Air Launched Rocket

In this example we have a booster rocket that is launched to orbit after being dropped from a carrier aircraft. The rocket has two stages and it carries an upper-stage payload. It is released from an altitude of 20,000 (ft) and it glides like an airplane for a while by means of a system of wings and tails that help it separate from the aircraft, provide lift and prevent it from losing altitude, and pointing it upwards before igniting a 400,000 (lb) booster engine. The wings and tails remain attached on the rocket for another 20 seconds providing lift and helping it to achieve a desirable flight path angle (γ). They separate at T=90 seconds and the vehicle continues to ascent into orbit like a typical booster rocket. At T=500 seconds the first stage separates and the second stage ignites. During the initial unpowered glide phase the vehicle is controlled by two elevons and a rudder located in the tail section. The wing has no controls. During the boost phase the vehicle is controlled by the TVC engine in pitch and yaw and also by the aero-surfaces. After the wings and tails separate a pair of RCS jets is used to control the vehicle in roll.

This operation consists of several phases, but in this example we will analyze only the first three phases during first stage:

1. Underlined: Unpowered Glide Phase. This phase is unpowered, from T=(0 through 72) seconds. That is, from the carrier aircraft separation to first stage engine ignition. The wing is attached on the vehicle and it uses three aero-surfaces for flight control which are located in the tail section. The aileron for roll control, the elevon for pitch, and the rudder for yaw control.

2. Boost Phase with Wings and Tails: This phase runs between T=(72 to 90) seconds, from stage-1 ignition to wing and tails separation. The TVC (thrust vector control) system is turned on while the vehicle retains its wings and tails for another 18 sec. In this phase the flight control system, in addition to the elevon and rudder, it also uses the TVC for pitch and yaw control. The aileron is used for roll control in combination with the rudder and TVC.

3. Boost Phase without Wings and Tails: This phase begins at wing and tail separation to first stage burnout. That is, between T=(90 to 150) seconds trajectory time. During this phase the rocket uses the TVC engine for pitch and yaw control and the two RCS jets for roll control.

This is a great example for demonstrating the capability of the Flixan/Trim program to analyze a vehicle that gradually transforms itself from an airplane to a rocket. The analysis data files are in directory "*C:\Flixan\Trim\Examples\Air Launched Vehicle*" and a detailed analysis will be performed for each phase in separate subdirectories. The analysis consists of trimming the effectors, stability, controllability against aero-disturbances, and an overall performance evaluation will be performed for each of the three phases separately. In addition, dynamic models will be created at specific flight conditions. The models will be used to design control laws, and the dynamic models will be used to perform Matlab simulations for each phase.
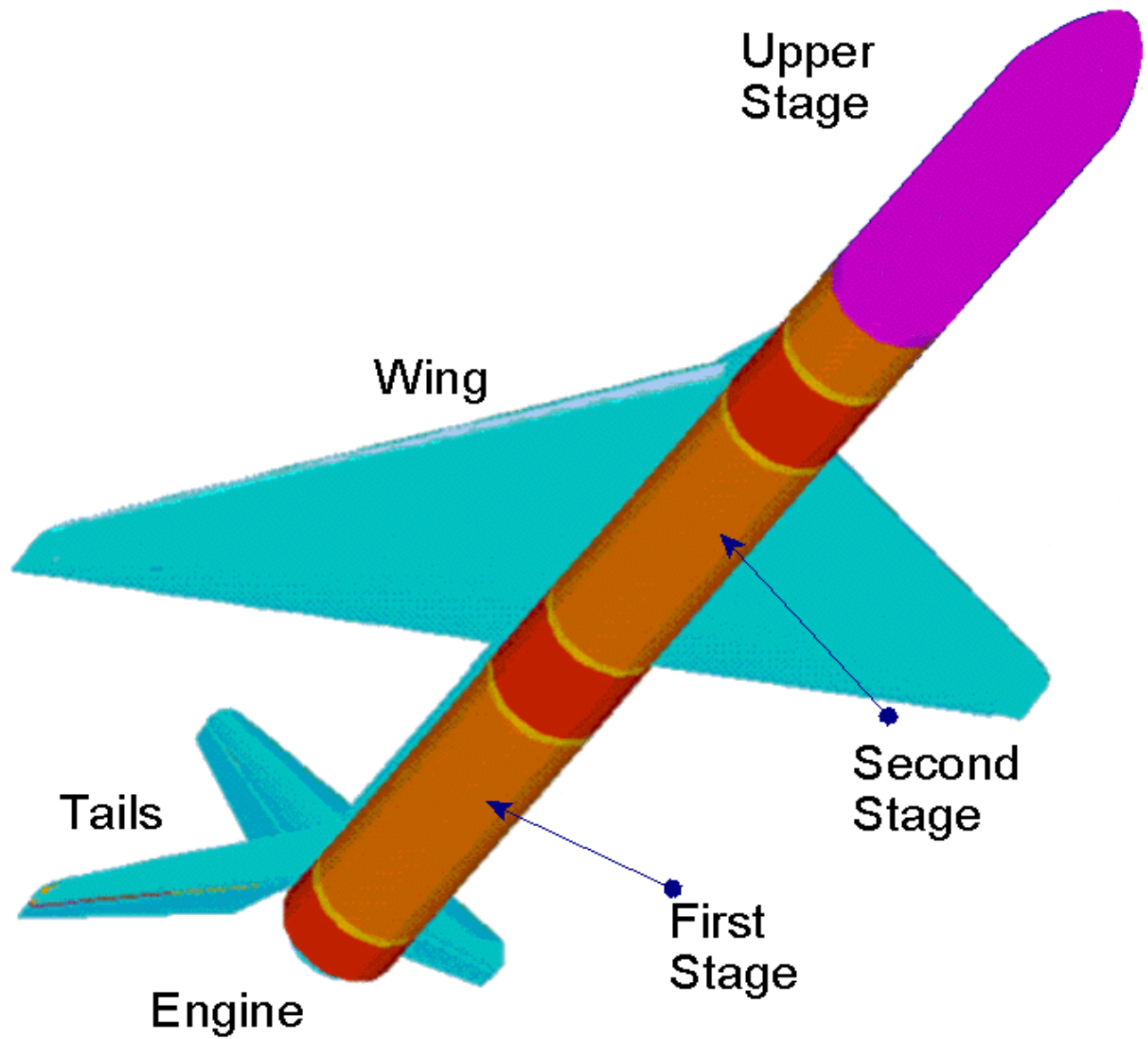
Figure 1 Air-Launched Rocket Vehicle
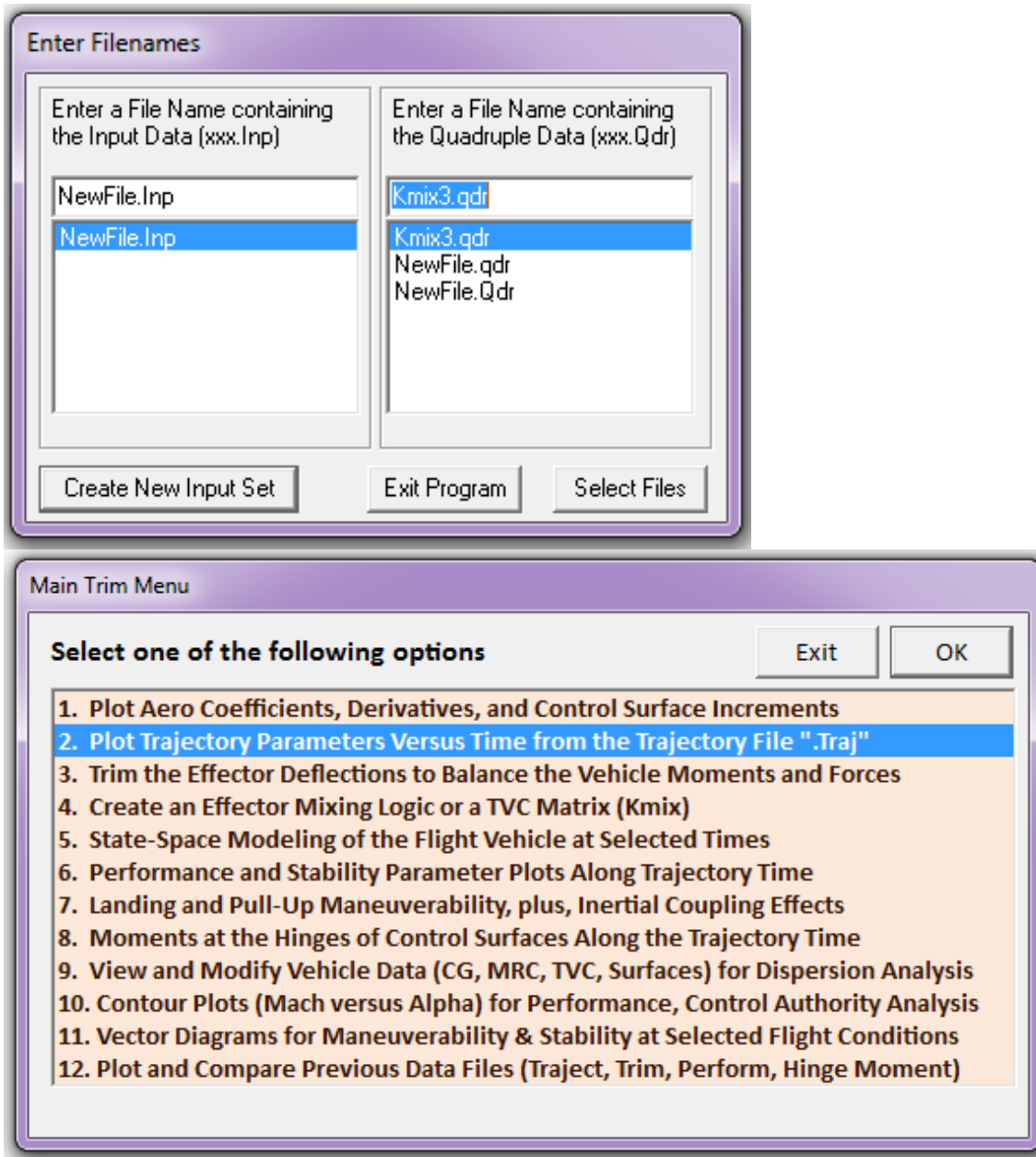
Unpowered Glide Phase with Wings and Tails

After being dropped from the carrier aircraft at an altitude of 24,000 (ft), during this phase the vehicle is gliding down using its wing and tails without an engine power for 72 seconds to a lower altitude. However, it is gaining speed and increasing its flight path angle before igniting the TVC engine. It is controlled by the Aileron, Elevon, and Rudder which are located in the tail section. The wings have no controls. The data files for the glide phase are in the subdirectory: "*C:\Flixan\ Trim\Examples\Air Launched Vehicle\Phase A Glide With Wing*". It includes the mass properties in file "*Air-Launch.Mass*", which contains weights and inertias for all phases. The mass data in the top line correspond to the glide phase and also the trajectory file "*AL_Glide.Traj*" which contains the trajectory parameters between zero and 72 seconds. The mass is constant (10,550 slugs) and the thrust is zero during this unpowered phase. The file "*Wing_On_Bas.Aero*" contains the basic aero data with the wings and tails attached, which corresponds to 6 Mach numbers, 13 angles of attack, and 3 sideslip angles. The file "*AL_AeroSurf.Delt*" contains the aero-surface increment coefficients for the Elevon, the Aileron, and the Rudder. There is no thruster data file for this phase. The file "*Kmix3.qdr*" is just a scaling and aero-surface re-ordering matrix that will be used later in the analysis. The files "*Glide_Phase_T20.Inp*" and "*Glide_Phase_T20.Qdr*" contain the vehicle input data and dynamic models that will be used later in the closed-loop dynamic analysis.

Trajectory Analysis

Let us begin the analysis by taking a look at the trajectory. Start Flixan and select the project folder that contains the analysis files. Then, from the Flixan main menu select "*Analysis Tools*", "*Flight Vehicle/ Spacecraft Modeling Tools*", and then "*Trim/ Static Performance Analysis*". From the Trim filename selection menu select the following files.
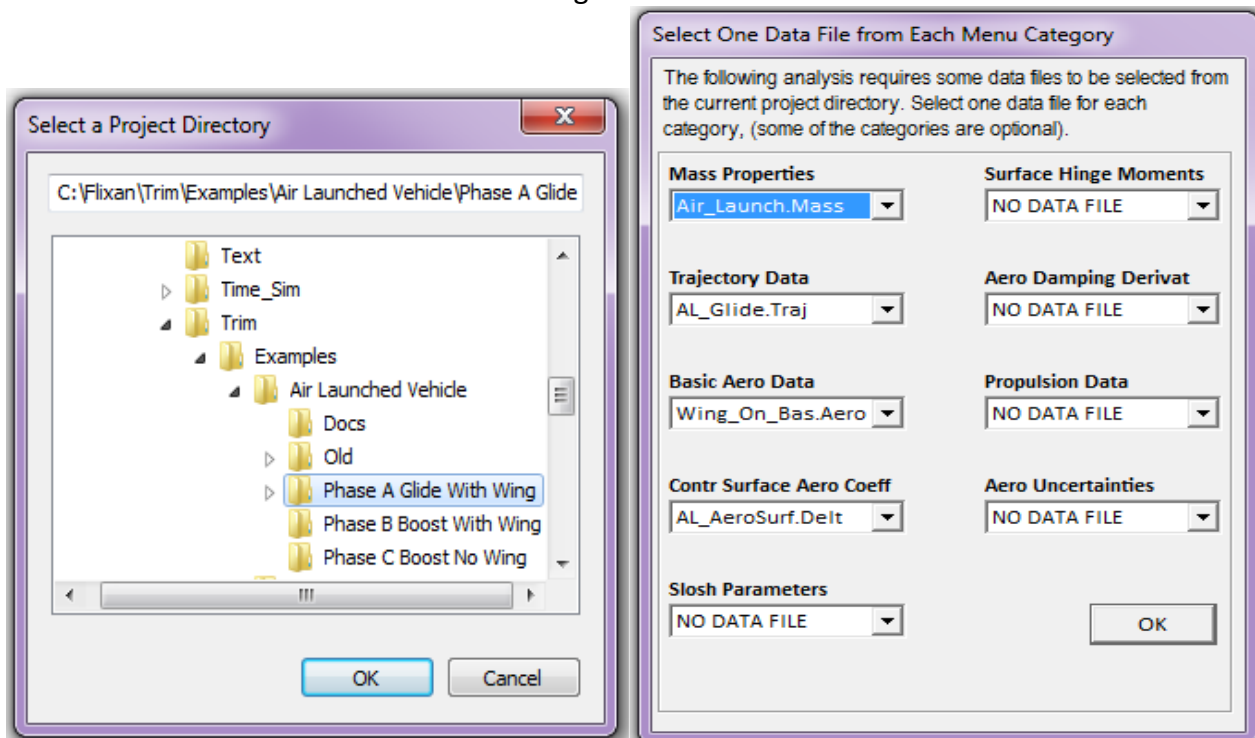
From the following filename selection menu select the file Kmix3.Qdr that contains the mixing logic matrix used for scaling and reordering the aero-surfaces, and from the Trim main menu select the 2nd option for plotting the trajectory data, as shown below.

Enter Filenames

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

NewFile.Inp
NewFile.Inp

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

Kmix3.qdr
Kmix3.qdr
NewFile.qdr
NewFile.Qdr

Create New Input Set   Exit Program   Select Files

Main Trim Menu

Select one of the following options   Exit   OK

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

The following plots show the trajectory parameters during this glide phase. The wings help achieve a $\gamma=+21°$ and $\alpha=+9°$ at an altitude of 14,000 (ft) before igniting the main engine. The normal load is 1.4 (g).
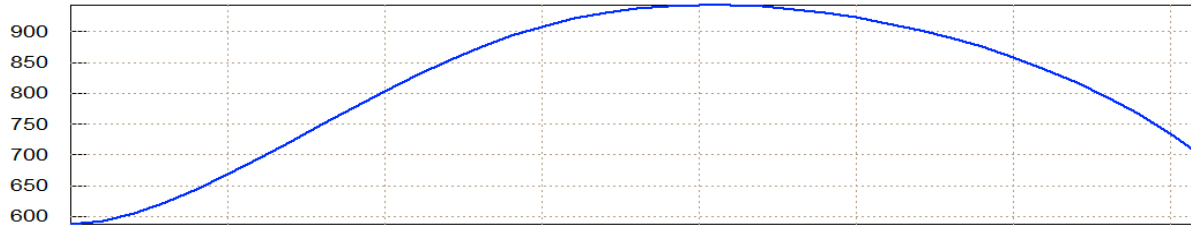
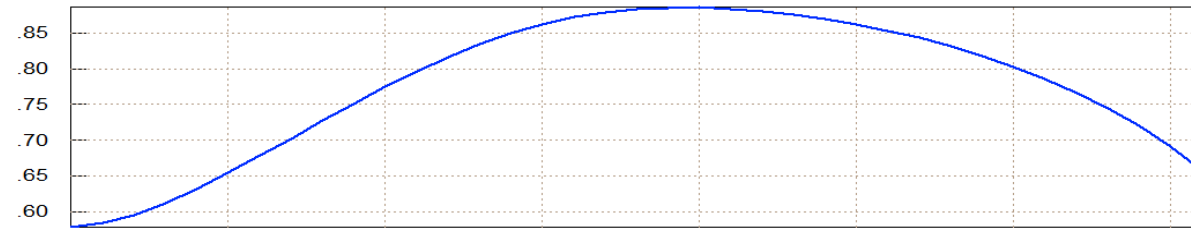## Angles of Attack/Sideslip/Flight Path (deg), Air Launched Vehicle Firs
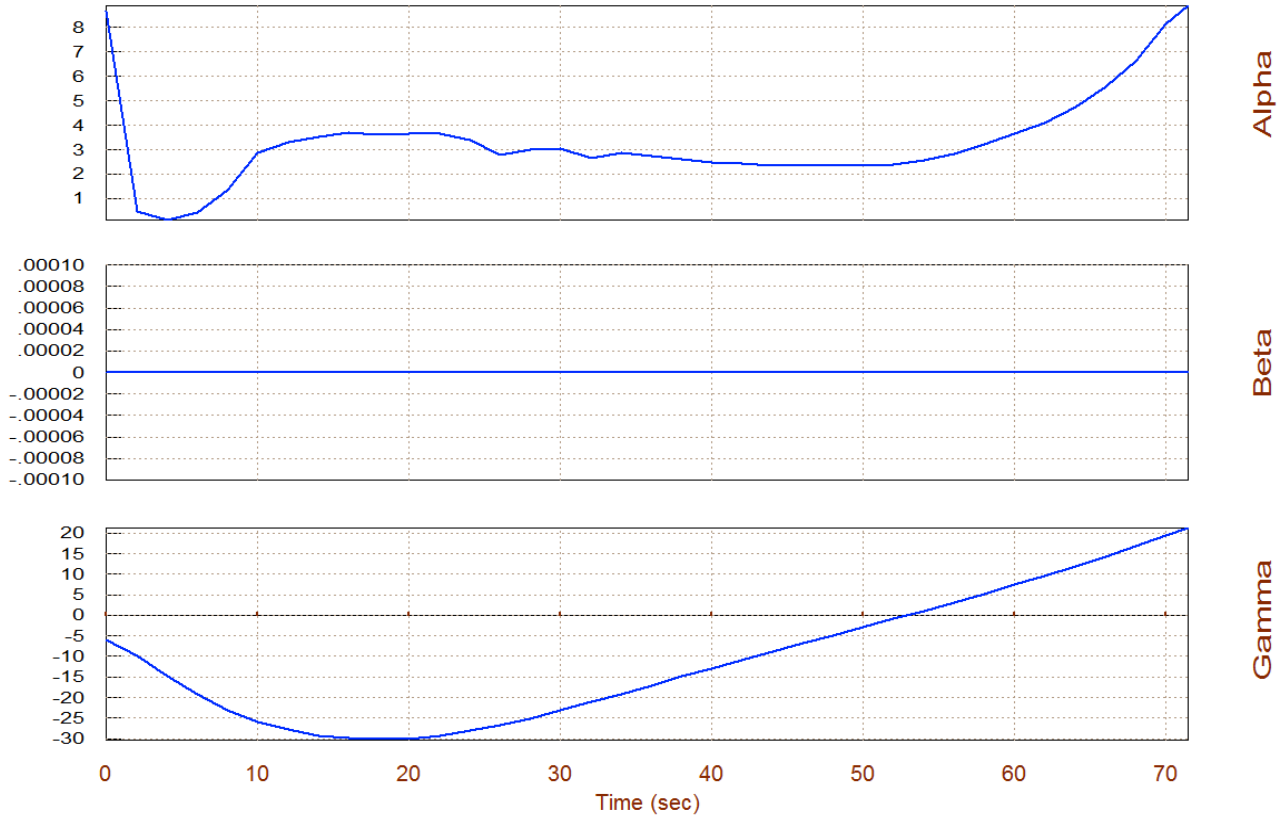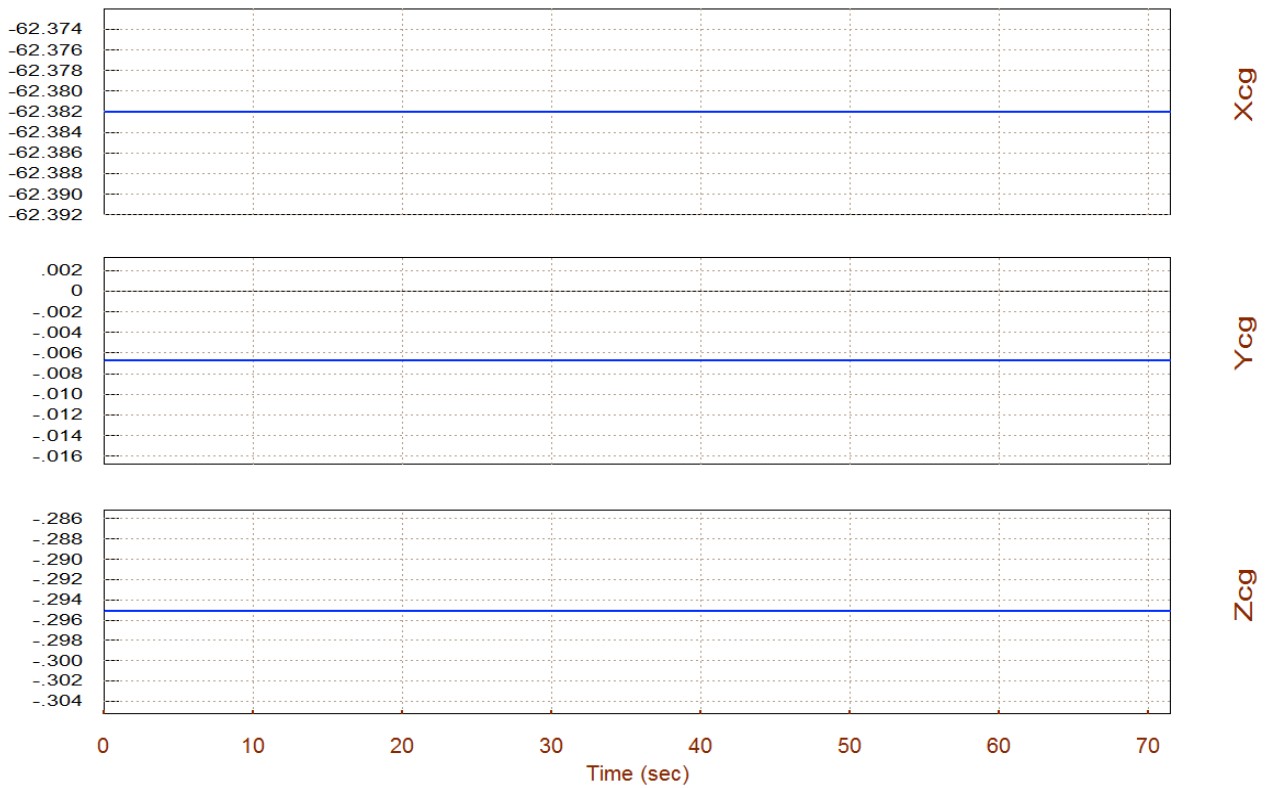
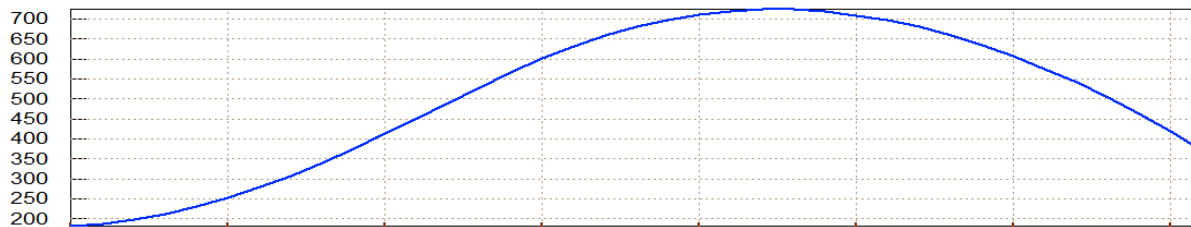## Vehicle CG in (feet), Air Launched Vehicle First Stage Glide Trajectory

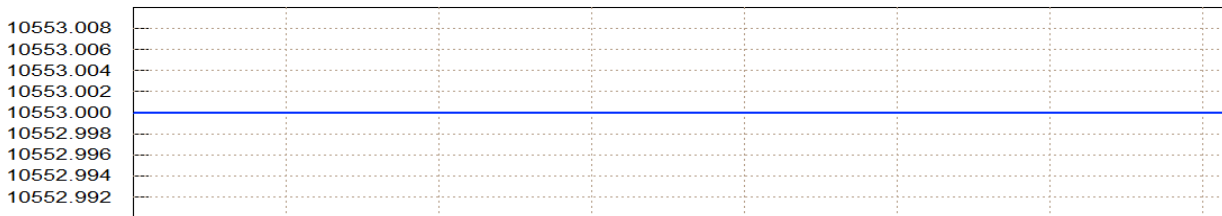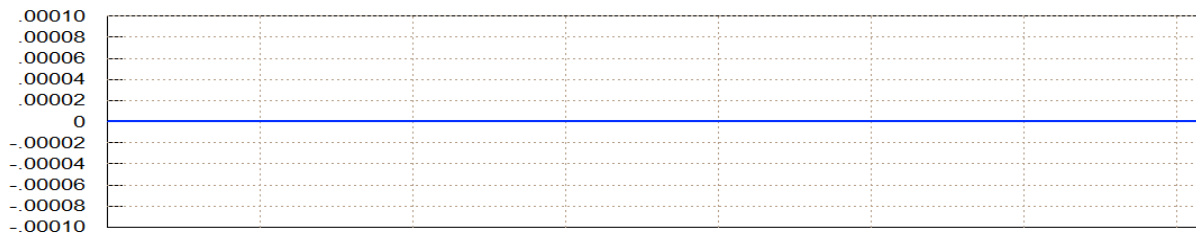## Velocity, Dynamic Pressure, Air Launched Vehicle First Stage Glide Trajectory
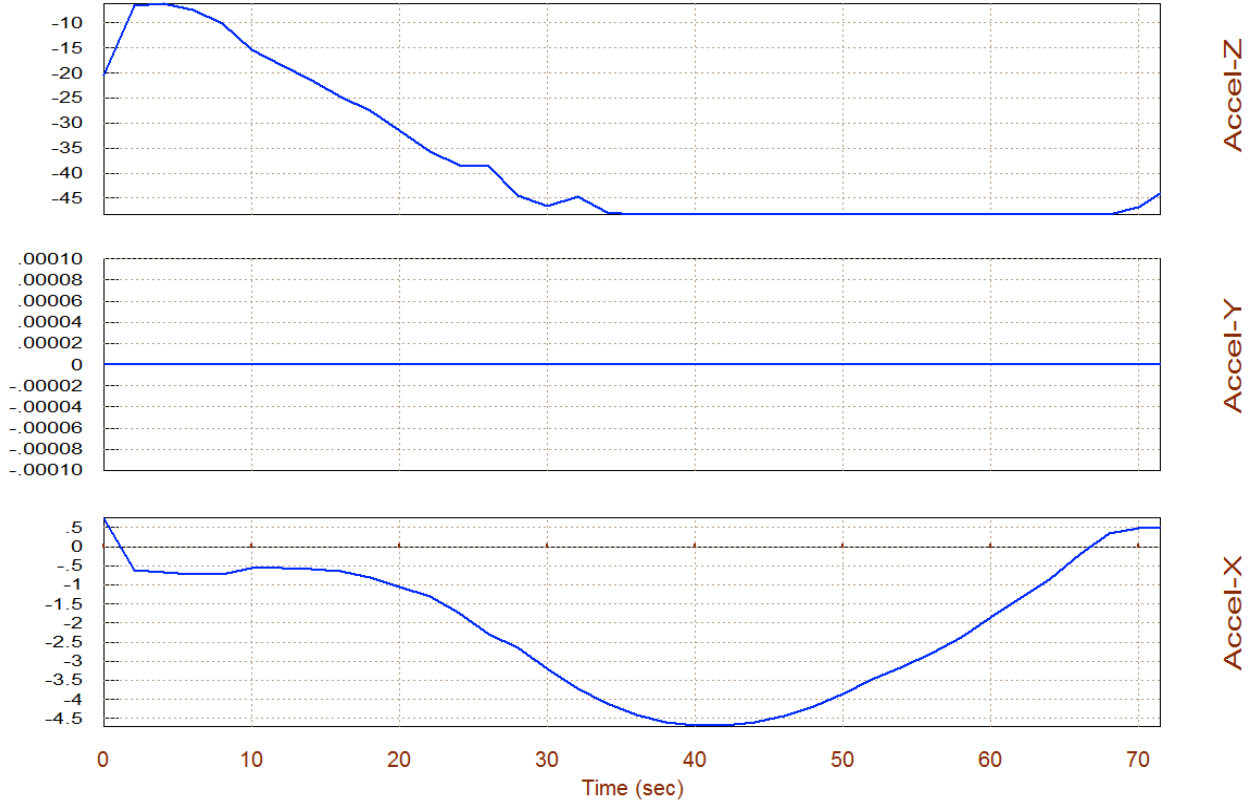

Vehicle Altitude, Mass, Bank Angle, Air Launched Vehicle First Stage G
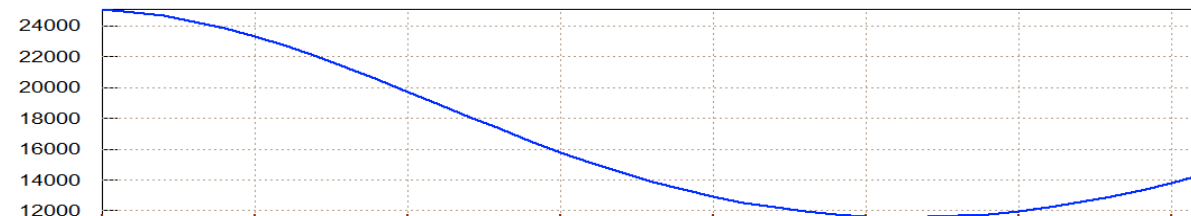
Sensed Acceleration in (ft/sec^2), Air Launched Vehicle First Stage Glide T

Aero Lift/Drag Forces, Eng. Thrust in (lb), Air Launched Vehicle First Stage
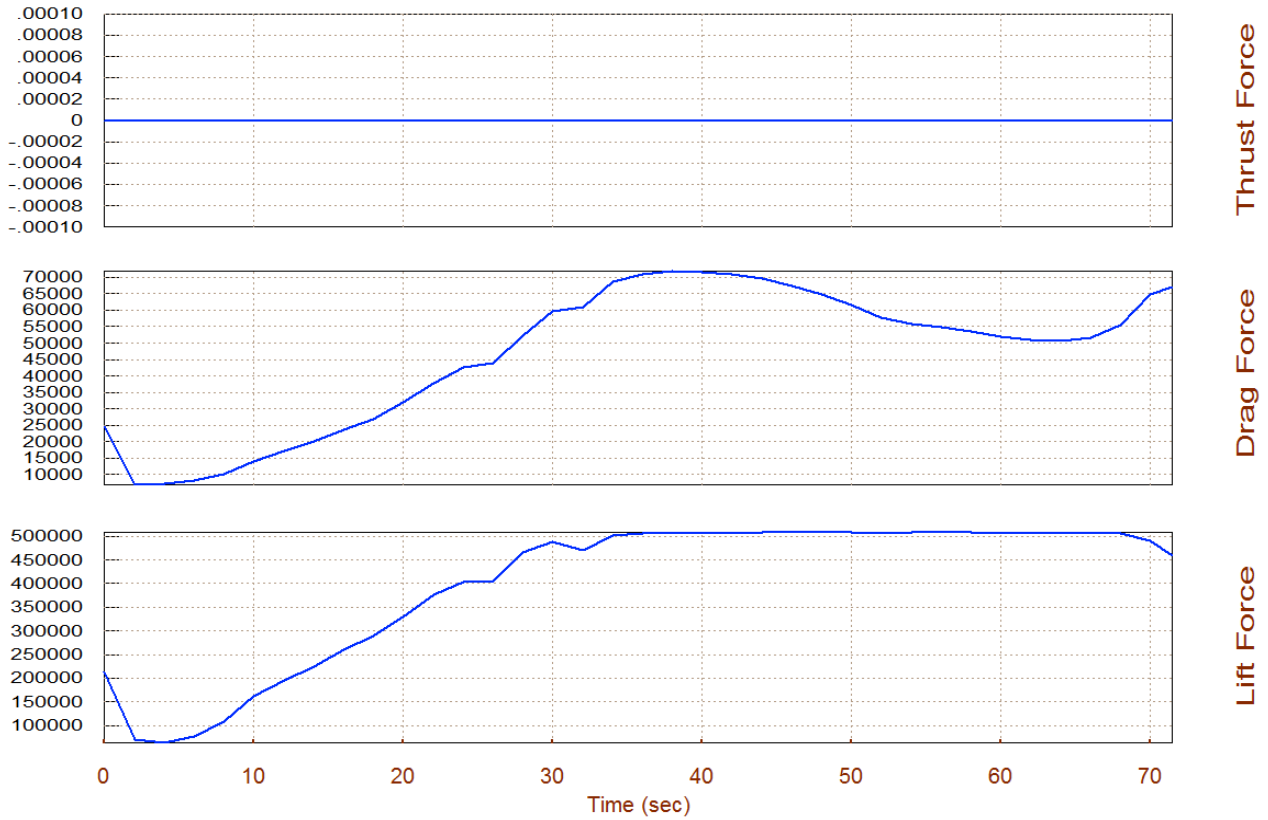
Trimming the Aero-Surfaces

The next step is to trim the aero-surfaces. That is, balancing the base moments with aero-surface moments along the trajectory. Return to the Trim main menu and choose the third option for trimming. Do not select an initialization file (if it is the first time you trim this trajectory), and trim only the three moments since in this case there are no translation control effectors.

Surface & Engine Deflections/ Thrusts, Air Launched Vehicle First Stage Glide Tr
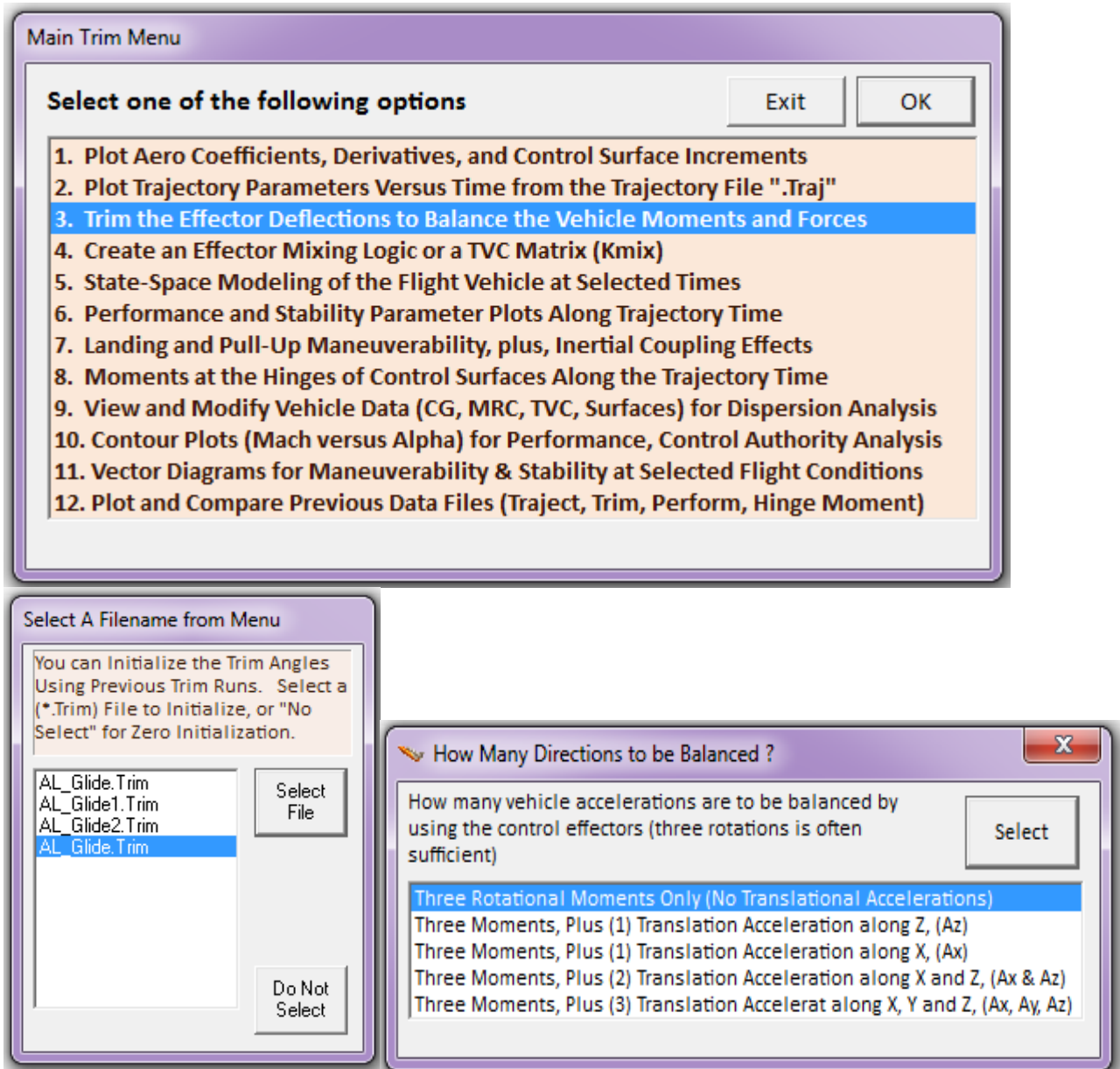
The trim results show that the vehicle uses some negative Elevon deflections to trim along the trajectory. Negative Elevon deflection is needed in order to balance the pitch moment created by the positive angle of attack. The Aileron and Rudder deflections are zero because there are no lateral disturbances in this case.
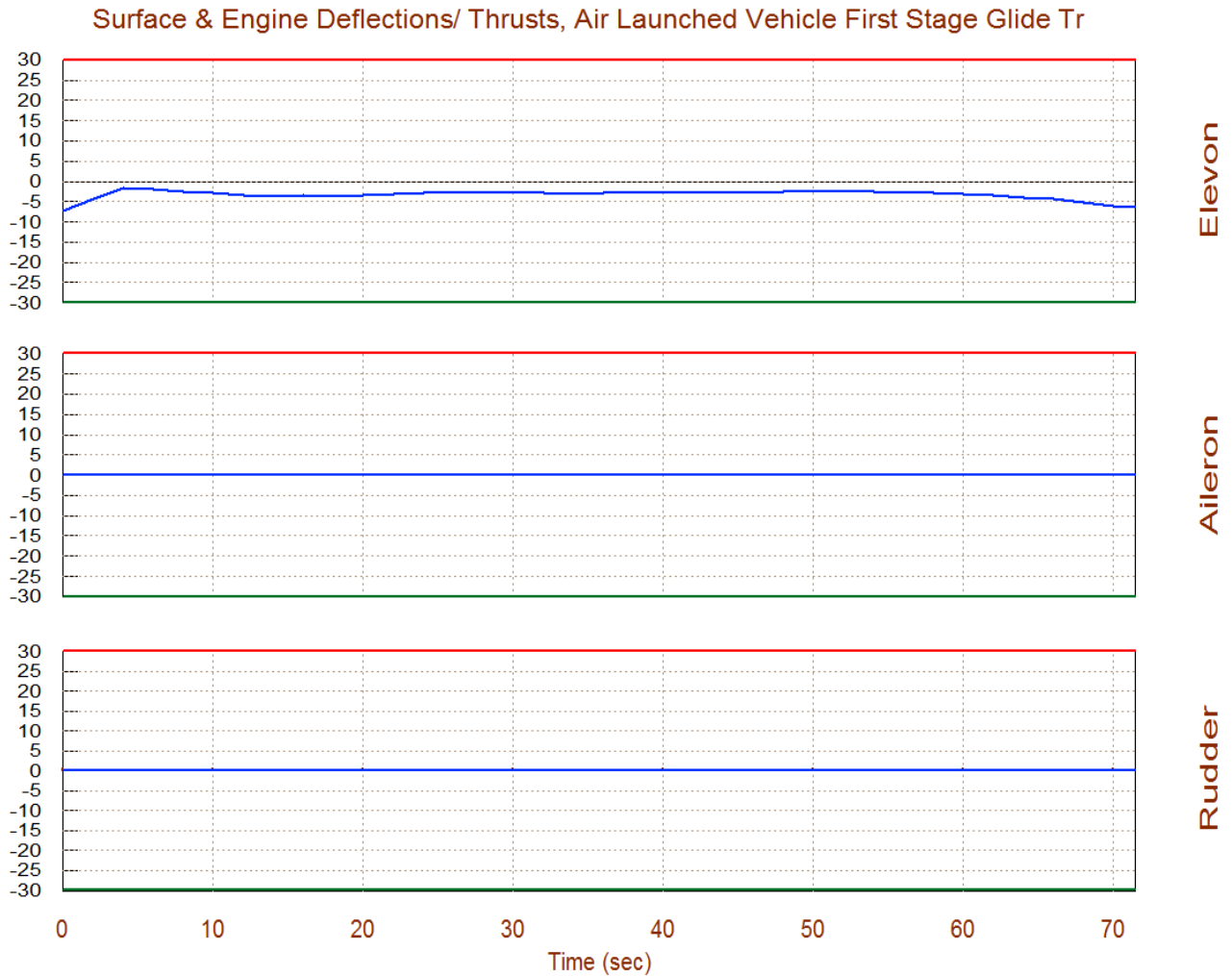
Performance Analysis Along Trajectory

You may now return to the main menu and select option 6 to evaluate the vehicle performance parameters along the trajectory. Performance analysis requires a mixing-logic matrix which in this case is an aero-surface reordering matrix. In the following menu click on "*Select a Mixing Matrix*" to select the matrix Kmix3 from file "Kmix3.Qdr". This matrix is simply changing the order between the Elevon and the Aileron, because the Elevon is defined first in the aero-surface data file. The proper order of the control demands in the mixing-logic matrix inputs must be (roll, pitch, yaw). Also it reverses the signs in the pitch and yaw moments.

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)

Notice ...

A (3 X 3) Mixing Logic Matrix is required

OK

Define the Effector Combination Matrix

The Mixing Logic Matrix translates the Flight Control (Roll, Pitch, Yaw, Ax, Ay, Az) demands to Effector commands (Aero-Surface, TVC, and Throttling).
You may either select a pre-calculated Mixing Logic Matrix (Kmix) from the Systems File: Kmix3.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

KMIX3   : Mixing Logic for Air Launched Vehicle First Stage, Glide Phase   , S

3-10

We must also define the max dispersions (α_{max}) & (β_{max}) due to wind-shear and also due to maneuvering. This is for control authority analysis. In this case we pick 4° for both (α_{max} & β_{max}).

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) 4.0000   Maximum Beta (deg) 4.0000   OK

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

The above plot shows that the vehicle is statically stable in both pitch and lateral. It has a max short period resonance ω_p=1.2 (rad/sec) at T=45 (sec) and a peak Dutch-Roll resonance ω_d=2.5 (rad/sec) at T=70 (sec). The (Q-alpha/ Q-beta) load factor at 4° of alpha and beta is 3,500 (psf-deg), which is reasonable. The plot below shows that the control authority parameters of the aero-surfaces in roll pitch and yaw are all acceptable (less than one). The worst case is in roll at high alphas.
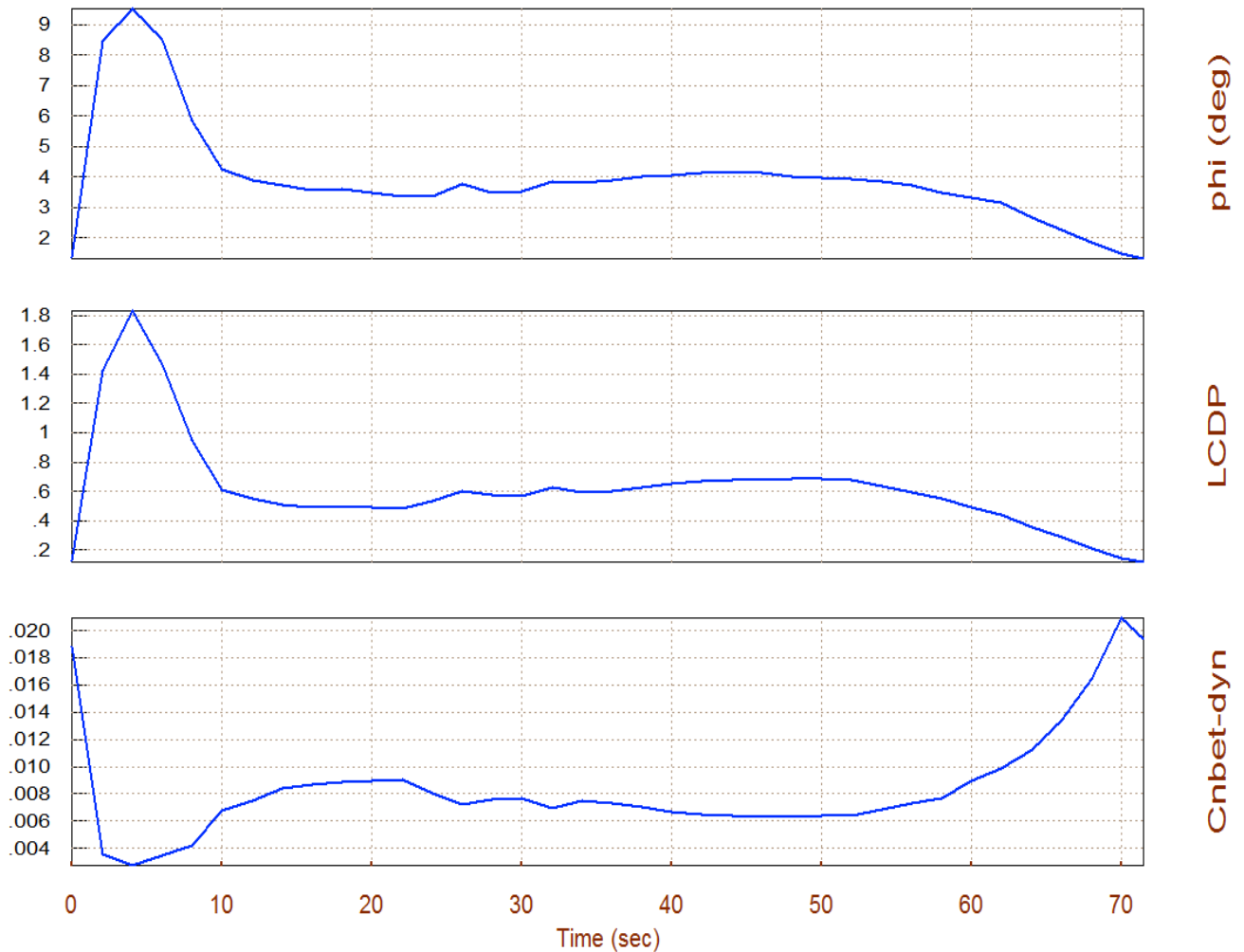
3-11

Static Margin, Center of Pressure, Aero-Center (ft), Air Launched Vehicle First
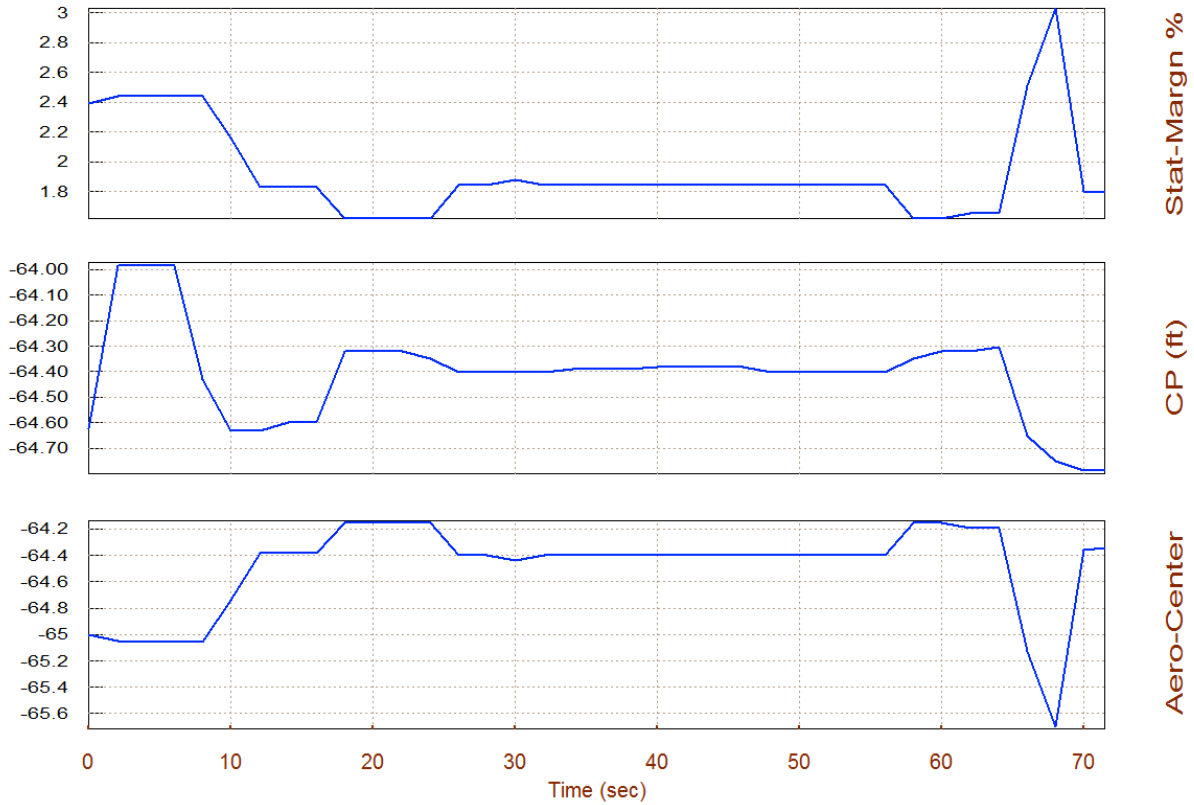
Rotation Control Authority (dQ/dQmax)<1 for 4 (deg) of Alpha & Beta Variation
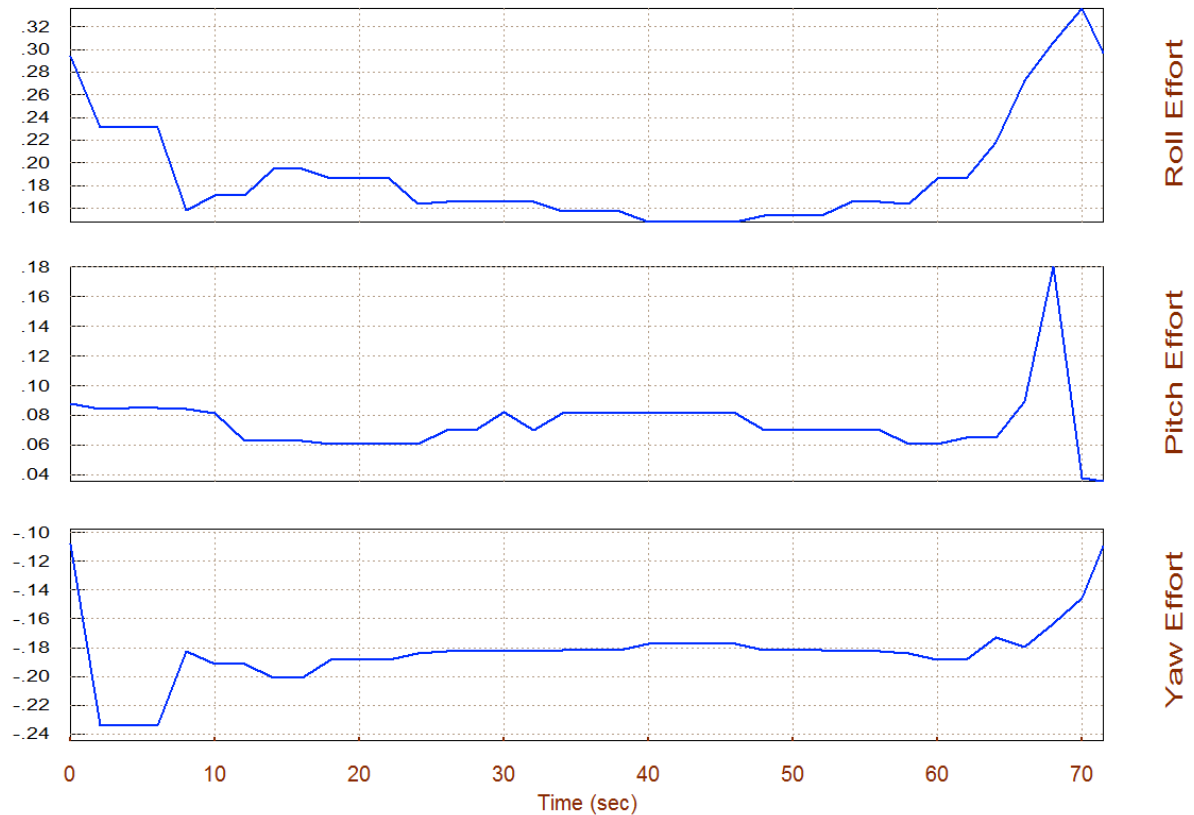
Bank Angle, LCDP Ratio, Cn_beta_dynam /deg, Air Launched Vehicle First Stage Gli

The above plot shows the roll angle (ϕ) that would occur when trimming along the trajectory at 4° of sideslip (β), due to cross-wind. The LCDP is acceptable for the most part. It is slightly low at high alphas which moderately reduces the roll maneuverability, but it does not change sign, which is good. The Cn-beta-dynamic is positive which indicates lateral stability. Its minimum value is around 0.003.

