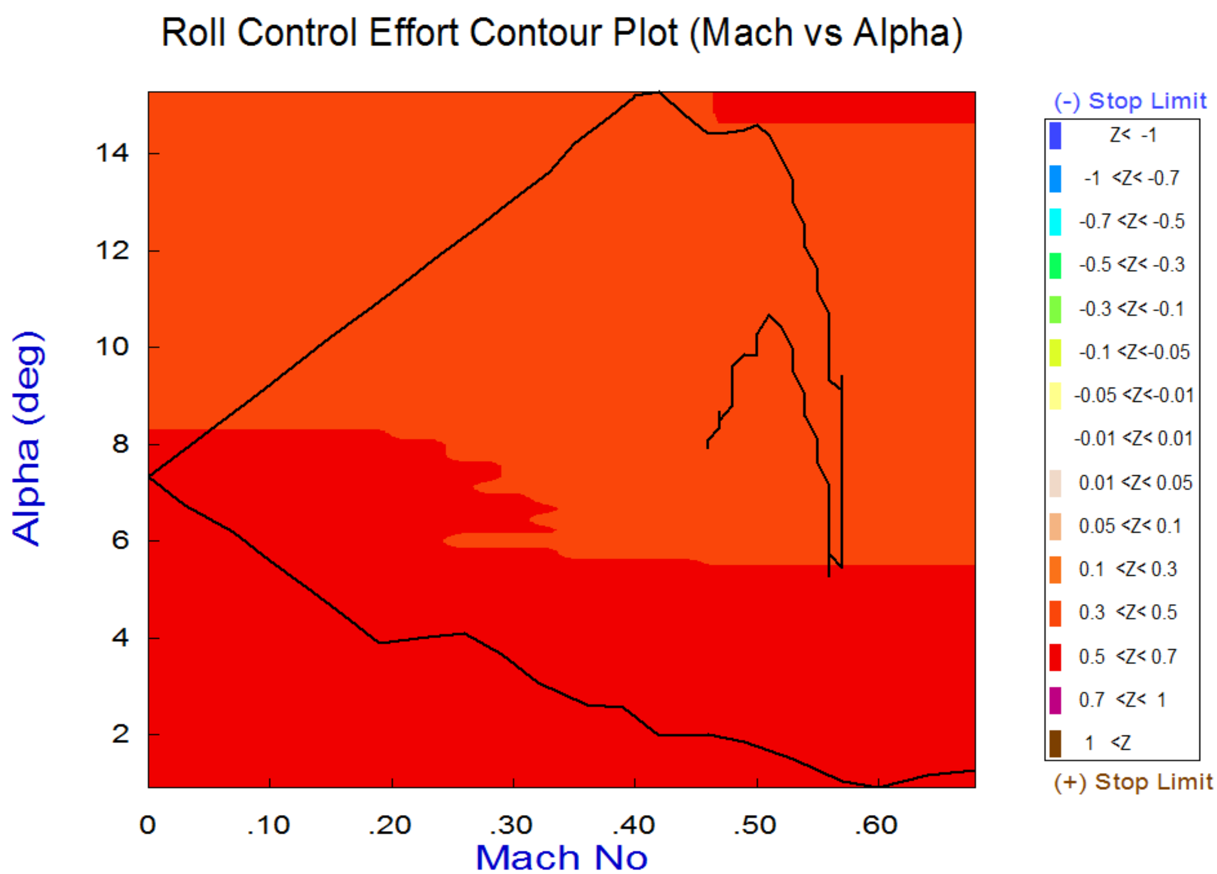


Pitch Stability Contour Plot (Mach vs Alpha)
Alpha (deg)
14
12
10
8
6
4
2
0
.10
.20
.30
.40
.50
.60
Mach No
Too Stable
Z< -5
-5 <Z< -4
-4 <Z< -3
-3 <Z< -2
-2 <Z< -1
-1 <Z< -0.5
-0.5 <Z< -0.2
-0.2 <Z< 0.2
0.2 <Z< 0.5
0.5 <Z< 1
1 <Z< 2
2 <Z< 3
3 <Z< 4
4 <Z< 5
5 <Z
Very Unstable