Contour Plots

Contour plots are 3-dimensional plots of some vehicle performance parameters versus alpha and Mach. They provide a broader performance perspective in the entire Mach versus alpha range, rather than in the vicinity of the trajectory. Occasionally the vehicle may deviate from its nominal alpha versus Mach trajectory and we would like to make sure that the trajectory is not close to regions of unacceptable performance. They also help reshaping the trajectory towards regions of improved performance. From the main menu select option (10) to create contour plots of some parameters against Mach and Alpha. Similar to our previous performance analysis we must specify the aero disturbance environment which in steady-state is defined by the maximum angles (α_{max} and β_{max}) relative to the wind. Enter 4° for both α_{max} and β_{max}, as shown below. The program also requires the aero-surface combination matrix (Kmix3) from file Kmix3.Qdr.

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)

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) `4.0000`   Maximum Beta (deg) `4.0000`   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: Kmix3.qdr, or let the program calculate it
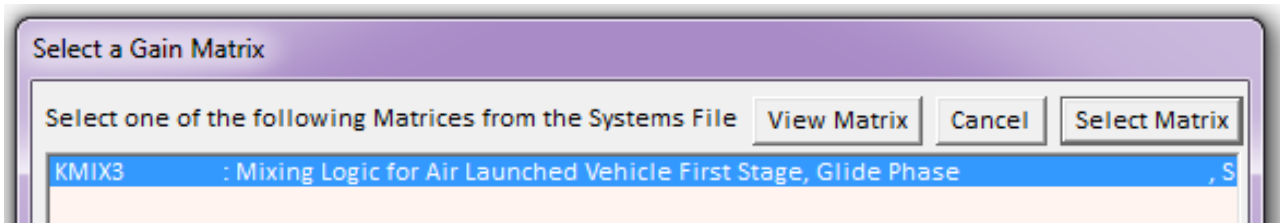
Select a Mixing Matrix from Systems File

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.
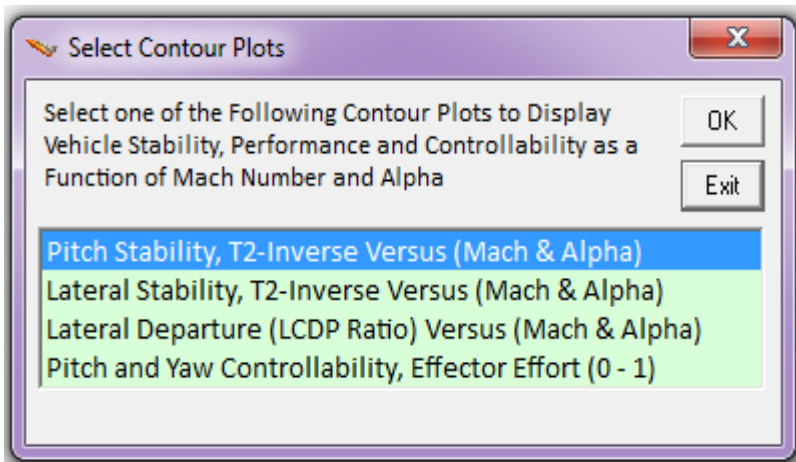
Create a Mixing Matrix Using All Effectors at 100% Participation

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

KMIX3   : Mixing Logic for Air Launched Vehicle First Stage, Glide Phase   , S

From the following menu the user must select one of the performance parameter to plot against Alpha and Mach number, as shown in the contour plots below.

Select Contour Plots

Select one of the Following Contour Plots to Display Vehicle Stability, Performance and Controllability as a Function of Mach Number and Alpha   OK   Exit

Pitch Stability, T2-Inverse Versus (Mach & Alpha)
Lateral Stability, T2-Inverse Versus (Mach & Alpha)
Lateral Departure (LCDP Ratio) Versus (Mach & Alpha)
Pitch and Yaw Controllability, Effector Effort (0 - 1)

The first two plots show the pitch and lateral stability parameters (T2-inverse) that were described in equations (3.14 & 3.15). The trajectory is shown with a black line crossing through the Mach versus Alpha field. It starts at T=0 (sec) in the upper left-hand corner where (α=8.6°, Mach=0.56) and it ends at T=72 (sec) at (α=9°, Mach=0.67). The color represents the value of the T2-inverse stability parameter over the entire of Mach and alpha range. We conclude that pitch and lateral stability are moderately stable in both cases.
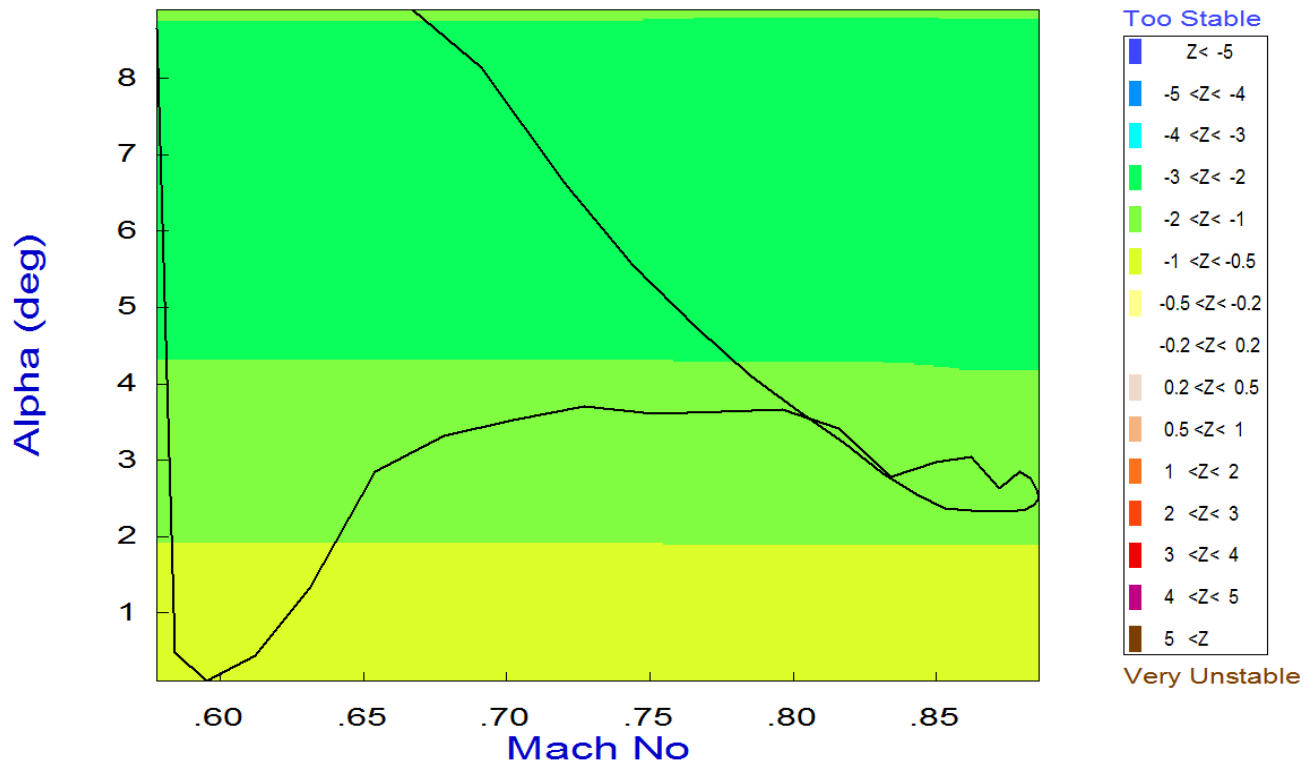
The next two contour plots show the control authority in pitch and yaw, which are mainly the Elevon and Rudder control surfaces. It shows how much effort is required to counteract against the 4° of α_{max} and β_{max} aero disturbances, as defined above, in the entire Mach versus alpha range. The control effort should be less than one, less than half is even better. As you can see, the color coded magnitudes are well below ±1, indicating that a relatively small amount of control effort is used against the 4° disturbances.

The last two contour plots show the control authority in roll and the LCDP parameter. The aileron is capable of balancing the rolling moment induced due to β_{max}=4° (the magnitude of roll control effort is less than one), but the capability is further reduced at high angles of attack. The LCDP parameter is also an indicator of roll controllability but in the dynamic sense. It is in the red region at angles of attack greater than 7°. However, there is no LCDP sign reversal observed in the entire Mach versus Alpha range, which is a good sign.
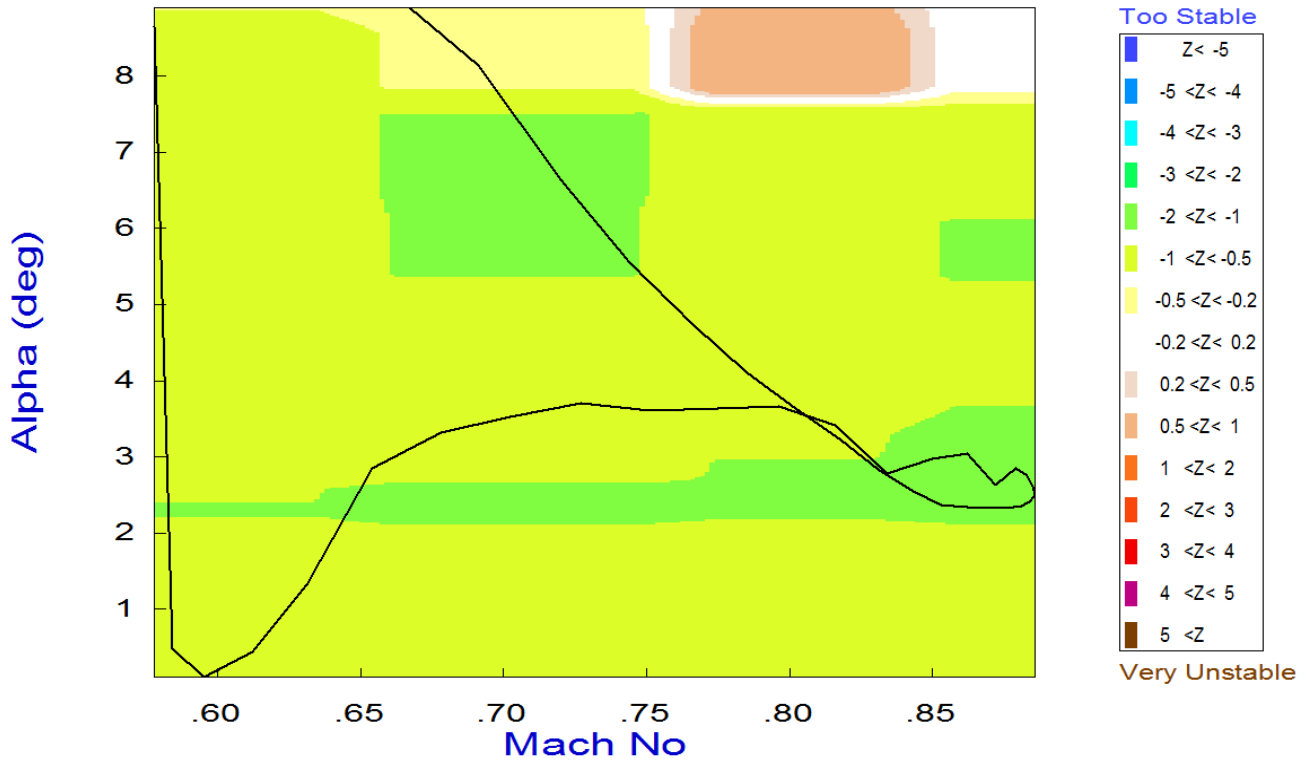
3-15

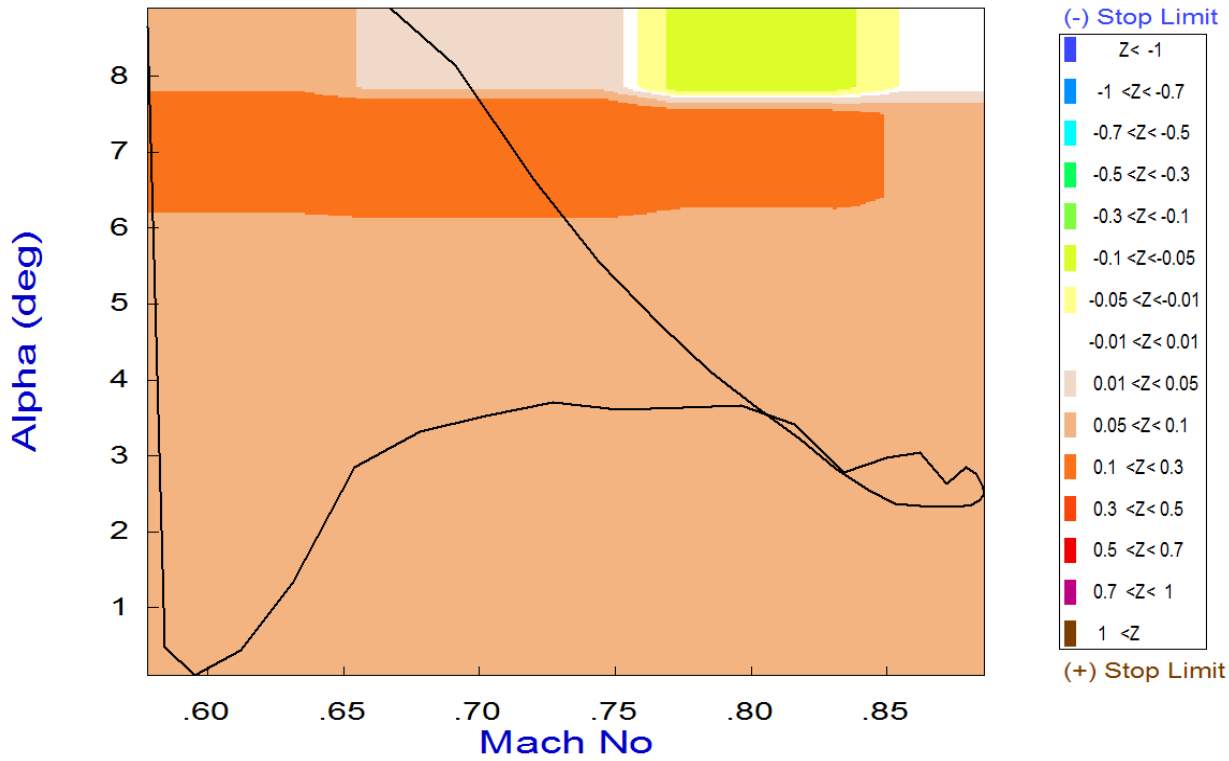# Pitch Stability Contour Plot (Mach vs Alpha)

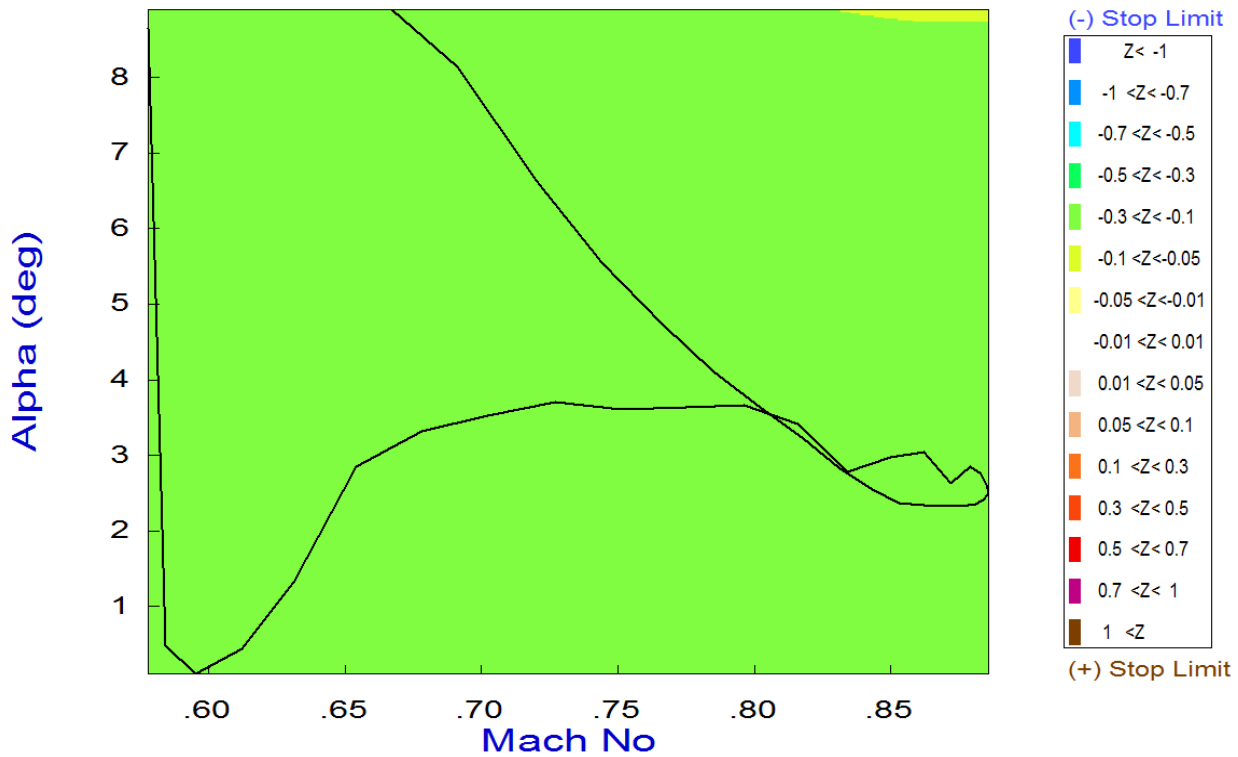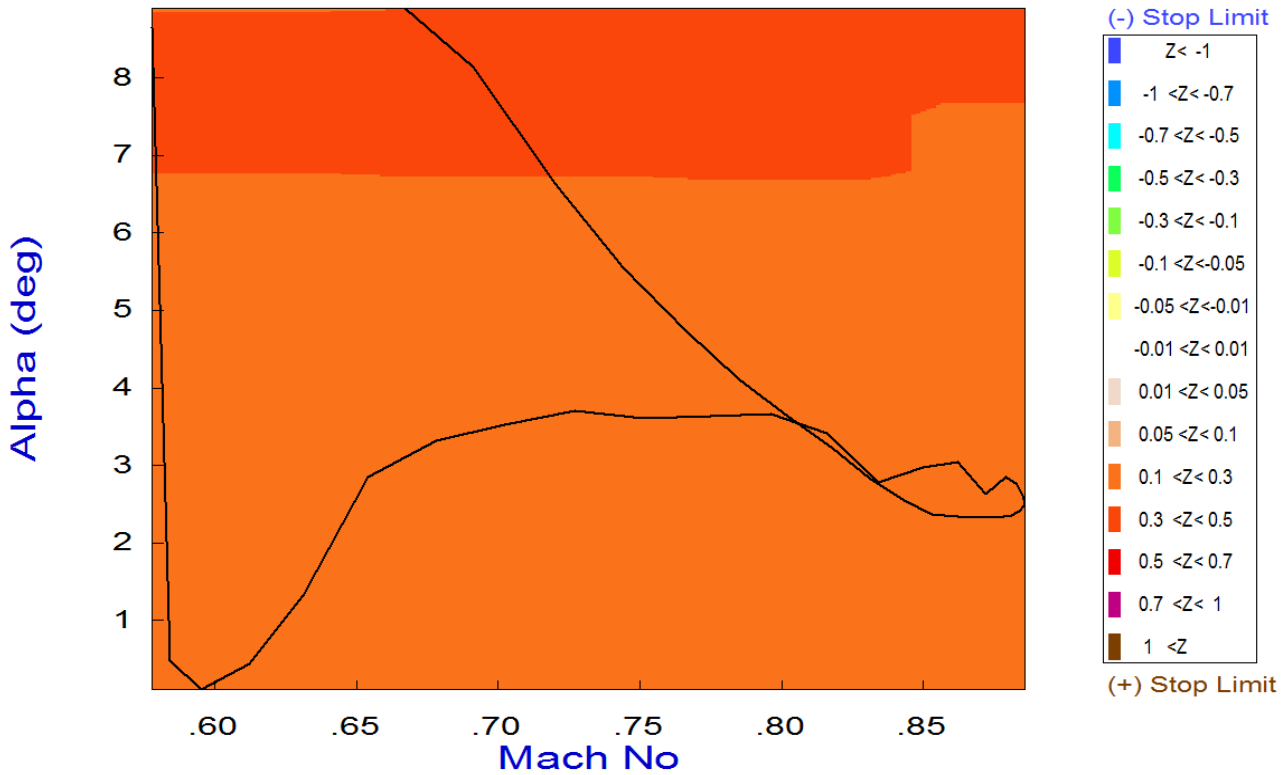# Lateral Stability Contour Plot (Mach vs Alpha)

Pitch Control Effort Contour Plot (Mach vs Alpha)

	(-) 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)

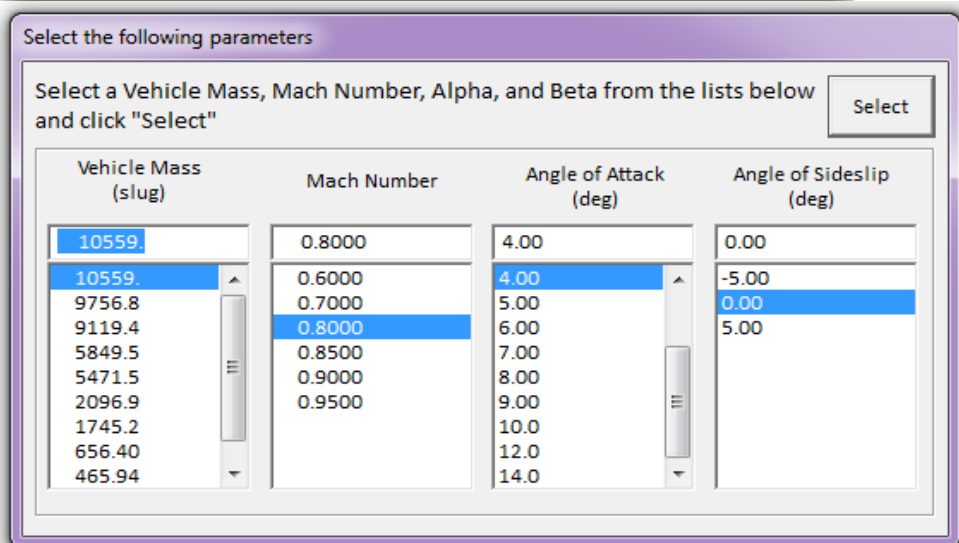|	(-) Stop Limit
■	Z< -1
■	-1 <Z< -0.7
■	-0.7 <Z< -0.5
■	-0.5 <Z< -0.3
■	-0.3 <Z< -0.1
■	-0.1 <Z<-0.05
■	-0.05 <Z<-0.01
	-0.01 <Z< 0.01
■	0.01 <Z< 0.05
■	0.05 <Z< 0.1
■	0.1 <Z< 0.3
■	0.3 <Z< 0.5
■	0.5 <Z< 0.7
■	0.7 <Z< 1
■	1 <Z
	(+) Stop Limit

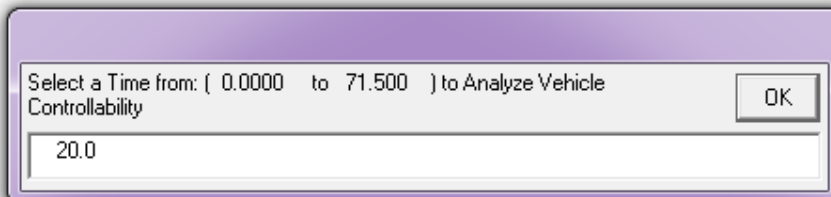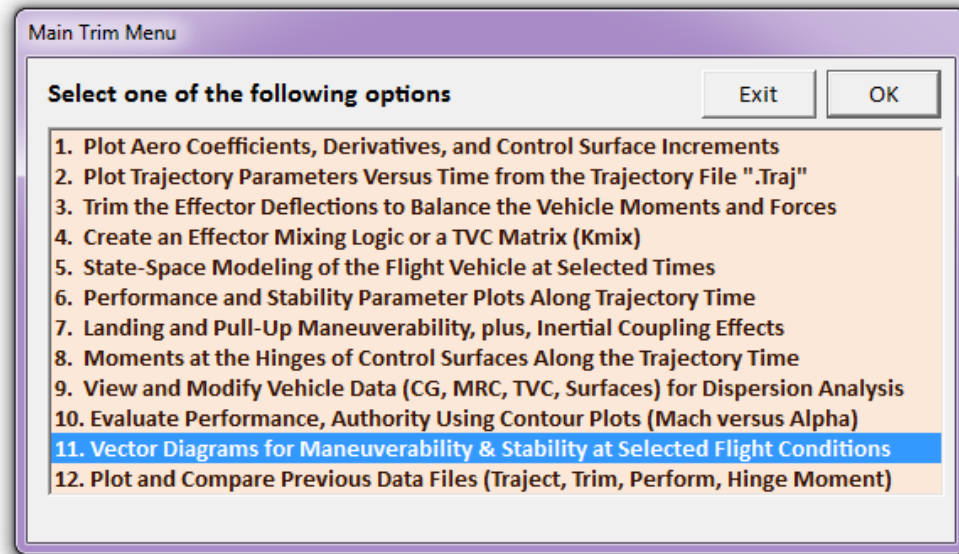# Roll Control Effort Contour Plot (Mach vs Alpha)

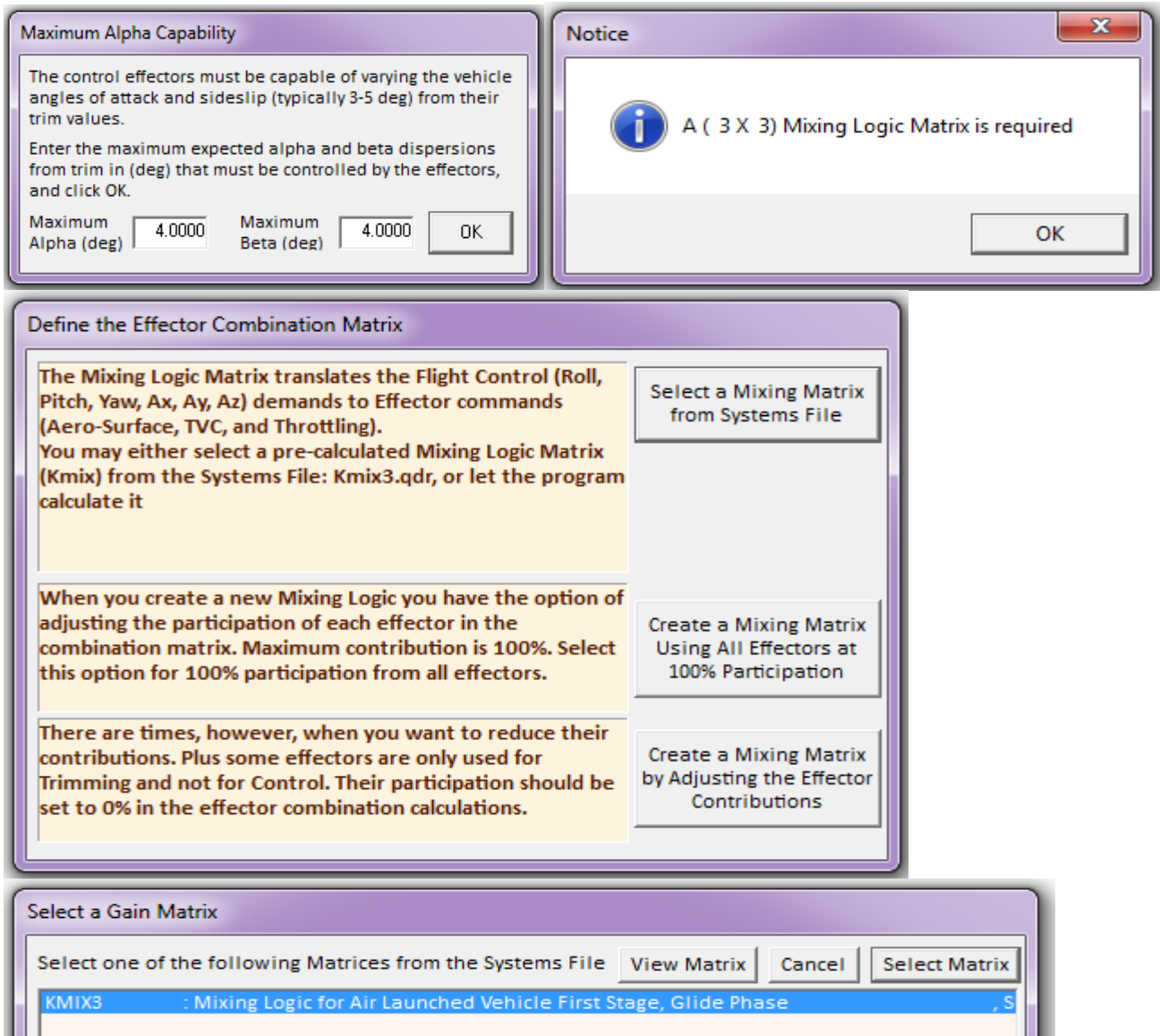# Roll Departure (LCDP) Contour Plot (Mach vs Alpha)
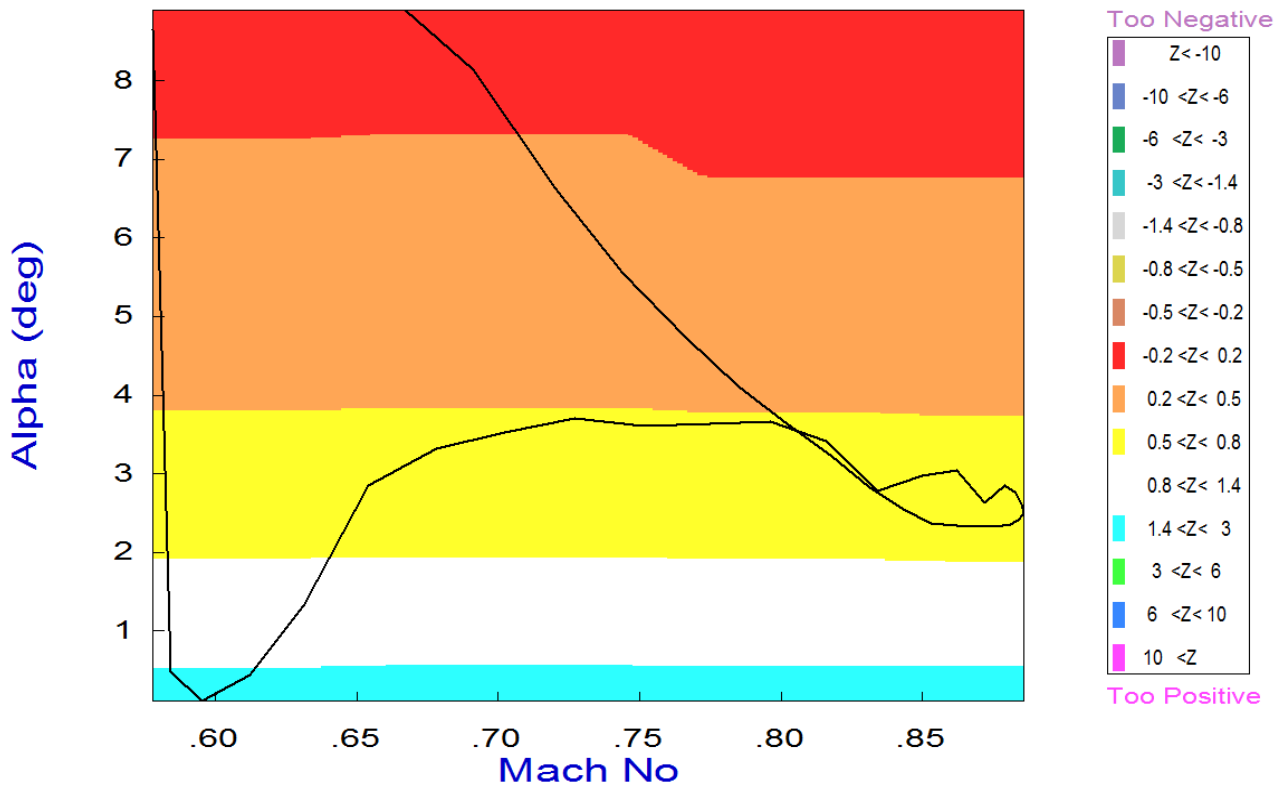
Controllability Analysis Using Vector Diagrams

Vector diagrams are used for visualizing the vehicle controllability against aerodynamic disturbances which are caused due to alpha and beta dispersions from trim. They are two-dimensional vector diagrams that compare the magnitudes and directions of the vehicle's response to flight control demands against its response to alpha and beta disturbances. The disturbance vectors must be small in comparison with the control vectors. Assuming that the initialization files and trim conditions are the same, from the main menu select option (11) for plotting vector diagrams. Select a flight condition at time=20 seconds, and from the following menu you may either keep the default values of Mass, Mach, α, and β which correspond to the selected time, or modify them to different values. In this case we select the default values.

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. Evaluate Performance, Authority Using Contour Plots (Mach versus Alpha)
11. Vector Diagrams for Maneuverability & Stability at Selected Flight Conditions
12. Plot and Compare Previous Data Files (Traject, Trim, Perform, Hinge Moment)

Select a Time from: (0.0000   to 71.500   ) to Analyze Vehicle Controllability   OK

20.0

Select the following parameters

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

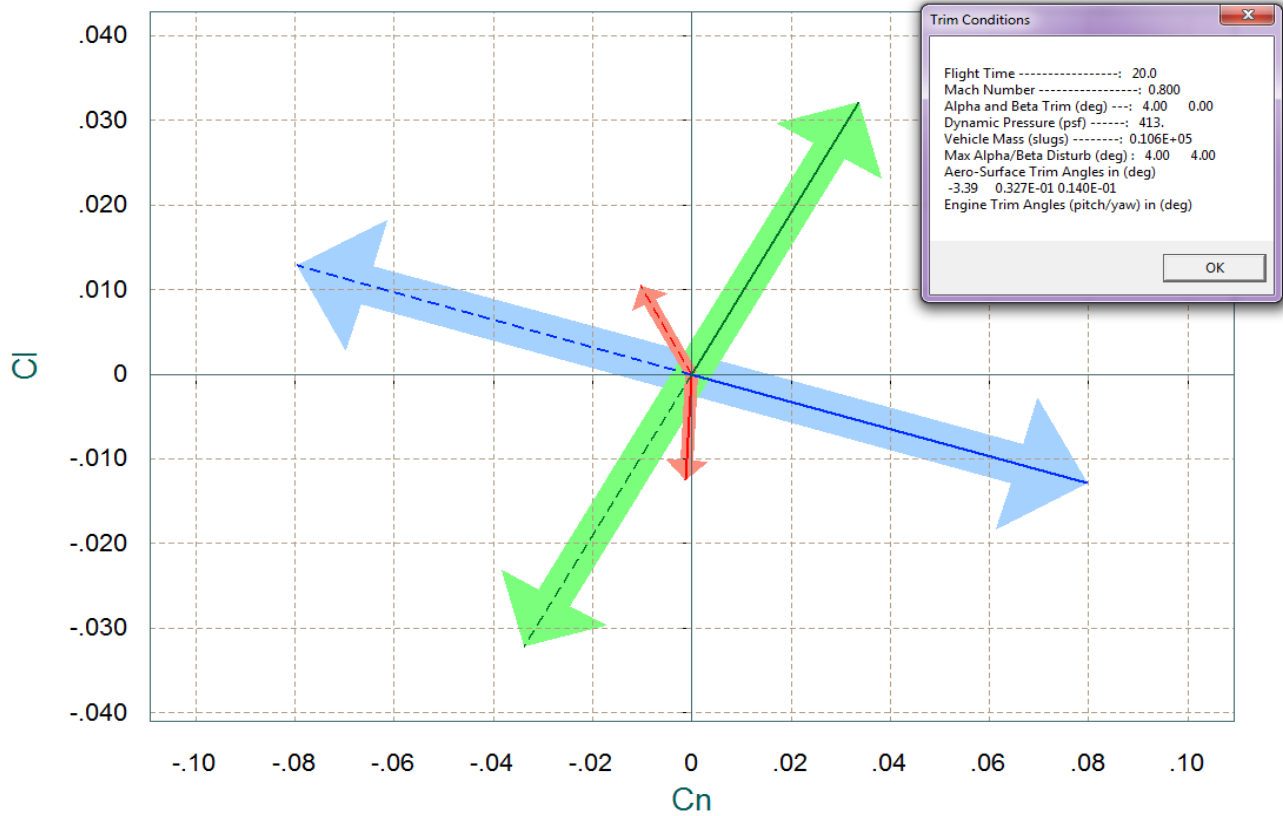| Vehicle Mass (slug)	Mach Number	Angle of Attack (deg)	Angle of Sideslip (deg)
10559.	0.8000	4.00	0.00
10559.	0.6000	4.00	-5.00
9756.8	0.7000	5.00	0.00
9119.4	0.8000	6.00	5.00
5849.5	0.8500	7.00	
5471.5	0.9000	8.00	
2096.9	0.9500	9.00	
1745.2		10.0	
656.40		12.0	
465.94		14.0	

We must also select the maximum alpha and beta dispersions like before, and the mixing-logic matrix which in this case is just a surface reordering and scaling matrix.
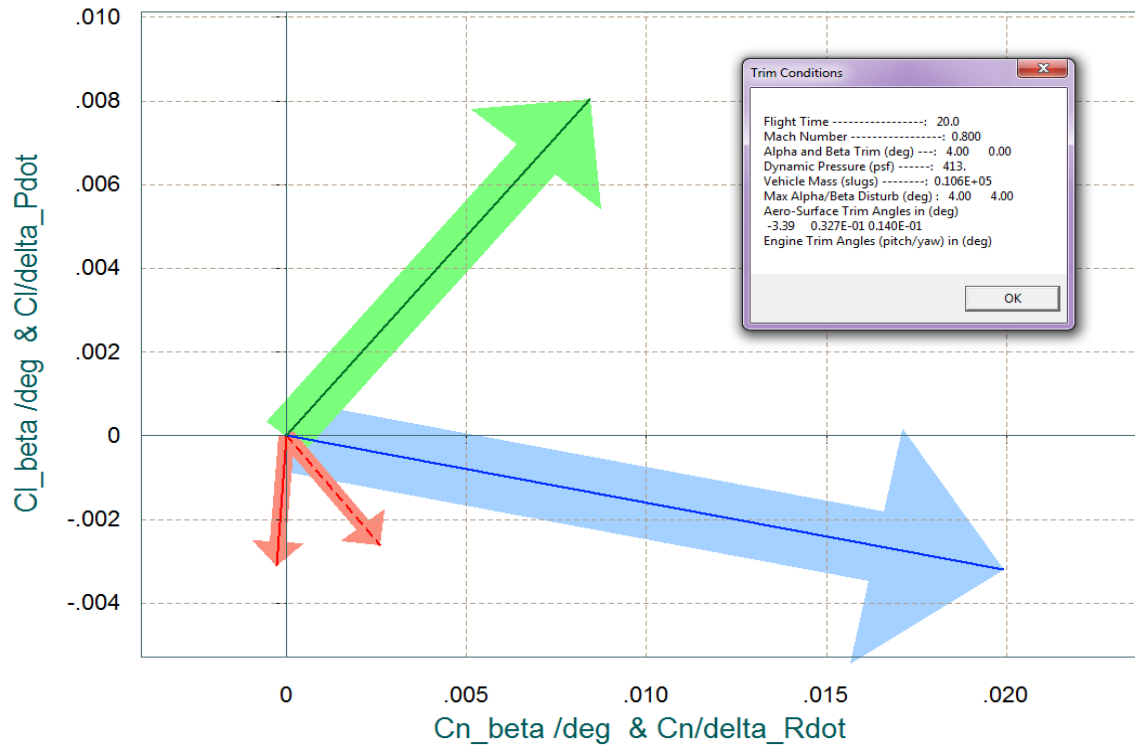
Maximum Alpha Capability

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): 4.0000   Maximum Beta (deg): 4.0000   OK

Notice

ℹ A (3 X 3) Mixing Logic Matrix is required

OK

Define the Effector Combination Matrix

The Mixing Logic Matrix translates the Flight Control (Roll, Pitch, Yaw, Ax, Ay, Az) demands to Effector commands (Aero-Surface, TVC, and Throttling).
You may either select a pre-calculated Mixing Logic Matrix (Kmix) from the Systems File: Kmix3.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

KMIX3   : Mixing Logic for Air Launched Vehicle First Stage, Glide Phase   , S

Two vector diagrams are shown below. The first one shows the max roll and yaw moments Cl and Cn (green and blue vectors respectively) due to the aileron and rudder at maximum deflections, in both positive (solid line) and in the negative (dashed line) directions. Both the aileron and rudder surfaces excite both, the roll and yaw directions. Despite the cross-coupling the control vectors are nicely orthogonal to each other, which is very good property. The disturbance moments due to $\pm\alpha_{max}$ and $\pm\beta_{max}$ are shown by the red vectors. A positive β_{max} causes negative rolling moment (solid red vector pointing down). Their magnitudes are significantly smaller than the moments due to the aero-surfaces. The second vector diagram shows the roll and yaw moment partials per roll and yaw acceleration demands $(\delta_P \ \& \ \delta_R)_{FCS,}$ green and blue vectors. The red vectors also show the roll and yaw partials per beta disturbance $(Cl\beta, Cn\beta)$, calculated at two extreme alphas. The control vectors are scaled as described in equations (7.1 through 7.4). As you can see, the control partials dominate significantly over the aero disturbance partials.

3-20

Comparison Between Maximum Control Moments Against Maximum Disturb Moments (red)
Roll & Yaw Control Moments (non-dimension) vers Disturb Moment due to Max Beta/Alpha
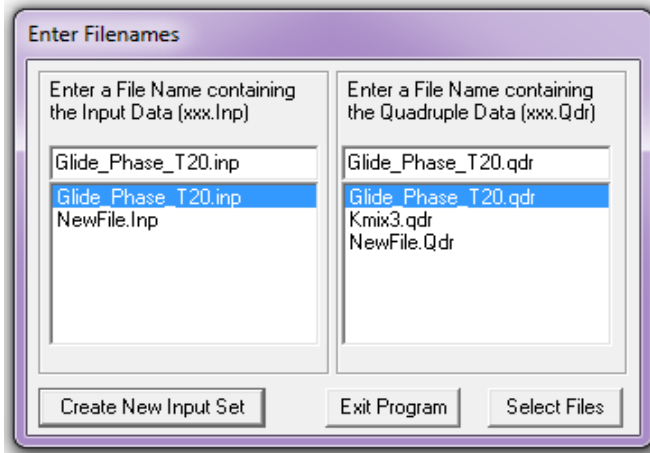

Trim Conditions

Flight Time ------------------: 20.0
Mach Number ------------------: 0.800
Alpha and Beta Trim (deg) ---: 4.00   0.00
Dynamic Pressure (psf) -------: 413.
Vehicle Mass (slugs) --------: 0.106E+05
Max Alpha/Beta Disturb (deg) : 4.00   4.00
Aero-Surface Trim Angles in (deg)
 -3.39   0.327E-01 0.140E-01
Engine Trim Angles (pitch/yaw) in (deg)

OK

Comparison Between Control Moment Partials Versus Aero-Disturb Moment Partials (red)
Yaw & Roll Control Partials Cn/delta_R and Cl/delta_P versus Cn/beta & Cl/beta

Trim Conditions

Flight Time ------------------: 20.0
Mach Number ------------------: 0.800
Alpha and Beta Trim (deg) ---: 4.00   0.00
Dynamic Pressure (psf) -------: 413.
Vehicle Mass (slugs) --------: 0.106E+05
Max Alpha/Beta Disturb (deg) : 4.00   4.00
Aero-Surface Trim Angles in (deg)
 -3.39   0.327E-01 0.140E-01
Engine Trim Angles (pitch/yaw) in (deg)

OK

3-21

Dynamic Modeling

We will now use the Trim program to create a linear model of the flight vehicle for control design and analysis. We will select an arbitrary flight condition at t=20 (sec) from separation to generate the vehicle input data and to create a linear state-space system using the Flixan FVMP. We will also create separate pitch and lateral subsystems for control design purposes. So let us begin the Trim program, as before, select the Trim data files, select also the Flixan input data file "*Glide_Phase_T20.Inp*" and the systems file "*Glide_Phase_T20.Qdr*".

Enter Filenames

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

Glide_Phase_T20.inp

Glide_Phase_T20.inp
NewFile.Inp

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

Glide_Phase_T20.qdr

Glide_Phase_T20.qdr
Kmix3.qdr
NewFile.Qdr

Create New Input Set   Exit Program   Select Files

The Trim program will generate the flight vehicle input data in file "*Glide_Phase_T20.Inp*", and the vehicle dynamic model will be created by the FVMP and it will save it in "*Glide_Phase_T20.Qdr*". However, in this case the input data file has already been prepared, and in addition to the vehicle data it contains also data sets that will be used by Flixan to further refine the vehicle modeling and analysis. The Trim program first generates the vehicle input data in file "*Glide_Phase_T20.Inp*". The additional data in that file were introduced in order to be processed by other Flixan utilities for the purpose of generating decoupled models and for re-formatting the systems for Matlab. From the Trim main menu we select Option (5) to generate the vehicle data for the dynamic model. The program plots the trajectory data and from one of the plots the user is prompted to select a flight time across the plot using the mouse. From the top menu bar, click on "*Graphic Options*" and from the vertical drop-down menu click on "*Select Time to Create a State-Space System*".

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)

Select Time Point

From the Top Menu of the Trajectory Plots, go to "Graphic Options" and select a Time to create a Linear System

OK

Trajectory Parameters

Copy Format: Send to: Graphic Options   Next Plot   Exit Plots

Magnify a Rectangle Section of the Plot
Modify a Trajectory Plot Using the Mouse
Restore Original Trajectory/ Trim Data
Select Time to Create State-Space System

Flight Path (deg),

8
7
6
5
4
3
2
1

Trajectory Parameters

Copy Format: Send to: Graphic Options   Next Plot   Exit Plots

Select Time

Using the Mouse select a Time-Slice to Create an Input Data Set for the Flight Vehicle Modeling Program

OK

8
7
6
5
4
3
2
1

Angles of Attack/Sideslip/Flight Path (deg),

State-Space Modeling

You have Selected Trajectory Time= 20.000   sec
to Create Input Data for State-Space Modeling

OK   Cancel

Flight Vehicle Parameters

Vehicle System Title
Air Launched Vehicle First Stage Glide Trajectory/ T= 20.0 sec

Edit Input File   Exit

Update Data   Run

Save in File

Number of Vehicle Effectors

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

Rotating Control Surfaces.   3   WITH TWD
Include Tail-Wags-Dog?   WITHOUT TWD

Reaction Wheels?   0   **Momentum Control Devices**

Single Gimbal CMGs?   0   Include a 3-axes Stabilized Double Gimbal CMG System?   Yes / No

Number of Sensors

Gyros   0

Acceleromet   3

Aero Vanes   0

External Torques   0

Modeling Options (Flags)

Output Rates in
Body Axes
Stability Axes

Turn Coordination ?
Include Turn Coordin
Without Turn Coordin

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

Attitude Angles
Euler Angles
Integrals of Rates
LVLH Attitude

Number of Modes

Structure Bending   0

Fuel Sloshing: 0

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

Vehicle Mass Properties

Moments/ Products of Inertia (slg-ft^2)

Ixx	172420.5	Ixy	-923.9487
Iyy	8743687.	Ixz	249112.8
Izz	8761729.	Iyz	1.977138

Location of Center of Gravity (ft)

Xcg	-62.38201
Ycg	-0.6757367E-02
Zcg	-0.2951795

Vehicle Mass in (slugs)	10553.00
Accelerat. due to Gravity (ft/sec^2)	32.17400
Earth Radius (Re) in (feet)	0.2089600E+08

The flight vehicle modeling program (FVMP) dialog comes up showing the vehicle data categorized in tabs (extracted from the Trim files). This dialog allows you edit some of the data or titles in the various fields and tabs. You must click on "*Update Data*" every time you modify a group of data before changing tabs. When you finish editing the dialog, click on "*Save in File*" button to save the vehicle data in "*Glide_Phase_T20.Inp*". You may also edit that file directly by clicking on "*Edit Input File*". Finally you may click on "Run" to generate the vehicle system in "*Glide_Phase_T20.Qdr*". But you are not ready to run it yet before including the remaining of the Flixan data sets for the additional processes described, so click on "Exit" for now, and take a look in the already prepared input file.

The already created input file "*Glide_Phase_T20*.Inp" includes a number of data sets and each set is to be processed by a separate Flixan utility. On the top of the file there is a batch set that is capable of processing the remaining data-sets together in batch mode. The first set of data below the batch generates the vehicle model. The next two data sets generate the reduced order pitch and lateral vehicle subsystems which are used for control design and analysis purposes. The last three data-sets convert the vehicle models to Matlab m-function format so that they can be loaded into Matlab for control analysis. To process the batch and data-sets from Flixan, go to "*Manage Input Files (*.Inp)*" and then click on "*Process/ Edit Input Data*". From the following dialog, first select the input file from the left menu, and then from the right menu select the batch set, which is the top title in that menu, and then click on "Execute" to run it. Answer "Yes" in the dialog question and Flixan will generate the vehicle models in file "*Glide_Phase_T20*.Qdr" and also in Matlab format. They are in files "vehicle.m", "pitch.m", and "lateral.m".
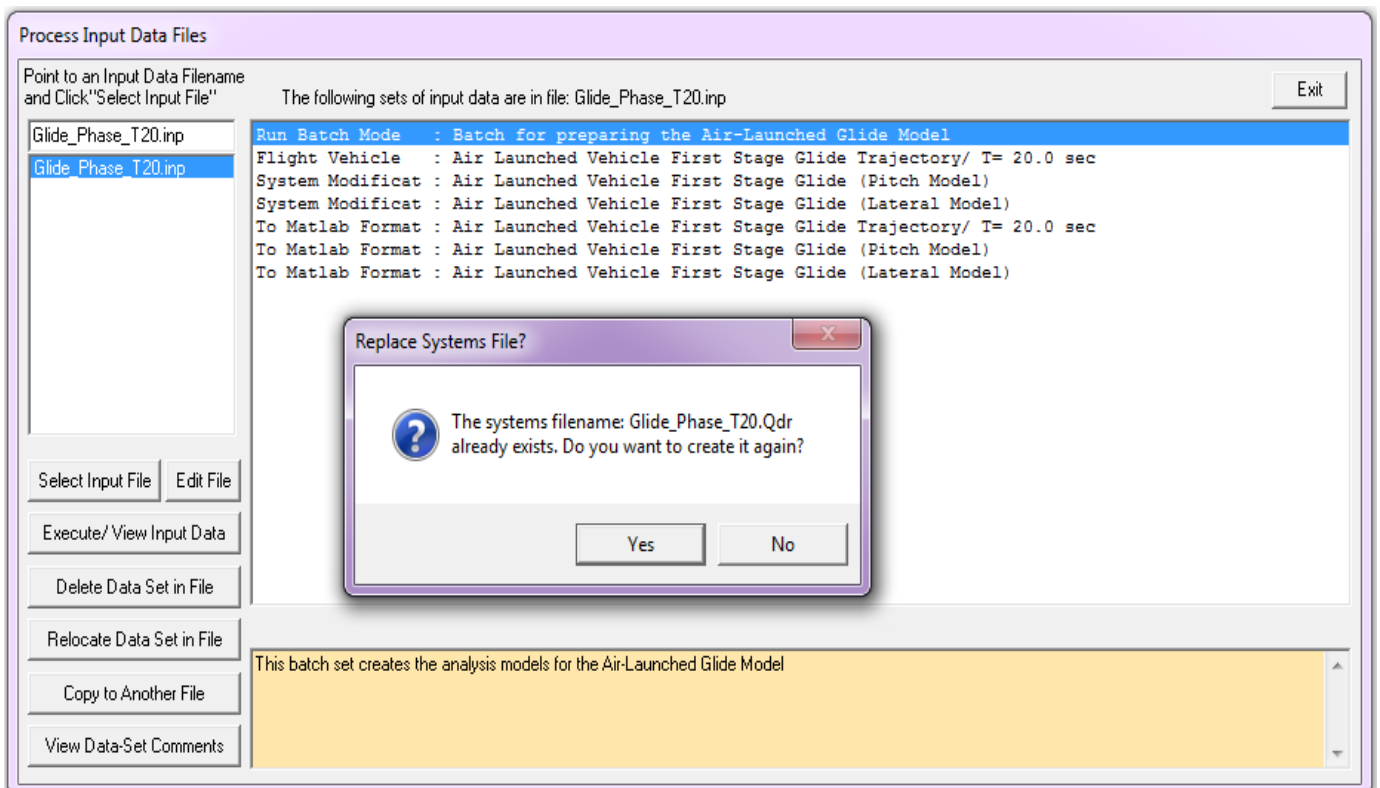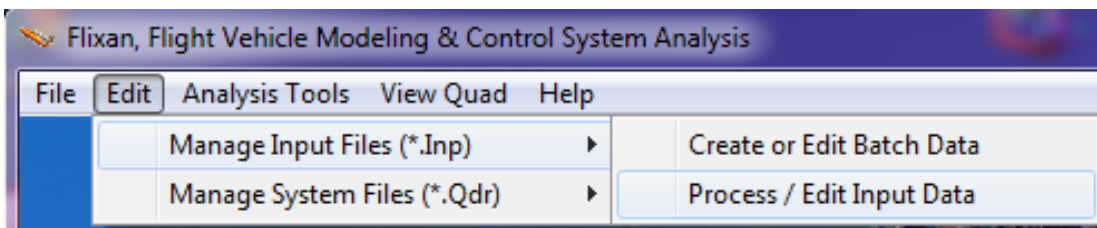
Control Design and Simulation Models

The models generated in the previous section will now be used for control design and simulations. The Matlab analysis will be performed in subdirectory "*C:\Flixan\Trim\Examples\Air Launched Vehicle\Phase A Glide With Wing\Mat_Anal*". The following script file "run.m" loads the 3 dynamic models and also the aero-surface scaling matrix Kmix3. It also loads the pitch flight control gains and designs LQR state-feedback gains for the lateral axes. In the lateral design model the state vector which originally consisted of: (ϕ, p, r, and β) is now augmented with one additional state (β-integral). This is done by linearizing (linmod) the Simulink model "*Ldes5x.Mdl*". K_{pr} is the (2x5) state-feedback matrix. The lateral control design weights are adjusted and refined by means of simple simulation model "*Sim_Lateral_Simple.Mdl*", shown below. The pitch gains were derived by classical means.

```
% Air-Launched Rocket Glide Phase Analysis Script
d2r=pi/180; r2d=180/pi;
[As, Bs, Cs, Ds] = vehicle;              % Load Big Simulation Model
[Ap, Bp, Cp, Dp] = pitch;                % Load Pitch Simulation Model
[Al, Bl, Cl, Dl] = lateral;              % Load Lateral Design Model
load Kmix3 -ascii                         % Surfaces Scaling Matrix

% Lateral LQR Design Using
[Al5,Bl5,Cl5,Dl5]= linmod('Ldes5x');     % 5-state model {p,r,bet,pint,betint}
R=[3,1]*2; R=diag(R);                     % CS LQR Weights R=[3,1]*2
Q=[0.2 0.1 0.5 0.5 0.04]*5.0; Q=diag(Q);  % CS LQR Weights Q=[0.2 0.1 0.5 0.5 0.04]*5.0;
[Kpr,s,e]=lqr(Al5,Bl5,Q,R)               % Perform LQR design on Jets

% Pitch FCS Gains
Kg=2.0; Kgi=0.2;
```


Lateral LQR Simulation (LQR analysis model)
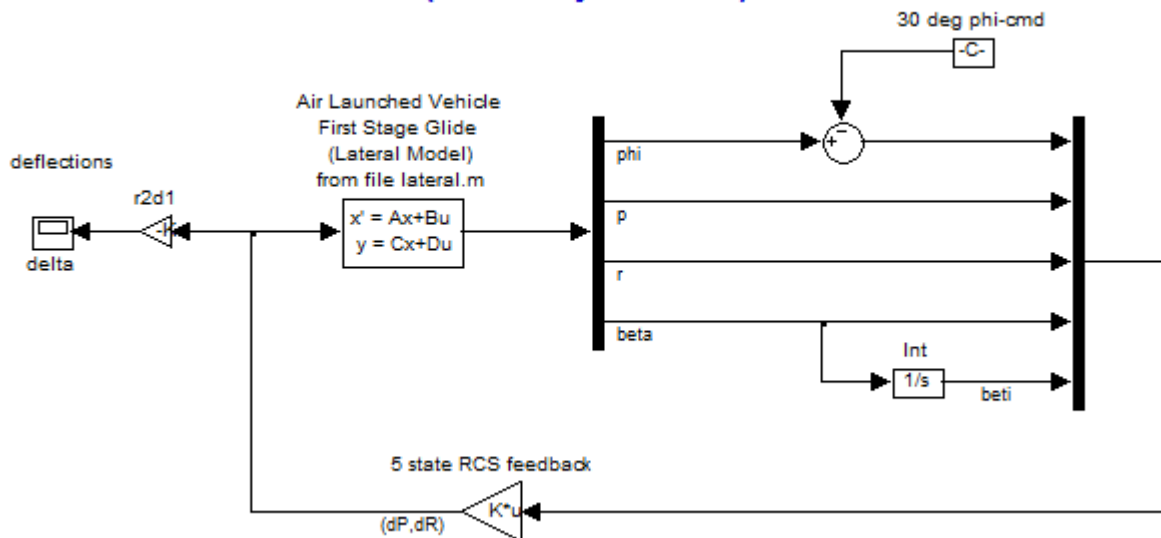
Figure 2.1 Lateral Simulation Model for LQR Gain Adjustments

The main simulation model is in file "*Sim_Air_Launch.mdl*", shown in Figure (1.2a). It consists of the vehicle dynamics (green block) wrapped around with two flight control loops: a pitch loop that controls the flight path angle (γ), and a lateral control loop that controls the bank angle (ϕ) and ultimately the cross-range velocity and flight direction. Simulation plots are generated automatically by the script file "pl.m" when the execution is complete.
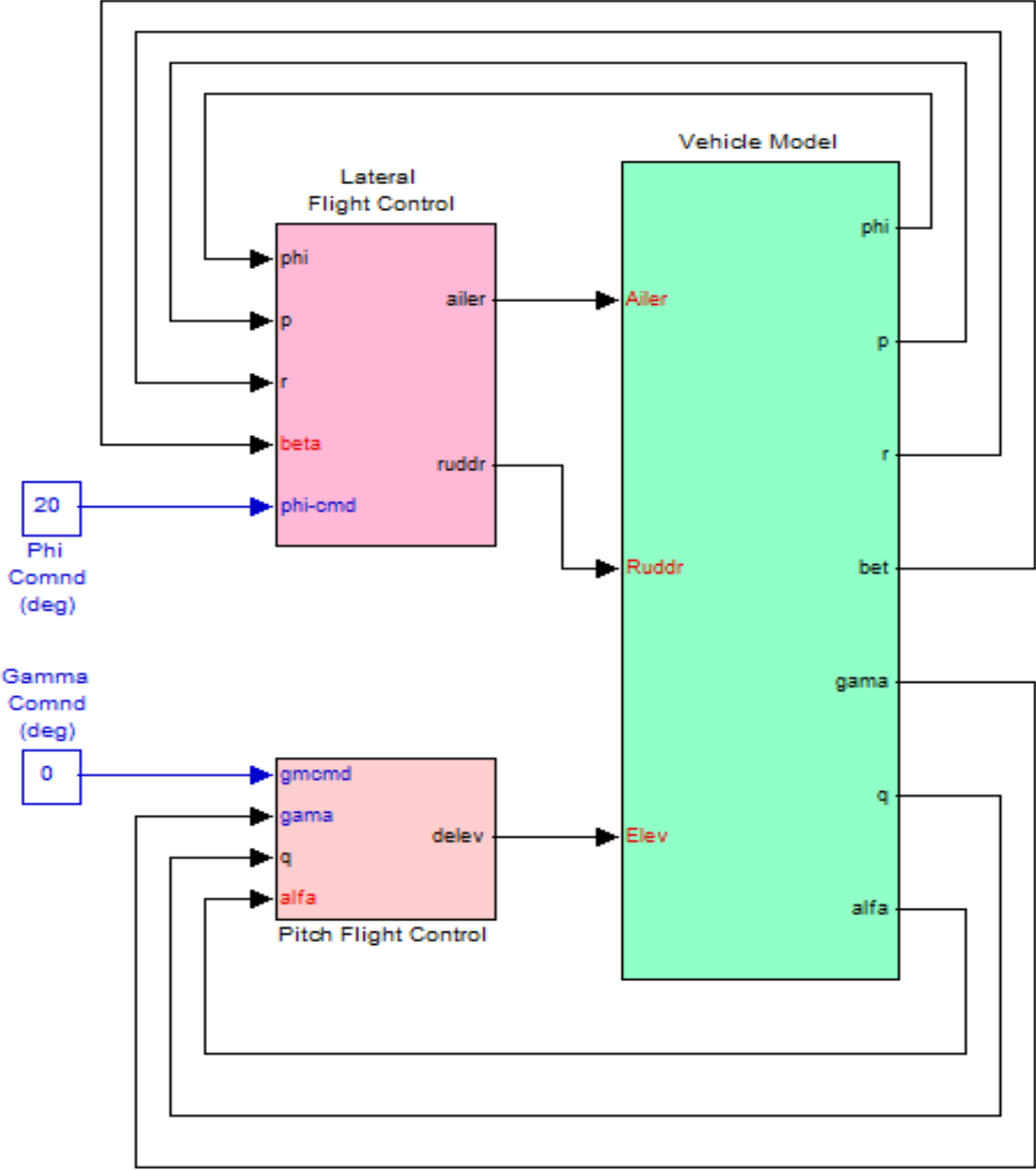
Figure 1.2a Air-Launched Vehicle Simulation Model in Simulink file "Sim_Air_Launch.mdl"

The following Figure (1.2b) shows the vehicle dynamic model. The model is based on the state-model system "*Air Launched Vehicle First Stage Glide Trajectory/ T= 20.0 sec*" which is loaded from file "*vehicle.m*". The inputs to the subsystem are: Aileron, Elevon, and Rudder deflections. The matrix Kmix3 is used to reorder the sequence of the effectors because in file "vehicle.m" the Elevon and Aileron are interchanged, plus some directions are reversed. This is how they are defined in the control surface aero-data file. There is also a gust input used as a disturbance. The direction of gust is set to excite both pitch and lateral directions and it is defined in the vehicle input data. Since our requirement in this case is to control the flight path angle the output from the model is gamma which is constructed by combining theta with alpha. A set of first order actuators is also included at the control surface inputs.
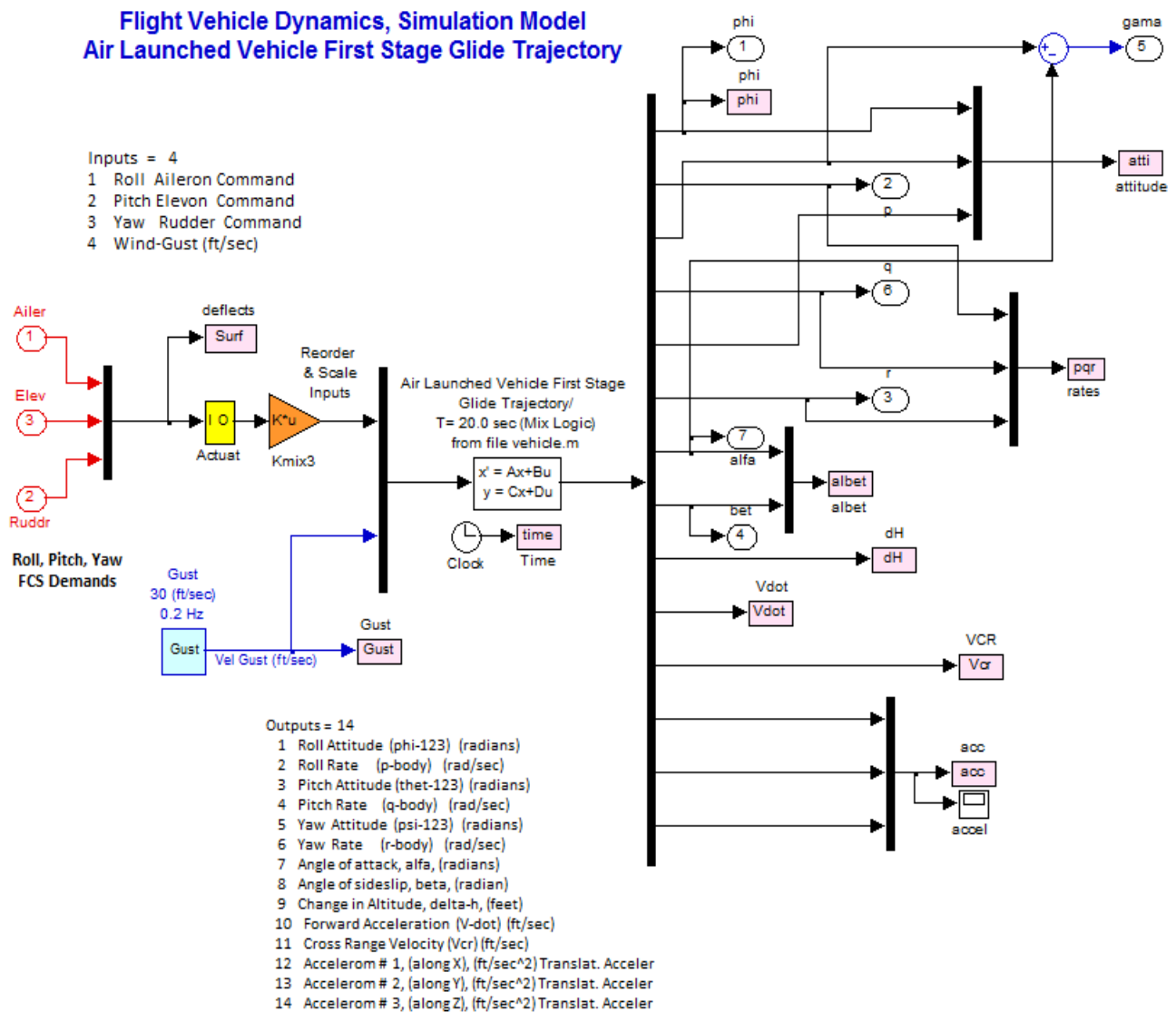
Figure 1.2b Air Launch Vehicle Dynamic Model from file "Vehicle.m"

The purpose of the pitch flight control system is to track the flight-path angle (γ) which is commanded by guidance (not included here). The gamma-error (plus integral) is used to drive the alpha-command. There should also be an alpha-command limiter that is not shown here. There is also a pitch rate feedback from the rate-gyro.
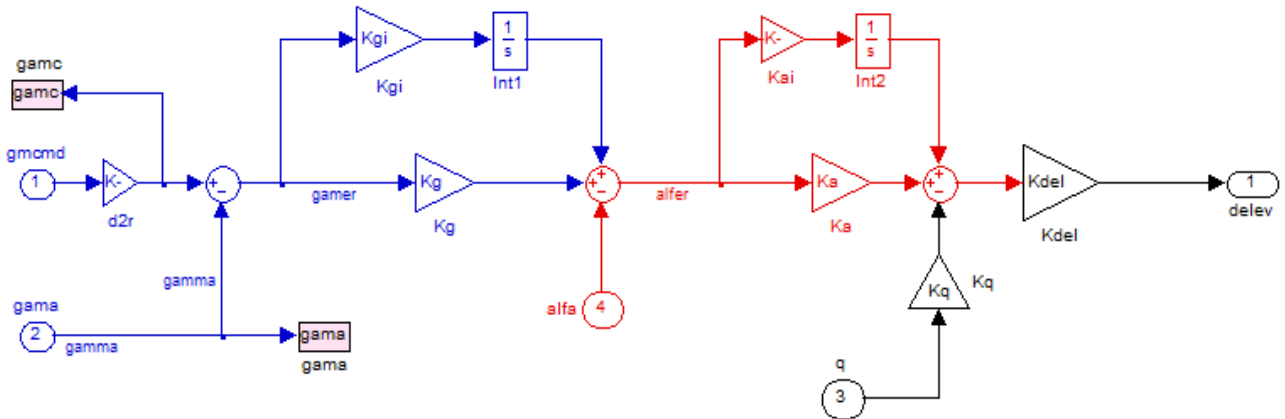
Figure 1.2c Pitch Flight Control System Controlling the Flight Path Angle (gamma)

The reduced vehicle model "*Air Launched Vehicle First Stage Glide (Lateral Model)*" from file "*lateral.m*" was used in the lateral control design. The original state-vector consisting of (phi, p, r, and beta) states was augmented by including integral of the sideslip angle. The lateral flight control system is a (2x5) state-feedback matrix Kpr that was designed using the LQR method. It translates the state-vector signals to aileron and rudder deflections.
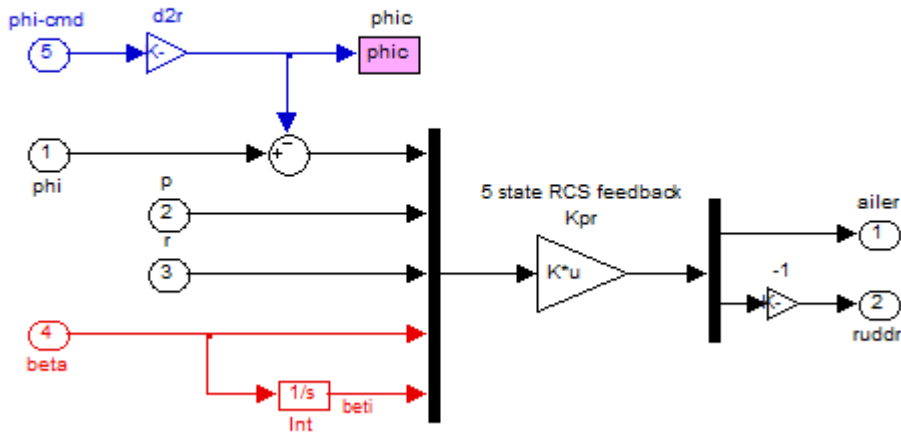
Figure 1.2d Lateral Flight Control System

The angles of attack and sideslip are not measured directly by the vehicle sensors and they must be estimated from the normal and lateral accelerometers. This detail, however, is beyond the scope of this example.

Simulation Results

The simulation model in Figure (1.2) can be excited with gamma and phi commands from guidance and also by winds. The wind-gust direction is perpendicular to the vehicle x-axis and skewed at 45° between the +y and +z axes, as it is defined in the vehicle input data file. Two wind excitation options have been implemented in the light blue block in Figure (1.2b), gust impulse and turbulence. We will use this model to calculate the vehicle responses to various excitations.

Phi-command Simulation

A phi-command= 20° is applied to the simulation model with all other inputs equal to zero. The figure below shows the Euler angles, and the body rates. The small steady-state error in phi is not an issue because our goal is not really to control phi, but banking is used by guidance as a means to control the flight direction and the cross-range velocity. The cross-range velocity is increasing due to banking. The maneuver causes a transient in beta and in the lateral acceleration. The next plot shows the aileron (red) and rudder (blue) deflections.
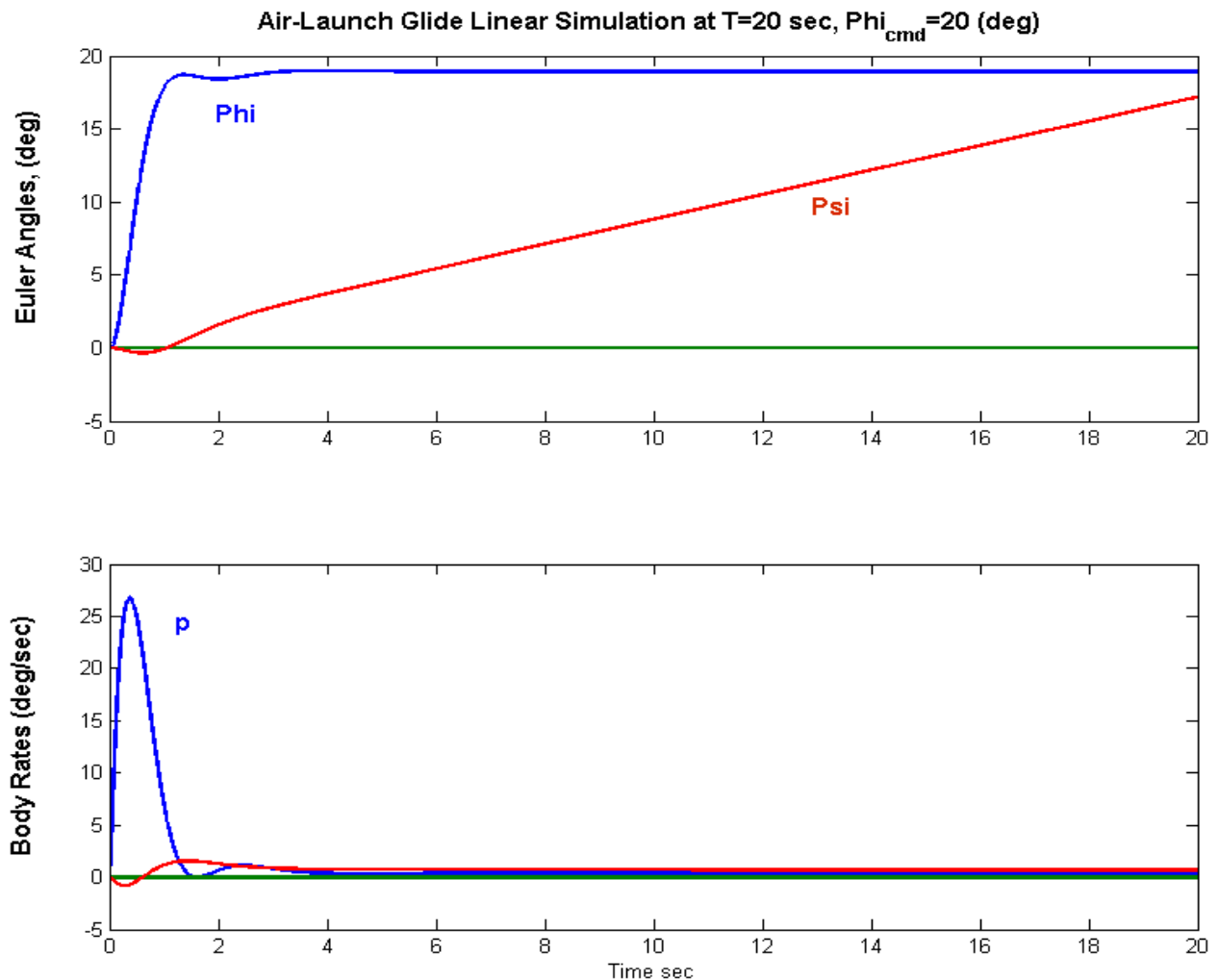
Air-Launch Glide Linear Simulation at T=20 sec, Phi$_{cmd}$=20 (deg)
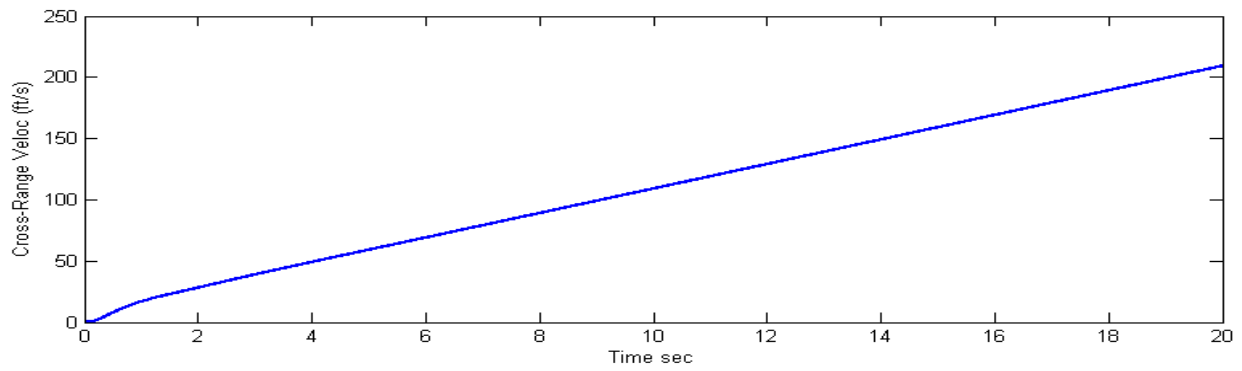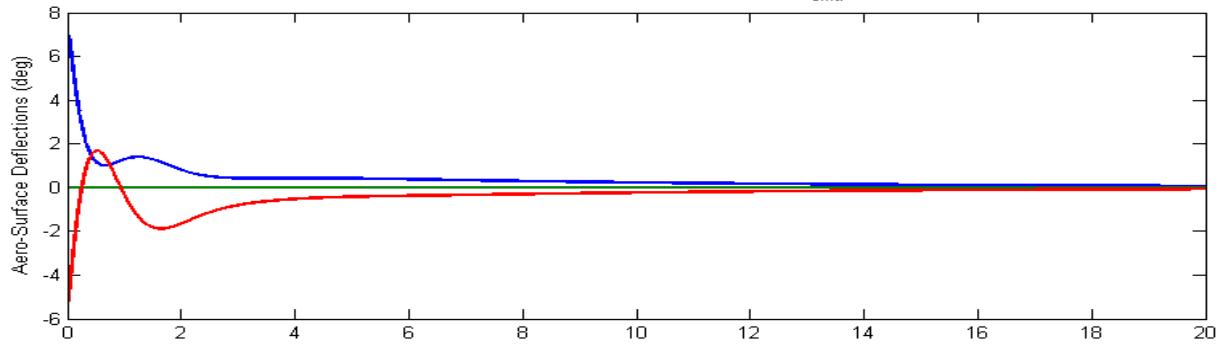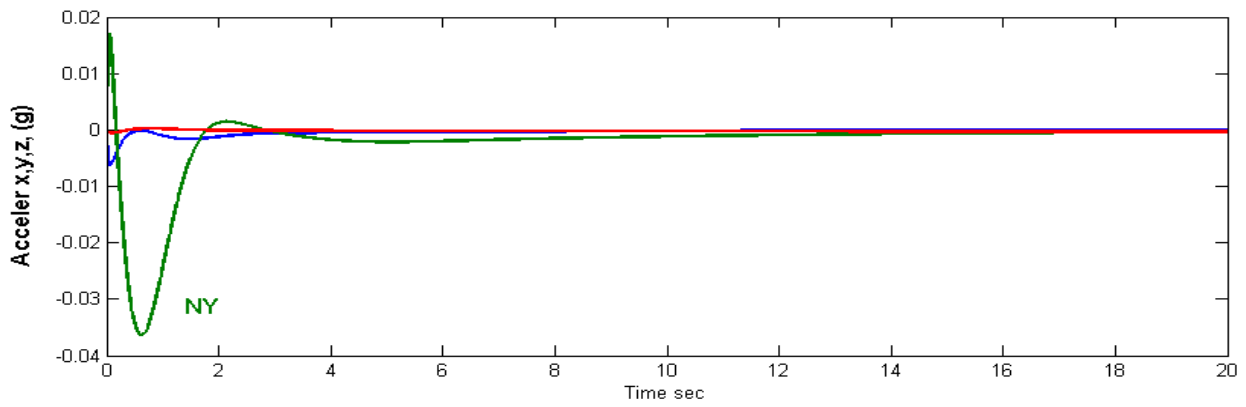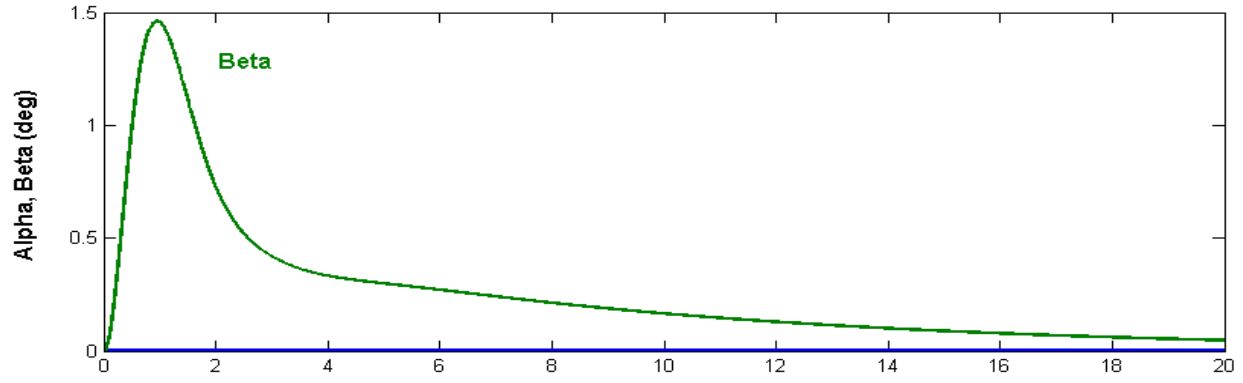
Wind-Gust Excitation

In this case the vehicle model is excited with a 30 (ft/sec) wind-gust impulse, shown below. The gust excites attitudes and rates in all directions, which are eventually damped by the control system.

Air-Launch Glide Linear Simulation at T=20 sec, Gust=30 (ft/sec)
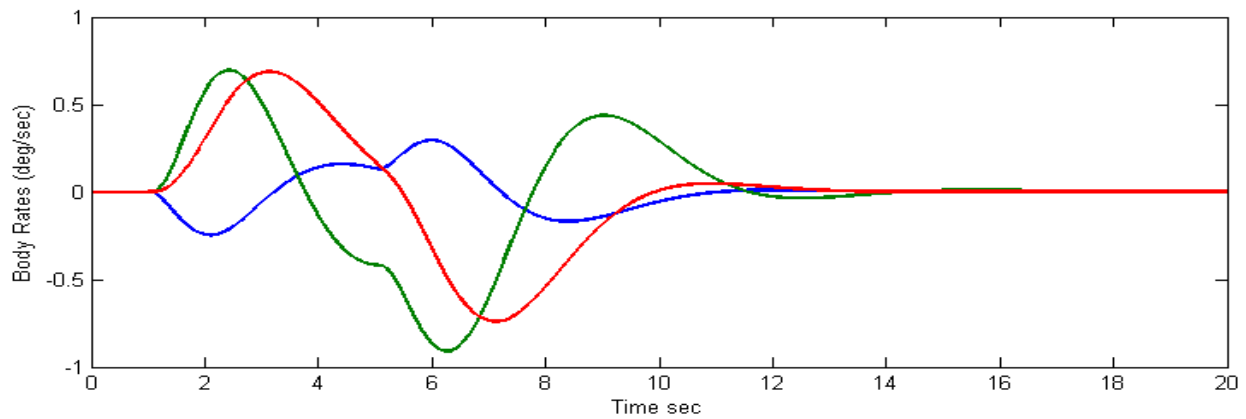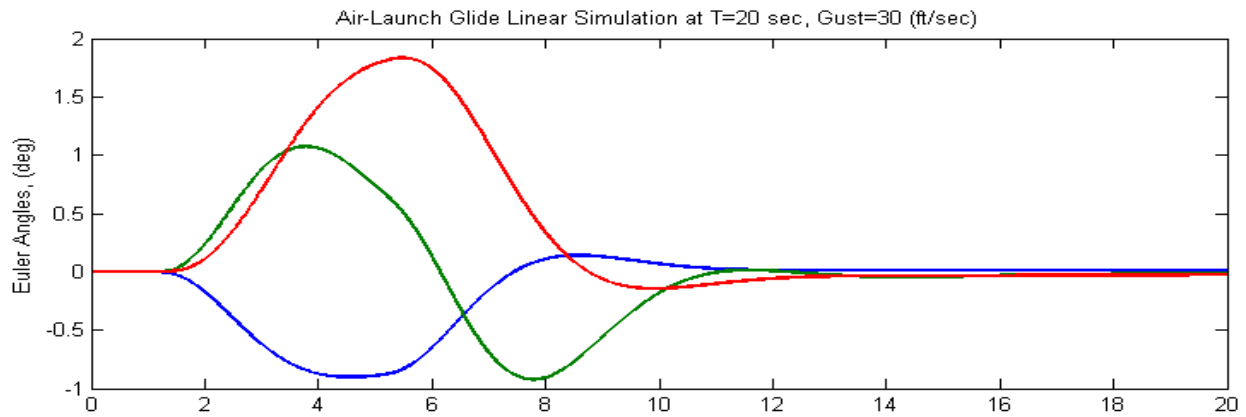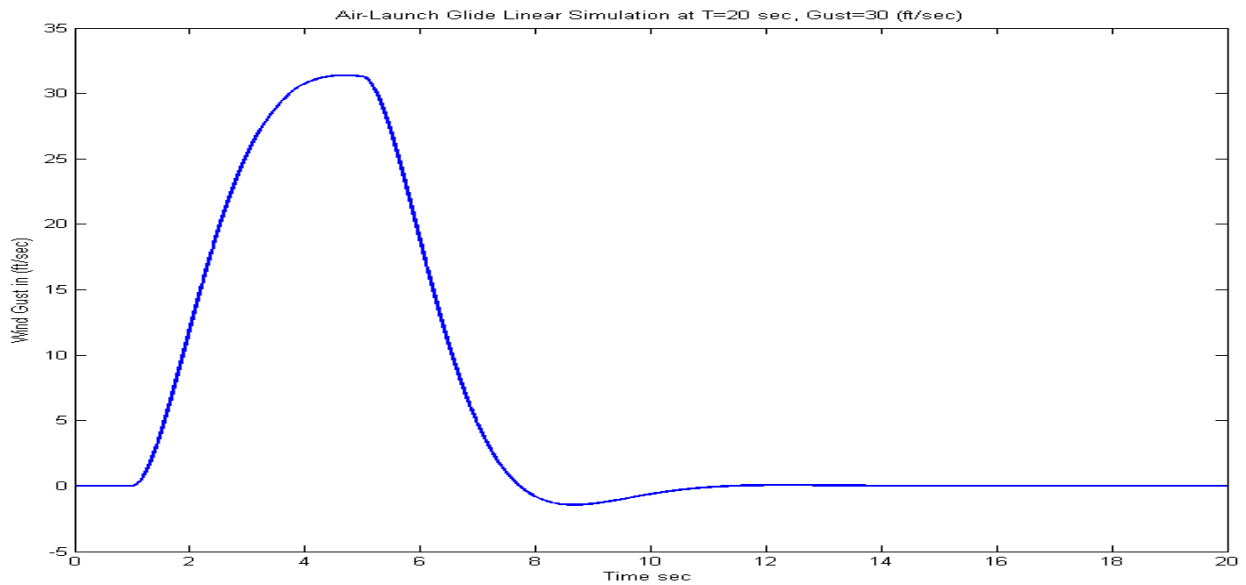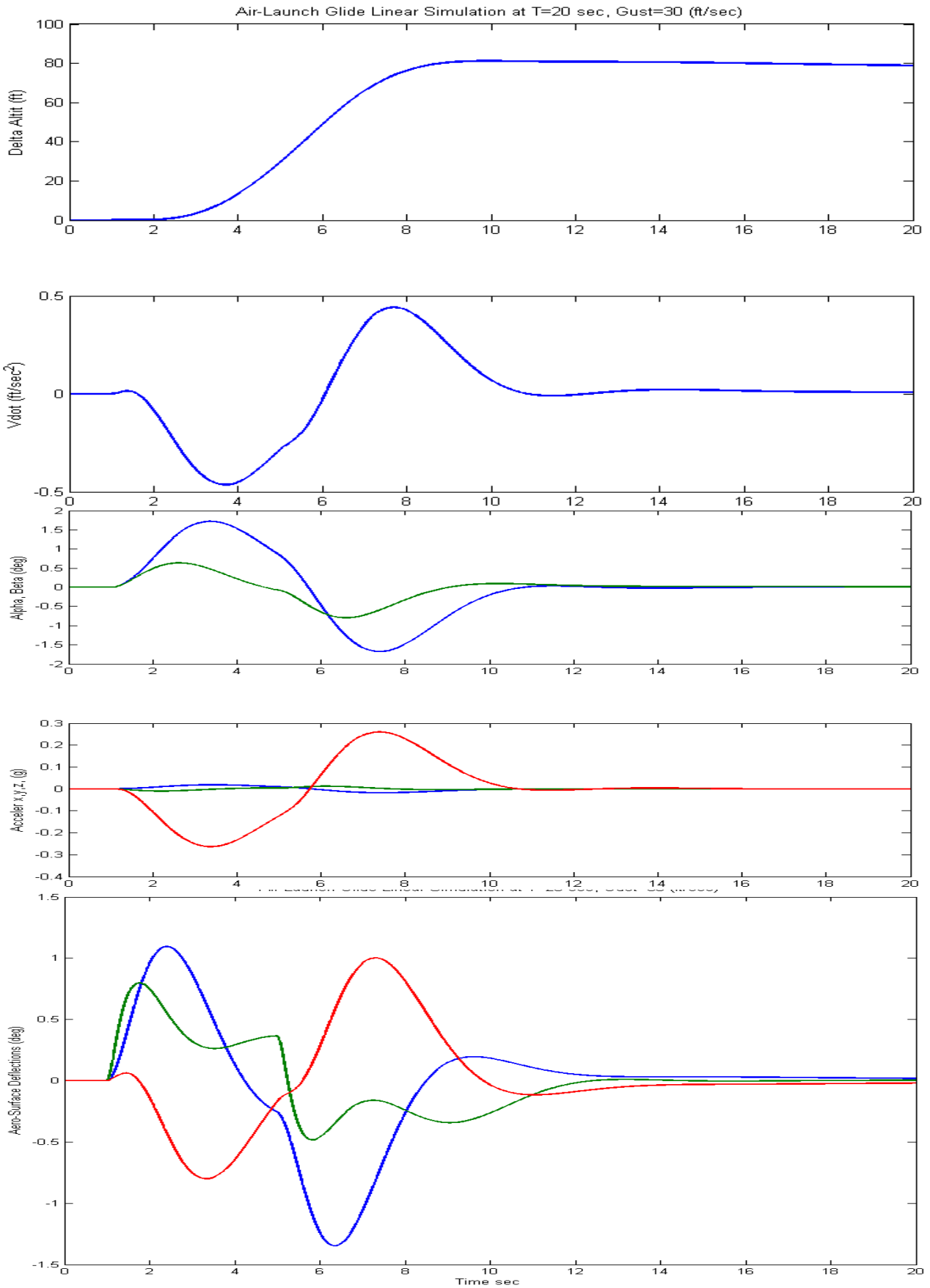
Gamma-Command Simulation

Now the vehicle model is commanded to increase its flight-path angle gamma by one degree from steady-state. All other commands and excitations are set to zero. This causes a steady increase in altitude and a drop in velocity. There is also a positive Elevon deflection transient that decays to zero. This causes a positive alpha and normal acceleration transients which increase gamma as commanded.

Air-Launch Glide Linear Simulation at T=20 sec, Gamma$_{cmd}$=1 (deg)

3-34

Air-Launch Glide Linear Simulation at T=20 sec, Gamma$_{cmd}$=1 (deg)
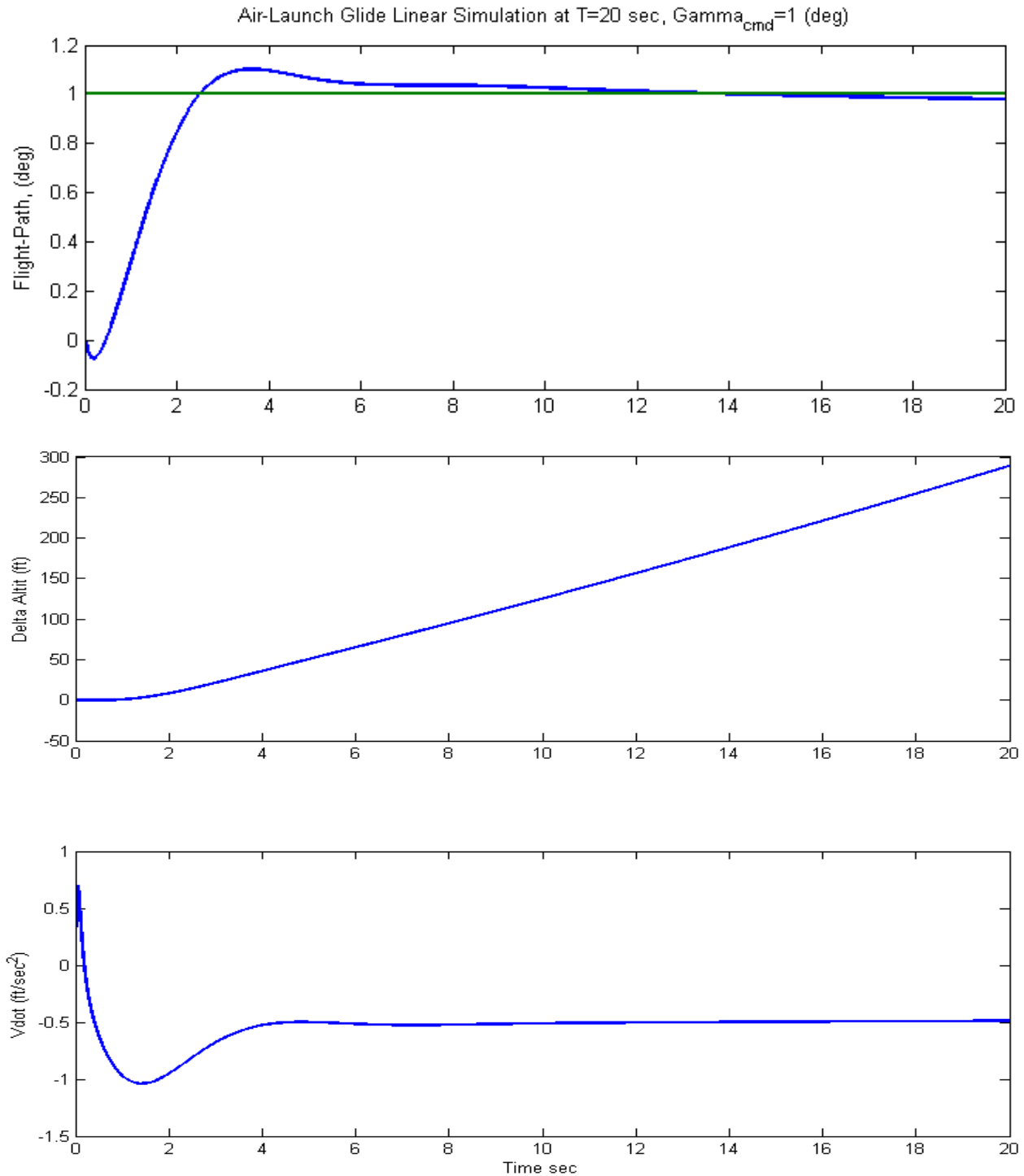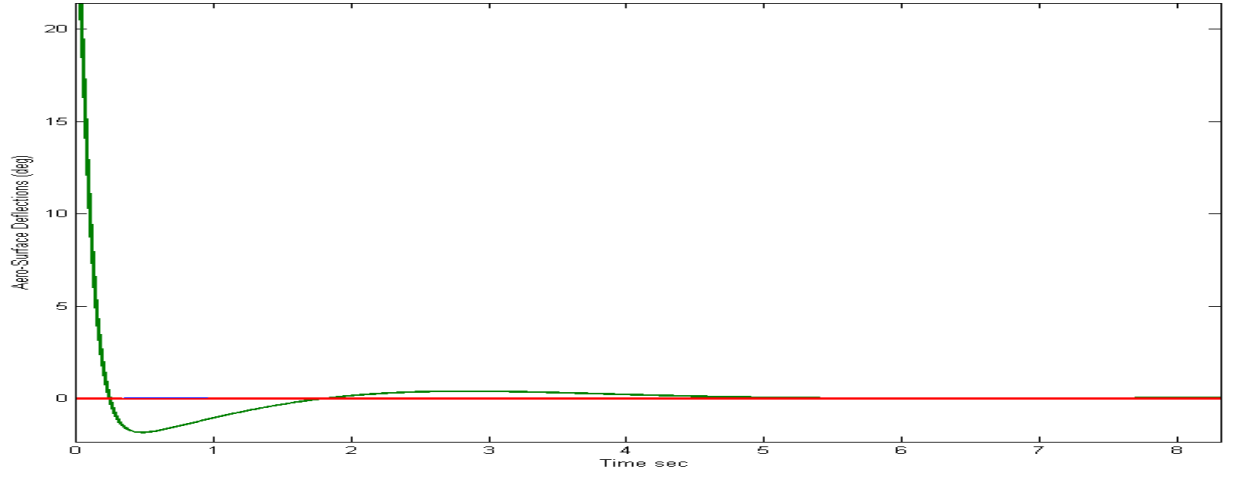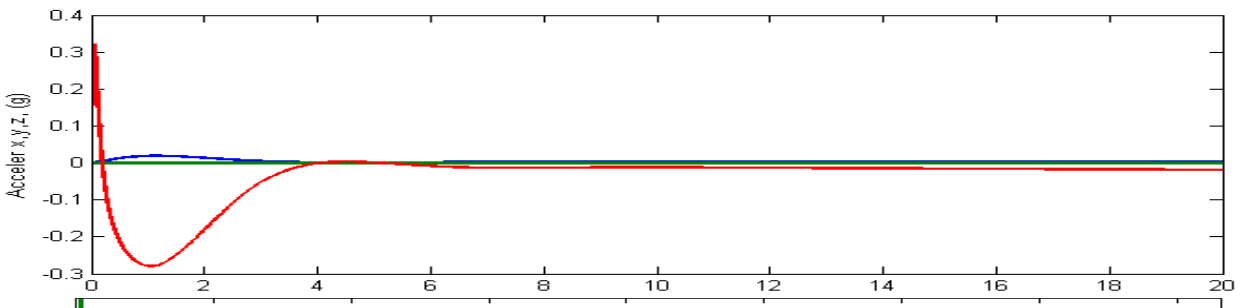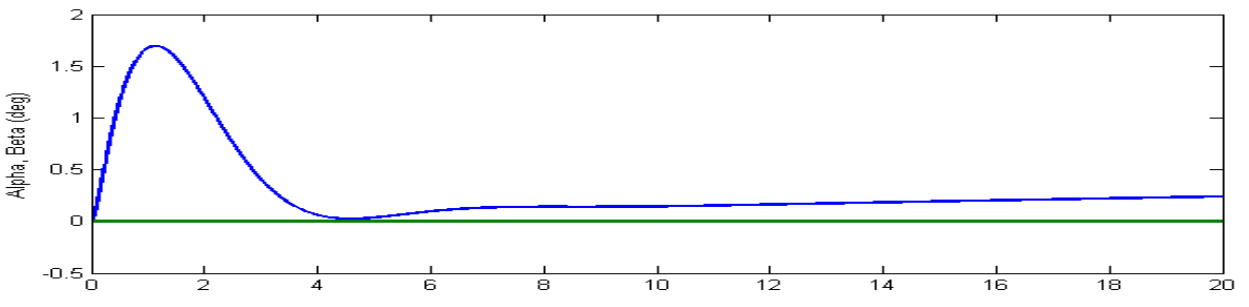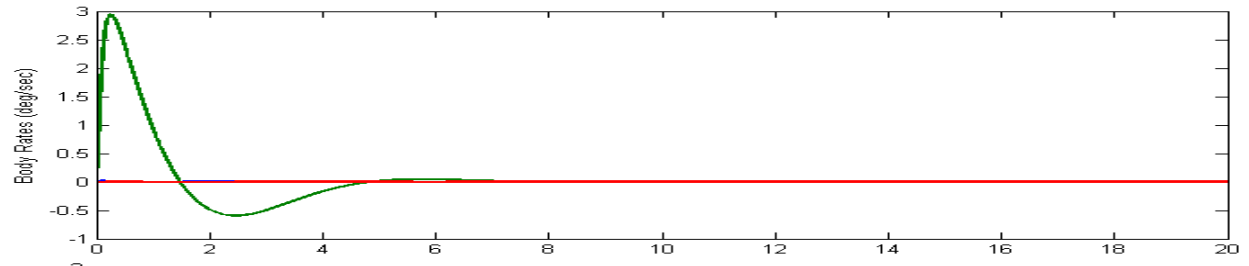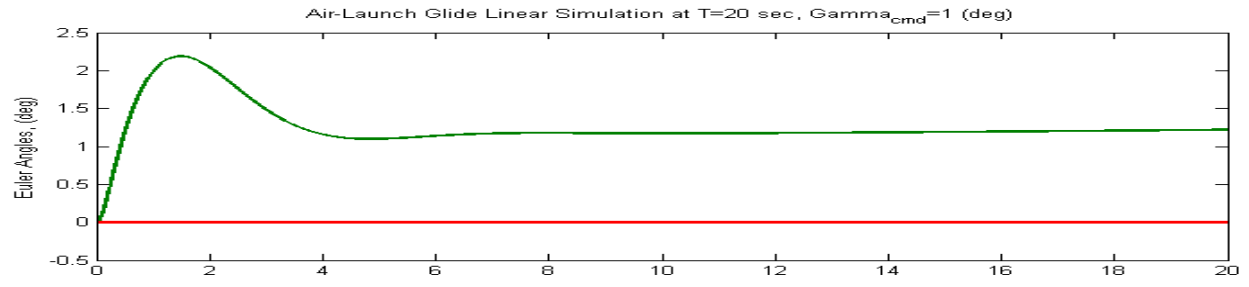
Gamma-Command Simulation with Turbulence

The previous gamma maneuver is now repeated with wind turbulence which is introduced in the wind disturbance block, see below. The next figure shows its effect on gamma which oscillates about 1°. It also causes small oscillations in the bank angle plus in other variables, as shown below.
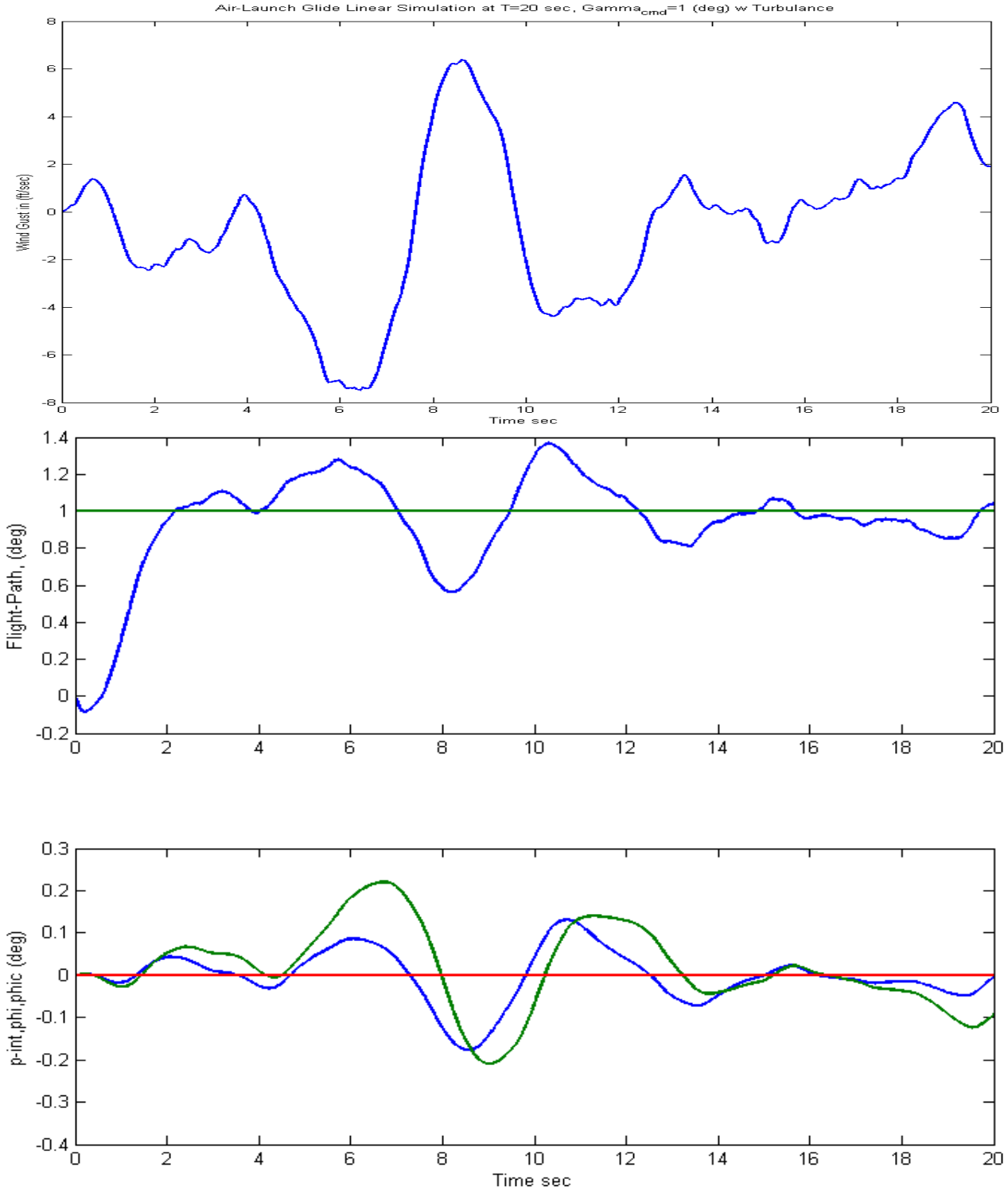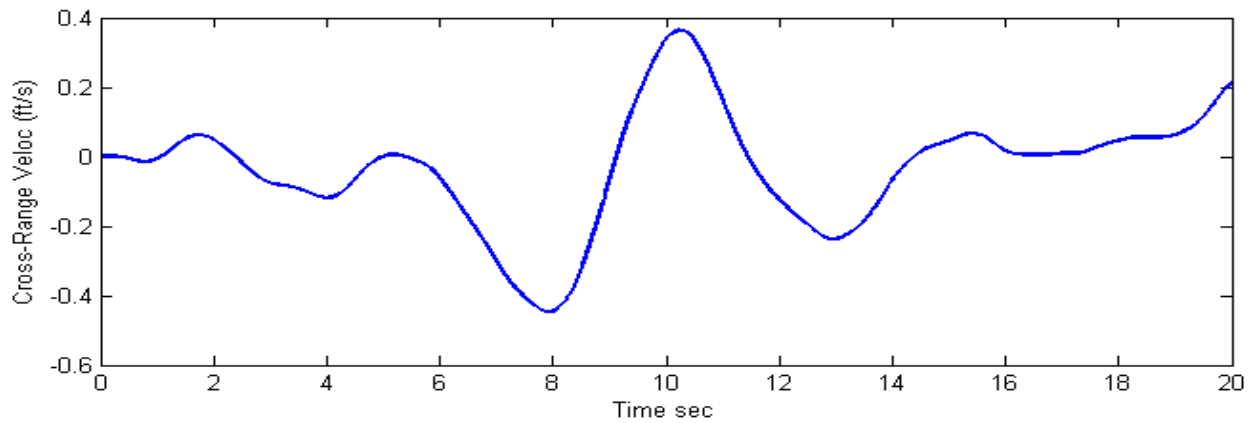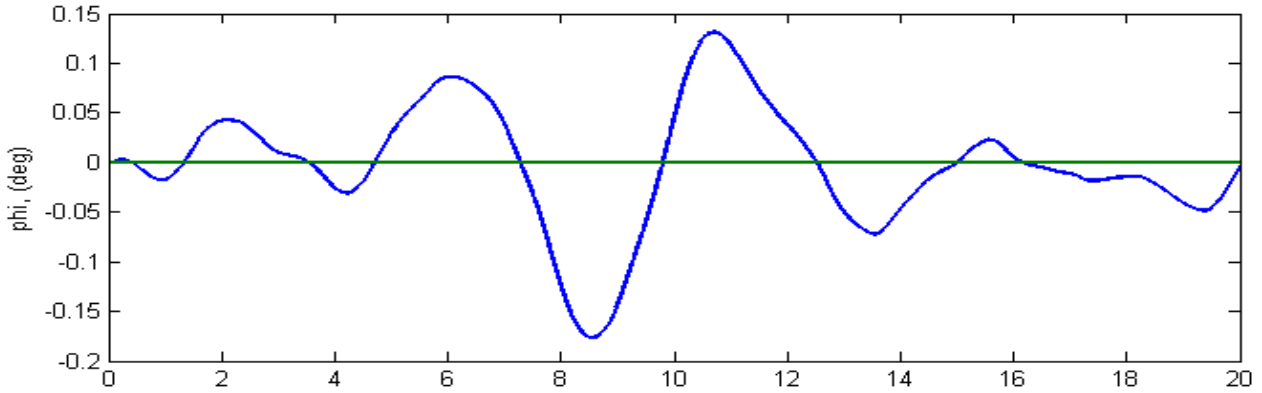