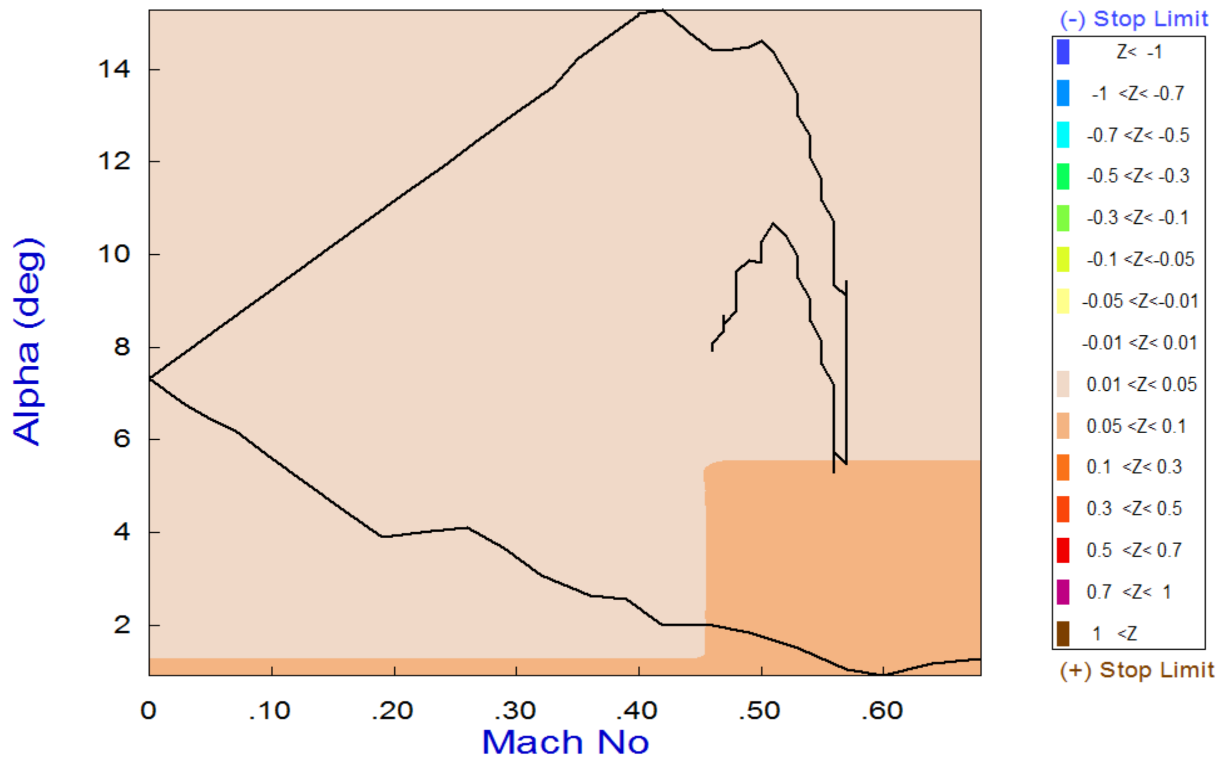


Lateral Stability Contour Plot (Mach vs Alpha)
Alpha (deg)
14
12
10
8
6
4
2
0
.10
.20
.30
.40
.50
.60
Mach No
Too Stable
Z< -5
-5 <Z< -4
-4 <Z< -3
-3 <Z< -2
-2 <Z< -1
-1 <Z< -0.5
-0.5 <Z< -0.2
-0.2 <Z< 0.2
0.2 <Z< 0.5
0.5 <Z< 1
1 <Z< 2
2 <Z< 3
3 <Z< 4
4 <Z< 5
5 <Z
Very Unstable