Air-Launch Glide Linear Simulation at T=20 sec, Gamma$_{cmd}$=1 (deg) w Turbulence
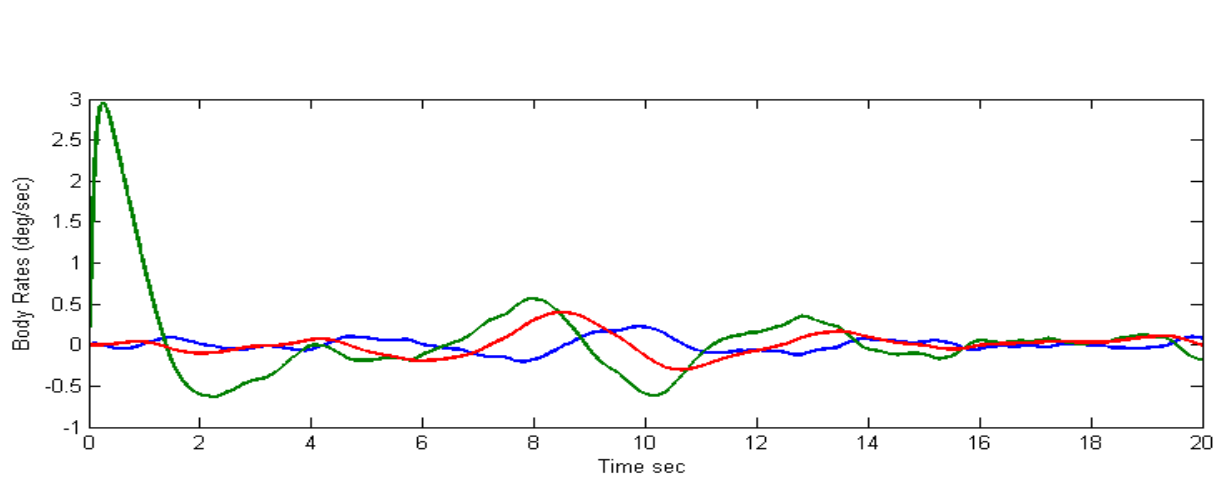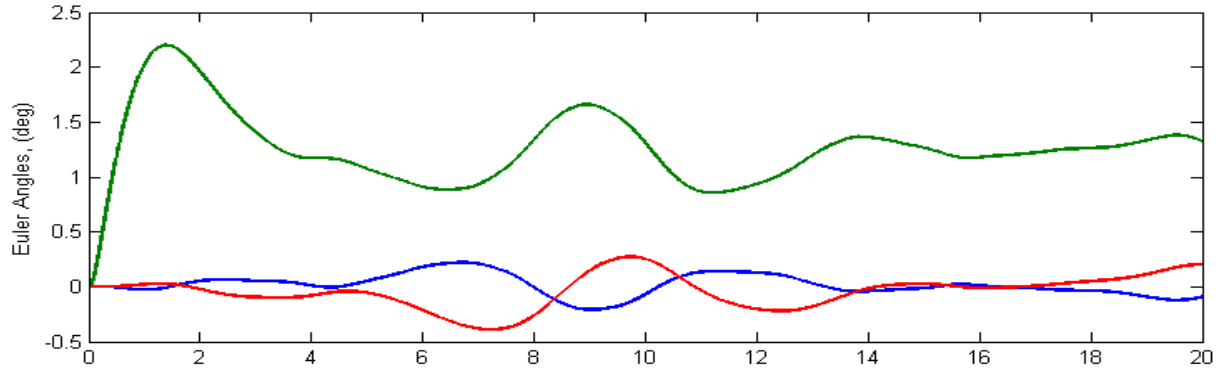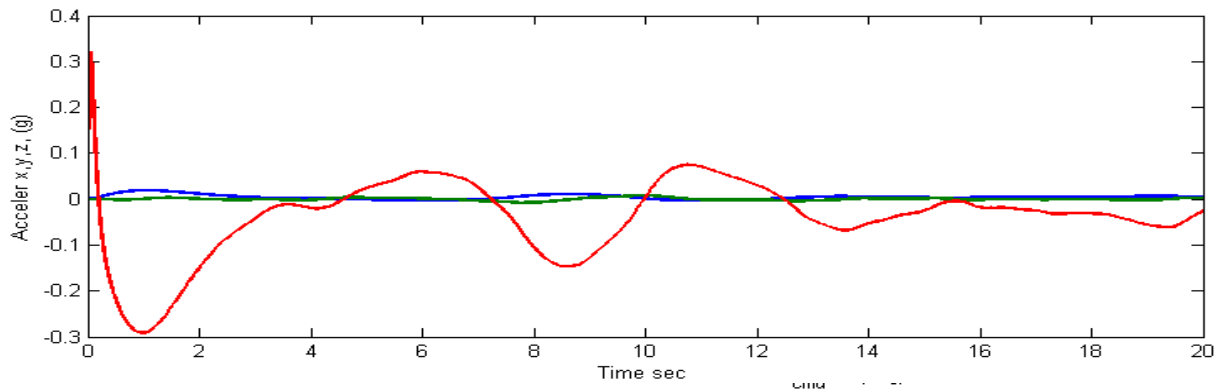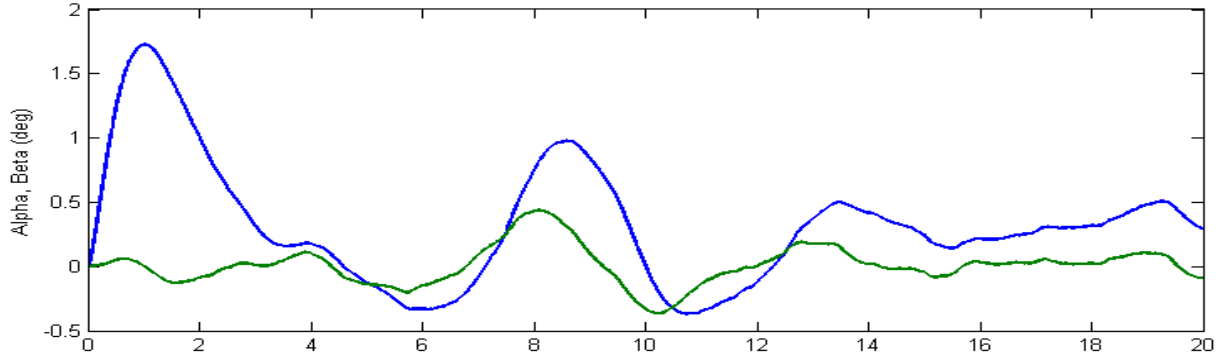
Air-Launch Glide Linear Simulation at T=20 sec, Gamma$_{cmd}$=1 (deg) w Turbulance

Air-Launch Glide Linear Simulation at T=20 sec, Gamma_cmd=1 (deg) w Turbulance
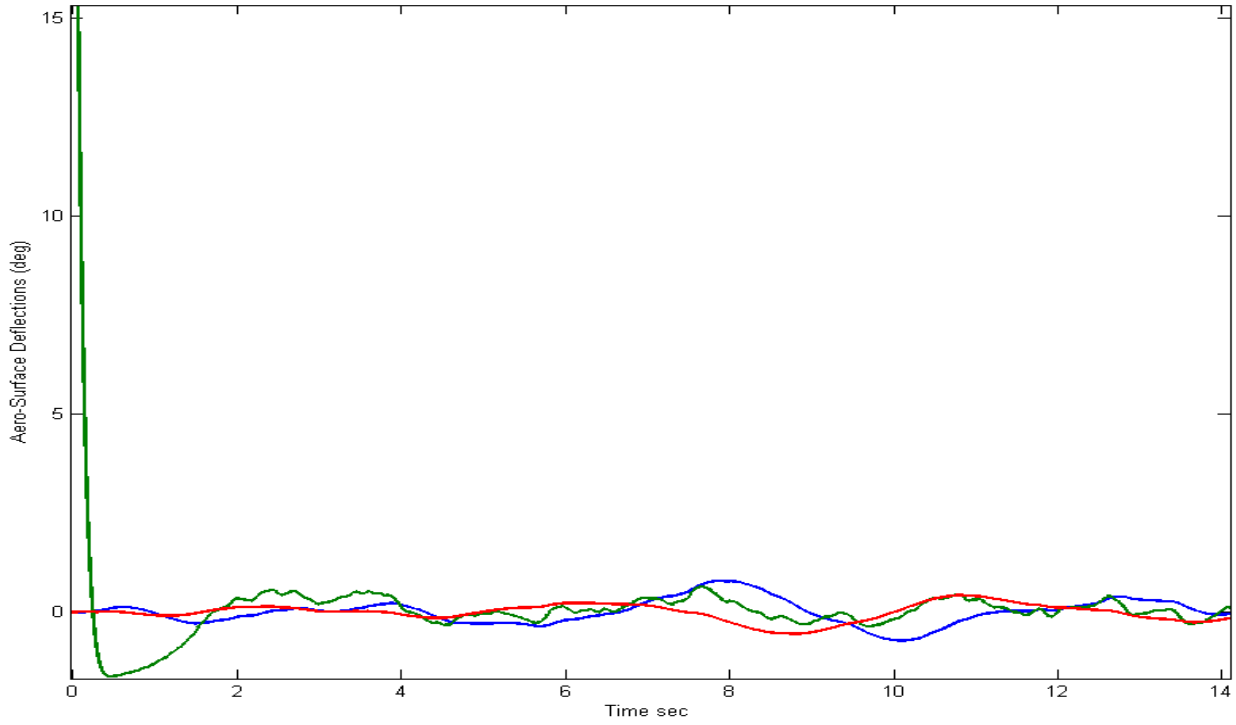
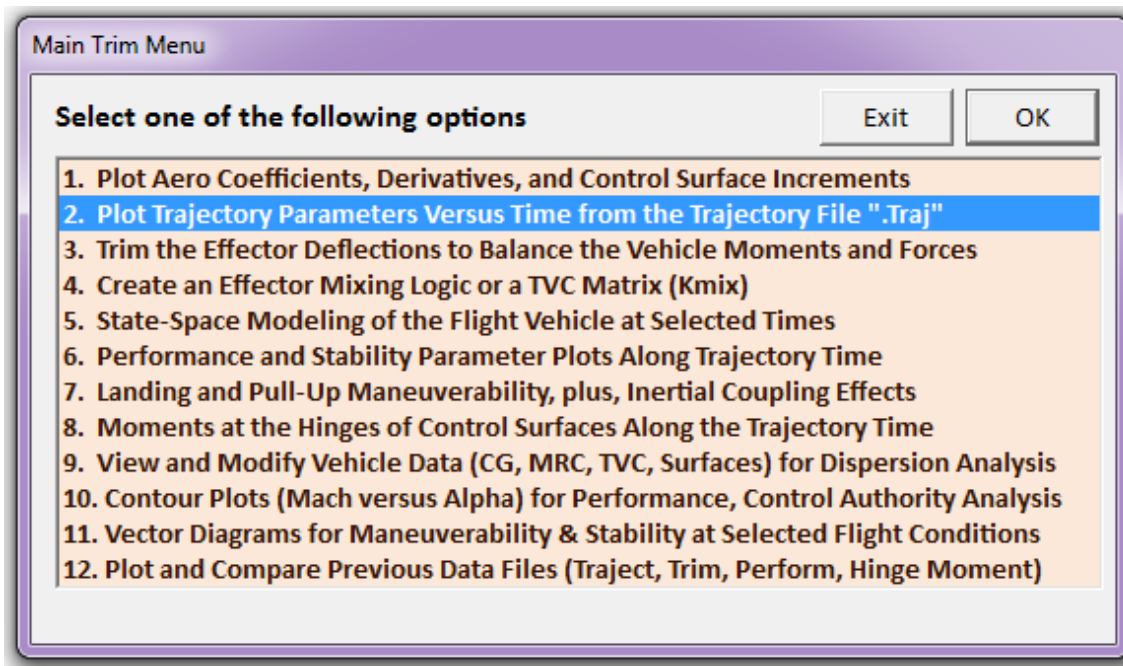Air-Launch Glide Linear Simulation at T=20 sec, Gamma_cmd=1 (deg) w Turbulance

First Stage Boost with Wings and Tails

At time=71.6 seconds the 400,000 (lb) first stage engine ignites, and the vehicle accelerates for 18.5 seconds with the wings and tails still attached. During this phase the flight control system uses both, the aero-surfaces and the TVC. The angle of attack remains positive and the wings help increase gamma to 55° before they are ejected at Mach 0.9. During pull-up the vehicle experiences a 1.5 (g) normal load. The data files for this phase are similar to the glide phase and they are located in the subdirectory: "*C:\Flixan\Trim\Examples\Air Launched Vehicle\Phase B Boost With Wing* ". This folder also includes the TVC engine data in file "*AL_Stg1.Engn*". The main engine has a 400,000 (lb) thrust. Its thrust direction is along the x axis. It can gimbal up to 5° in pitch and yaw, and it can vary its thrust ±60% from nominal. The file Kmix4.Qdr contains the effector combination mixing logic matrix Kmix4b. This matrix converts the four flight control demands (which are: roll, pitch, yaw, and axial acceleration), to effector deflection commands, (which are: TVC pitch and yaw deflections, engine throttle command, Elevon, Aileron, and Rudder deflections).

Trajectory Analysis

We can first take a look at the trajectory as we did for the glide phase. Start Flixan, select the project folder "*C:\Flixan\Trim\Examples\Air Launched Vehicle\Phase B Boost With Wing*", and then from the Flixan main menu select "*Analysis Tools*", "*Flight Vehicle/ Spacecraft Modeling Tools*", and "*Trim/ Static Performance Analysis*". From the Trim filename selection menu select the following files, and from the next filename selection menu select the file Kmix4.Qdr that contains the effector combination matrix. From the Trim main menu select the 2nd option for plotting the trajectory data.

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)

## Select One Data File from Each Menu Category

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

Mass Properties
Air_Launch.Mass ▼

Surface Hinge Moments
NO DATA FILE ▼

Trajectory Data
AL_Stg1_Won.Traj ▼

Aero Damping Derivat
NO DATA FILE ▼

Basic Aero Data
Wing_On_Bas.Aero ▼

Propulsion Data
AL_Stg1.Engn ▼

Contr Surface Aero Coeff
AL_AeroSurf.Delt ▼

Aero Uncertainties
NO DATA FILE ▼

Slosh Parameters
NO DATA FILE ▼

OK

Enter Filenames

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

NewFile.Inp

NewFile.Inp

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

Kmix4.qdr

Kmix4.qdr
NewFile.qdr
NewFile.Qdr

Create New Input Set   Exit Program   Select Files

Vehicle CG in (feet), Air Launched Vehicle First Stage Boost Trajectory
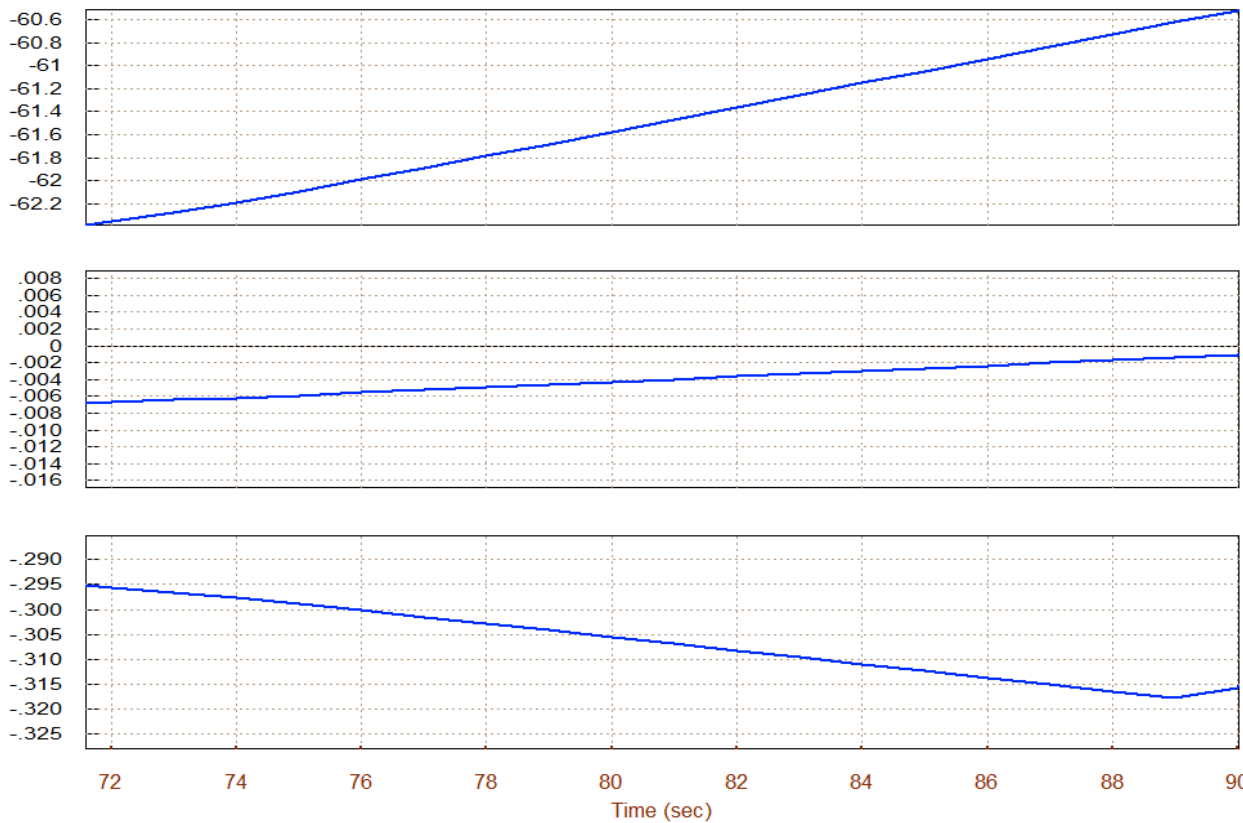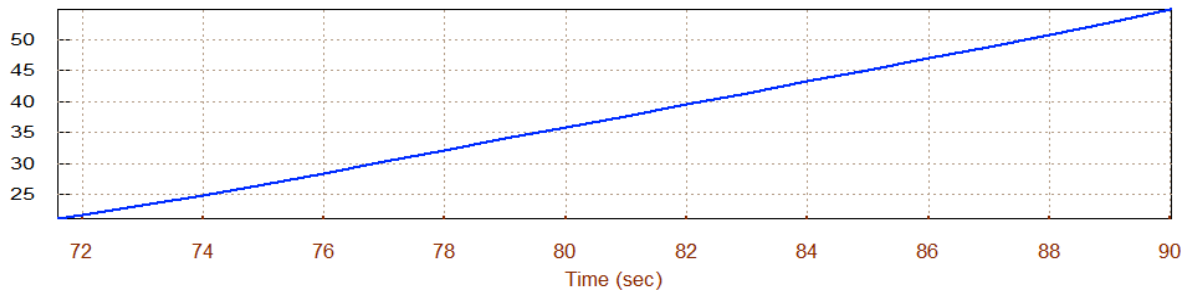
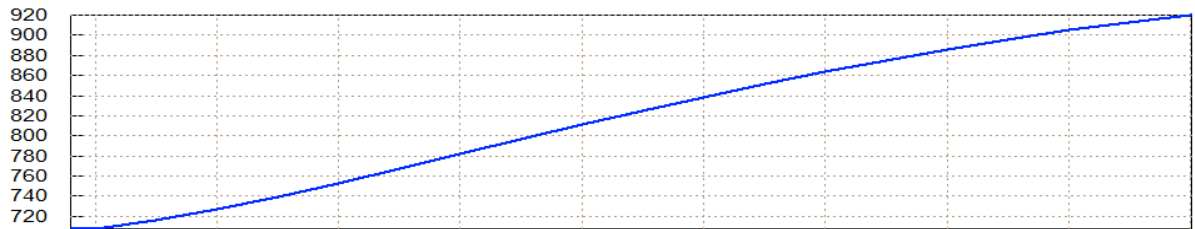## Angles of Attack/Sideslip/Flight Path (deg), Air Launched Vehicle Firs
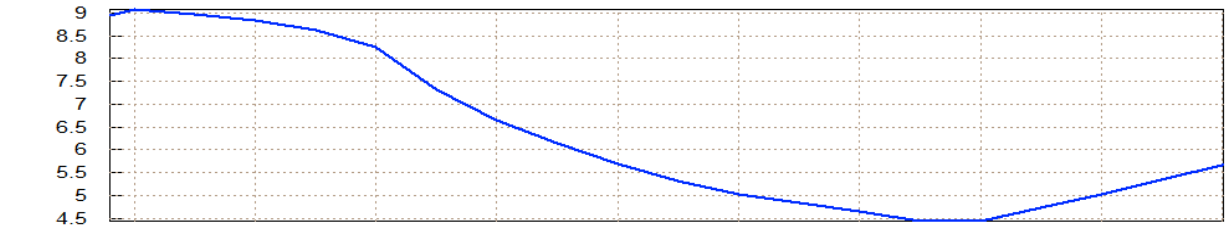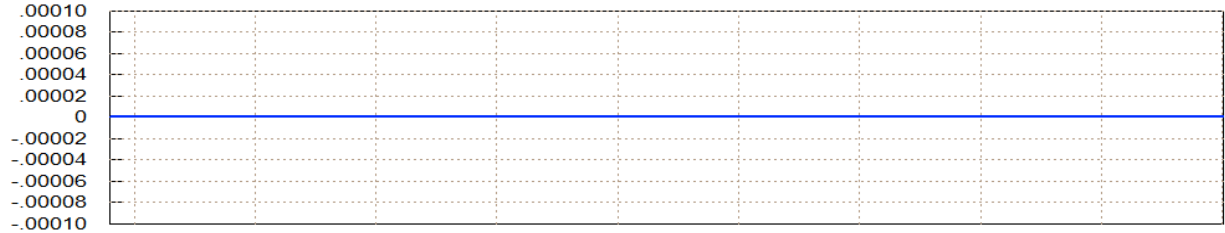
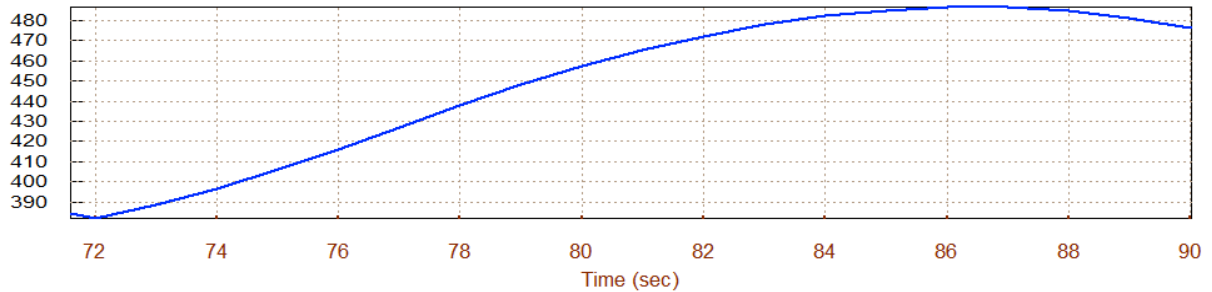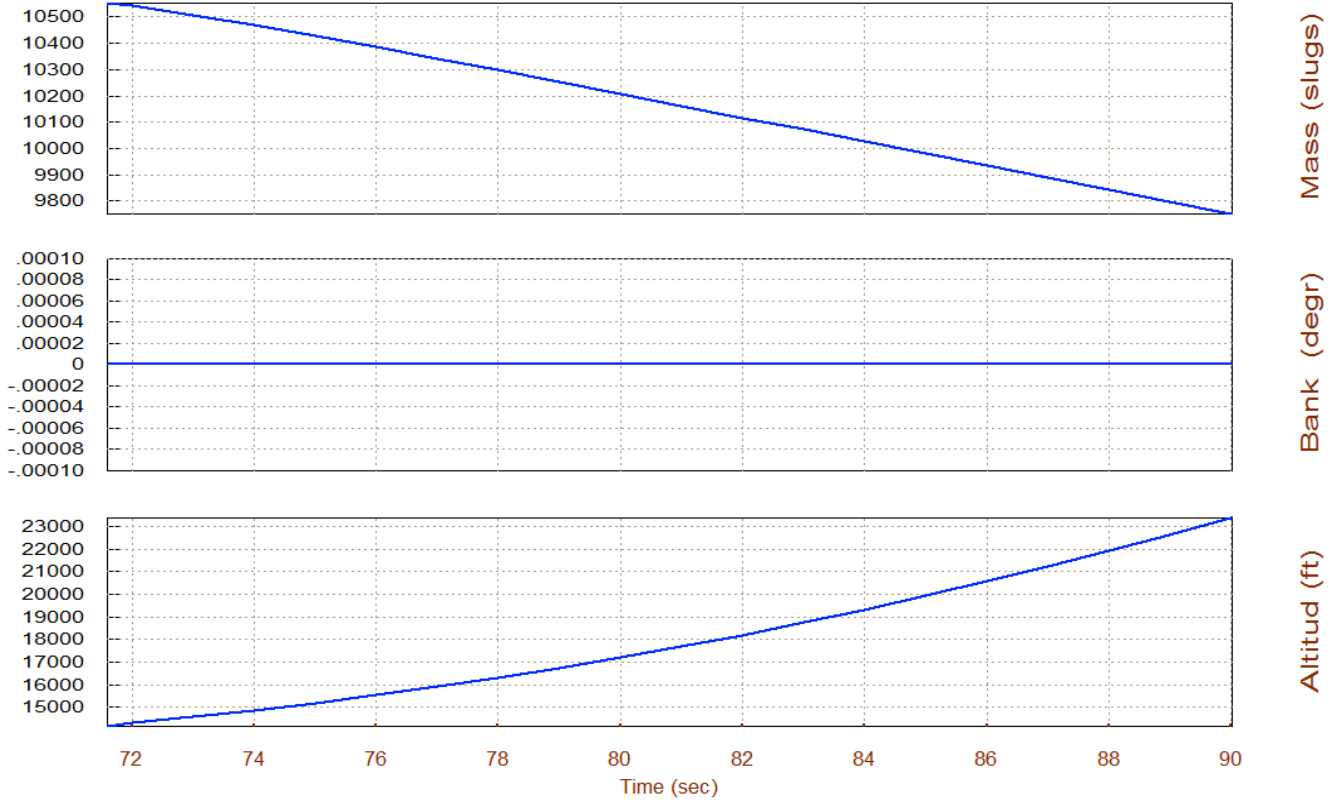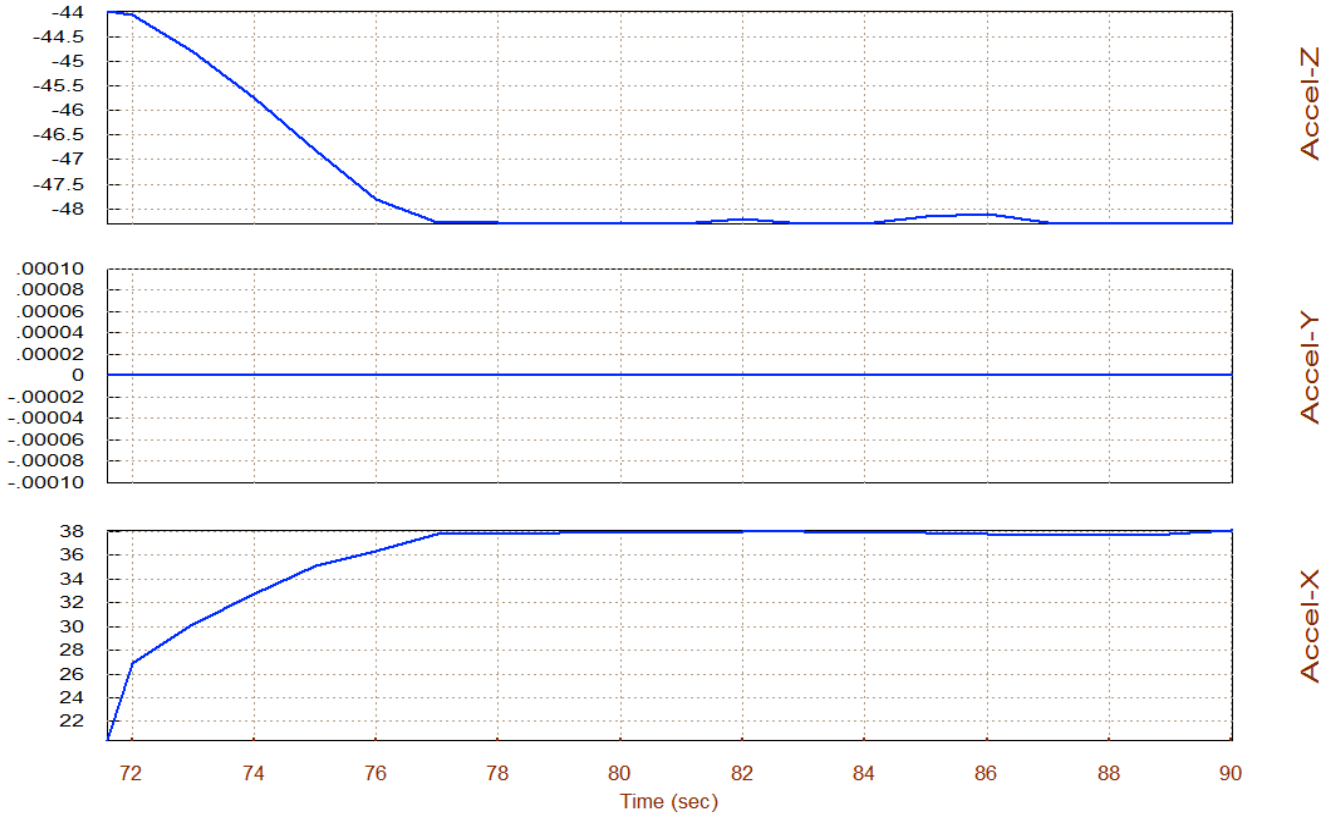## Velocity, Dynamic Pressure, Air Launched Vehicle First Stage Boost Trajectory

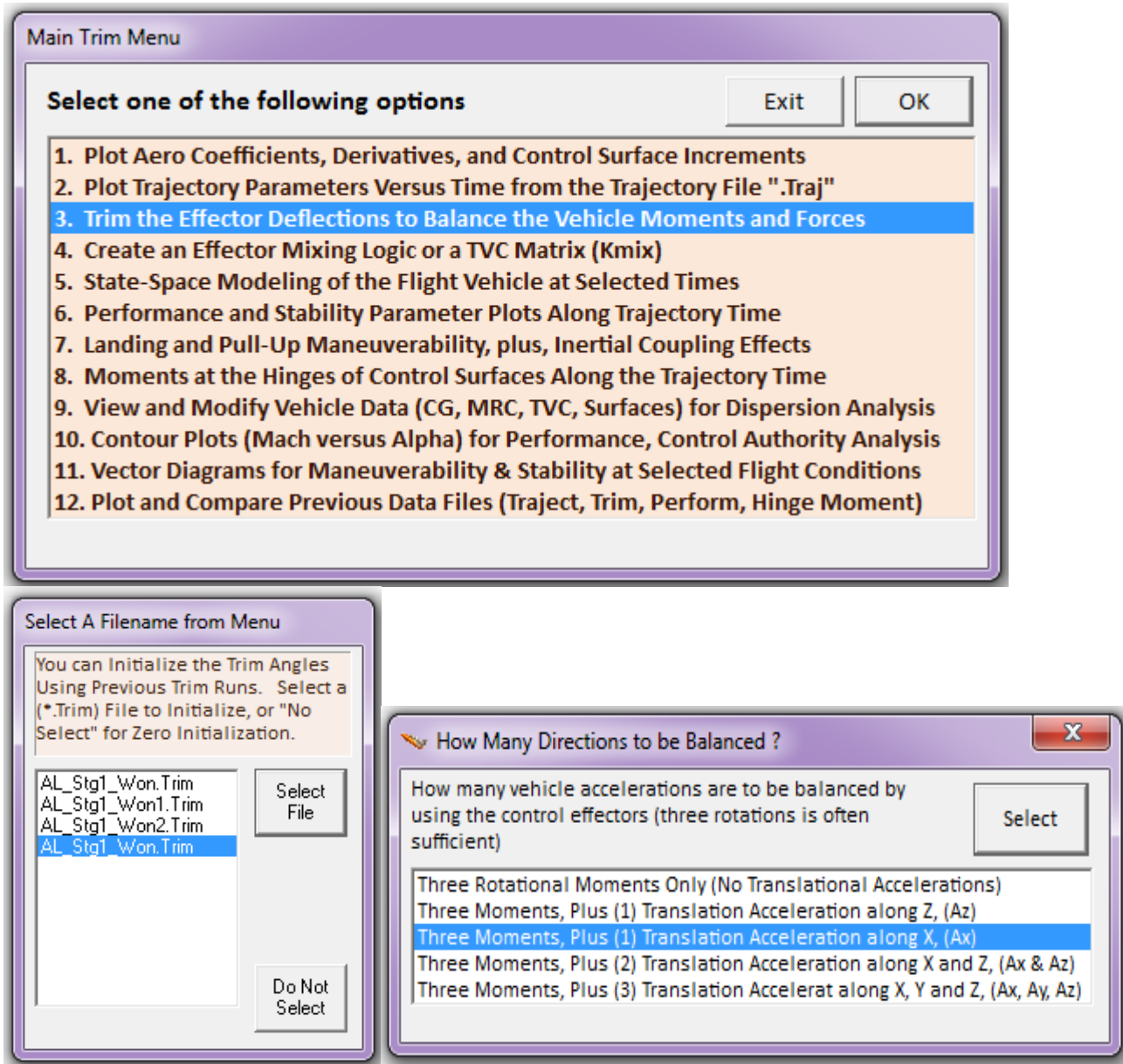## Vehicle Altitude, Mass, Bank Angle, Air Launched Vehicle First Stage B

Sensed Acceleration in (ft/sec^2), Air Launched Vehicle First Stage Boost T
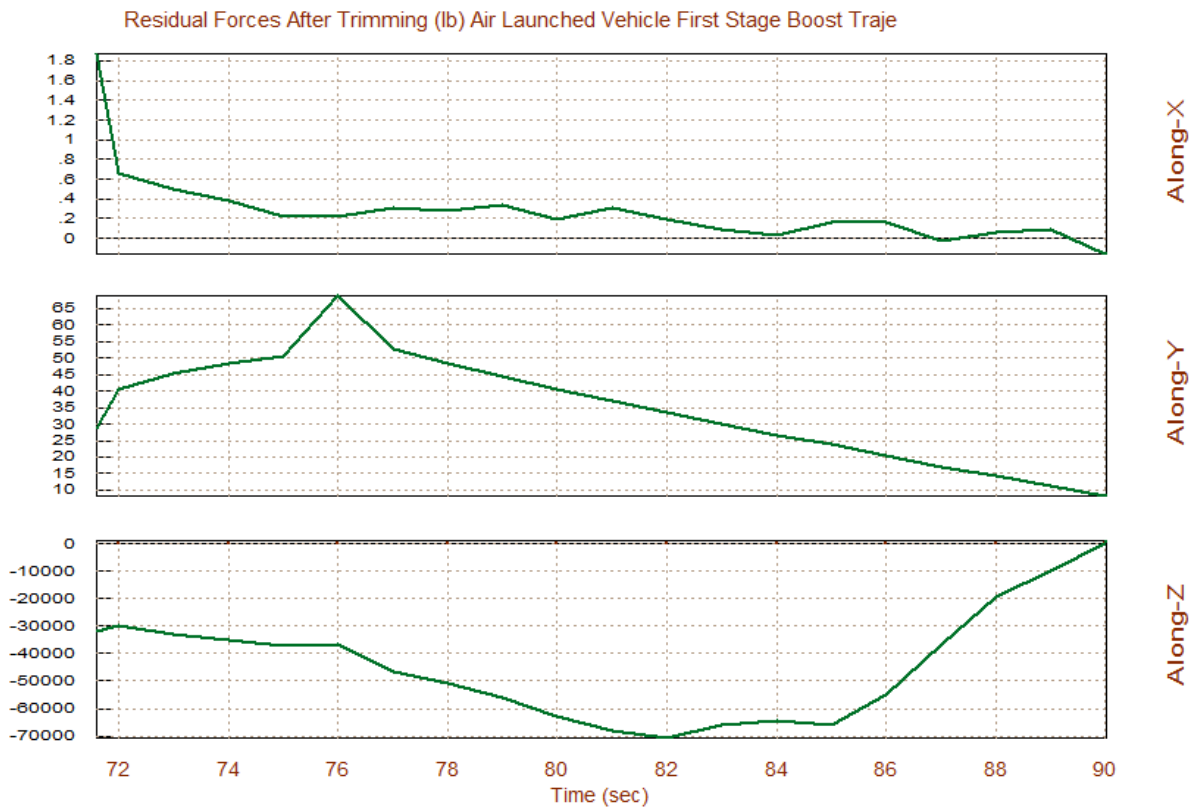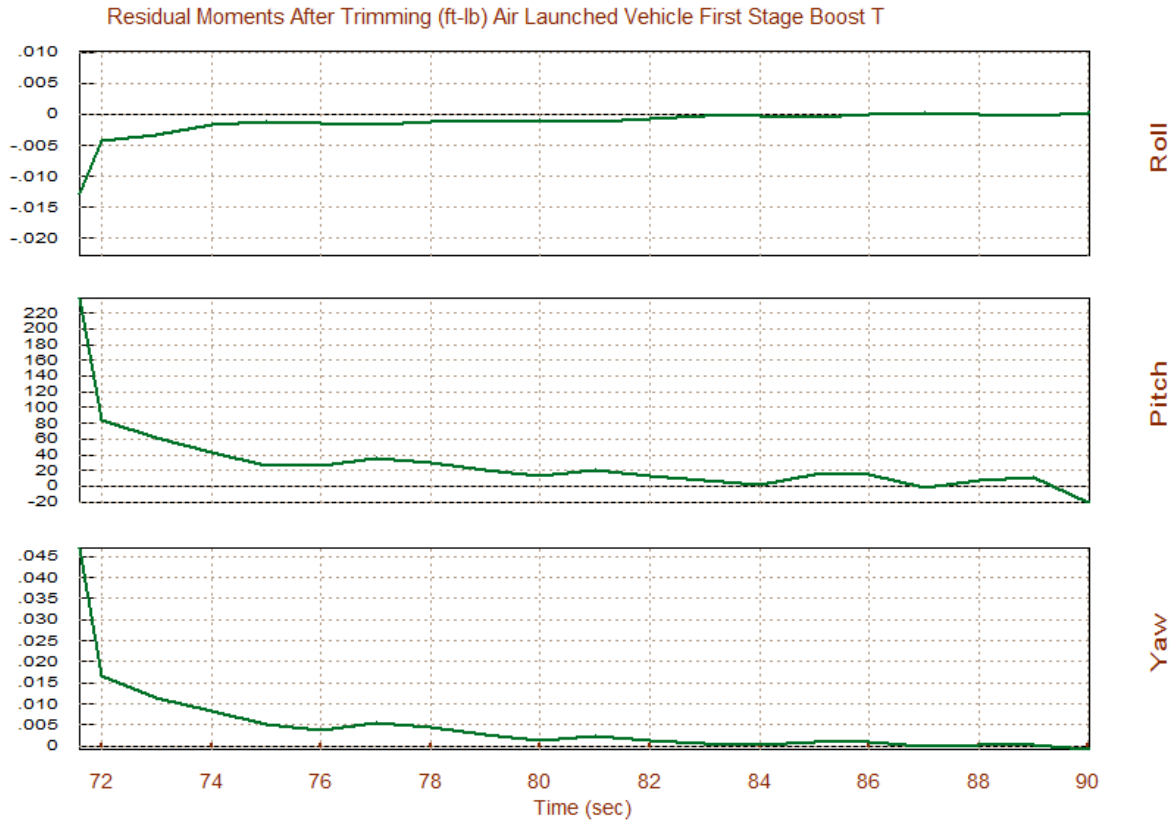

3-42
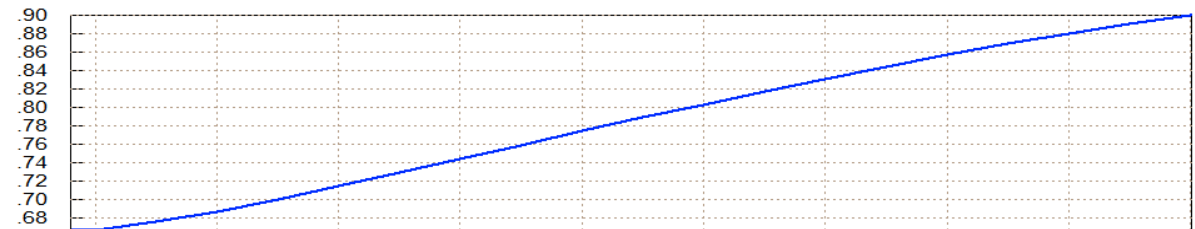
Trimming the TVC and Aero-Surfaces

The next step is to trim the aero-surfaces along the trajectory. Return to the Trim main menu and choose the third option for trimming. Do not select an initialization file (if it is the first time you trim). This time, in addition to the three moments, we must also trim along the x acceleration in order to match the x-acceleration dictated by the trajectory. This is accomplished by varying the engine thrust.

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)

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.

AL_Stg1_Won.Trim
AL_Stg1_Won1.Trim
AL_Stg1_Won2.Trim
AL_Stg1_Won.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)

The next two plots show the residual moments and forces after trimming. They are reasonably small along the trimmed directions, as expected. The Elevon is trimmed in the negative direction in order to provide the required positive pitching moment. The engine also deflects in the negative pitch direction for the same reason. The engine thrust varies in order to match the x-acceleration along the trajectory.

Residual Moments After Trimming (ft-lb) Air Launched Vehicle First Stage Boost T

Residual Forces After Trimming (lb) Air Launched Vehicle First Stage Boost Traje

Surface & Engine Deflections/ Thrusts, Air Launched Vehicle First Stage Boost Tr
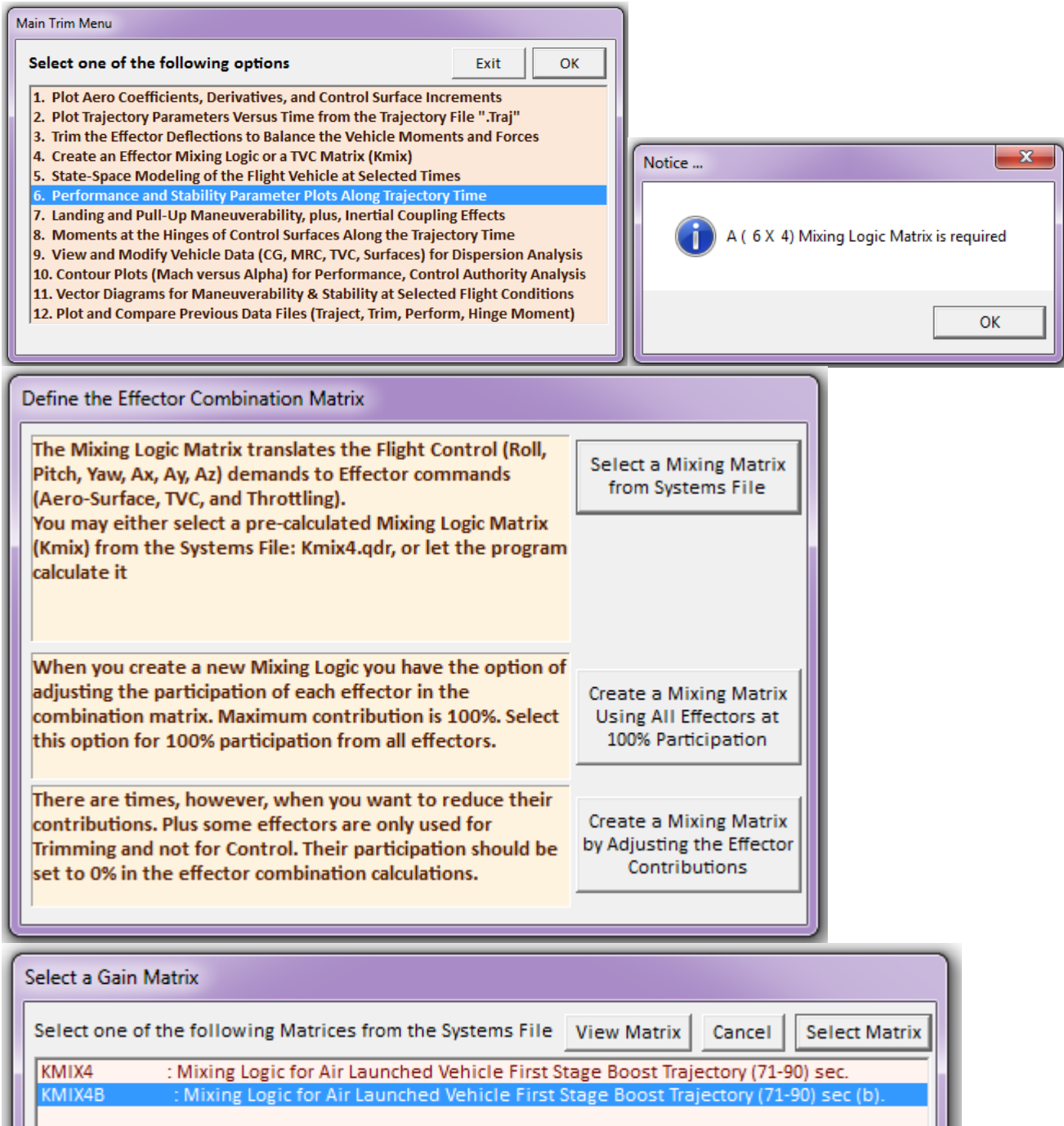

Surface & Engine Deflections/ Thrusts, Air Launched Vehicle First Stage Boost Tr

3-45
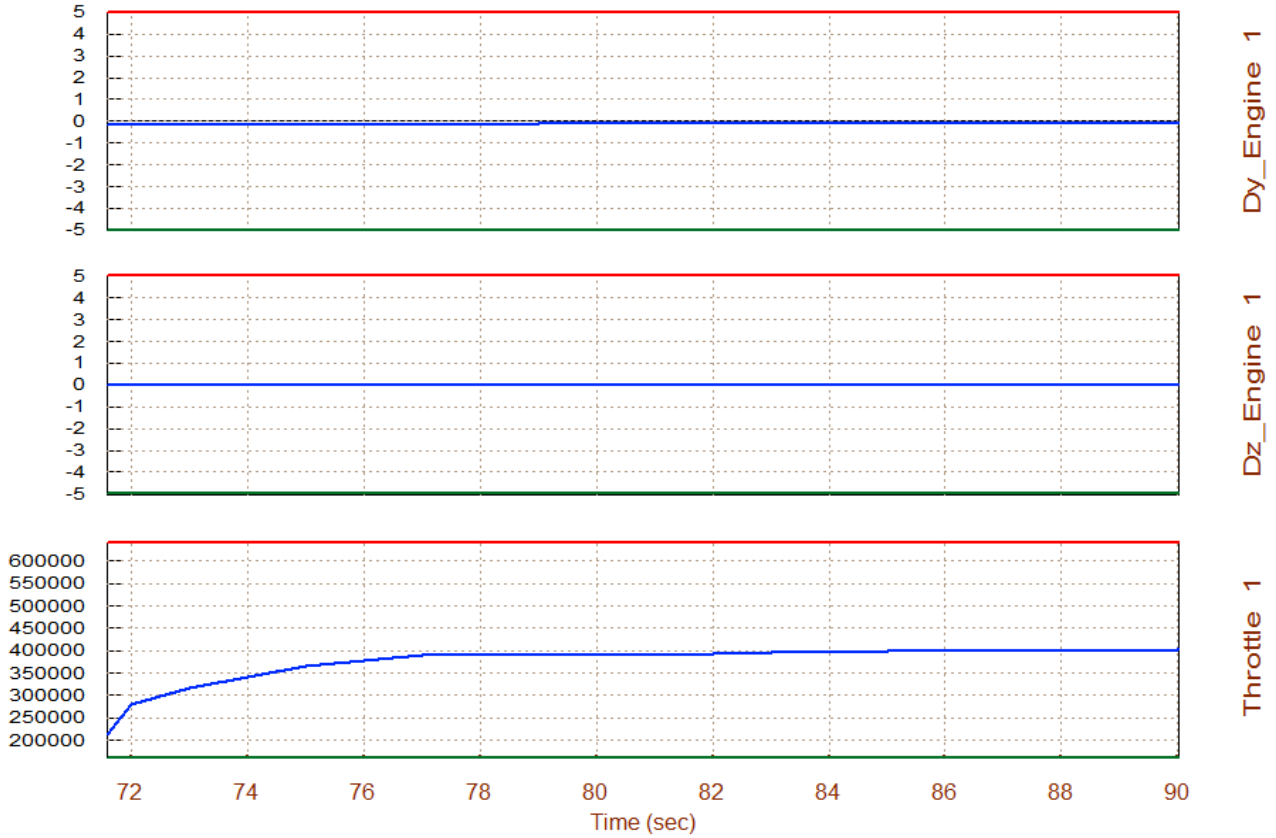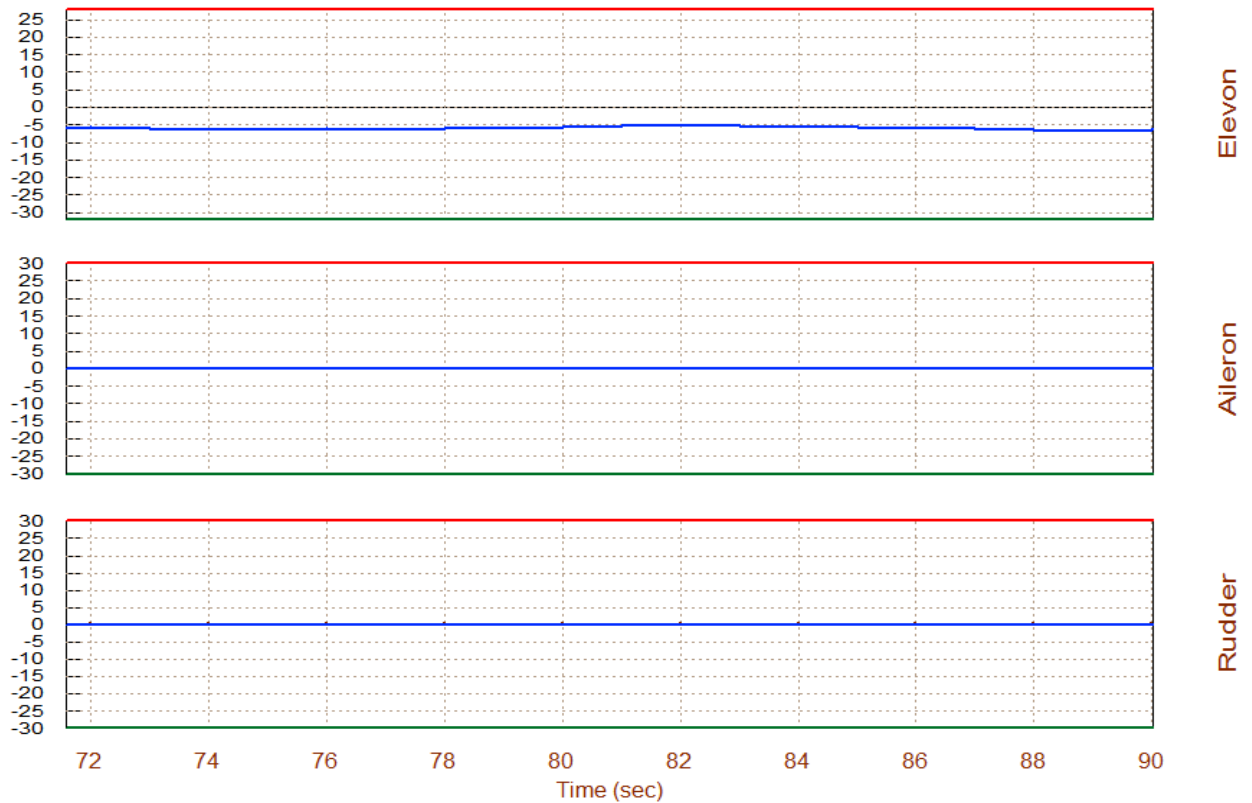
Performance Analysis Along Trajectory

Now after returning to the main menu select option 6 to evaluate the vehicle performance parameters along the trajectory. Performance analysis requires a (6x4) mixing-logic matrix which in this case it has already been defined (Kmix4b), and it is located in file "Kmix4.Qdr". It converts the (roll, pitch, yaw, plus axial acceleration) demands to effector commands. In the following effector combination selection menu click on "*Select a Mixing Matrix*" to select the second matrix in that file.

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)

Notice ...

A (6 X 4) Mixing Logic Matrix is required

OK

Define the Effector Combination Matrix

The Mixing Logic Matrix translates the Flight Control (Roll, Pitch, Yaw, Ax, Ay, Az) demands to Effector commands (Aero-Surface, TVC, and Throttling).
You may either select a pre-calculated Mixing Logic Matrix (Kmix) from the Systems File: Kmix4.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

KMIX4   : Mixing Logic for Air Launched Vehicle First Stage Boost Trajectory (71-90) sec.
KMIX4B   : Mixing Logic for Air Launched Vehicle First Stage Boost Trajectory (71-90) sec (b).

We must also define the max alpha and beta excursions from nominal due to winds and also for maneuvering. This is required for determining the maneuverability and control authority of the vehicle. In this case we pick 3° for both angles.


The performance plots indicate that this vehicle is statically stable in both pitch and lateral directions. The 3,500 (psf-deg) Q-alpha, Q-beta load factor at 3° of alpha and beta is reasonable. The control authority parameters in roll pitch yaw and x-acceleration are all acceptable (they are less than one). The roll angle (ϕ) which would occur along the trajectory at 3° of sideslip (β), due to cross-wind, is less than 2.2°. The LCDP in this case is negative. Its magnitude is slightly low but it does not change sign, which is good. The Cn-beta-dynamic is positive which indicates lateral stability, and its minimum value is around 0.011.

Static Margin, Center of Pressure, Aero-Center (ft), Air Launched Vehicle First
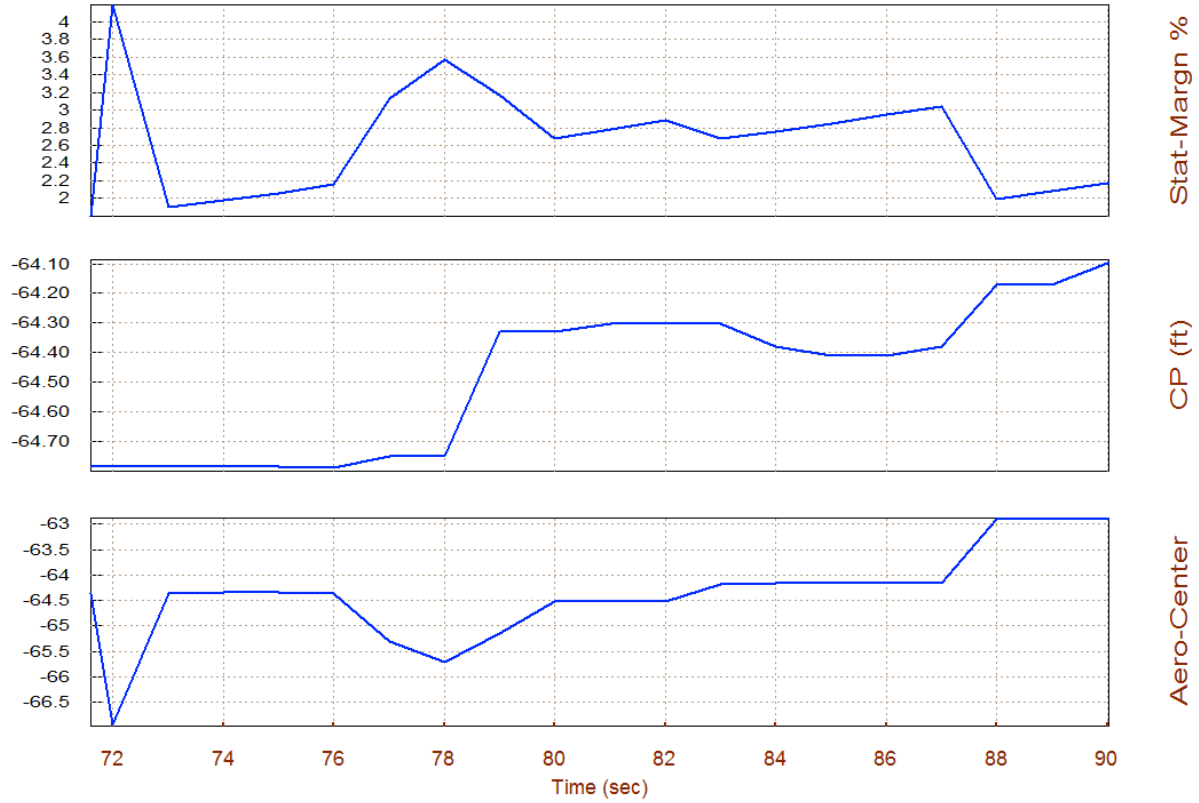
Short-Period (w)/ Time-to-Double-Ampl-Inverse (/sec), Q_alpha_beta (deg-lb/ft^2)

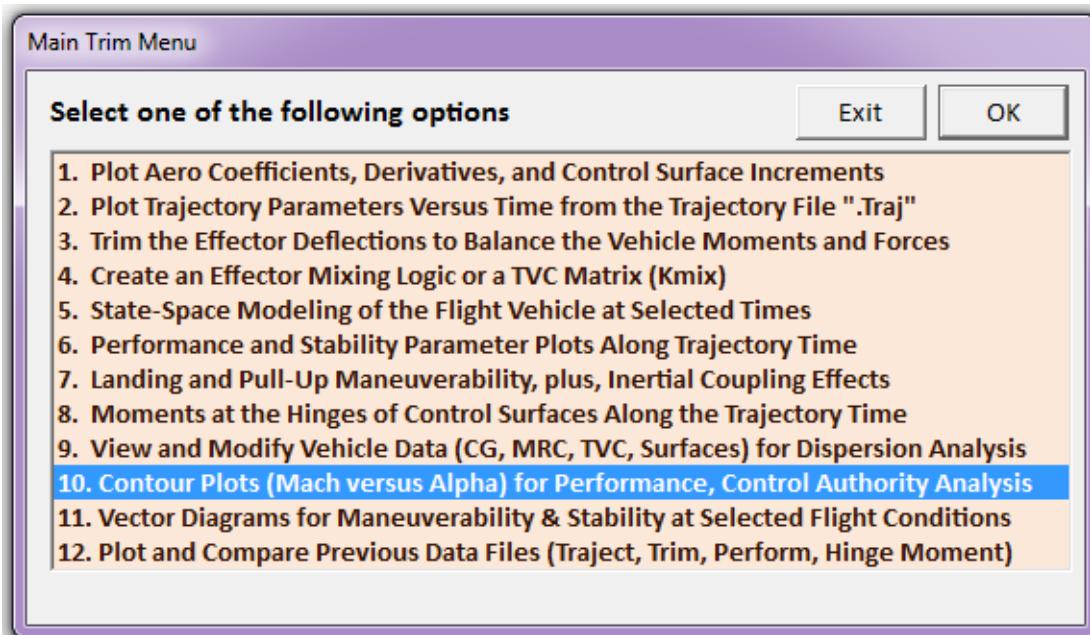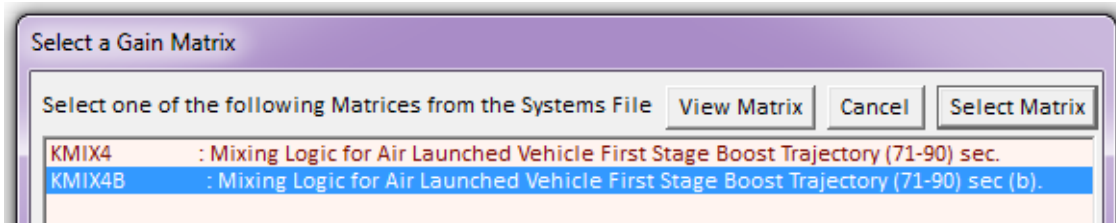Rotation Control Authority (dQ/dQmax)<1 for 3 (deg) of Alpha & Beta Variation
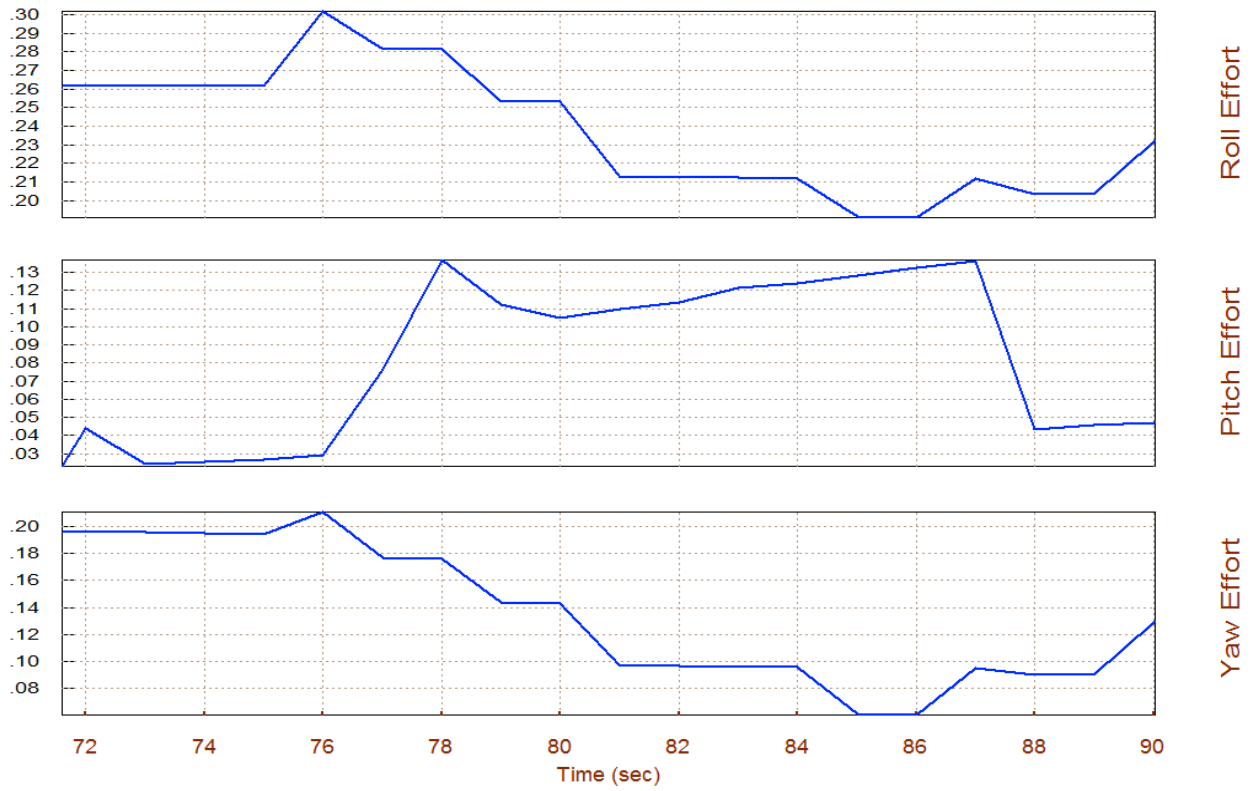
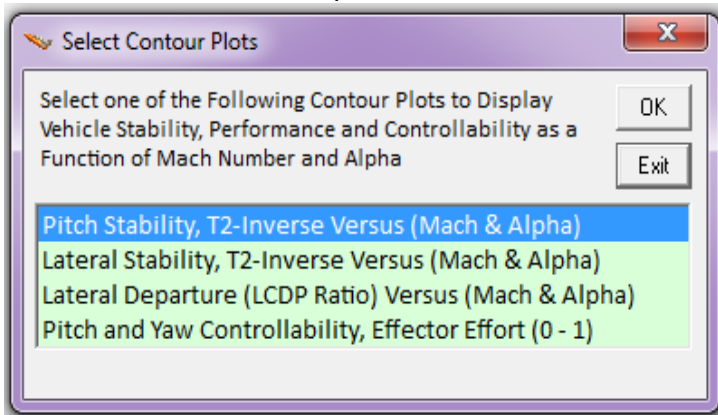Bank Angle, LCDP Ratio, Cn_beta_dynam /deg, Air Launched Vehicle First Stage Boo

3-49
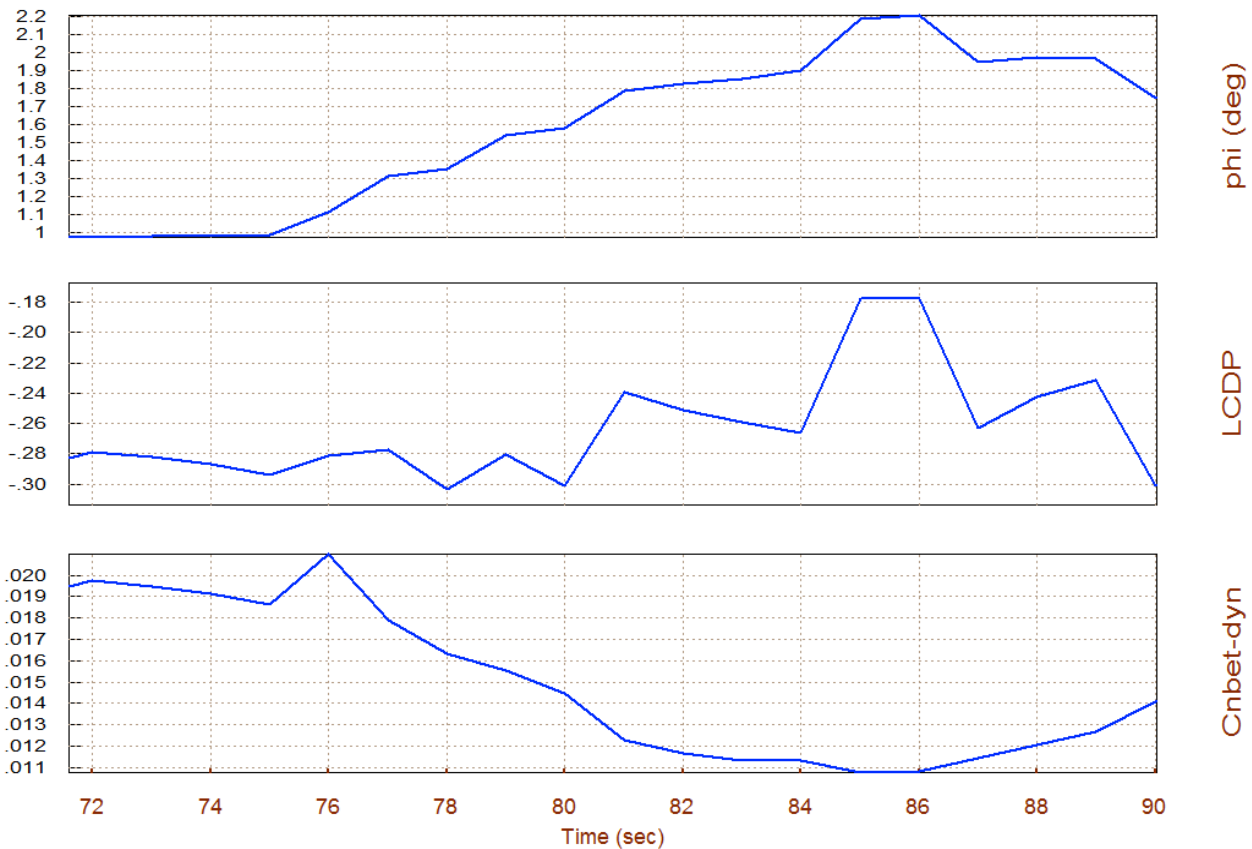
Contour Plots

Contour plots are 3-dimensional plots of some vehicle performance parameters versus alpha and Mach. They provide a broader performance perception in the entire Mach versus alpha range, rather than in the vicinity of the trajectory. Occasionally the vehicle may deviate from its nominal alpha versus Mach trajectory and we would like to make sure that the trajectory is not close to regions of unacceptable performance. From the main menu select option (10) to create contour plots of some important parameters against Mach and Alpha. Similar to our previous analysis we must specify the aero disturbance environment which at steady-state it is defined by the maximum dispersion angles (α_{max} and β_{max}) relative to the velocity vector. Enter 3° for both α_{max} and β_{max}, as shown below. The program also requires the effector combination matrix Kmix4b from file Kmix4.Qdr.

Main Trim Menu

Select one of the following options   Exit   OK

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

Define the Effector Combination Matrix

The Mixing Logic Matrix translates the Flight Control (Roll, Pitch, Yaw, Ax, Ay, Az) demands to Effector commands (Aero-Surface, TVC, and Throttling).
You may either select a pre-calculated Mixing Logic Matrix (Kmix) from the Systems File: Kmix4.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) `3.0000`   Maximum Beta (deg) `3.0000`   OK

Using the following menu we must select the performance parameter to plot against alpha and Mach number, as shown in the plots below.


The first two plots show the pitch and lateral stability parameter T2-inverse that were described in equations (3.14 & 3.15). The trajectory is shown with a black line across the Mach versus Alpha field. It starts at T=71.6 (sec) in the upper left-hand corner where (α=9.1°, Mach=0.67), and it ends at T=90 (sec) in the lower right-hand side, at (α=5.7°, Mach=0.9). The color represents the value of the T2-inverse stability parameter over the entire of Mach and alpha range and it shows how our trajectory (black line) crosses through the (Mach versus Alpha) field. We conclude that in the lateral direction the entire Mach versus alpha range is statically stable. In the pitch direction, however, although the field is mostly stable, there are some regions of neutral stability and mild static instability in the upper right-hand corner. The trajectory, however, travels only through the stable regions of the alpha versus Mach field.

The next two contour plots show the control authority of the pitch and yaw effectors which are mainly the TVC in combination with the elevon and the rudder. It shows how much effort is required to counteract against the 3° of α_{max} and β_{max} aero disturbances in the entire Mach versus alpha range. The color coded magnitudes show that the control efforts are below ±1, which indicate that a relatively small amount of control effort is used against the 3° disturbances.

The last two contour plots show the roll control effort and the LCDP parameter. The roll effector which is defined to be a combination of aileron, rudder, plus yaw TVC is capable of balancing the rolling moment induced due to β_{max}=3° (because the magnitude of roll control effort is less than one). The LCDP is in the negative region between -0.5 and -0.2. It means that reversal of the roll control is required in this phase. This is not a problem, however, because the LCDP sign is consistently negative and it does not reverse. Notice, that in the selection of the mixing matrix Kmix4b we traded lateral control authority in order to increase the LCDP magnitude. With our original effector mixing matrix Kmix4 the LCDP was mostly in the red region (not shown).
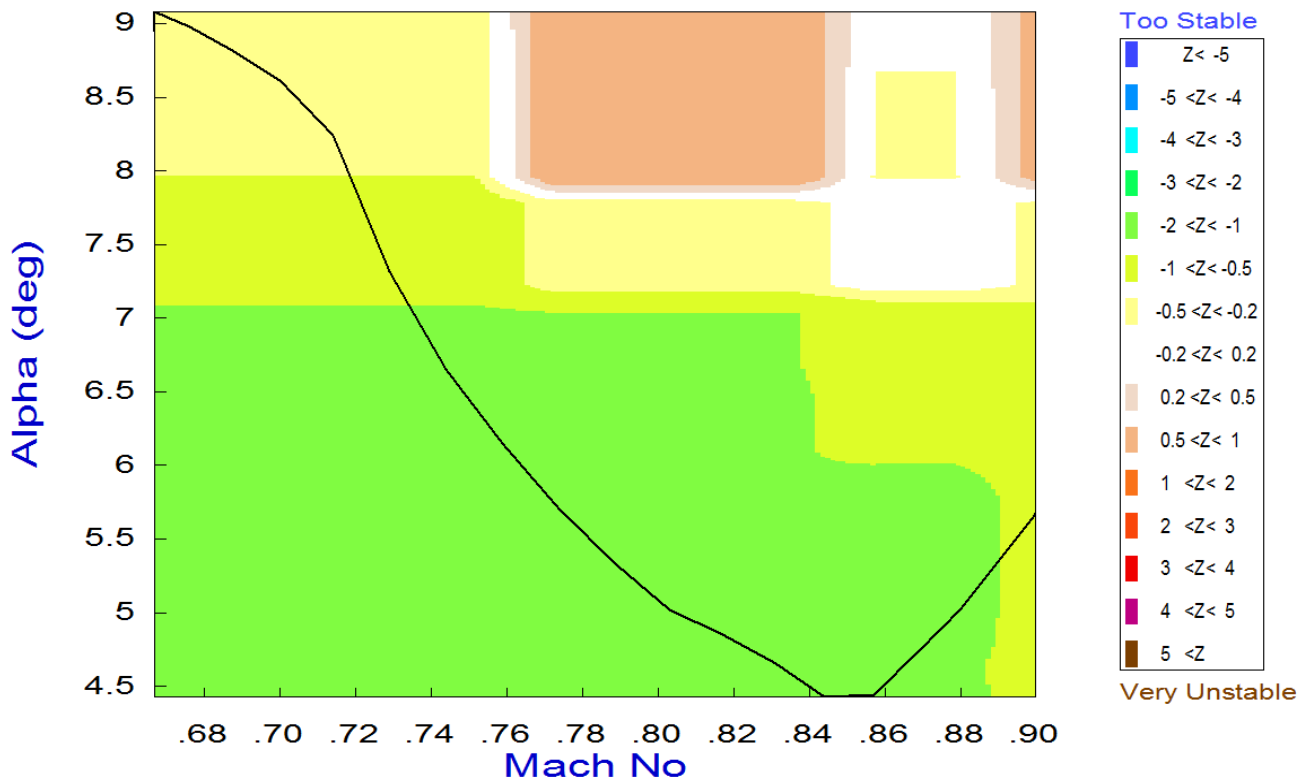
3-51

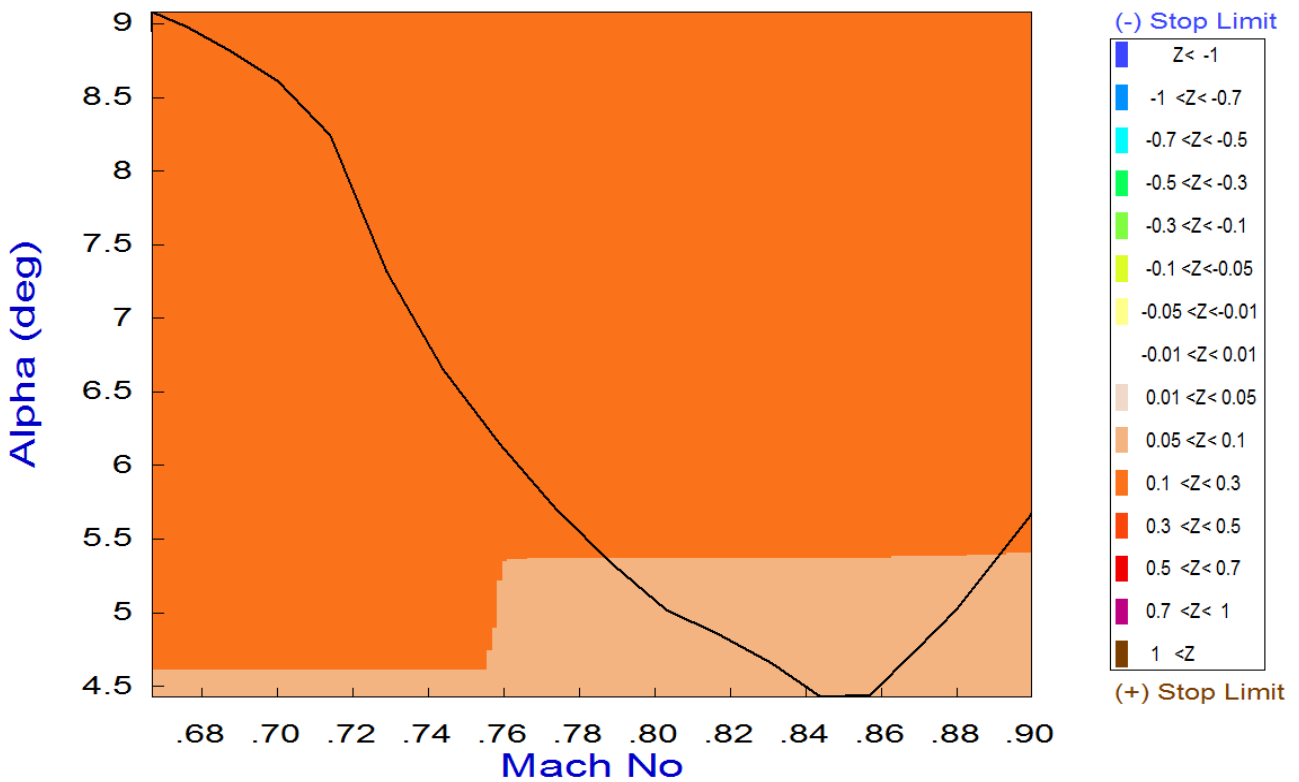# Pitch Stability Contour Plot (Mach vs Alpha)

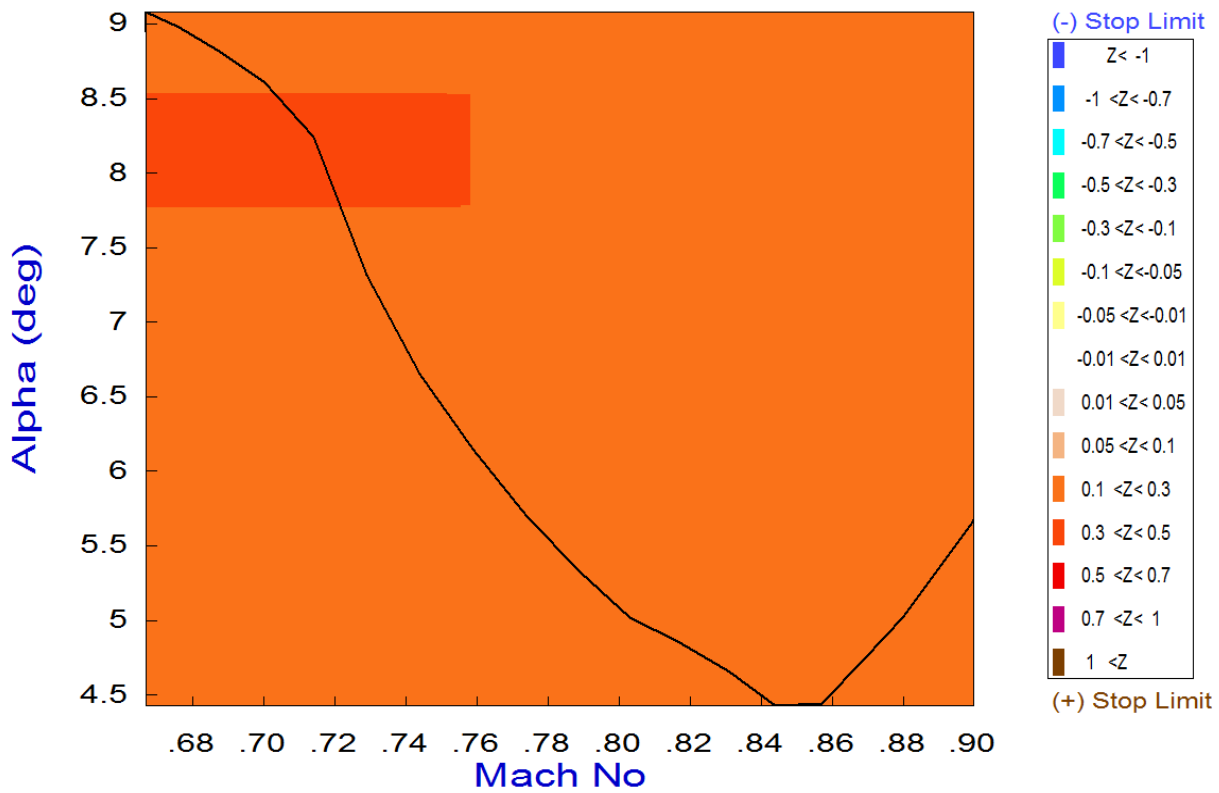# Lateral Stability Contour Plot (Mach vs Alpha)
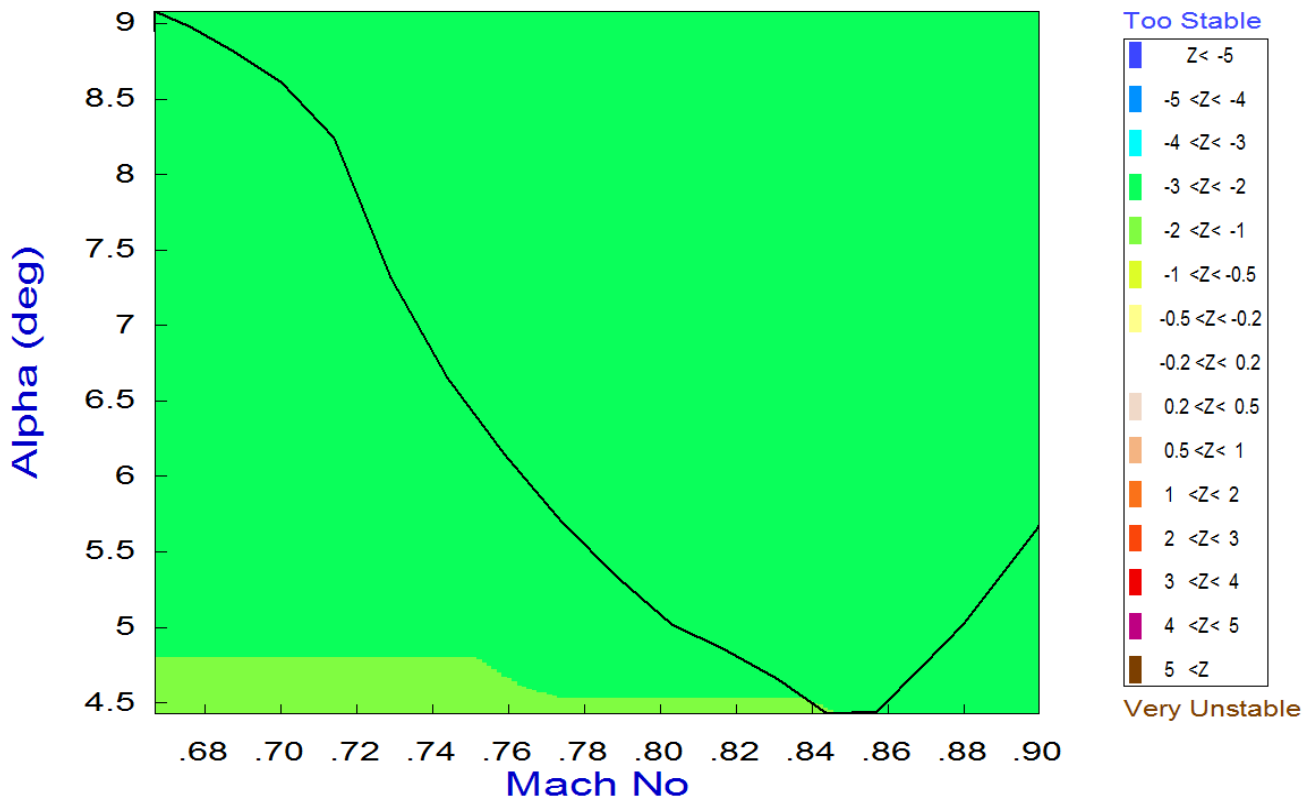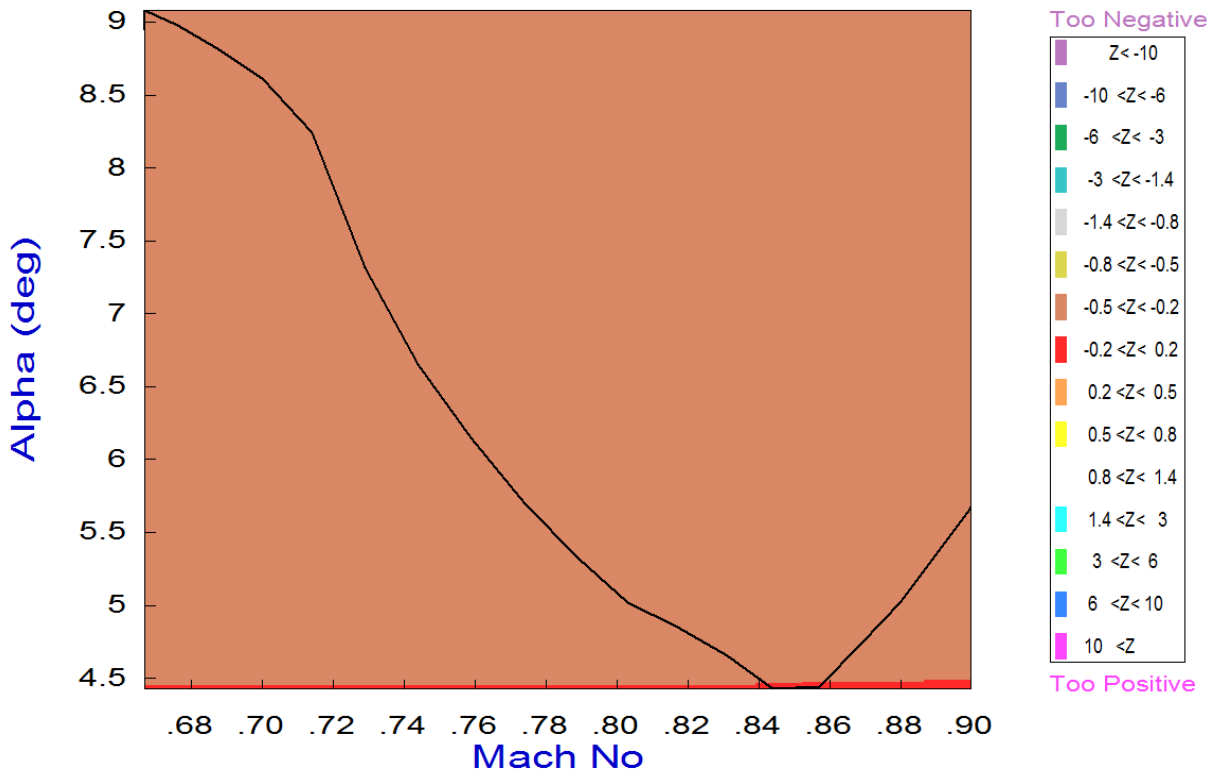
Pitch Control Effort Contour Plot (Mach vs Alpha)
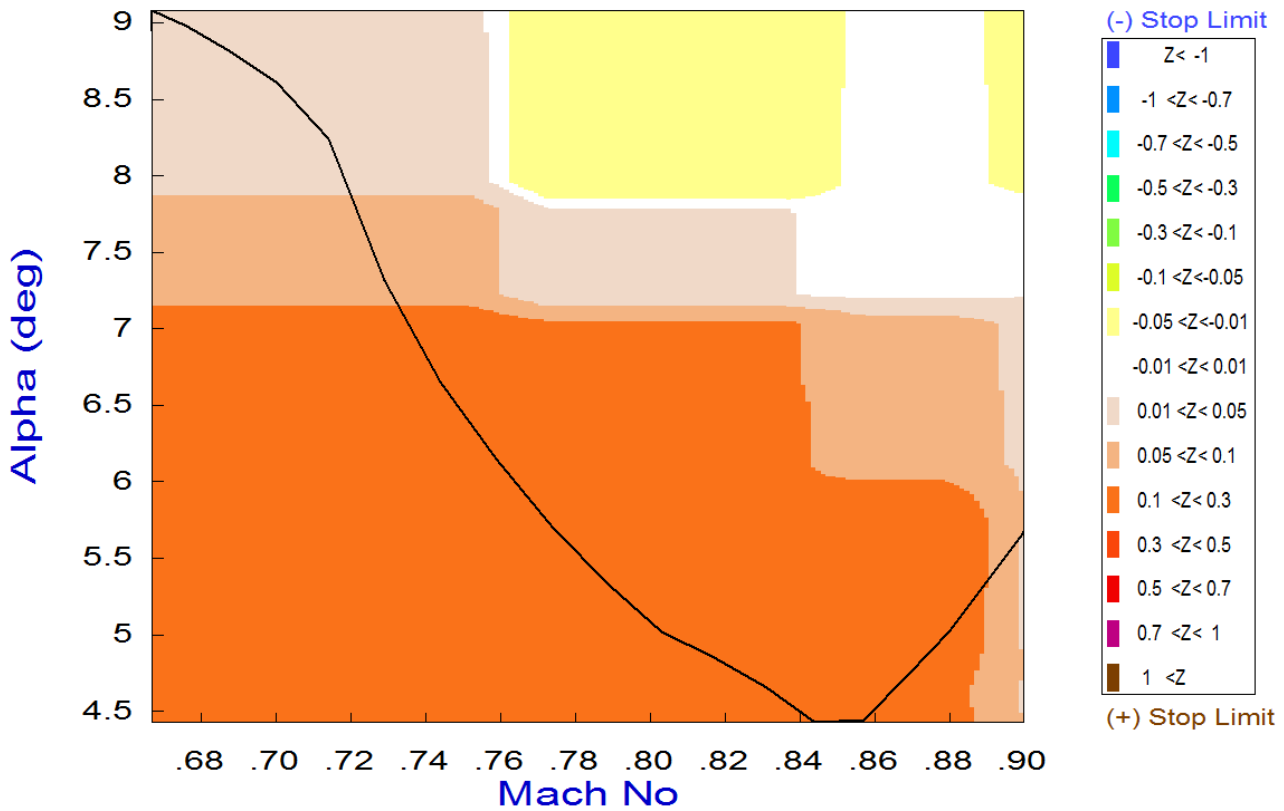
Yaw Control Effort Contour Plot (Mach vs Alpha)

# Roll Control Effort Contour Plot (Mach vs Alpha)

(-) 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)

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

Controllability Analysis Using Vector Diagrams

Vector diagrams are used for visualizing the vehicle controllability against aerodynamic disturbances which are caused due to alpha and beta dispersions from trim. They are two-dimensional diagrams of vectors that compare the magnitudes and directions of the vehicle's response to flight control demands against its response to alpha and beta disturbances. The disturbance vectors must be small in comparison with the control vectors. Assuming that the initialization files and trim conditions are the same as before, from the main menu select option (11) for plotting vector diagrams. Select a flight condition at time=90 seconds, and from the following menu you may either keep the default values of Mass, Mach, α, and β which correspond to the selected time, or modify them to different values. In this case we select the default values.
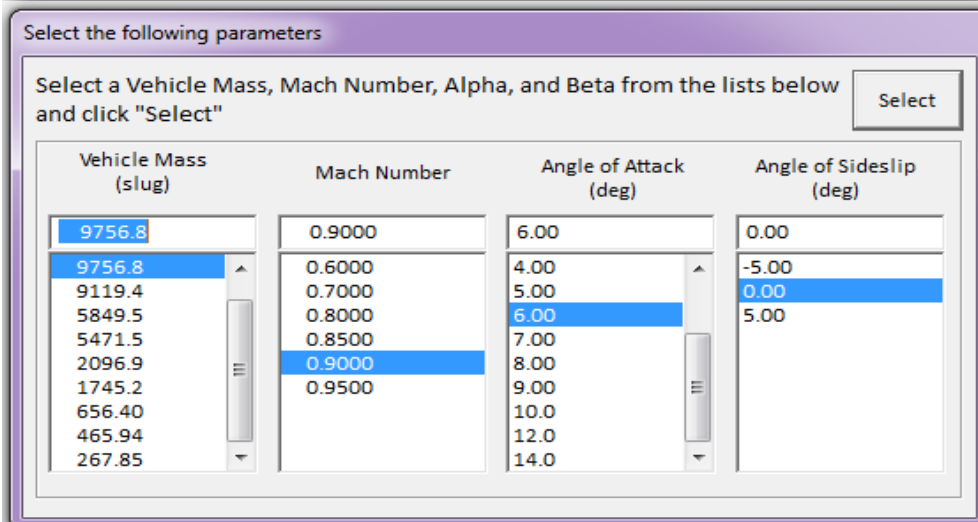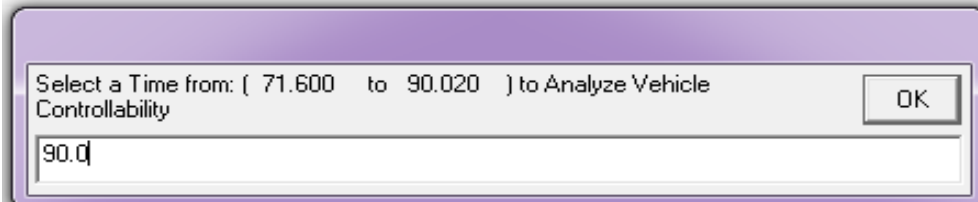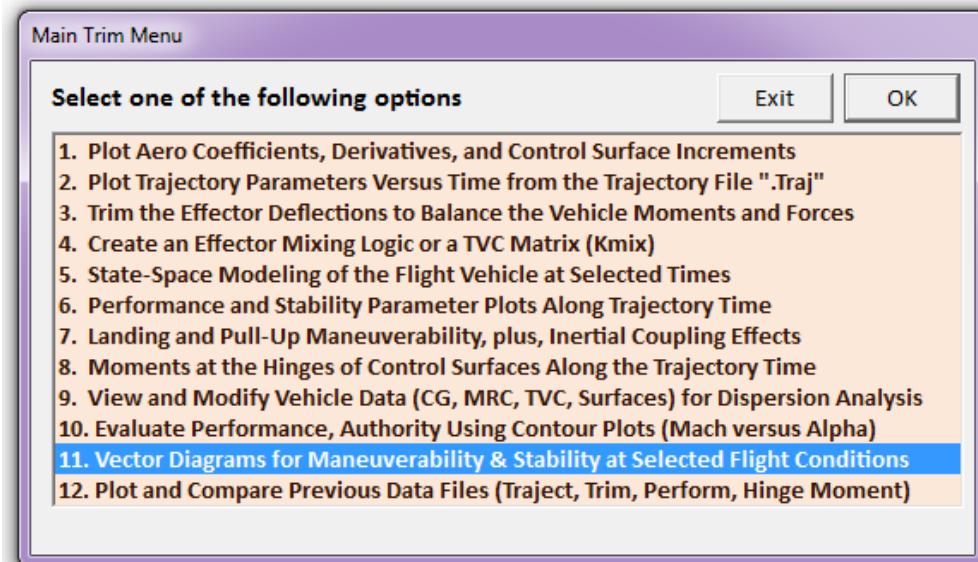
We must also select the maximum alpha and beta dispersions and the mixing-logic matrix, like before.

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) `3.0000`   Maximum Beta (deg) `3.0000`   OK

Notice ...

A (6 X 4) Mixing Logic Matrix is required

OK

Define the Effector Combination Matrix

The Mixing Logic Matrix translates the Flight Control (Roll, Pitch, Yaw, Ax, Ay, Az) demands to Effector commands (Aero-Surface, TVC, and Throttling).
You may either select a pre-calculated Mixing Logic Matrix (Kmix) from the Systems File: Kmix4.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

KMIX4   : Mixing Logic for Air Launched Vehicle First Stage Boost Trajectory (71-90) sec.
KMIX4B   : Mixing Logic for Air Launched Vehicle First Stage Boost Trajectory (71-90) sec (b).

The first two vector diagrams are similar. They show the maximum roll and yaw moments or the maximum roll and yaw accelerations (green and blue vectors respectively), produced when the roll and yaw FCS demands are maximized, in positive (solid line) and in the negative (dashed line) directions. The roll control (which is mainly aileron) excite both, roll and yaw directions. The red vectors show the disturbance moments or accelerations due to $\pm\beta_{max}$. Their magnitudes are significantly smaller than the control moments.

The next two vector diagrams are also similar. The first one shows the effects of maximizing the pitch controls, which are: pitch and engine throttle, in the longitudinal directions, which are: pitch and axial accelerations. The second one is similar and it shows the effects of the max pitch controls on the pitching moment and the axial force. The small red vectors represent the effects of the $\pm\alpha_{max}$ disturbance in the same directions and they are negligible.

Comparison Between Maximum Control Accelerations and Max Accels due to Beta (red)
Roll & Yaw Accelerations due to Maximum Roll/ Yaw Control and due to Max Beta

Trim Conditions

Flight Time -----------------; 90.0
Mach Number -----------------; 0.900
Alpha and Beta Trim (deg) ---: 6.00   0.00
Dynamic Pressure (psf) ------; 476.
Vehicle Mass (slugs) --------; 0.975E+04
Max Alpha/Beta Disturb (deg) : 3.00   3.00
Aero-Surface Trim Angles in (deg)
 -6.58   0.680E-02 0.629E-03
Engine Trim Angles (pitch/yaw) in (deg)
 -0.134   -0.254E-03

OK

Comparison Between Maximum Control Moments Against Maximum Disturb Moments (red)
Roll & Yaw Control Moments (non-dimension) vers Disturb Moment due to Max Beta/Alpha

3-57

Comparison Between Maximum Control Accelerations and Max Accels due to Alpha (red)
Pitch Accelerat and Axial X-Accelerations due to Max Control and due to Max Alpha

X-ddot (g)

Q-dot (rad/sec2)

Comparison Between Maximum Control Moment/Forces Against Maximum Disturbance (red)
Pitch Control Moment and Axial X-Force (non-dimens) versus Disturb due to Max Alpha

CX

Cm

Comparison Between Control Moment Partials Versus Aero-Disturb Moment Partials (red)
Yaw & Roll Control Partials Cn/delta_R and Cl/delta_P versus Cn/beta & Cl/beta

Comparison Between Control Force & Moment Partials Against Disturb Partials (red)
Cm/alpha & CX/alpha versus Pitch and Axial Force Controls: Cm/delt_Q & CX/delt_X

The next plot shows the roll and yaw moment partials per roll and yaw FCS acceleration demands (δ_{PFCS} & δ_{RFCS}), green and blue vectors respectively. It also shows the roll and yaw moment partials per beta disturbance (Clβ & Cnβ). It is calculated at two extreme alphas. The control vectors are scaled as described in equations (7.1 through 7.4) to make them better comparable with (Clβ & Cnβ). The control partials dominate significantly over the aero disturbance partials, as expected.

The next vector diagram shows the control versus disturbance partials in the longitudinal directions. It is the partials of pitch and axial force per pitch and x-acceleration FCS demands (δ_{QFCS} & δ_{XFCS}). That is, (Cmδ_Q, CXδ_Q) blue vector and (Cmδ_X, CXδ_X) green vector respectively. The red vectors show the pitch moment partial per alpha and the axial force partial per alpha (Cmα, C$_X\alpha$). There are two of these red vectors calculated at two extreme betas.

The plot below shows the roll and yaw acceleration partials per acceleration demands. The green vector shows the roll and yaw acceleration partials per roll demand (δ_{PFCS}). The blue vector shows the roll and yaw acceleration partials per yaw demand (δ_{PFCS}). As you can see, they are not entirely decoupled like in other examples, but this is OK, they don't have to be, as long as they are sufficiently orthogonal.

Ratios of Roll and Yaw Accelerations Over Corresp Control Acceleration Demands
(Rdot & Pdot)/Pdot_Demand and (Rdot & Pdot)/Rdot_Demand, (rad/sec2) / (rad/sec2)
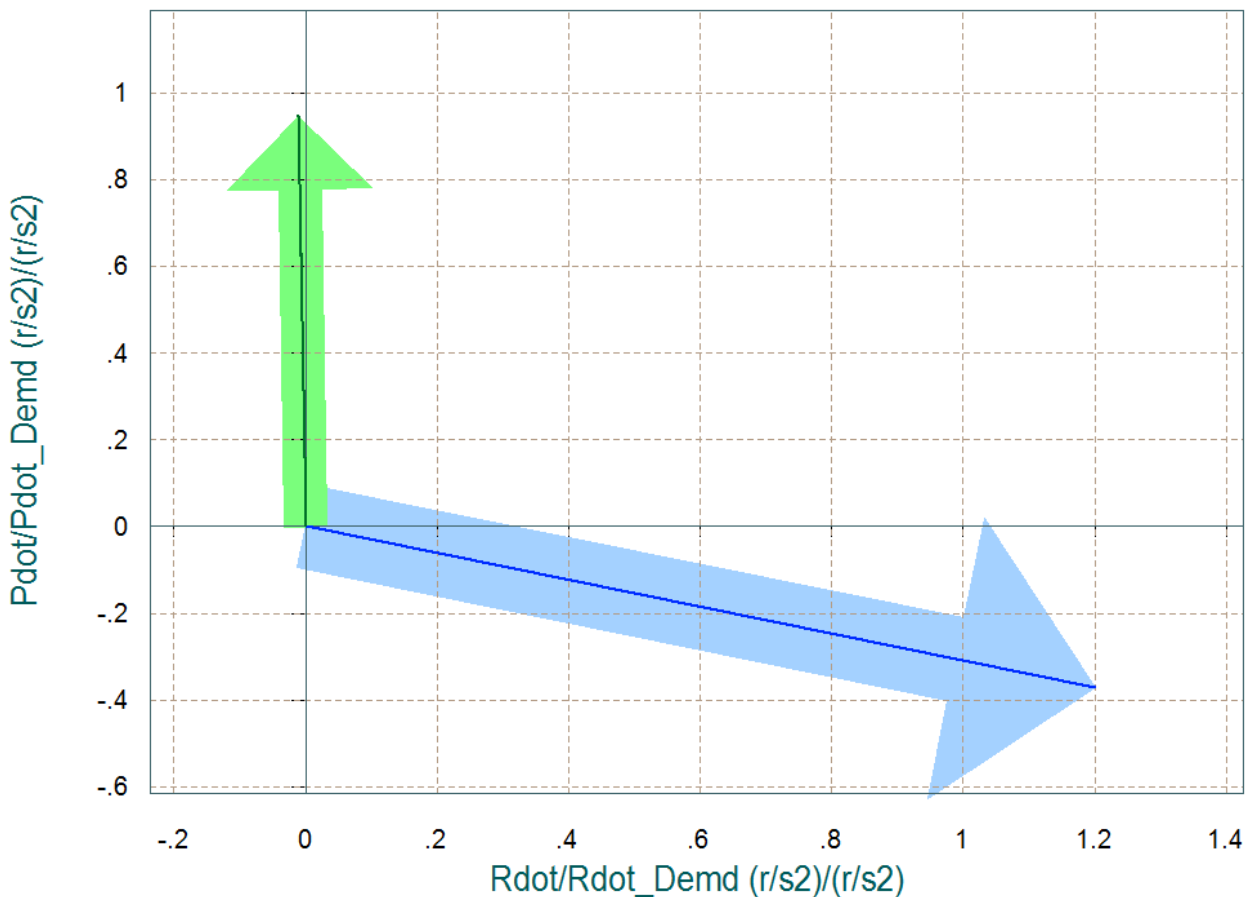
Dynamic Modeling

We will now use the Trim and Flight Vehicle modeling programs to create a linear model of the flight vehicle that will be used for control design and simulations. We will select an arbitrary flight condition at t=89 (sec) from separation, (which is just before the ejection of the wings) and generate a linear dynamic system for control analysis. We will also create additional reduced order pitch and lateral subsystems for control design purposes. So let us begin the Trim program, as before, select the same Trim data files, and also select the Flixan input data file "*Stg1_WOn_T89.Inp*" and the systems file "*Stg1_WOn_T89.Qdr*" in directory "*C:\Flixan\Trim\Examples\Air Launched Vehicle\Phase B Boost With Wing*".
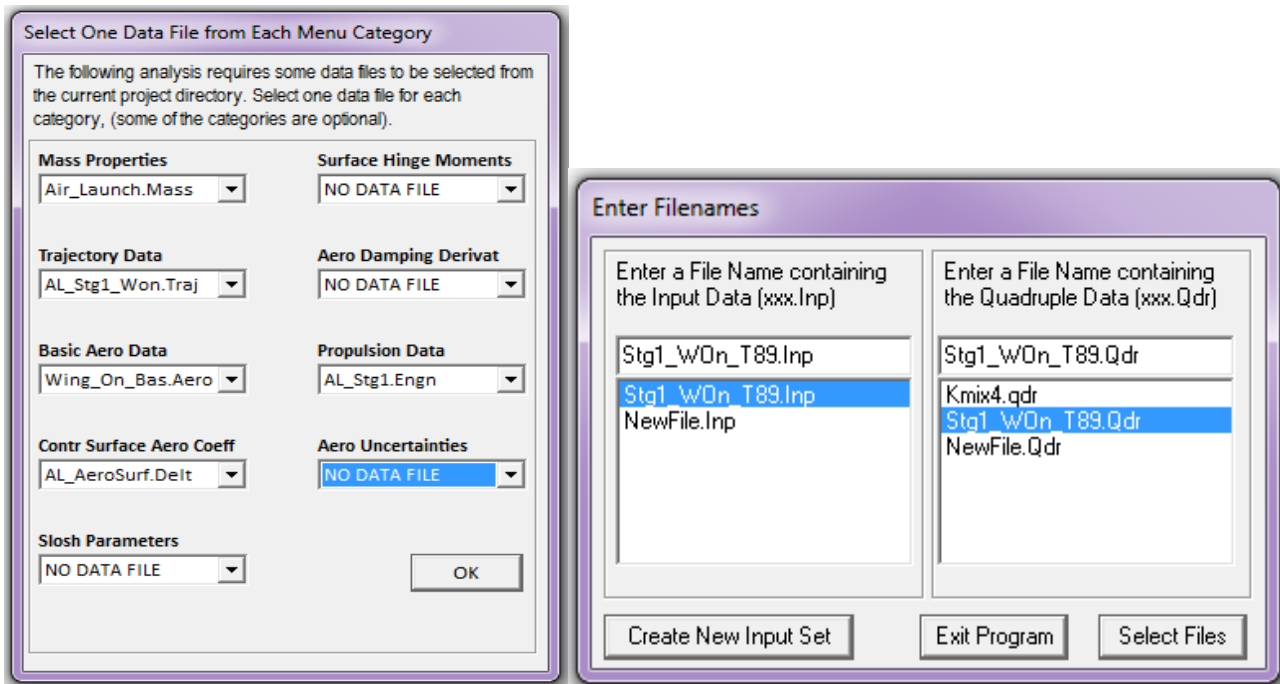
The Trim program will generate the flight vehicle input data in file "*Stg1_WOn_T89.Inp*", and the vehicle dynamic model will be created by the FVMP and it will be saved in "*Stg1_WOn_T89.Qdr*". However, in this case this input data file is already prepared, and in addition to the vehicle data it also contains data sets that will be used by Flixan to create reduced and decoupled models for control analysis. The Trim program first generates the vehicle input data in file "*Stg1_WOn_T89.Inp*". The additional data in that file are processed by other Flixan utilities that generate decoupled models and also reformat the systems for Matlab.