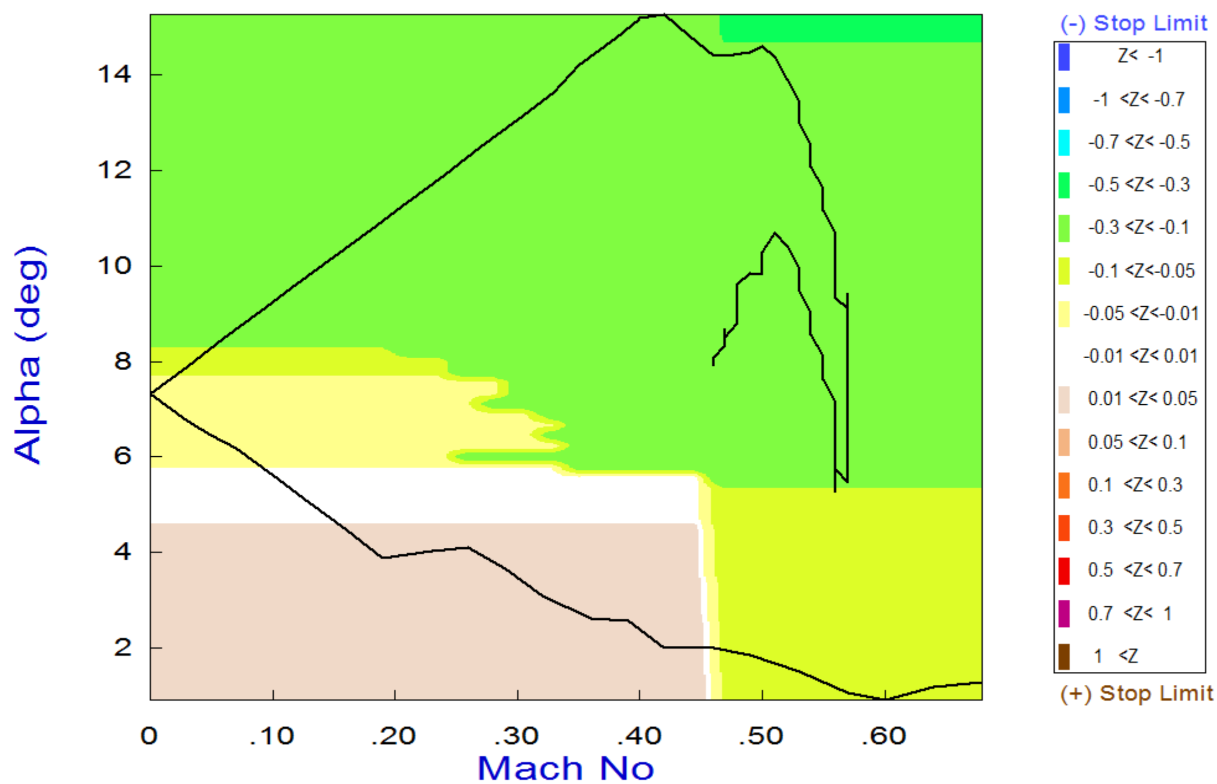

Roll Departure (LCDP) Contour Plot (Mach vs Alpha)
Alpha (deg)
Mach No
Too Negative
Z< -10
-10 <Z< -6
-6 <Z< -3
-3 <Z< -1.4
-1.4 <Z< -0.8
-0.8 <Z< -0.5
-0.5 <Z< -0.2
-0.2 <Z< 0.2
0.2 <Z< 0.5
0.5 <Z< 0.8
0.8 <Z< 1.4
1.4 <Z< 3
3 <Z< 6
6 <Z< 10
10 <Z
Too Positive


Roll Control Effort Contour Plot (Mach vs Alpha)
Alpha (deg)
Mach No
(-) Stop Limit
Z< -1
-1 <Z< -0.7
-0.7 <Z< -0.5
-0.5 <Z< -0.3
-0.3 <Z< -0.1
-0.1 <Z<-0.05
-0.05 <Z<-0.01
-0.01 <Z< 0.01
0.01 <Z< 0.05
0.05 <Z< 0.1
0.1 <Z< 0.3
0.3 <Z< 0.5
0.5 <Z< 0.7
0.7 <Z< 1
1 <Z
(+) Stop Limit

Pitch Control Effort Contour Plot (Mach vs Alpha)



Yaw Control Effort Contour Plot (Mach vs Alpha)




United States