From the Trim main menu we select Option (5) that will generate vehicle data for the dynamic model. The program plots the trajectory data and from one of the plots the user is prompted to select a flight time across the plot using the mouse. From the top menu bar, click on "*Graphic Options*" and from the vertical drop-down menu click on "*Select Time to Create a State-Space System*".

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)

Select Time Point   [X]

    (i)   From the Top Menu of the Trajectory Plots, go to "Graphic Options"
             and select a Time to create a Linear System

                                      [OK]

Trajectory Parameters

Copy Format: Send to: **Graphic Options**   Next Plot   Exit Plots

                 Magnify a Rectangle Section of the Plot
                 Modify a Trajectory Plot Using the Mouse   Flight
                 Restore Original Trajectory/ Trim Data
                 Select Time to Create State-Space System

8
7
6
5

...arameters

Send to: Graphic Options   Next Plot   Exit Plots

Select Time   [X]

    (i)   Using the Mouse select a Time-Slice to Create an Input
             Data Set for the Flight Vehicle Modeling Program

8
7
6
5
4
                                [OK]

State-Space Modeling

You have Selected Trajectory Time= 89.000 sec
to Create Input Data for State-Space Modeling

OK   Cancel

84   86   88   90

The program confirms that you have selected the trajectory time 89 sec to create input data for the dynamic model. Click "OK" to continue. The flight vehicle modeling program (FVMP) dialog comes up showing the vehicle data categorized in tabs (extracted from the Trim files).

Flight Vehicle Parameters

Vehicle System Title
Air Launched Vehicle First Stage Boost Trajectory/ T= 89.0 sec

Edit Input File   Exit
Update Data   Run

Number of Vehicle Effectors

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

Rotating Control Surfaces. Include Tail-Wags-Dog?   3   WITH TWD / WITHOUT TWD

Reaction Wheels?   0

Momentum Control Devices

Single Gimbal CMGs?   0

Include a 3-axes Stabilized Double Gimbal CMG System?   Yes / No

Number of Sensors

Gyros   0
Acceleromet   3
Aero Vanes   0
External Torques   0

Modeling Options (Flags)

Output Rates in
Body Axes / Stability Axes

Turn Coordination ?
Include Turn Coordin / Without Turn Coordin

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

Attitude Angles
Euler Angles
Integrals of Rates
LVLH Attitude

Save in File

Number of Modes

Structure Bending   0
Fuel Sloshing: 0

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

This Vehicle has 3 Control Surfaces   Control Surface No: 1   Elevon   Surface Definition   Next Surface

Surface Rotation Angles

Surface Trim Position (deg)   -4.655400
Largest Positive Deflection from Trim (deg)   30.00000
Largest Negative Deflection from Trim (deg)   -30.00000

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

Xcs   -12.00000
Ycs   -6.000000   Phi_cs   0.000000
Zcs   0.6000000   Lambda_cs   0.000000

Control Surface Mass Properties

Contol Surface Mass in (Slugs)   1.000000
Moment of Inertia about Hinge (slug-ft^2)   0.2867000
Moment Arm (feet), Surface CG to Hinge   0.3000000
Control Surface Chord (feet)   17.64000
Control Surface Reference Area (ft^2)   1355.000

Aero Force Derivatives

Ca_delta   -0.2179000E-02   Ca_delta_dot   0.000000
Cy_delta   0.000000   Cy_delta_dot   0.000000
Cz_delta   -0.6330001E-02   Cz_delta_dot   0.000000

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

Aero Moment Derivatives

Cl_delta   0.000000   Cl_delta_dot   0.000000
Cm_delta   -0.1097000E-01   Cm_delta_dot   0.000000
Cn_delta   0.000000   Cn_delta_dot   0.000000

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

Hinge Moment Derivatives

Chm_Alpha   0.000000
Chm_Beta   0.000000
Chm_Delta   0.000000
Chm_Mach   0.000000

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

3-63

This dialog allows you edit some of the data or titles in the various fields and tabs. You must click on "*Update Data*" every time you modify a group of data before changing tabs. When you finish editing the dialog click on "*Save in File*" button to save the vehicle data in "*Stg1_WOn_T89.Inp*". You may also edit that file directly by clicking on "*Edit Input File*". Finally you may click on "Run" to generate the state-space system in "*Stg1_WOn_T89.Qdr*". But you are not ready to run it yet before including the remaining of the Flixan data sets for the additional processes described. So click on "Exit" for now, and take a look in the already prepared input file.

The already created input file "*Stg1_WOn_T89*.Inp" includes a number of data sets and each set is processed by a separate Flixan utility. On the top of the file there is a batch set that processes the remaining data-sets together. The first set of data below the batch generates the vehicle model. The next two data sets generate pitch and lateral vehicle subsystems for control design purposes. The last three data-sets convert the vehicle models to Matlab m-function format so that they can be loaded into Matlab for control analysis. To process the batch and data-sets from Flixan, go to "*Manage Input Files (*.Inp)*" and then click on "*Process/ Edit Input Data*". From the following dialog, first select the input file from the left menu, and then from the right menu select the batch set, which is the top title in the menu, and then click on "Execute" to run it. Answer "Yes" in the dialog question and Flixan will generate the vehicle models in file "*Stg1_WOn_T89*.Qdr" and also in Matlab format. They are in files "vehicle.m", "pitch.m", and "lateral.m".
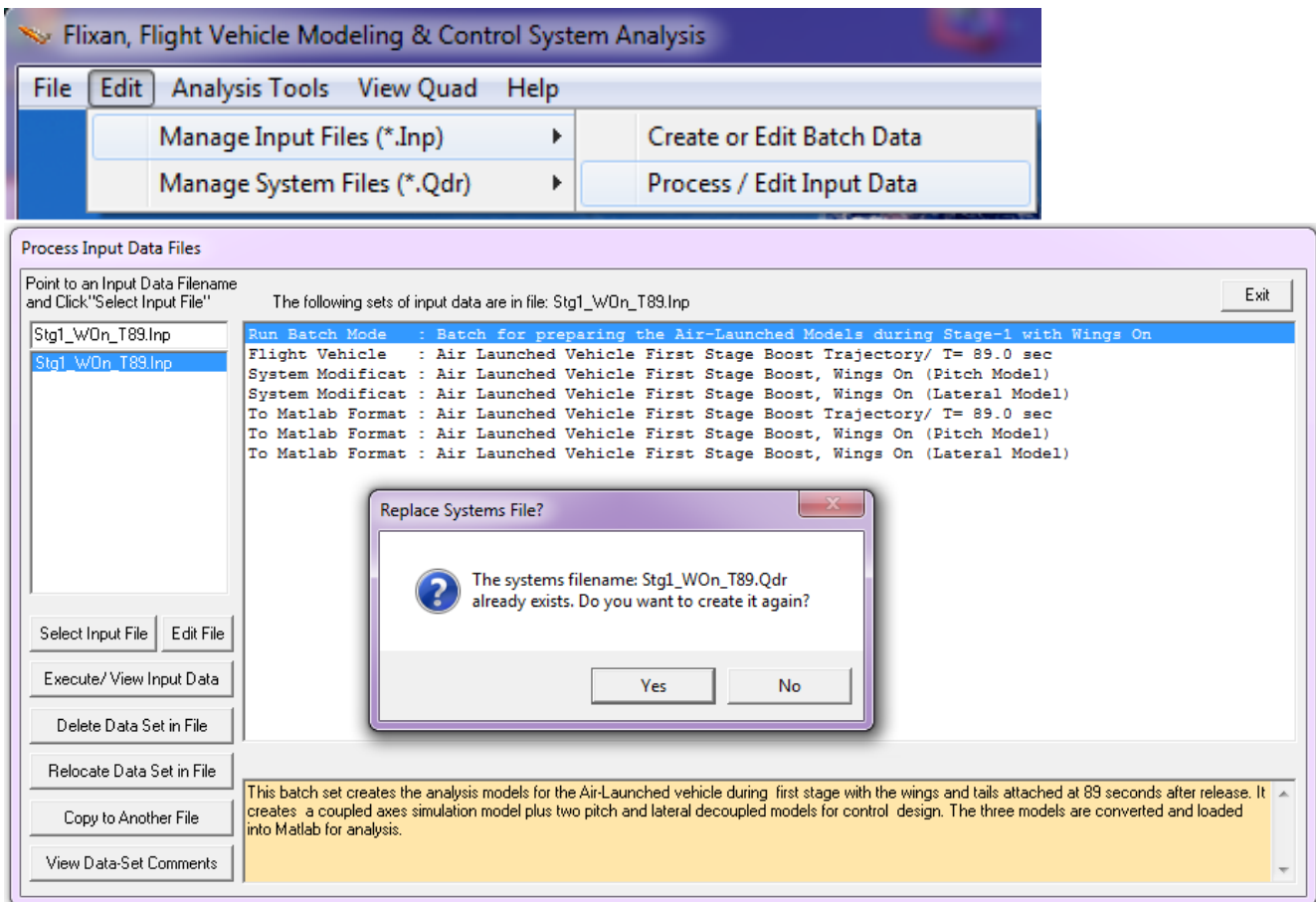
Control Design and Simulation Models

We will now use the models generated in the previous section to perform pitch and lateral control designs and create simulation models in Simulink. This is performed in subdirectory "*C:\Flixan\Trim\ Examples\Air Launched Vehicle\Phase B Boost With Wing\Mat_Anal*". The following script file "run.m" loads the 3 dynamic models and also the effector combination matrix Kmix4b. It also loads the pitch flight control gains and designs LQR state-feedback gains for the lateral axes. In the lateral design model the state vector originally consists of: (phi, p, r, and β). It is augmented by adding one more state (β-integral). This is done by linearizing (linmod) the Simulink model "*Ldes5x.Mdl*". K_{pr} is the (2x5) state-feedback matrix. The lateral control design weights are adjusted by means of simple simulation model "*Sim_Lateral_Simple.Mdl*", shown below. The pitch simulation model is in file "Pitch_Sim.Mdl". The gains were derived by classical methods.

```
% Air-Launched Rocket First Stage With Wings & Tails Analysis Script
d2r=pi/180; r2d=180/pi;
[As, Bs, Cs, Ds] = vehicle;              % Load Big Simulation Model
[Ap, Bp, Cp, Dp] = pitch;                % Load Pitch Simulation Model
[Al, Bl, Cl, Dl] = lateral;              % Load Lateral Design Model
load Kmix4b -ascii                       % Surfaces Scaling Matrix

% Lateral LQR Design Using
[A15,B15,C15,D15]= linmod('Ldes5x');     % 5-state model {phi,p,r,bet,betint}
R=[1,1]*20; R=diag(R);                    % CS LQR Weights R=[3,1]*2
Q=[5.0 0.1 0.1 0.01 0.001]*5.0; Q=diag(Q);  % CS LQR Weights Q=[0.2 0.1 0.5 0.5 0.04]*5.0;
[Kpr,s,e]=lqr(A15,B15,Q,R)               % Perform LQR design on Jets

% Pitch FCS Gains
Kg=3.4; Kgi=0.3;
Ka=2.0; Kai=0.4;
```
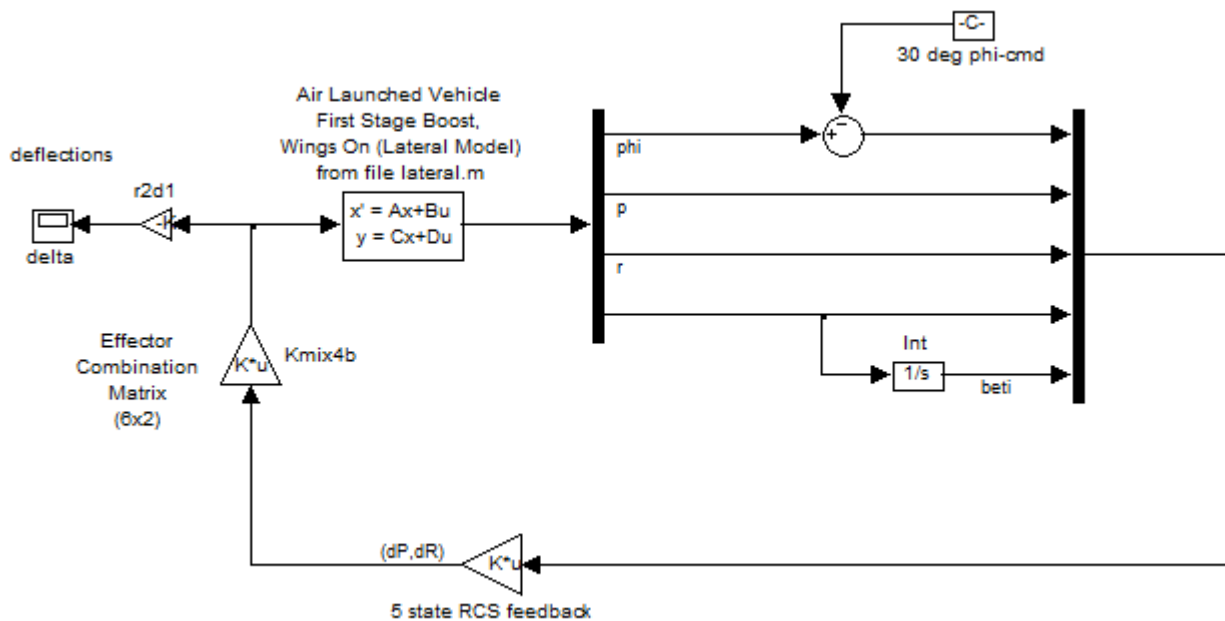

Figure 2.1 Lateral Simulation Model Used for LQR Evaluation, file "*Sim_Lateral_Simple.Mdl*".

3-65

Air-Launched Rocket Longitudinal Simulation Model
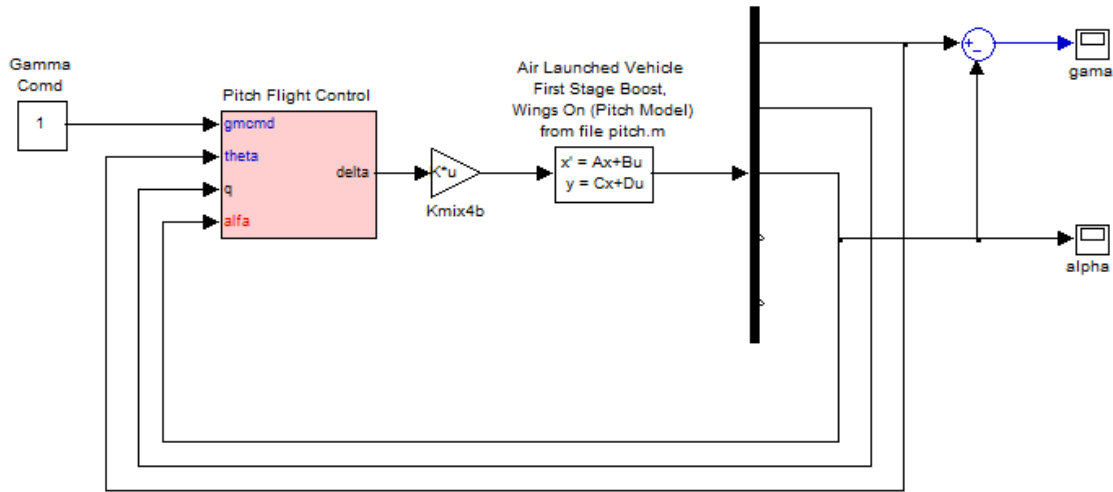
Figure 2.2 Longitudinal Simulation Model from file "*Sim_Pitch.mdl*".

The main simulation model is file "*Sim_Air_Launch.mdl*", shown in Figure (2.3a). It consists of the vehicle dynamics (green block) that is controlled by three flight control loops: a pitch loop that controls the flight path angle (γ), a lateral control loop that controls the bank angle (ϕ) and ultimately the cross-range position, and a speed control loop by throttling the main engine. Simulation plots are generated automatically by the script file "pl.m" when the execution is complete.

Figure (2.3b) shows the vehicle dynamic model. The model is based on the state-model system "*Air Launched Vehicle First Stage Boost Trajectory/ T= 89.0 sec*" that is loaded from file "*vehicle.m*". The inputs to the subsystem are roll, pitch, yaw, and axial acceleration demands from the FCS. The matrix Kmix4b is used to convert these demands to effector commands. The effectors are: pitch and yaw TVC deflections, throttle control, and elevon, aileron, and rudder surface deflections. There is also a gust input used as a disturbance. The direction of gust is set to excite both pitch and lateral directions and it is defined in the vehicle input data. The pitch control requirement in this vehicle is to track a pre-calculated flight path angle from a table, so the output from the model is gamma which is constructed by combining theta with alpha. The angles of attack and sideslip are not measured directly by the vehicle sensors and they must be estimated from the normal and lateral accelerometers. This detail, however, is beyond the scope of this example.

The decoupled vehicle model "*Air Launched Vehicle First Stage Boost, Wings On (Lateral Model)*" from file "*lateral.m*" was used in the lateral control design. Its state-vector was augmented by including integral of the sideslip angle. The lateral flight control system is a (2x5) state-feedback matrix Kpr that was designed using the LQR method. This matrix converts the state-vector signals into roll and yaw acceleration demands (δP, δR)$_{FCS}$. The demands are then converted into deflections by matrix Kmix4b.

Air-Launched Rocket Simulation (Coupled Model)
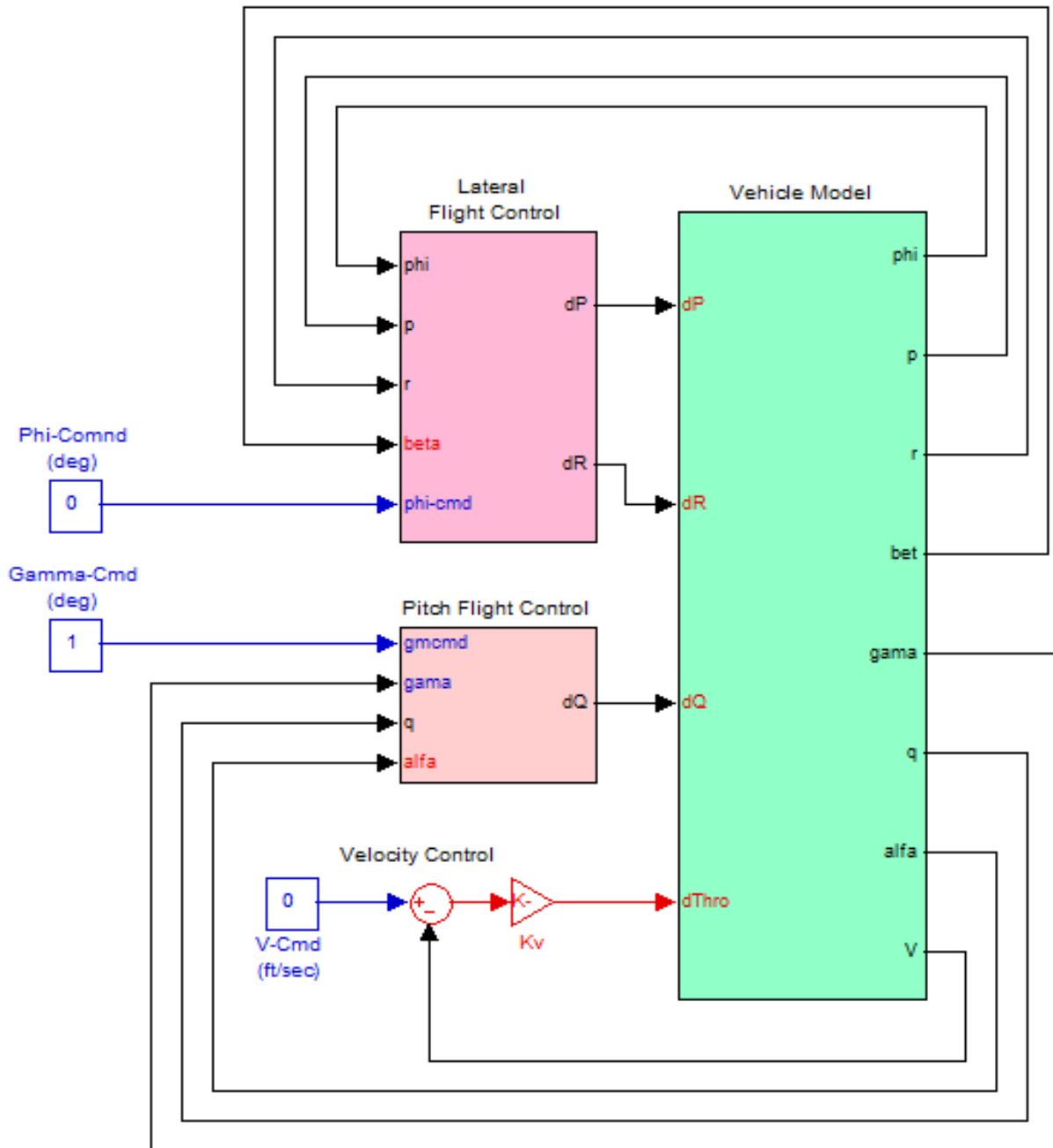
Figure 2.3a Air-Launched Vehicle Simulation Model in Simulink file "*Sim_Air_Launch.mdl*"

Flight Vehicle Dynamics, Simulation Model
Air Launched Vehicle First Stage Boost Trajectory/ T= 89.0 sec

Inputs = 7
1 Engine No 1 Pitch Deflect. (rad), Dymax= 5.0000 deg
2 Engine No 1 Yaw Deflect. (rad), Dzmax= 5.0000 deg
3 Throttle Input dTh/Th for Engine No 1 (-)
4 Aero Surface No 1 Elevon Deflection (radians)
5 Aero Surface No 2 Aileron Deflection (radians)
6 Aero Surface No 3 Rudder Deflection (radians)
7 Wind Gust Azim, Elev Angles=(45.0 90.0) (deg)

Effector Deflects

Mixing Logic

Kmix4b

Air Launched Vehicle
First Stage Boost Traject.
T= 89.0 sec
from file vehicle.m

x' = Ax+Bu
y = Cx+Du

Clock   Time

Roll, Pitch, Yaw &
Axial Accelerat.
FCS Demands

Gust
30 (ft/sec)
0.2 Hz

Gust   Vel Gust (ft/sec)   Gust

Outputs = 14
1 Roll Attitude (phi-123) (radians)
2 Roll Rate (p-body) (rad/sec)
3 Pitch Attitude (thet-123) (radians)
4 Pitch Rate (q-body) (rad/sec)
5 Yaw Attitude (psi-123) (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 Accelerom # 1, (along X), (ft/sec^2) Translat. Acceler
13 Accelerom # 2, (along Y), (ft/sec^2) Translat. Acceler
14 Accelerom # 3, (along Z), (ft/sec^2) Translat. Acceler

Figure 2.3b Vehicle Dynamic Model Using the System in File "*Vehicle.M*"
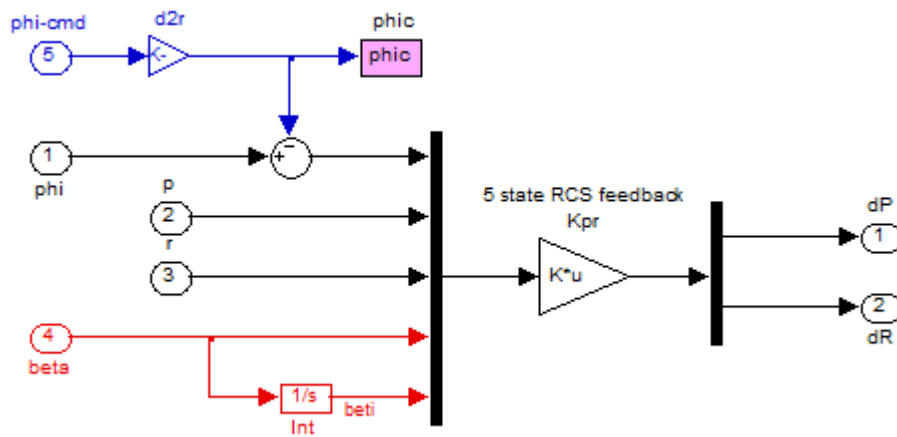
Figure 2.3c Lateral Flight Control System that uses LQR State-Feedback

3-68

Simulation Results

The simulation model in Figure (2.3) can be excited from guidance signals (shown as step inputs here) of changes in gamma, phi, and velocity commands. It can also be excited by wind gusts and turbulence. The wind-gust direction is perpendicular to the vehicle x-axis and skewed at 45° between the +y and +z axes, as it is defined in the vehicle input data file. We will use this model to calculate the vehicle responses to various excitations.

Phi-command Simulation

A phi$_{-command}$= 20° is applied to the simulation model with all other inputs set to zero. The figures below show the bank angle which responds to the command and the yaw attitude which begins to drift due to the steady turn. The cross-range velocity also increases due to banking. Banking is used by guidance as a means to control the flight direction and the cross-range velocity.
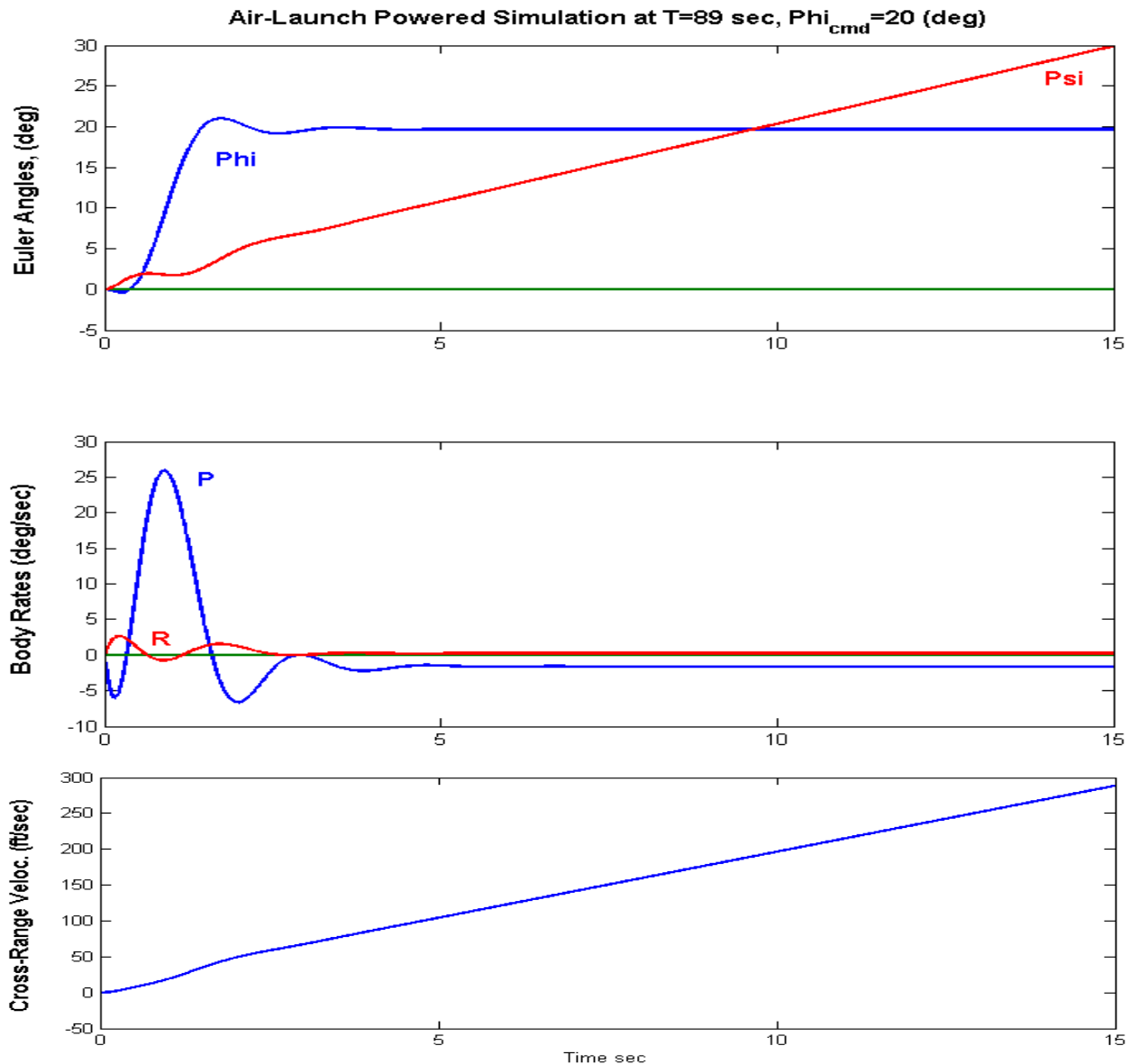
Air-Launch Powered Simulation at T=89 sec, Phi$_{cmd}$=20 (deg)
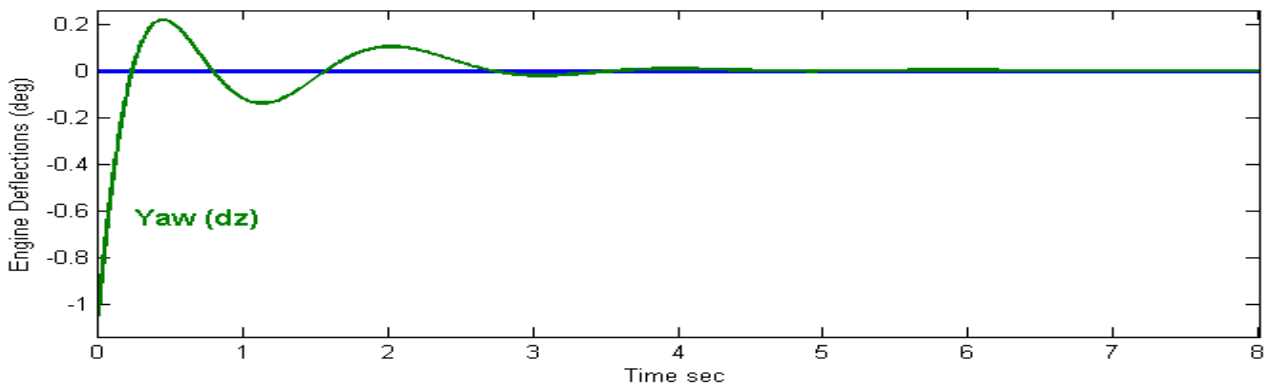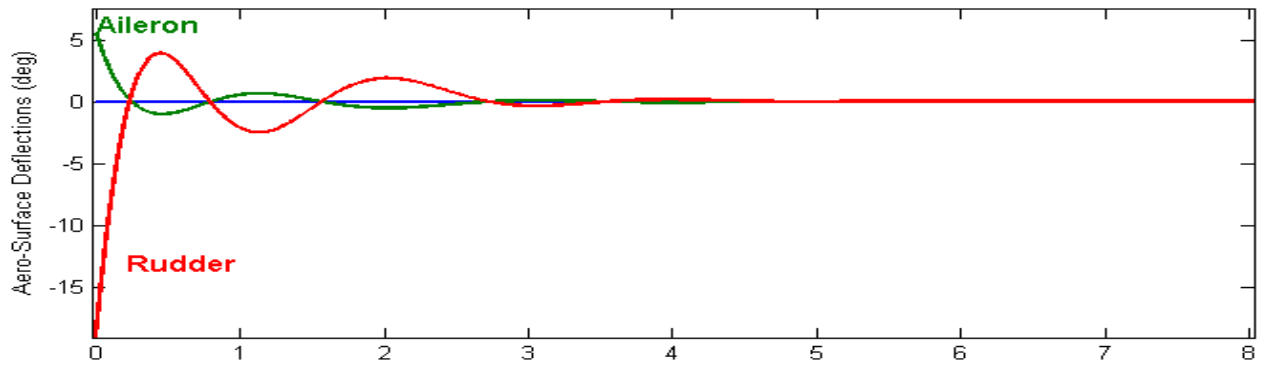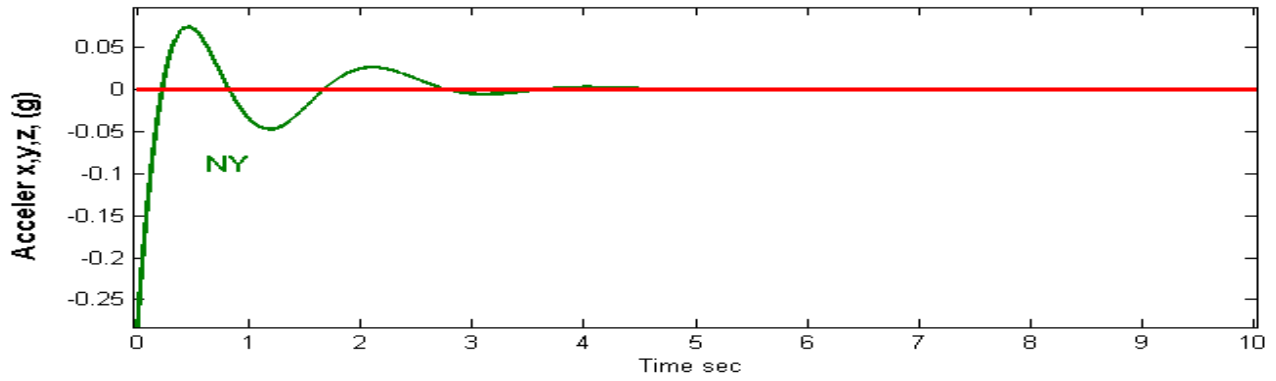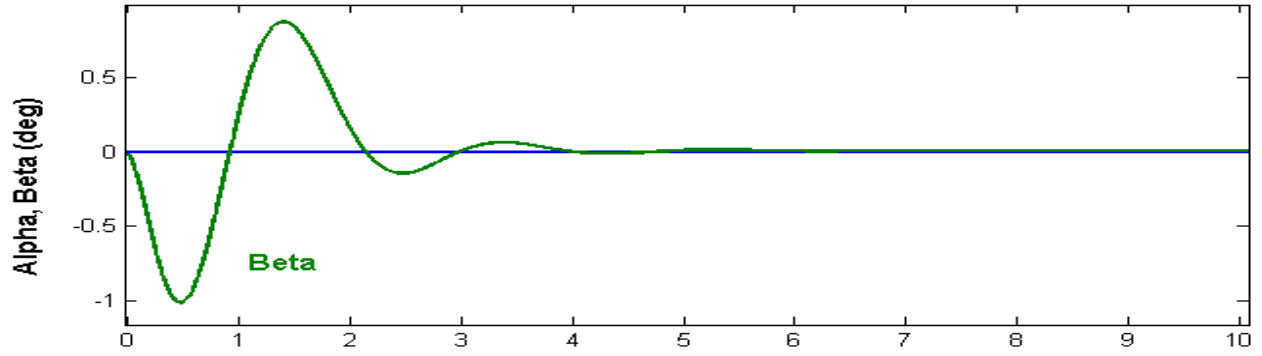
Gamma-Command Simulation

In this case the simulation model is commanded to increase its flight-path angle gamma by one degree from steady-state. All other commands and excitations are set to zero. This causes a positive alpha, a steady increase in altitude and a drop in velocity that is compensated by throttling up. The elevon and the engine briefly deflect in the negative direction to cause the pitch-up, and they decay to zero (or trim positions).
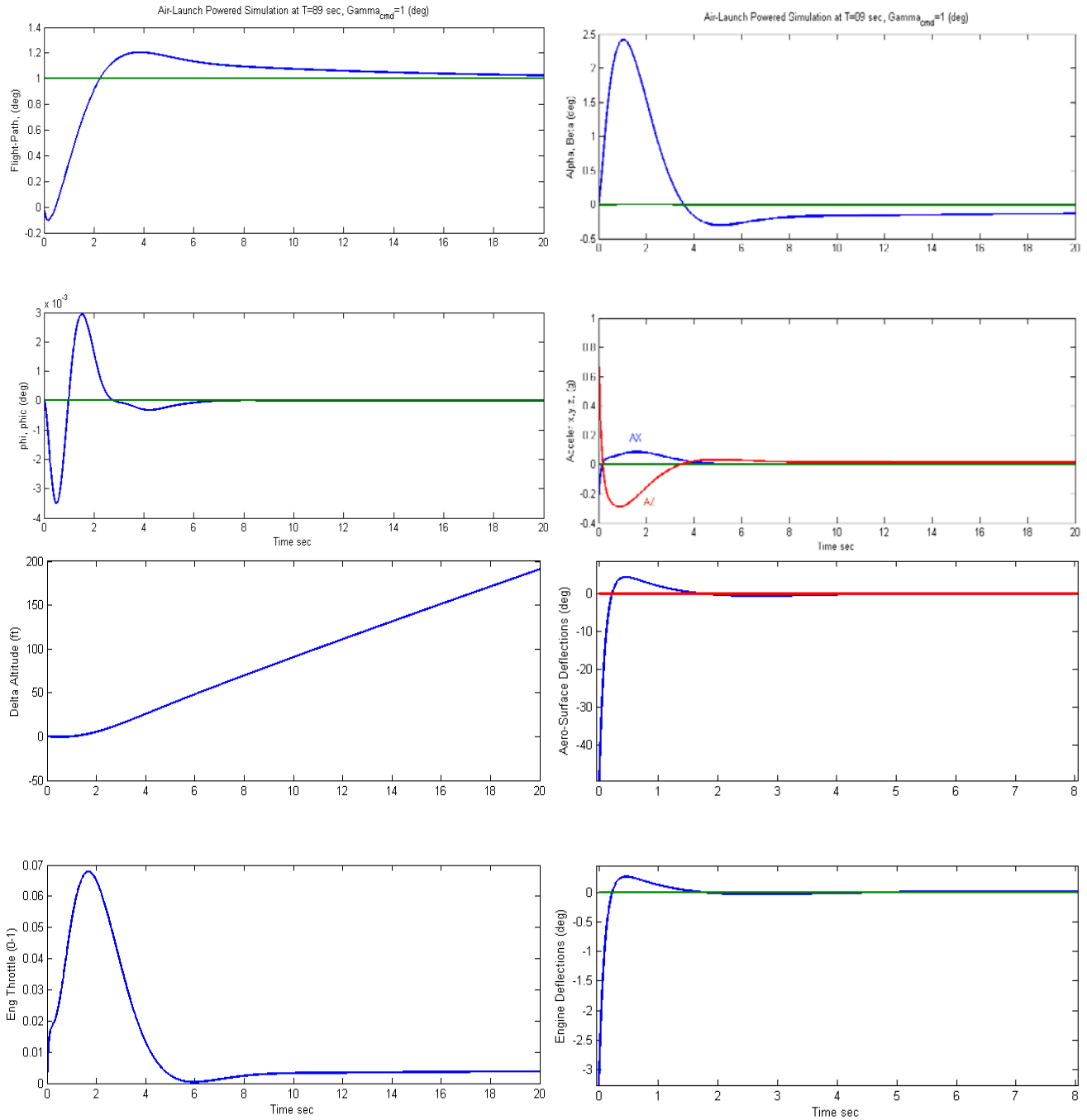
Change in Velocity Simulation

In this case the simulation model is commanded to increase its velocity by 10 (ft/sec). This causes a brief positive throttle up, a transient in the acceleration, and a steady increase in altitude. It also causes a drop in alpha in order to prevent an increase in gamma.
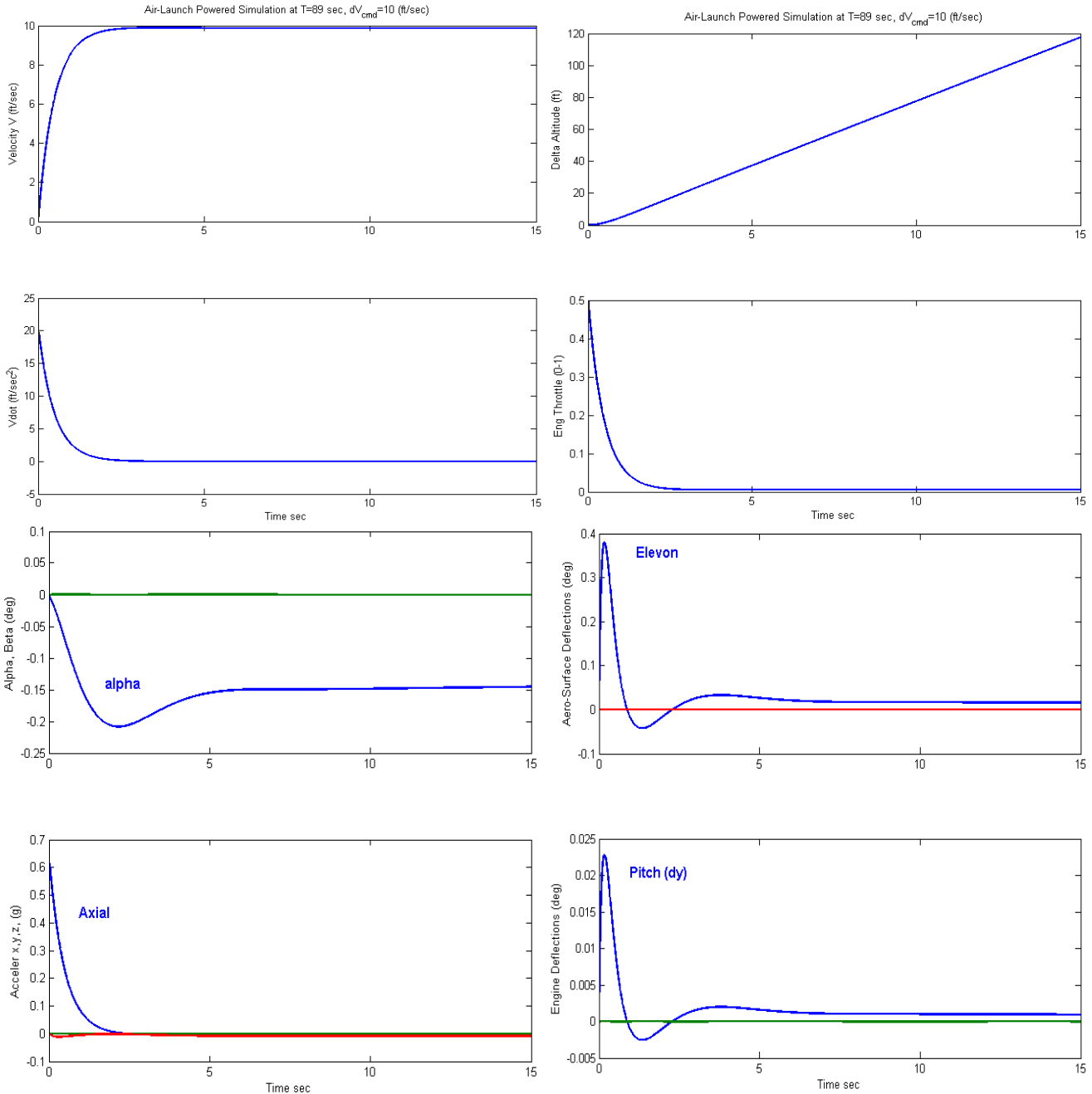
First Stage Boost without Wings and Tails

The wings provided the lift required for the vehicle to achieve a desired gamma trajectory without losing much altitude but they are extra weight and drag and at a certain point they are no longer needed. After ejecting the wings and tails at time=90 seconds, the vehicle no longer looks like an aircraft, but it is a typical booster rocket, still at first stage. This rocket, however, is not a perfect cylinder but there is some unsymmetry in the payload that causes aerodynamic coupling between the roll and yaw axes. A significant amount of rolling moment is introduced due to beta that cannot be ignored. The vehicle in this configuration has lost its aero-surface controls. The TVC provides plenty of pitch and yaw control. For roll it uses two pairs of back-to-back RCS jets firing in the ±z direction. Each pair is located on the left and right sides, 3.6 (ft) away from the cylinder centerline. The sizing of the jet thrust is based on controllability requirements. Roll disturbances are mainly caused by the Y_{CG} offset and also due to sideslip disturbances from cross-winds or maneuvering. The rocket should be controllable with a Y_{CG} offset of 0.1 foot. It should also have enough roll control to handle one degree of sideslip angle dispersion. We will use Trim to make sure that those requirements are satisfied with two 500 (lb) thruster pairs.
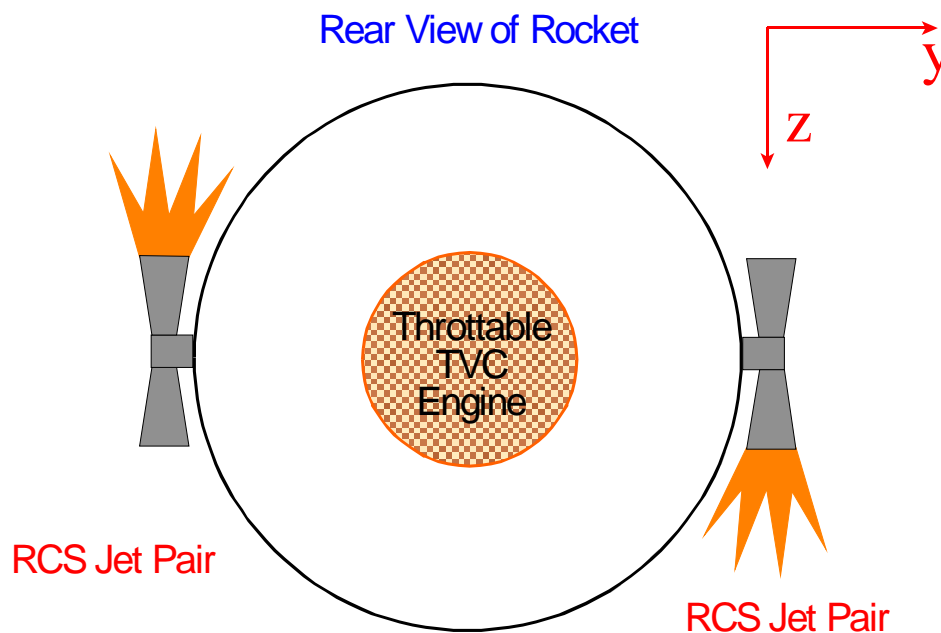
Figure 3.1 The vehicle has three effectors in this configuration, a main engine that gimbals and throttles, and two RCS jet pairs for roll control.

The data files for this phase are located in the subdirectory: "*C:\Flixan\Trim\Examples\Air Launched Vehicle\Phase C Boost No Wing* ". This folder includes a basic aero-data coefficients file of the vehicle without wings and tails in "*Wing_0ff_Stg1.Aero*". There is no aero-surfaces file (.Delt). It has a propulsion data file "*AL_Stg1.Engn*" that includes the TVC engine and the two RCS jet pairs. The main engine is defined as having 300,000 (lb) of nominal thrust along the x axis. It can gimbal up to ±8° in pitch and yaw, and it can vary its thrust ±80% from nominal. The RCS jets are 500 (lb) each and their thrust direction is along the ±z axis.

```
Air Launched Booster Rocket Engines
Engine Description, Thrust    Mass      Ieng       Mom Arm  Location (x,y,z)   Mounting Angles (Dy, Dz)  Max Deflection  Max Throt
                     (lb)     (slug)    (slug-ft2) (ft)     (feet)             Elevat, Azimuth (degr)    Dym,Dzm (deg)   (0-1)
TVC Engine  1        300000.0 160.0     3500.0     3.5      -100.1  0.0  -0.2   0.0    0.0                8.0  8.0        0.8
RCS Jet Lft 2        500.0    0.0       0.0        0.0      -60.0  -3.6   0.0   90.0   0.0                0.0  0.0        1.0
RCS Jet Rht 3        500.0    0.0       0.0        0.0      -60.0  +3.6   0.0   90.0   0.0                0.0  0.0        1.0
```

The trajectory data is in file "*AL_Stg1_Woff.Traj*". It runs between 90 and 150 seconds, from wings ejection to stage-1 separation. A second (modified) trajectory was created in file "*AL_Stg1_Mod.Traj*", from the nominal trajectory. It includes YCG and (β) disturbances. It is used for sizing the RCS jets. The file "Kmix4.Qdr" contains a couple effector combination mixing logic matrices Kmix4a and Kmix4b. The first one was derived using the mixing-logic algorithm and the second one is a user modified version that improves roll controllability. This mixing matrix converts the four flight control demands (which are: roll, pitch, yaw, and axial acceleration), to TVC deflection commands (pitch and yaw), main engine throttle command, and two RCS throttle commands. The input data file "*Stg1_WOff_T110.Inp*" and the systems file "*Stg1_WOff_T110.Qdr*" are used by the Flixan program to generate dynamic models at t=110 sec (Max-Qbar). The mass properties file is the same as in other phases.

Trajectory Analysis

We may begin by first looking at the trajectory. Start Flixan, select the project folder "*C:\Flixan\Trim\ Examples\Air Launched Vehicle\ Phase C Boost No Wing*", and then from the Flixan main menu select "*Analysis Tools*", "*Flight Vehicle/ Spacecraft Modeling Tools*", and "*Trim/ Static Performance Analysis*". From the Trim filename selection menu select the following files, and from the next filename selection menu select the file Kmix4.Qdr that contains the effector combination matrix. From the Trim main menu select the 2nd option for plotting the trajectory data.

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)

Vehicle CG in (feet), Air Launched Vehicle First Stage Boost Trajectory

During this phase the rocket reaches a maximum dynamic pressure Qbar=540 (psf) at t=108 sec. The altitude reaches 75,000 (ft) at stage-1 separation at Mach 2.7, the flight path angle steadily decreases to 20° before staging as it approaches towards a circular orbit. The CG shifts forward as the fuel mass is depleted. The main engine thrust is around 400,000 (lb) and it decays towards the end of the first stage. The lift force and the z-acceleration are much smaller now than when the wing was present.

Angles of Attack/Sideslip/Flight Path (deg), Air Launched Vehicle Firs
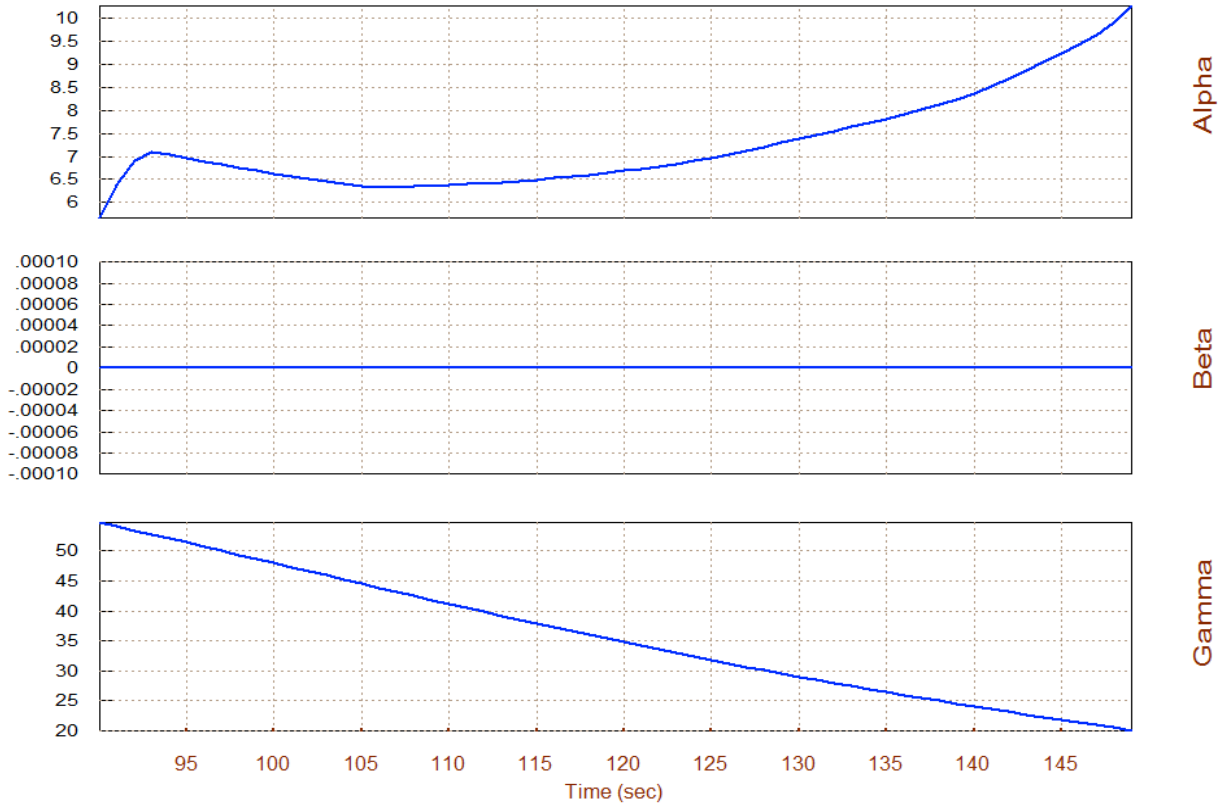
Velocity, Dynamic Pressure, Air Launched Vehicle First Stage Boost Trajectory
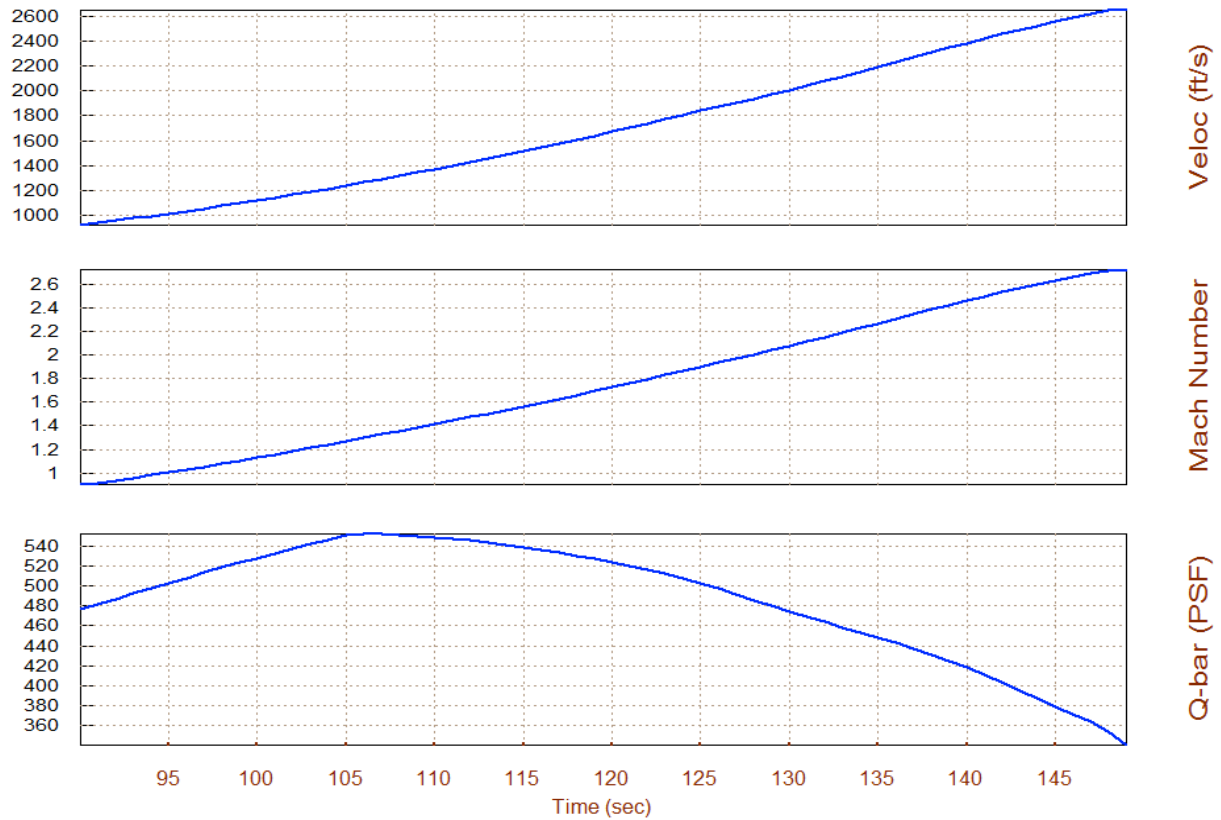
Vehicle Altitude, Mass, Bank Angle, Air Launched Vehicle First Stage B
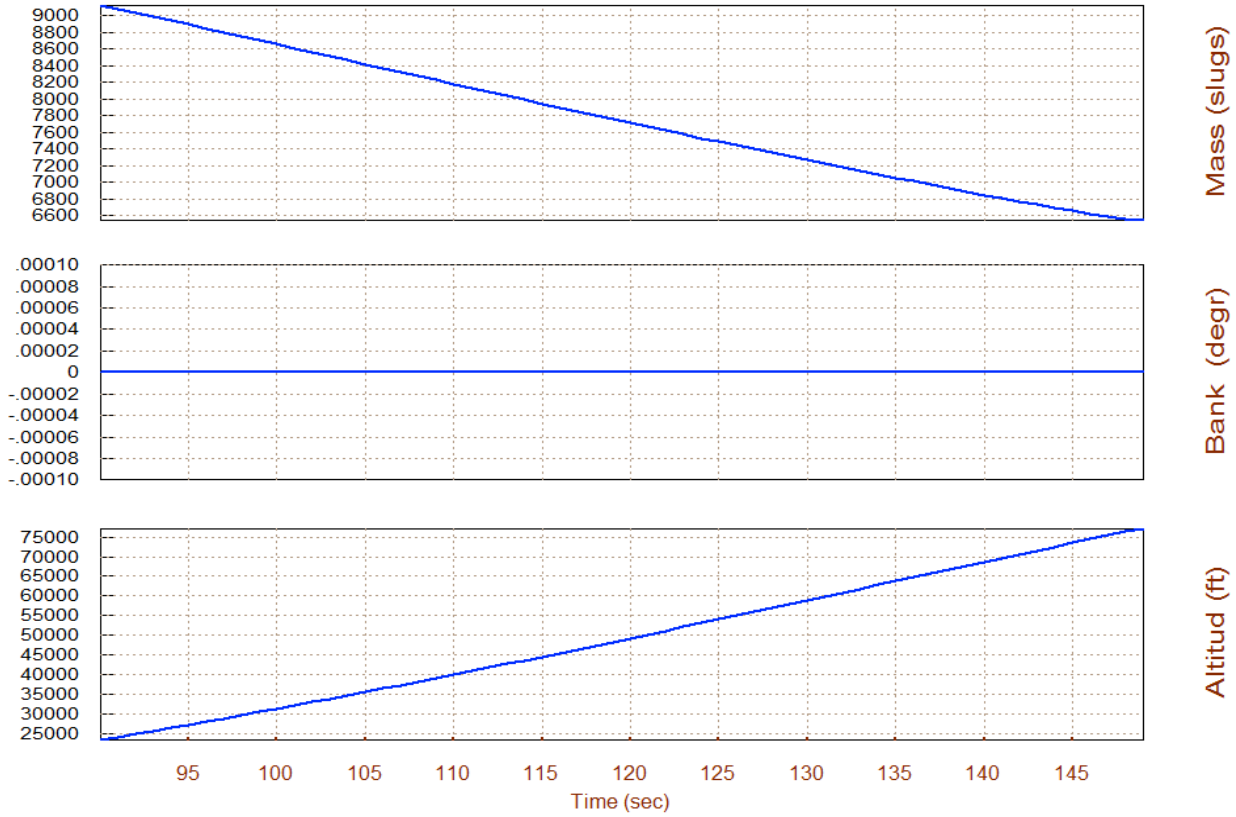
Sensed Acceleration in (ft/sec^2), Air Launched Vehicle First Stage Boost T
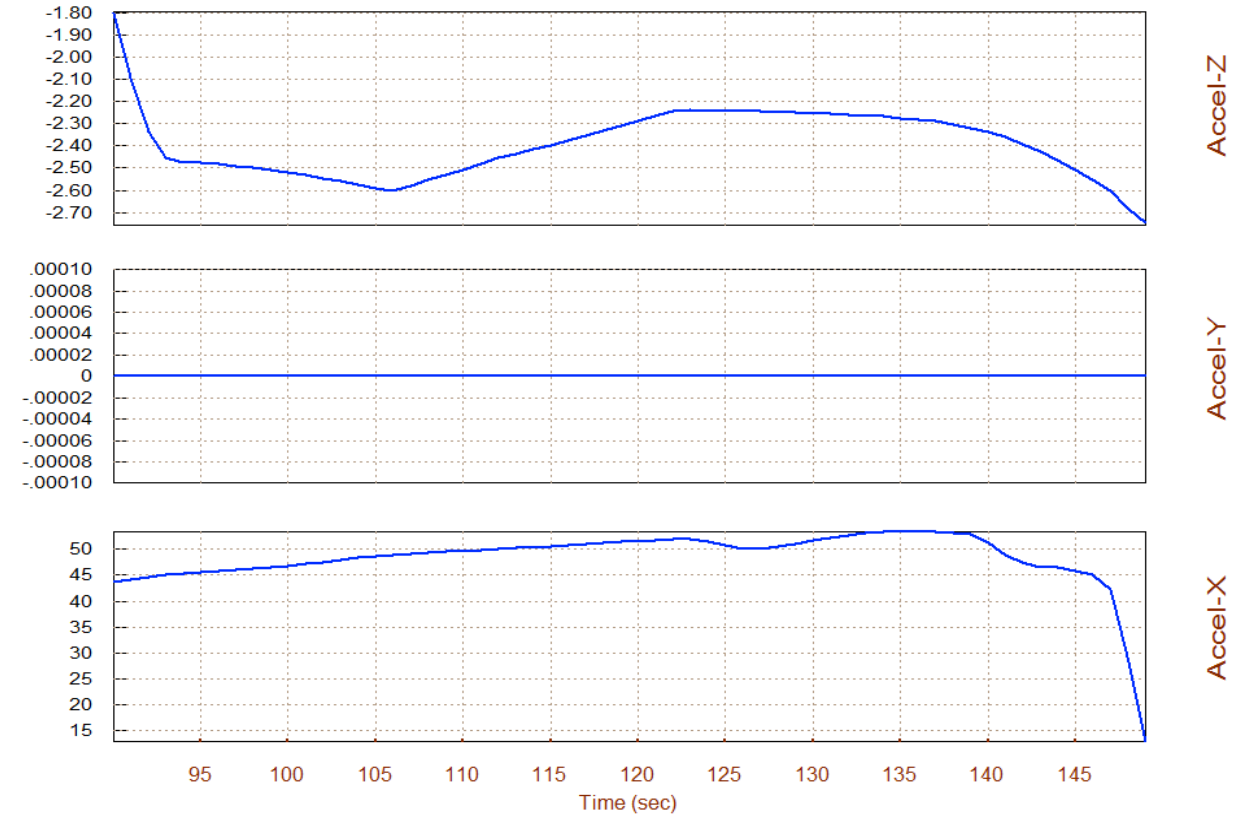
Angular Rates (rad/sec), Air Launched Vehicle First Stage Boost Trajectory
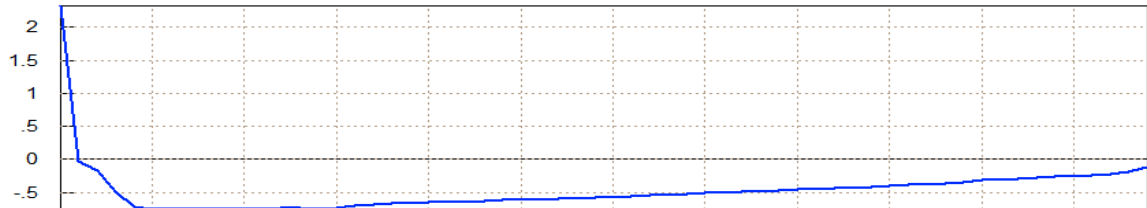
Aero Lift/Drag Forces, Eng. Thrust in (lb), Air Launched Vehicle First Stage
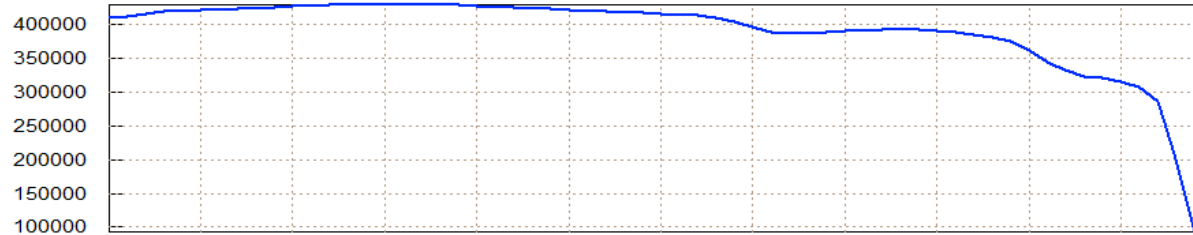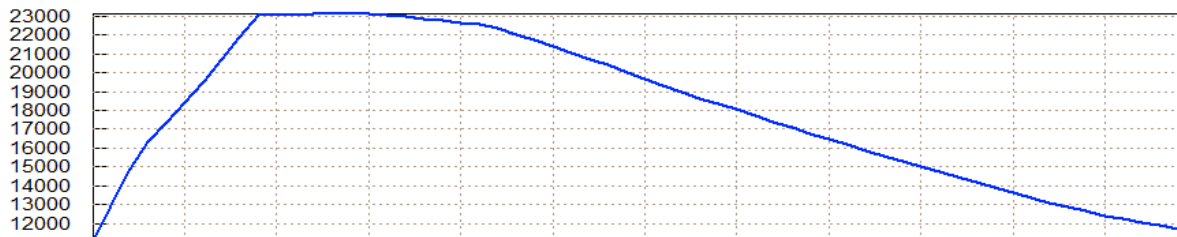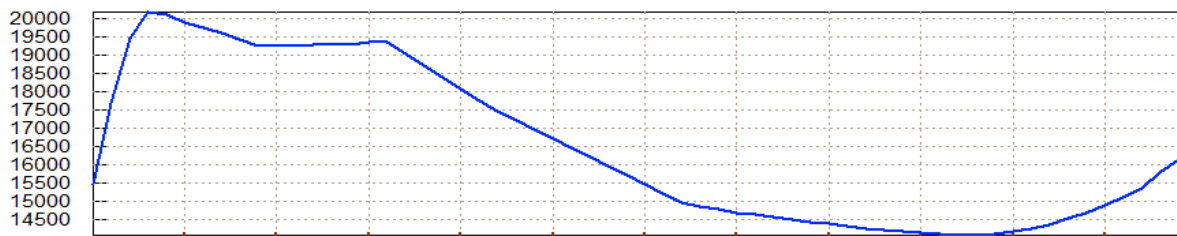
Obtaining a User Modified Trajectory

Our nominal trajectory is not qualified to size the RCS jets because it does not include lateral disturbances. We must, therefore, create another trajectory for trimming that will include a beta disturbance and a Y_{CG} offset. From one of the trajectory plot windows go to the top menu bar, click on "*Graphic Options*" and from the drop-down menu select "*Modify a Trajectory Plot Using the Mouse*", as shown below. The following trajectory parameters menu lists the trajectory parameters that can be modified using the mouse. Select the sideslip angle (beta) and click on "*Select a Variable to Modify*".
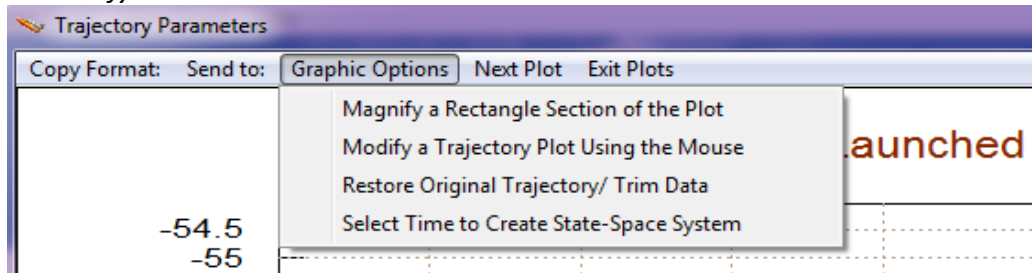
The dialog below shows the sideslip angle beta which is zero (green line). We must modify this line to a different profile in the time period between 100 and 110 seconds. It is like introducing a square beta-gust of 1° in that time period, as shown below. This can be done graphically by modifying the green curve one section at a time, using the mouse. The final beta profile is shown by the yellow line below. Click on "*Continue with Another Variable to Modify*" and this time select "*CG Location Along Y (ft)*". The nominal Y_{CG} is very small. Similarly introduce another square pulse of amplitude 0.1 (ft) in the time period between 120 and 135 seconds. Click on "*Save the Modified Trajectory*" and it will be saved in file "*AL_Stg1_Woff1.Traj*" which was renamed to "*AL_Stg1_Mod.Traj*". The modified parameters are shown in the following trajectory figures.

3-79
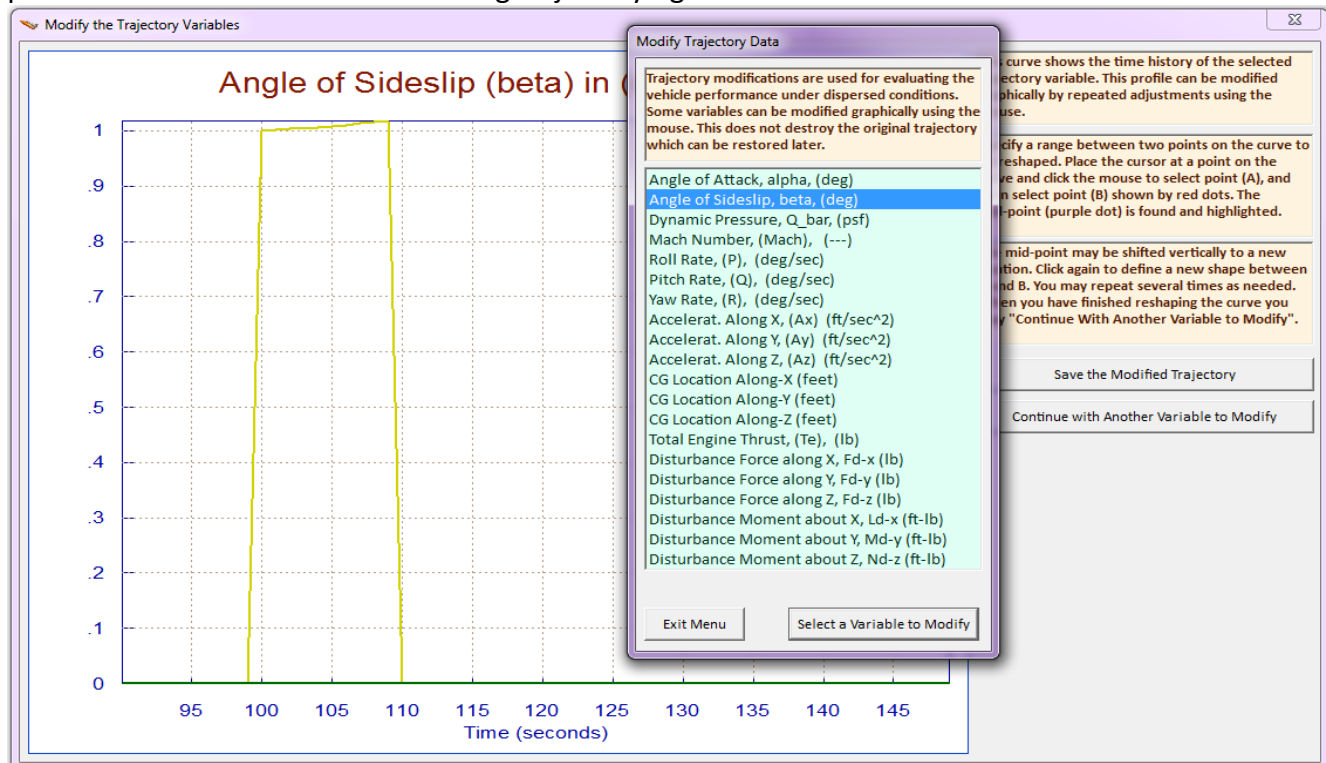
Angles of Attack/Sideslip/Flight Path (deg), User Modified Trajectory
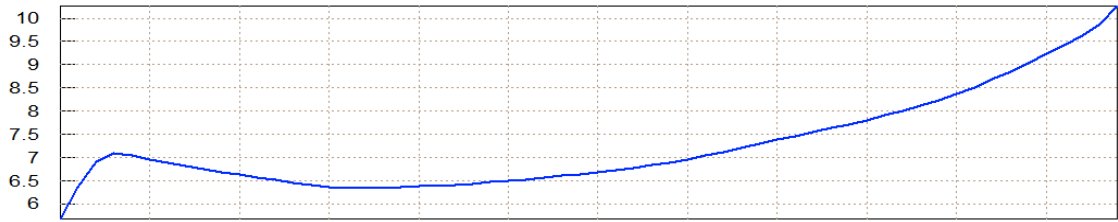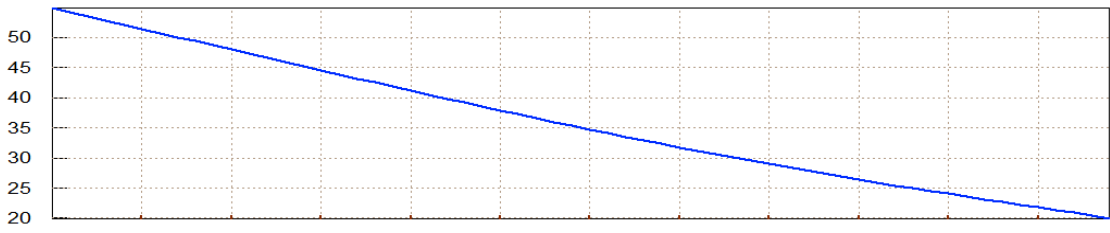
Vehicle CG in (feet), User Modified Trajectory ...
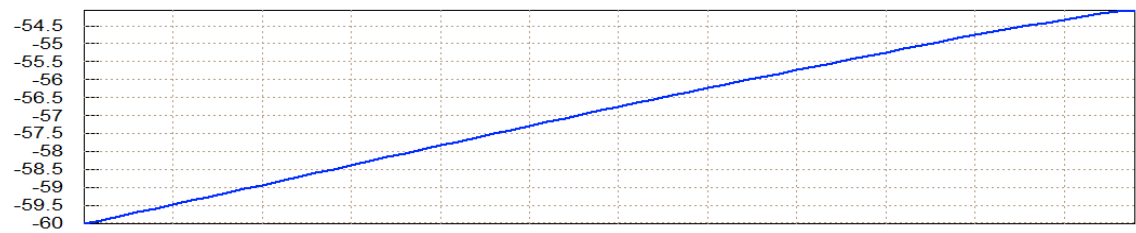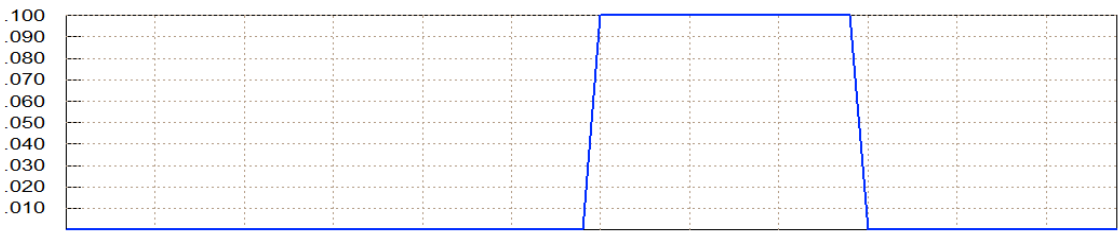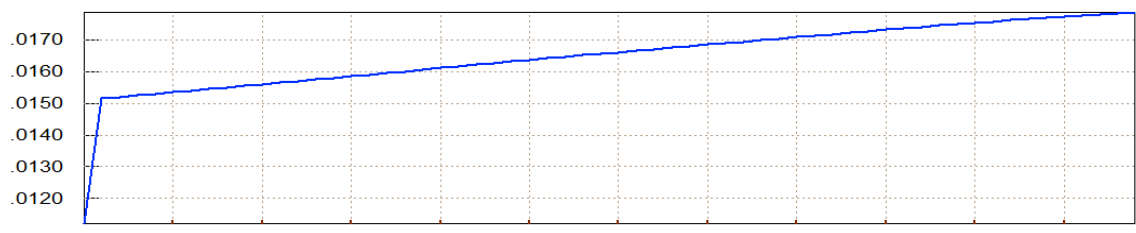
Trimming the Effectors

We must now trim using the modified trajectory file "*AL_Stg1_Mod.Traj*" that includes the disturbances to make sure that we have enough jet thrust to take them out. Do not select an initialization file (if it is the first time you trim that trajectory). In addition to the three moments we must also trim along the x-axis in order to match the x-acceleration dictated by the trajectory. From the Trim main select the third option for trimming.
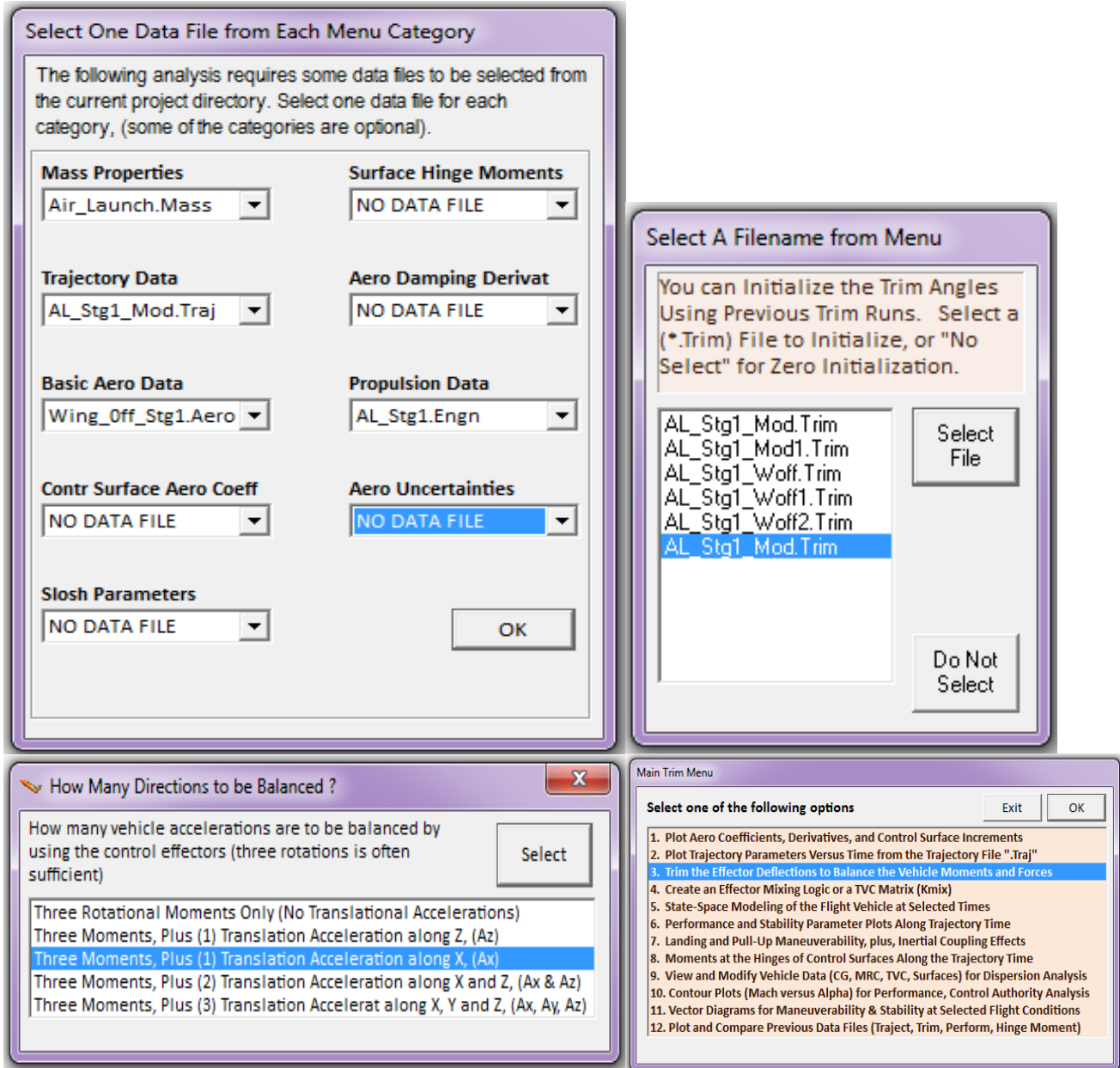
The next two plots show the residual moments and forces in the 4 controlled directions, which are practically zero after trimming. This is good, because it shows that the trajectory moments and forces are well balanced by the vehicle effectors, as they should be. The directions along y and z are not trimmed.

Residual Moments After Trimming (ft-lb) User Modified Trajectory ...

Roll

Pitch

Yaw

Time (sec)
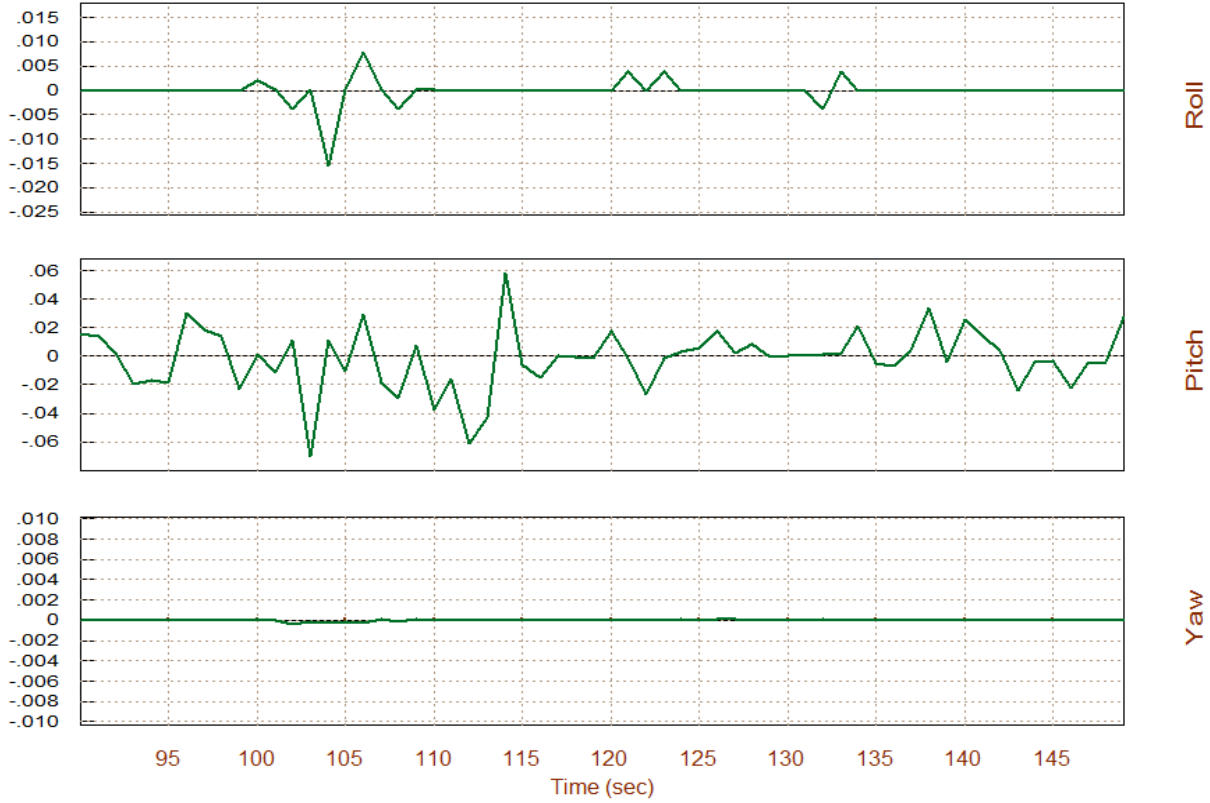
Residual Forces After Trimming (lb) User Modified Trajectory ...

Along-X

Along-Y

Along-Z

Time (sec)

Alpha, Beta, and Bank Angle (phi), Assuming Effectors are Trimmed (deg)
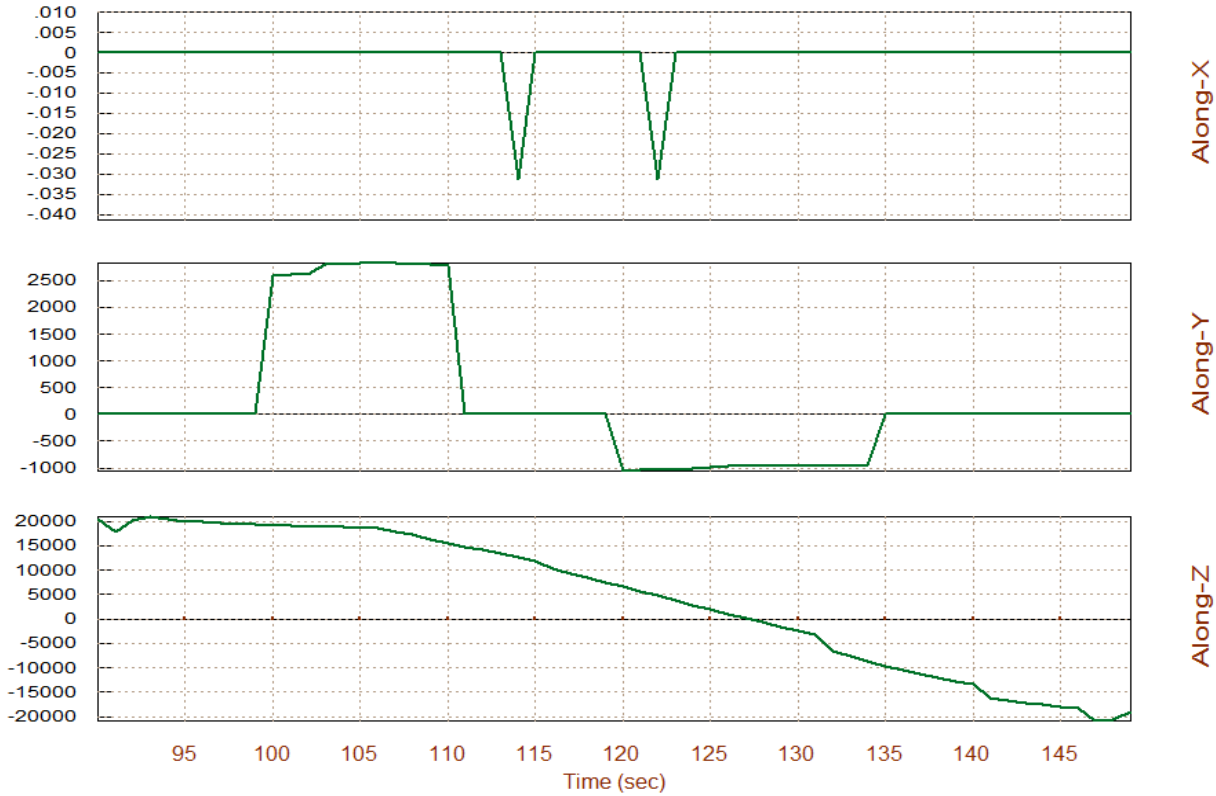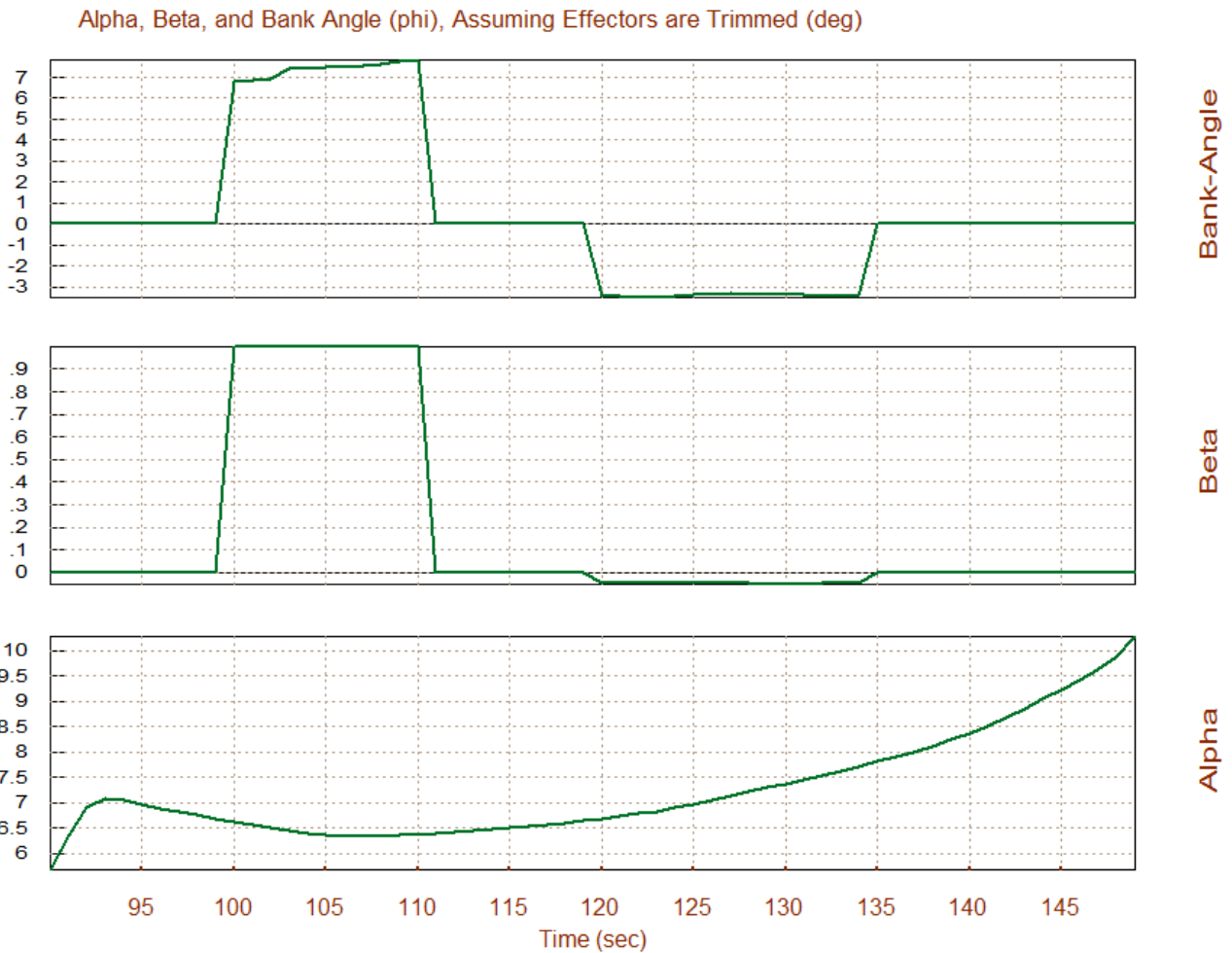
The plot above shows that 1° of beta causes the vehicle to trim by banking 7° towards the wind. The next two plots show the trim results in the presence of the disturbances. The engine TVC deflects in pitch to provide the required pitching moment to trim in pitch. It also varies its thrust in order to match the axial acceleration of the trajectory. The left and right RCS jets, labeled as Throttle 2 & 3, vary their thrust differentially in order to trim by counteracting the beta disturbance and the YCG offset which occur at different times. There is also a small amount of yaw gimbaling due to the disturbances. The trimming of the RCS jets did not exceed the 500 (lb) thrust limit set in the propulsion data file. It means that 500 (lb) thrusters are sufficient for roll control. Notice, that in Trim we always assume that the RCS jets are continuous and not "on-off" devices because its purpose is sizing and not for dynamic modeling. Flixan dynamic models, however, can be used to simulate the effects of "on-off" firing of the RCS jets and to perform non-linear control analysis using Simulink models, as it will be shown later in this example.

Surface & Engine Deflections/ Thrusts, User Modified Trajectory ...
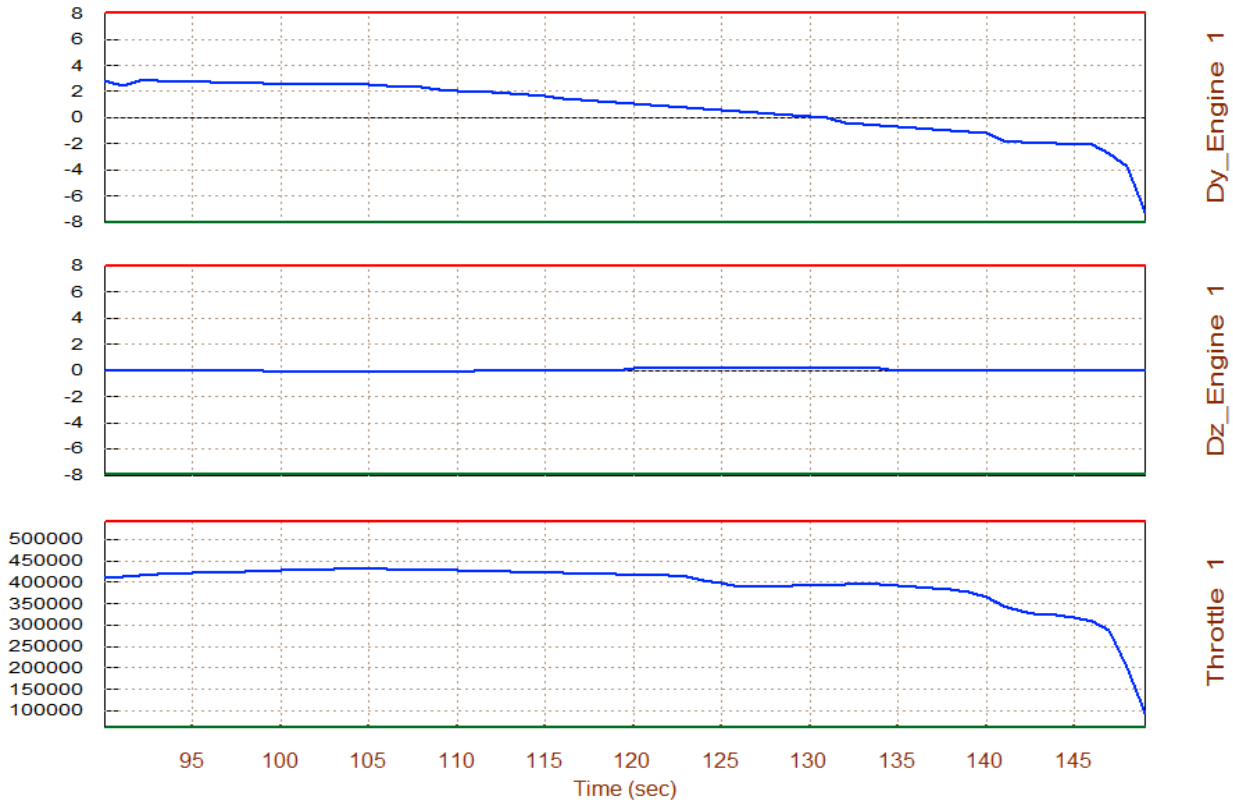
Dy_Engine 1

Dz_Engine 1

Throttle 1

Time (sec)

Surface & Engine Deflections/ Thrusts, User Modified Trajectory ...

Throttle 2

Throttle 3

Throttle 3

Time (sec)
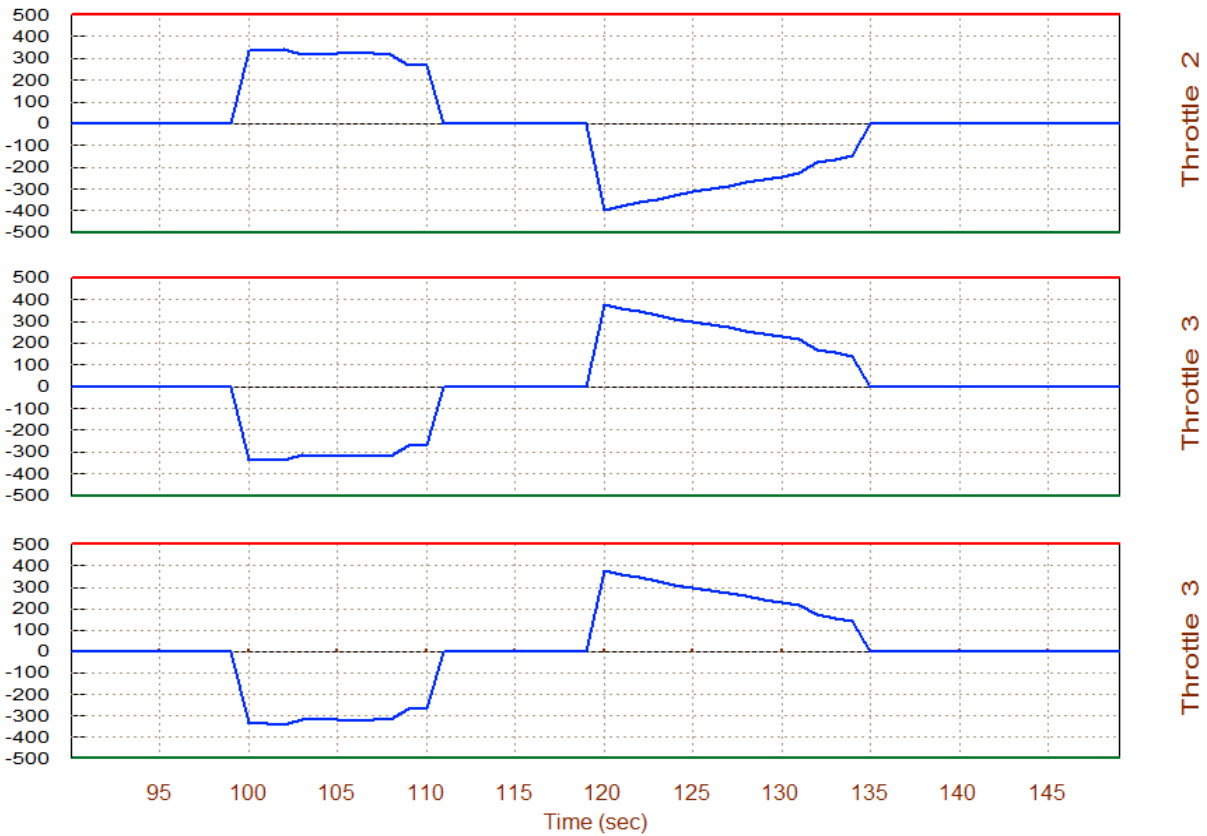
Performance Analysis Along the Original Trajectory

Performance analysis requires a trim trajectory. The purpose of trimming with the modified trajectory was for sizing the thrusters. In the remaining analysis we will be using trim results from the nominal trajectory. So let us repeat the effector trimming process that was described in the previous section, this time using the original trajectory "*AL_Stg1_Woff.Traj*". Then return to the main menu and select option 6 to evaluate the vehicle performance parameters along the original trajectory. Performance analysis requires a (5x4) mixing-logic matrix which in this case it has already been defined (Kmix4c) and it is located in file "Kmix4.Qdr". The mixing matrix converts the (roll, pitch, yaw, plus axial acceleration) demands to effector commands. The Kmix4.Qdr file also contains a mixing matrix (Kmix4a) that was derived using the mixing-logic algorithm, but it was not used in this example because its roll control authority was not as good as with (Kmix4c), even though it provides perfect diagonalization between axes. In the following matrix selection menu click on "*Select a Mixing Matrix*" to select the second matrix in that file.

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)

Notice ...

A (5 X 4) Mixing Logic Matrix is required

OK

Define the Effector Combination Matrix

The Mixing Logic Matrix translates the Flight Control (Roll, Pitch, Yaw, Ax, Ay, Az) demands to Effector commands (Aero-Surface, TVC, and Throttling).
You may either select a pre-calculated Mixing Logic Matrix (Kmix) from the Systems File: Kmix4.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

We must also define the max alpha and beta dispersions from nominal caused by winds and also due to maneuvering. This is required for determining the maneuverability and control authority of the vehicle. In this case we at higher altitude and the wind disturbances are smaller. We pick 1° for both angles.
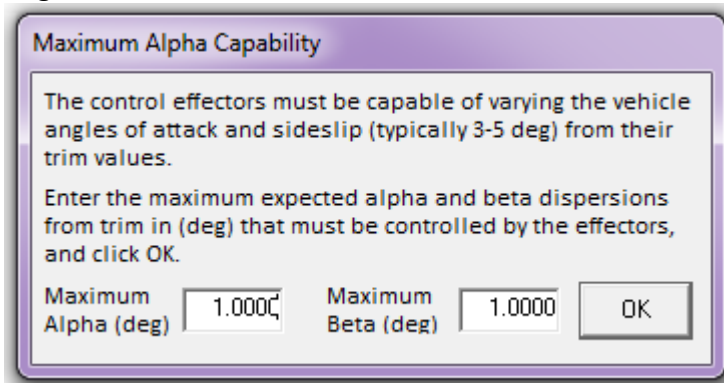

This vehicle is statically unstable in both pitch and lateral directions with times to double amplitude equal to 0.5 sec and 1 sec respectively. Rockets are usually unstable, as long as they do not diverge too fast. The Q-alpha, Q-beta load factor (with 1° of alpha and beta) remains flat at an acceptable level of 3,500 (psf-deg). The control authority parameters in roll pitch yaw and x-acceleration are all acceptable (they are less than one in all 4 directions). The worst one is in roll because it is using the jets that have limited power. Some improvement in roll authority was obtained by introducing some roll and yaw coupling in the mixing matrix, at the expense, of course, in yaw control authority. But there is plenty of yaw authority. The X-translational control authority parameter is very small which indicates that the vehicle has plenty of throttle capability to overcome forces in the x direction due to the winds defined.

The roll angle (ϕ) that would occur along the trajectory at 1° of sideslip (β), due to cross-wind, is less than 6°. The LCDP is positive and sizeable showing good maneuverability in roll. The Cn-beta-dynamic is negative because the vehicle is directionally unstable. The static margin is also negative indicative of pitch instability.

Static Margin, Center of Pressure, Aero-Center (ft), Air Launched Vehicle First
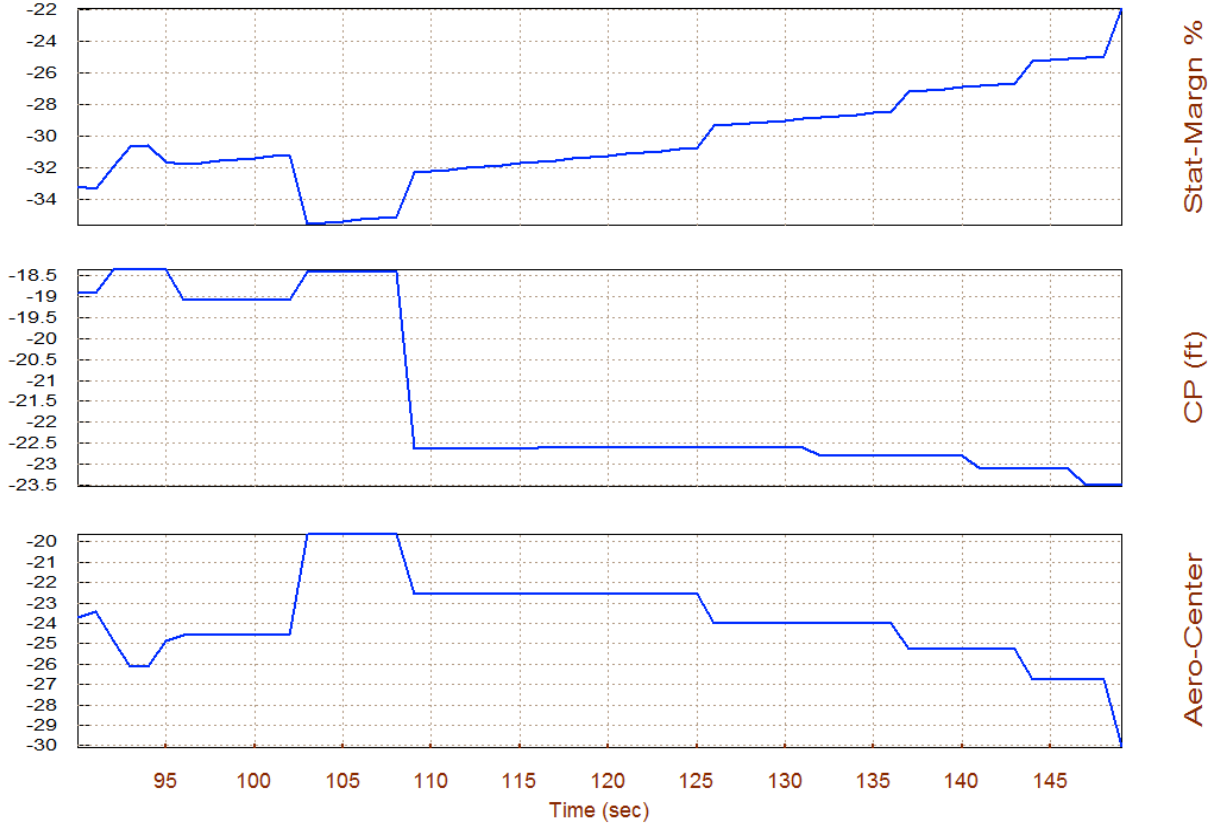
Short-Period (w)/ Time-to-Double-Ampl-Inverse (/sec), Q_alpha_beta (deg-lb/ft^2)
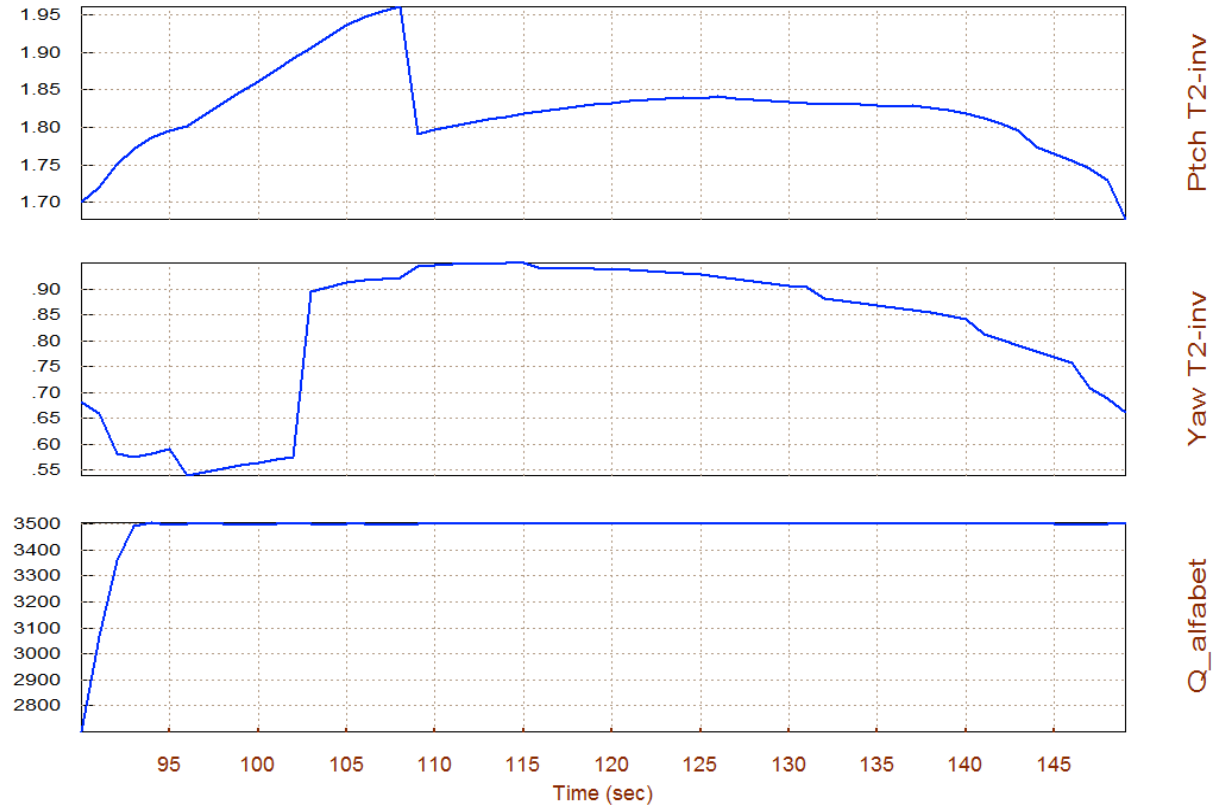
Bank Angle, LCDP Ratio, Cn_beta_dynam /deg, Air Launched Vehicle First Stage Boo
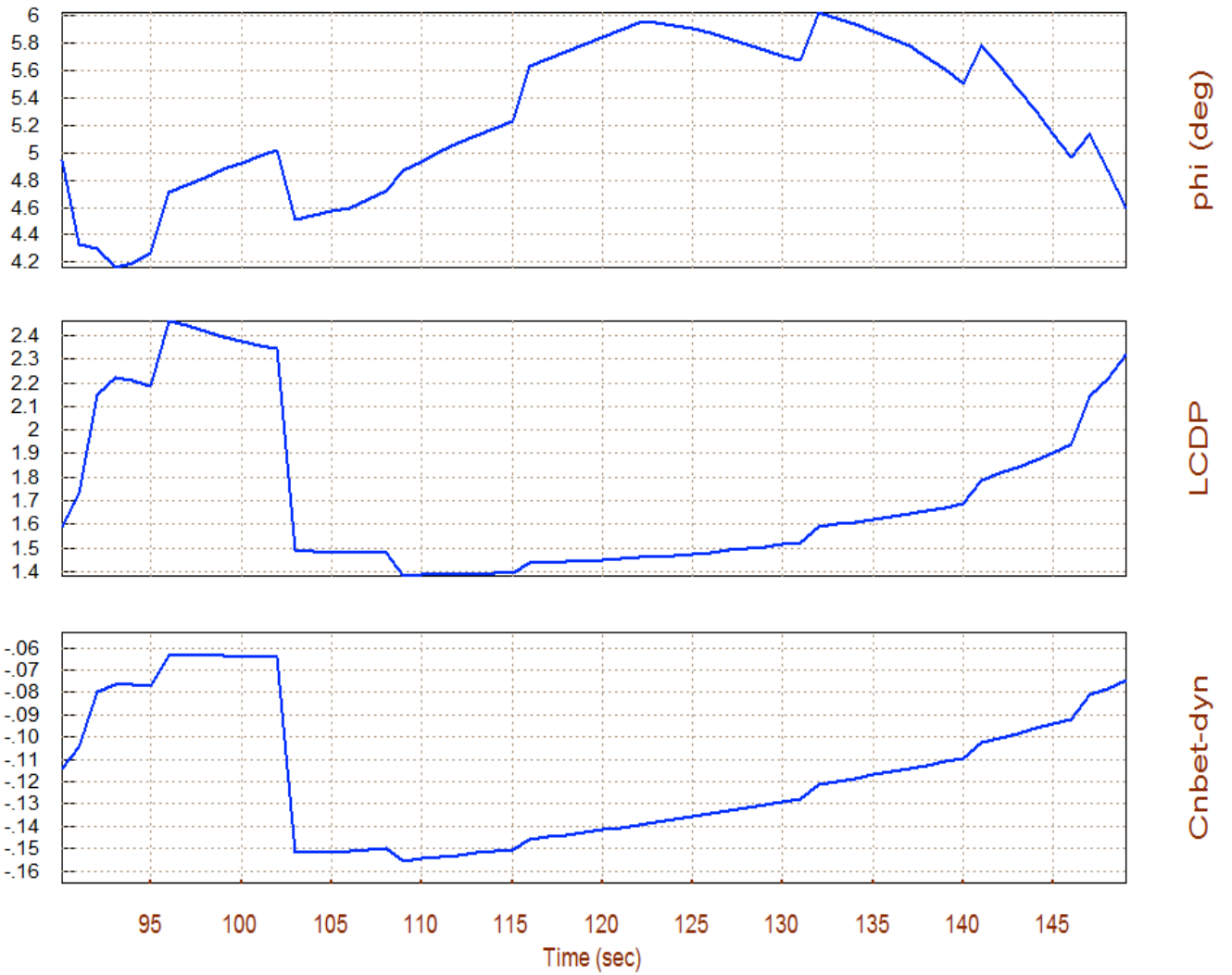
Rotation Control Authority (dQ/dQmax)<1 for 1 (deg) of Alpha & Beta Variation
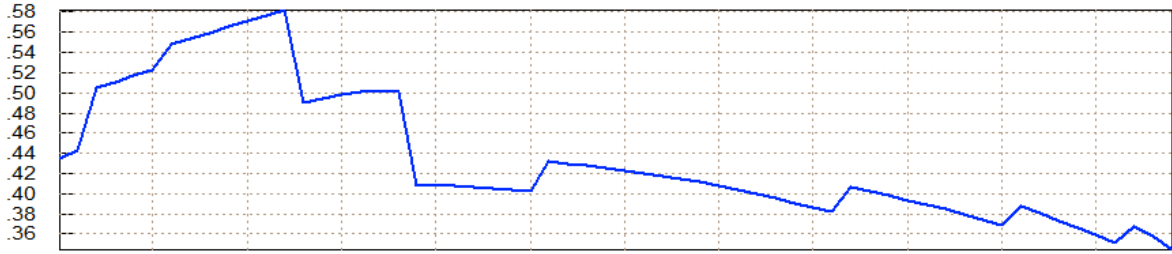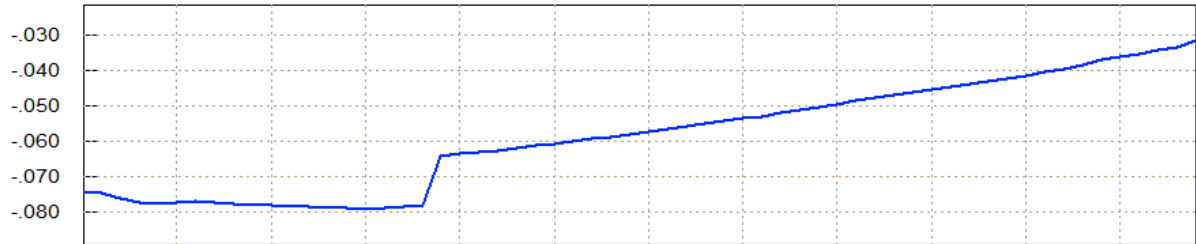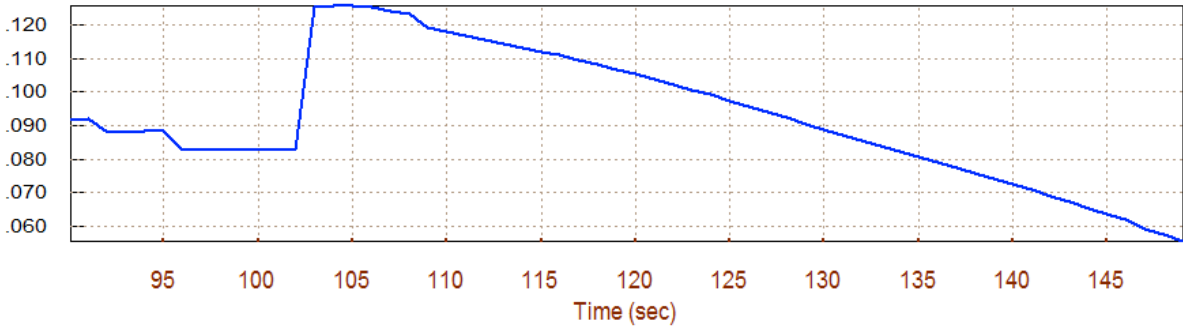
Translation Control Authority (dX/dXmax)<1 for 1 (deg) of Alpha/ Beta Variation

3-89
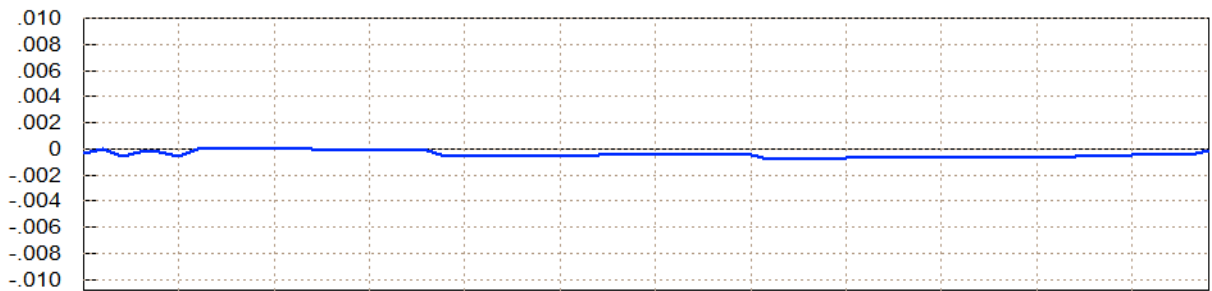
Max Angular Accelerat (deg/sec^2), at Max Control Demand Air Launched Vehicle Fi
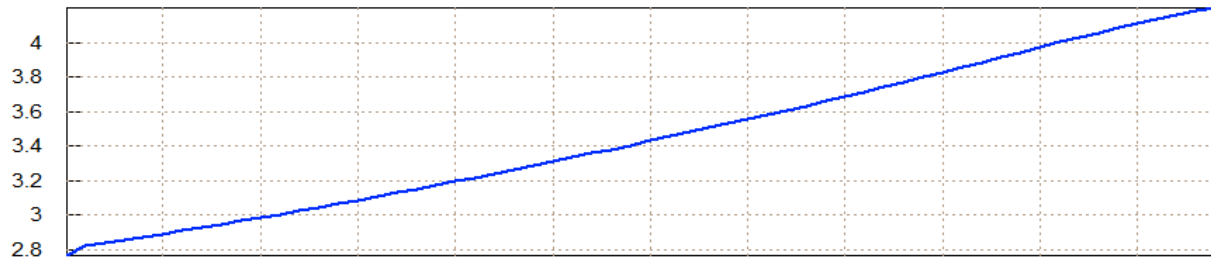
P dot (Max)

Q dot (Max)

R dot (Max)

Time (sec)
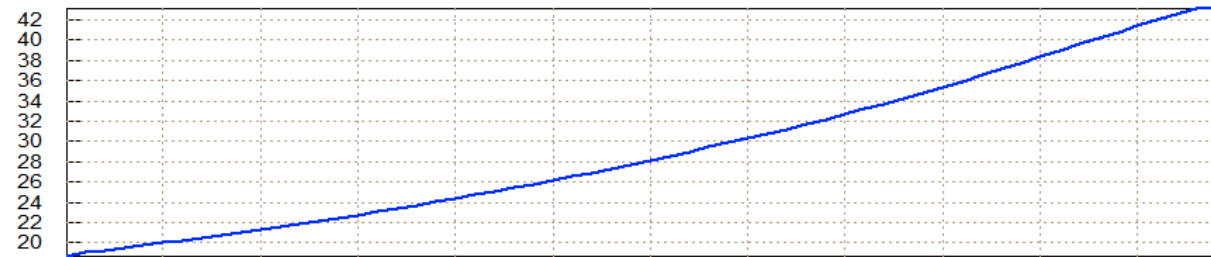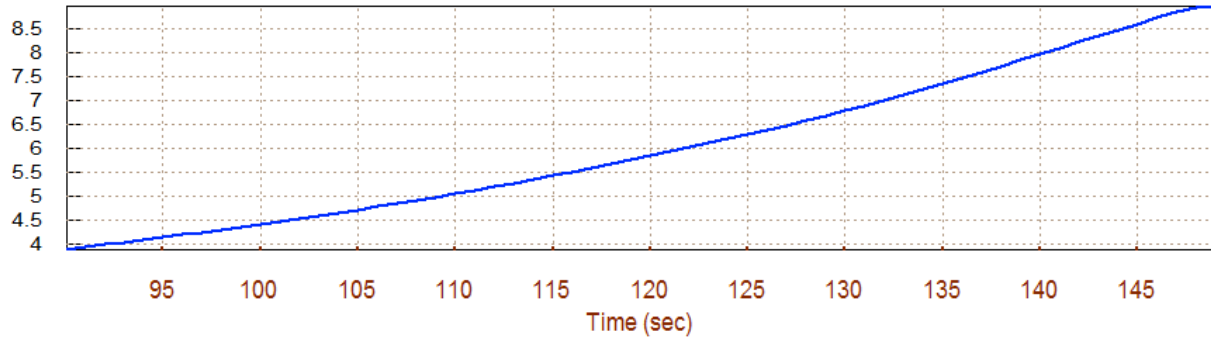
Max Linear Accelerat. (ft/sec^2), at Max Control Comd Air Launched Vehicle First
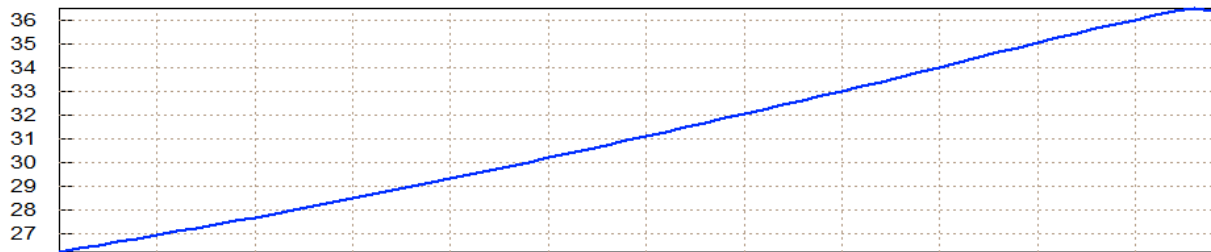
X-accel(Max)

Contour Plots

Contour plots are 3-dimensional plots of some vehicle performance parameters versus alpha and Mach. They give us a wider performance perspective rather than in the vicinity of the trajectory. Occasionally the vehicle may deviate from its nominal alpha versus Mach trajectory and we would like to make sure that the trajectory does not approach regions of unacceptable performance. They also help us reshaping the trajectory in order to improve performance. From the main menu select option (10) to create contour plots against Mach and Alpha. Similar to our previous analysis we must specify the aero disturbance environment which in steady-state is defined by the maximum angles (α_{max} and β_{max}) relative to the wind. Enter 1° for both α_{max} and β_{max}, as shown below. The program also requires the definition of a mixing-logic matrix. In the effector combination matrix definition dialog click on the top option "*Select a Mixing Matrix*" to select a matrix from the systems file "Kmix4.Qdr", and from the matrix menu select the second matrix Kmix4c.


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)

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

Notice ...

A (5 X 4) Mixing Logic Matrix is required

OK

Define the Effector Combination Matrix

The Mixing Logic Matrix translates the Flight Control (Roll, Pitch, Yaw, Ax, Ay, Az) demands to Effector commands (Aero-Surface, TVC, and Throttling).
You may either select a pre-calculated Mixing Logic Matrix (Kmix) from the Systems File: Kmix4.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

KMIX4A   : Mixing Logic for Air Launched Vehicle First Stage Boost Trajectory at Time: 119.52
KMIX4C   : Mixing Logic for Air Launched Vehicle First Stage Boost (User Modified)

From the following menu we must select the performance parameter to plot against alpha and Mach number, see the contour plots below.

Select Contour Plots   X

Select one of the Following Contour Plots to Display Vehicle Stability, Performance and Controllability as a Function of Mach Number and Alpha

OK

Exit

Pitch Stability, T2-Inverse Versus (Mach & Alpha)
Lateral Stability, T2-Inverse Versus (Mach & Alpha)
Lateral Departure (LCDP Ratio) Versus (Mach & Alpha)
Pitch and Yaw Controllability, Effector Effort (0 - 1)

The first two plots show the pitch and lateral stability parameters (T2-inverse) that were described in equations (3.14 & 3.15). The trajectory is shown with a black line across the Mach versus Alpha field. It starts below Mach #1, at T=90 (sec) in the lower left-hand corner, and it ends in the upper right-hand corner at T=150 (sec) at (α=10°, Mach=2.7). The color represents the value of the T2-inverse stability parameter over the entire of Mach versus alpha range and our trajectory (black line) traverses through this field. The colors in both fields are in the unstable regions (below white which is neutral stability), the pitch axis being more unstable than lateral. There are some regions of neutral stability in yaw which are not crossed by the trajectory.

Pitch Stability Contour Plot (Mach vs Alpha)
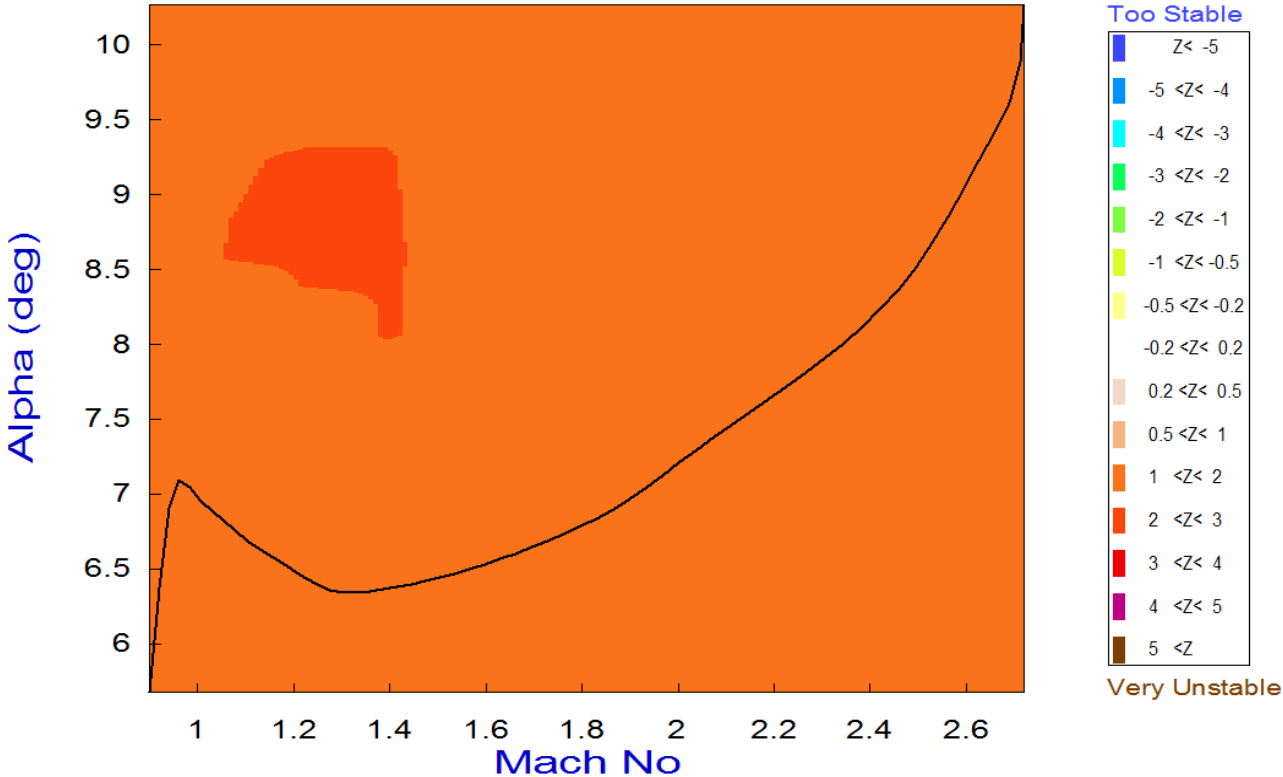
Lateral Stability Contour Plot (Mach vs Alpha)
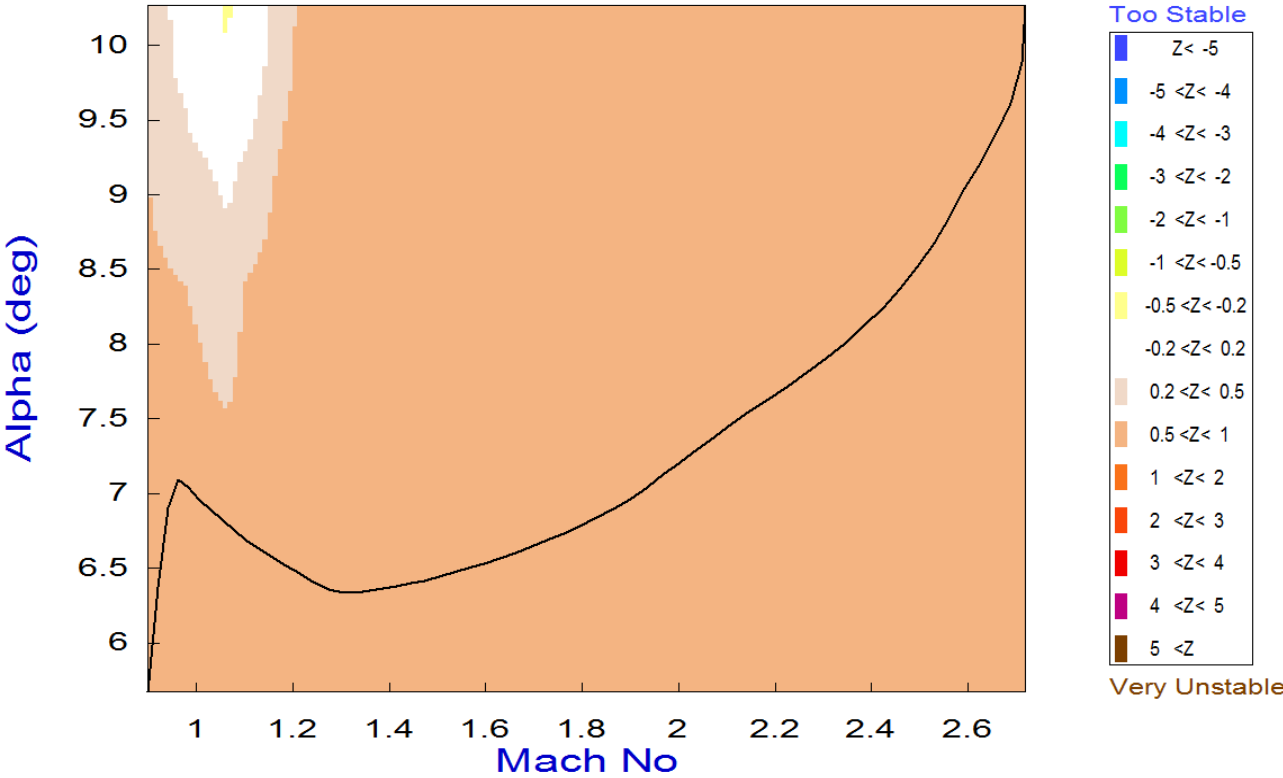
Roll Departure (LCDP) Contour Plot (Mach vs Alpha)
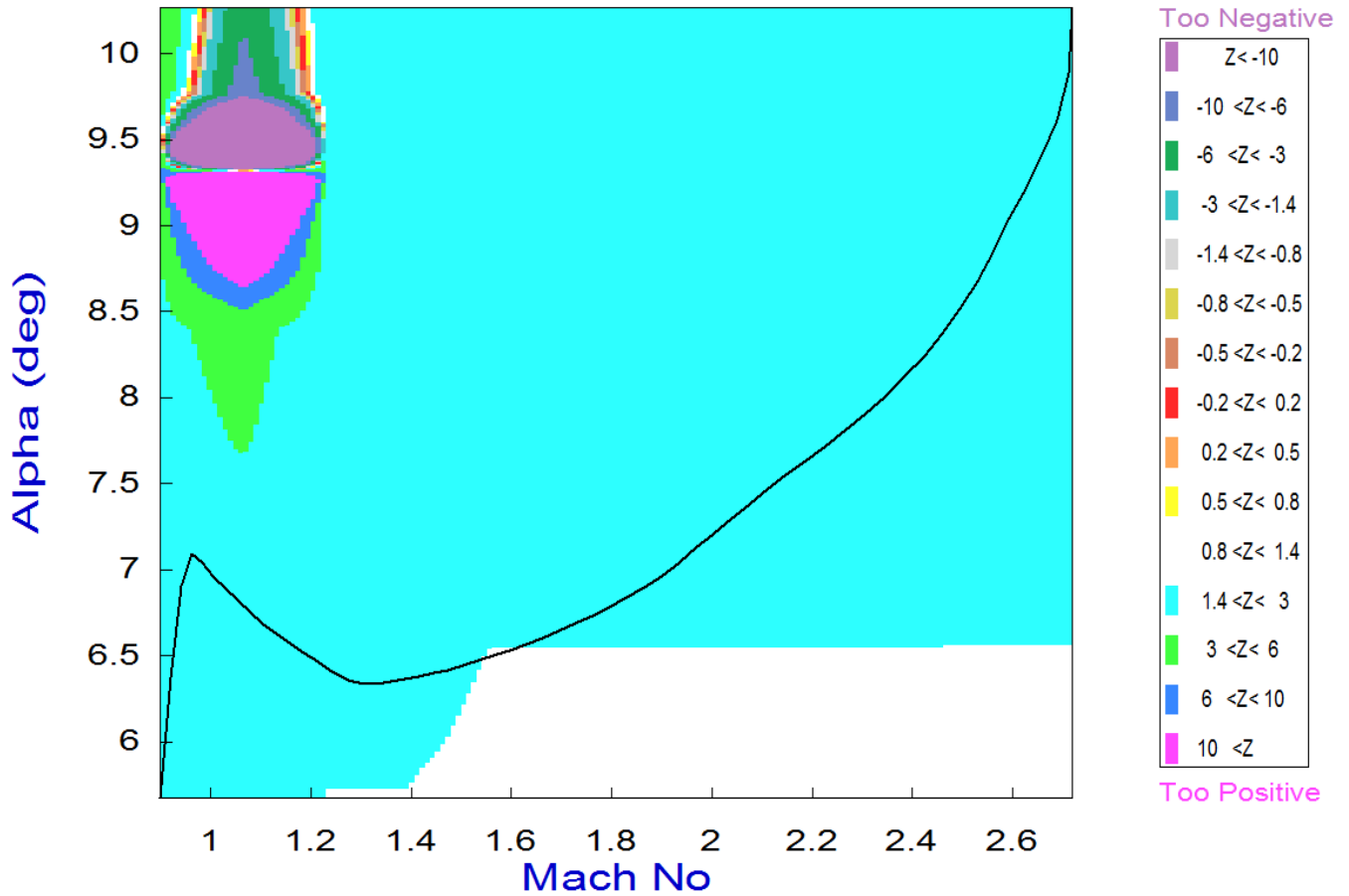
The above plot is a perfect example of the advantages offered by the contour plots. It shows the LCDP parameter which is an indicative of roll maneuverability (not the control authority). It indicates the dynamic controllability in the roll axis, which is very good in this case, positive and in a good range of values (light cyan). The white areas indicate perfect roll/yaw coordination. There is a bad region, however, in the upper left-hand corner where the parameter changes sign and crosses in the negative direction, indicating roll-reversal. Negative LCDPs are represented with dark colors (red and above in the chart). Our trajectory, however, is far from crossing that region.

Roll Control Effort Contour Plot (Mach vs Alpha)
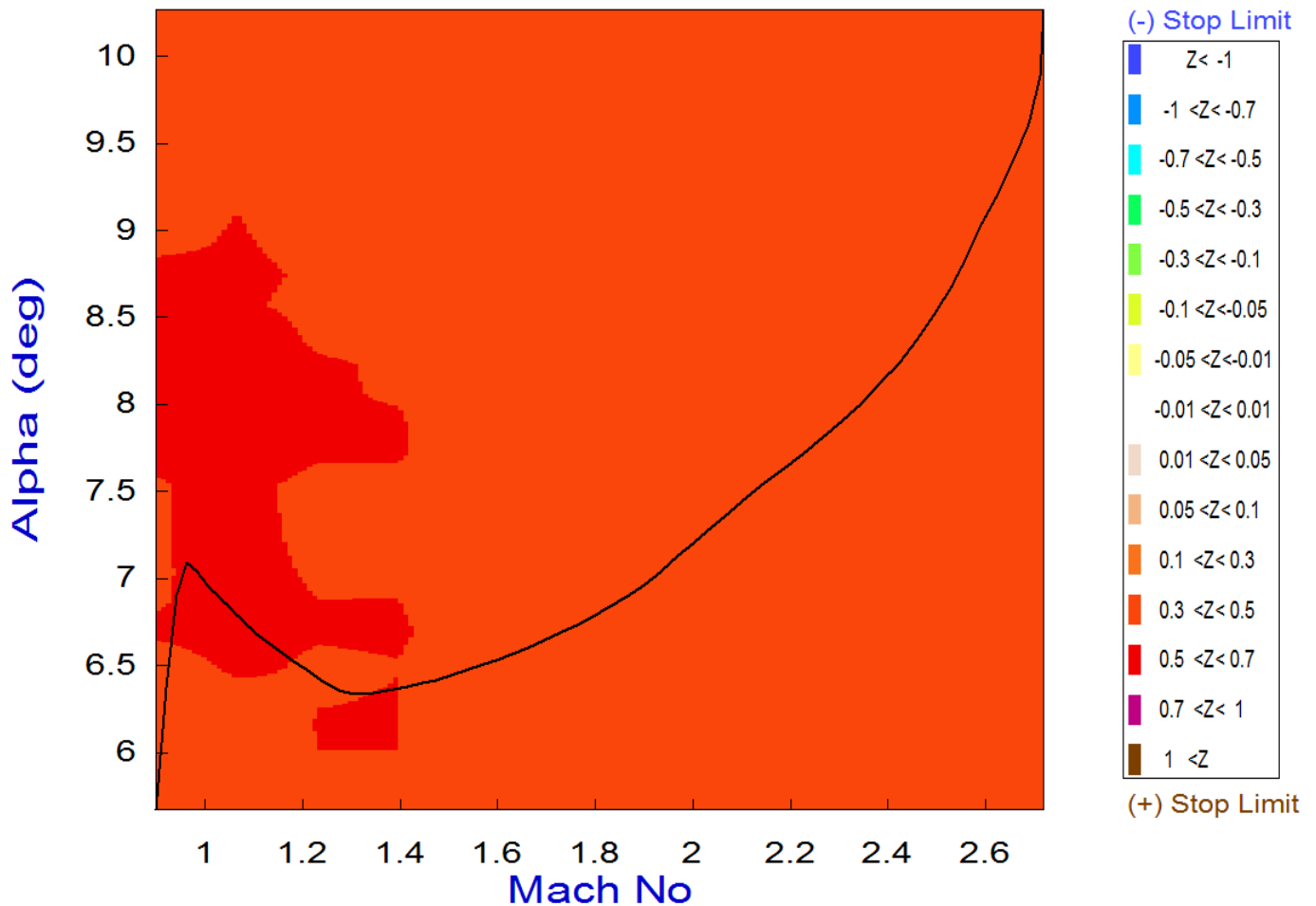
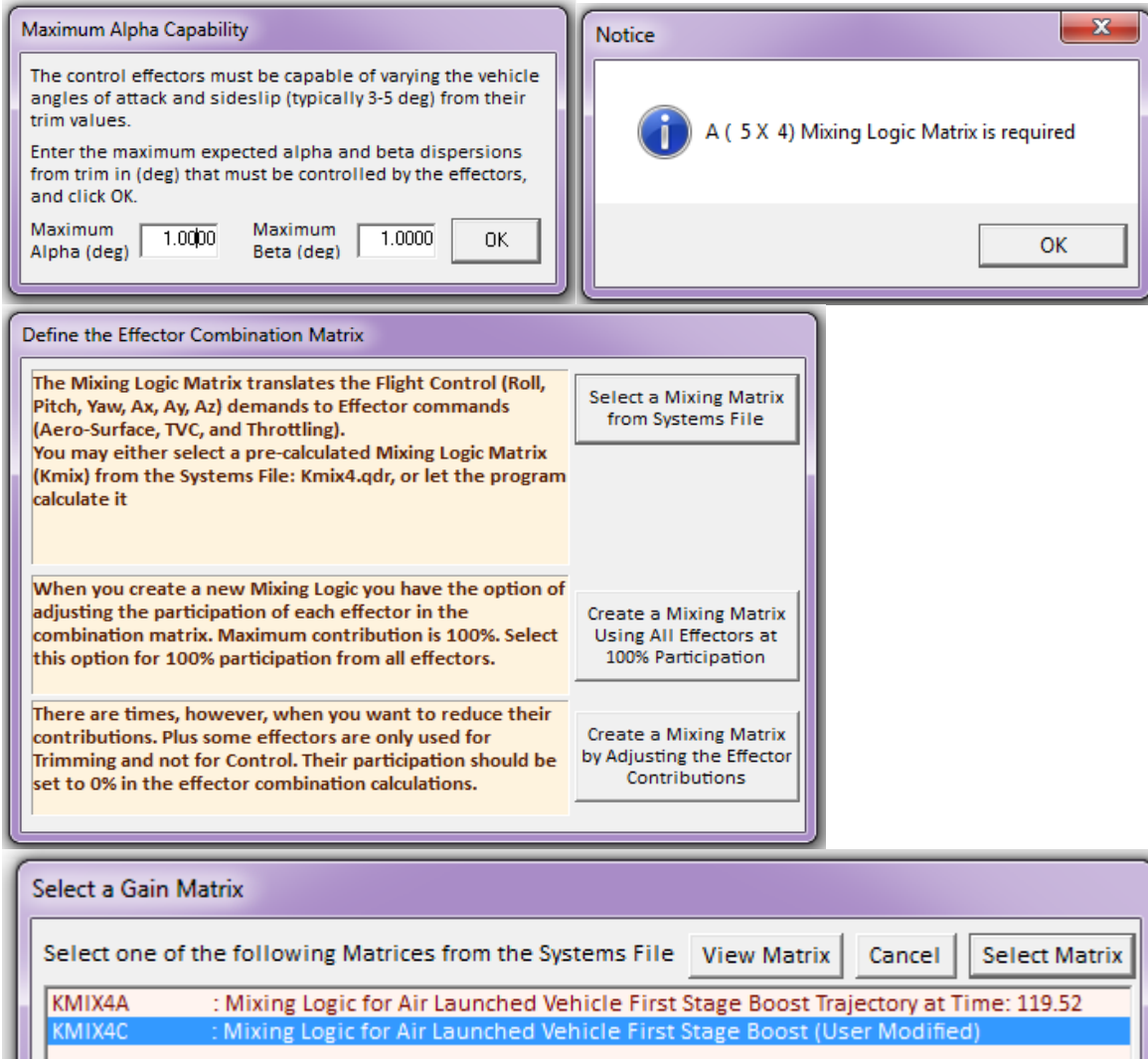This plot shows the roll control effort parameter which is an indicator of control authority in roll. It tells us how far we are from exceeding the available control torque in roll, which in this case it is dictated by the RCS jets. The effort parameter should be less than one (no brown or dark-blue regions). White is ideal meaning the vehicle is controlled with very little effort. The color not only indicates magnitude but also direction of effort. In this case, however, a significant amount of effort is required in order to fly along the trajectory with 1° of beta. The magnitude is mainly in the 0.5 range (dark orange region). It would come down if we used bigger thrusters, but we don't have to. It meets our requirement.

The next two plots show the control effort (authority) in pitch and yaw. The TVC is powerful enough and both directions have a lot more controllability margin than roll, especially pitch. The yaw authority was intentionally compromised (effort parameter increased) by introducing a small amount of roll/yaw dynamic coupling in the mixing-logic matrix Kmix4c. This coupling is helping to improve the roll controllability.

Pitch Control Effort Contour Plot (Mach vs Alpha)
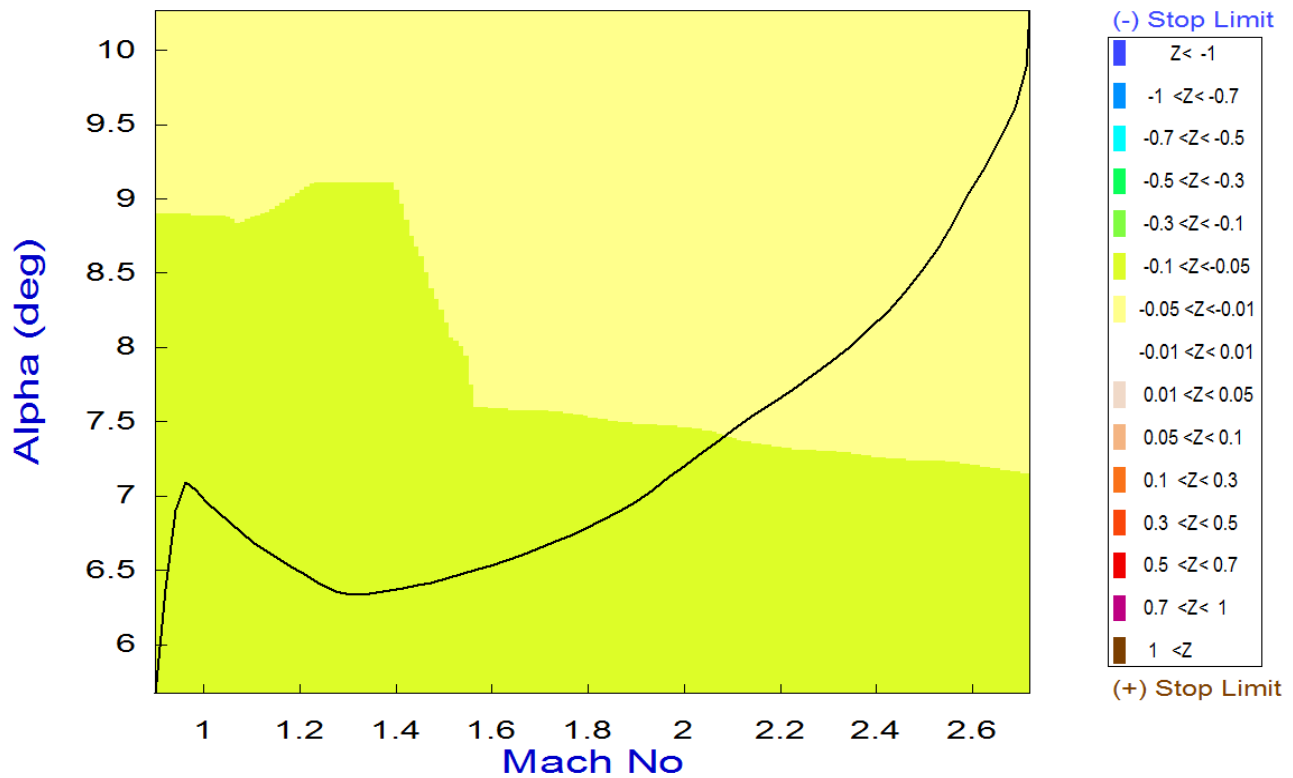
Yaw Control Effort Contour Plot (Mach vs Alpha)
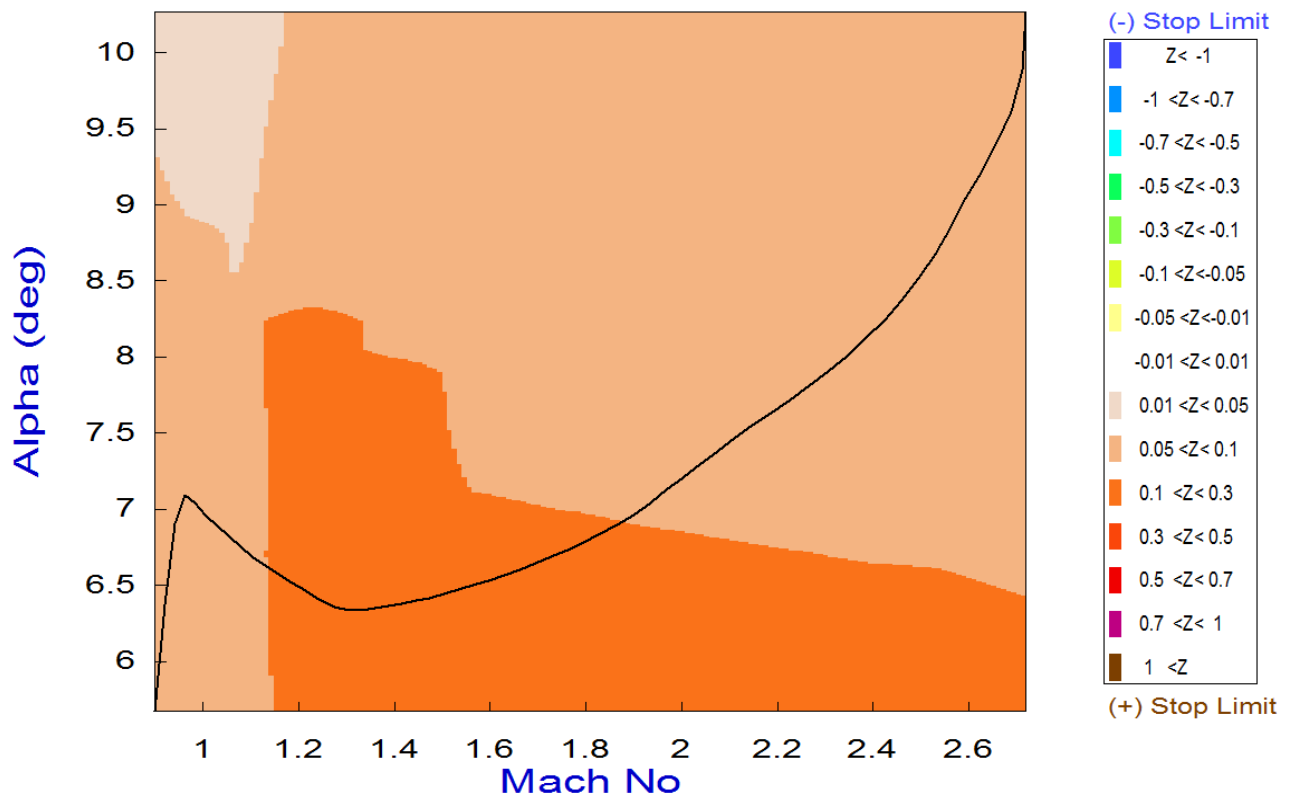
Analysis Using Vector Diagrams

Vector diagrams are used for analyzing vehicle controllability against aerodynamic disturbances that cause alpha and beta dispersions from trim. They are two-dimensional diagrams comparing the magnitude and direction of the vehicle's response to an alpha or beta disturbance against vehicle response to flight control demands. Assuming that the initialization files and trim conditions are the same as before, from the main menu select option (11) for plotting vector diagrams. Select an arbitrary flight condition (at t=110 seconds), and from the following menu you may keep the default values of Mass, Mach, α, and β corresponding to the selected 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. Evaluate Performance, Authority Using Contour Plots (Mach versus Alpha)
11. Vector Diagrams for Maneuverability & Stability at Selected Flight Conditions
12. Plot and Compare Previous Data Files (Traject, Trim, Perform, Hinge Moment)

Select a Time from: (90.040   to   149.00   ) to Analyze Vehicle Controllability   OK

110.0

Select the following parameters

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

Vehicle Mass (slug)	Mach Number	Angle of Attack (deg)	Angle of Sideslip (deg)
9119.4	1.460	6.00	0.00
9756.8	0.8000	5.00	-5.00
9119.4	0.9000	6.00	0.00
5849.5	0.9500	7.00	5.00
5471.5	1.100	8.00	
2096.9	1.300	9.00	
1745.2	1.460	10.0	
656.40		12.0	
465.94		14.0	
267.85		16.0	

The next step is to select the worst case alpha and beta dispersions and the mixing-logic matrix.

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]

Notice   [X]

ⓘ A (5 X 4) Mixing Logic Matrix is required

[OK]

Define the Effector Combination Matrix

The Mixing Logic Matrix translates the Flight Control (Roll, Pitch, Yaw, Ax, Ay, Az) demands to Effector commands (Aero-Surface, TVC, and Throttling).
You may either select a pre-calculated Mixing Logic Matrix (Kmix) from the Systems File: Kmix4.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]

KMIX4A   : Mixing Logic for Air Launched Vehicle First Stage Boost Trajectory at Time: 119.52
KMIX4C   : Mixing Logic for Air Launched Vehicle First Stage Boost (User Modified)

The first two vector diagram below show the maximum roll and yaw moments and the maximum roll and yaw accelerations (green and blue vectors respectively). They are produced by maximizing the roll and yaw FCS demands, in the positive (solid line) and in the negative (dashed line) directions. The roll effector (RCS) produces a moment and acceleration entirely along the roll axis. The yaw effector, however, (TVC) in addition to yaw it produces also some roll. The disturbance moments due to $\pm\alpha_{max}$ and $\pm\beta_{max}$ are shown by the red vectors. Their magnitudes are significantly smaller than the control moments.

The next two vector diagrams show the maximum effects of the pitch and engine throttle demands in the longitudinal directions. That is: (a) pitching moment versus axial force (non-dimensional), and (b) pitch acceleration versus axial acceleration, when the effector pitch and throttle demands are maximized. The small red vectors (hardly visible) represent the effects of the $\pm\alpha_{max}$ and $\pm\beta_{max}$ disturbances in the corresponding directions, and they are negligible. Notice the unsymmetry. The positive pitching moment vector is longer than the negative. This is because α_0 is positive and it is easier to pitch up than down. It is also easier to slow down due to drag than it is to accelerate in the x-direction.

Comparison Between Maximum Control Moments Against Maximum Disturb Moments (red)
Roll & Yaw Control Moments (non-dimension) vers Disturb Moment due to Max Beta/Alpha

Comparison Between Maximum Control Accelerations and Max Accels due to Beta (red)
Roll & Yaw Accelerations due to Maximum Roll/ Yaw Control and due to Max Beta

Trim Conditions

```
Flight Time ----------------: 110.
Mach Number ----------------: 1.46
Alpha and Beta Trim (deg) ---: 6.00  0.00
Dynamic Pressure (psf) ------: 549.
Vehicle Mass (slugs) --------: 0.818E+04
Max Alpha/Beta Disturb (deg): 1.00  1.00
Aero-Surface Trim Angles (deg)

Engine Pitch Trim Angles (deg)
 2.09
Engine Yaw Trim Angles  (deg)
 0.175E-03
```

OK

Comparison Between Maximum Control Moment/Forces Against Maximum Disturbance (red)
Pitch Control Moment and Axial X-Force (non-dimens) versus Disturb due to Max Alpha

(Y-axis: CX, X-axis: Cm)

Comparison Between Maximum Control Accelerations and Max Accels due to Alpha (red)
Pitch Accelerat and Axial X-Accelerations due to Max Control and due to Max Alpha

(Y-axis: X-ddot (g), X-axis: Q-dot (rad/sec2))

The next plot shows the roll and yaw moment partials per roll and yaw FCS acceleration demands (δ_{PFCS} & δ_{RFCS}), green and blue vectors respectively. It also shows the roll and yaw moment partials per beta disturbance (Clβ & Cnβ), calculated at two extreme alphas (red vectors). The control vectors are scaled as described in equations (7.1 through 7.4) in order to be compared with (Clβ & Cnβ). The control partials are significantly bigger than the aero disturbance partials. The plot below shows the acceleration partials per acceleration demands. The green vector shows the roll and yaw acceleration partials per roll demand (δ_{PFCS}). The blue vector shows the roll and yaw acceleration partials per yaw demand (δ_{PFCS}). The acceleration partials are almost entirely decoupled (orthogonal).

Comparison Between Control Moment Partials Versus Aero-Disturb Moment Partials (red)
Yaw & Roll Control Partials Cn/delta_R and Cl/delta_P versus Cn/beta & Cl/beta
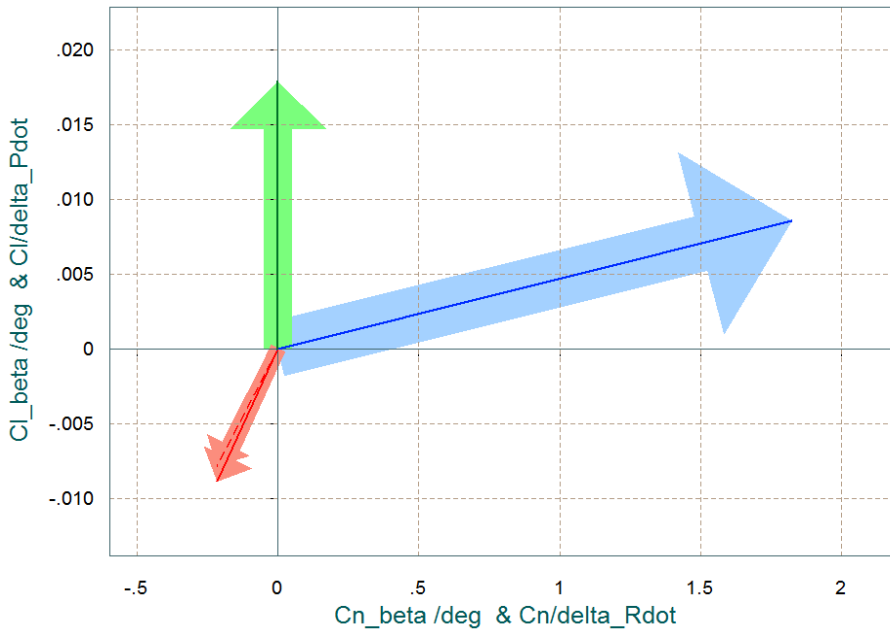
Ratios of Roll and Yaw Accelerations Over Corresp Control Acceleration Demands
(Rdot & Pdot)/Pdot_Demand and (Rdot & Pdot)/Rdot_Demand, (rad/sec2) / (rad/sec2)
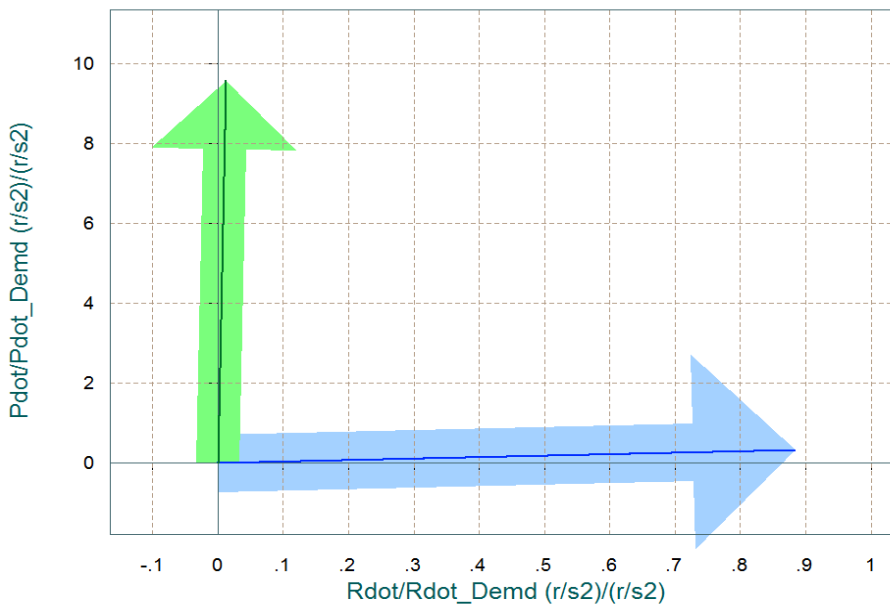
Similarly, the next vector diagram shows the controls versus disturbance partials in the longitudinal directions. It shows the pitch and axial accelerations per pitch and x-acceleration FCS demands (δ_{QFCS} & δ_{XFCS}), that is: (Cmδ_Q, CXδ_Q) blue vector and (Cmδ_X, CXδ_X) green vector respectively. The small red vector is the pitch moment partial per alpha (Cmα), and the axial force partial per alpha (C$_X\alpha$). The next plot shows the acceleration partials per acceleration demands. The green vector shows the x and pitch acceleration partial per x-acceleration demand (δ_{XFCS}), and the blue vector shows the x and pitch acceleration partial per pitch acceleration demand (δ_{QFCS}).

Comparison Between Control Force & Moment Partials Against Disturb Partials (red)
Cm/alpha & CX/alpha versus Pitch and Axial Force Controls: Cm/delt_Q & CX/delt_X
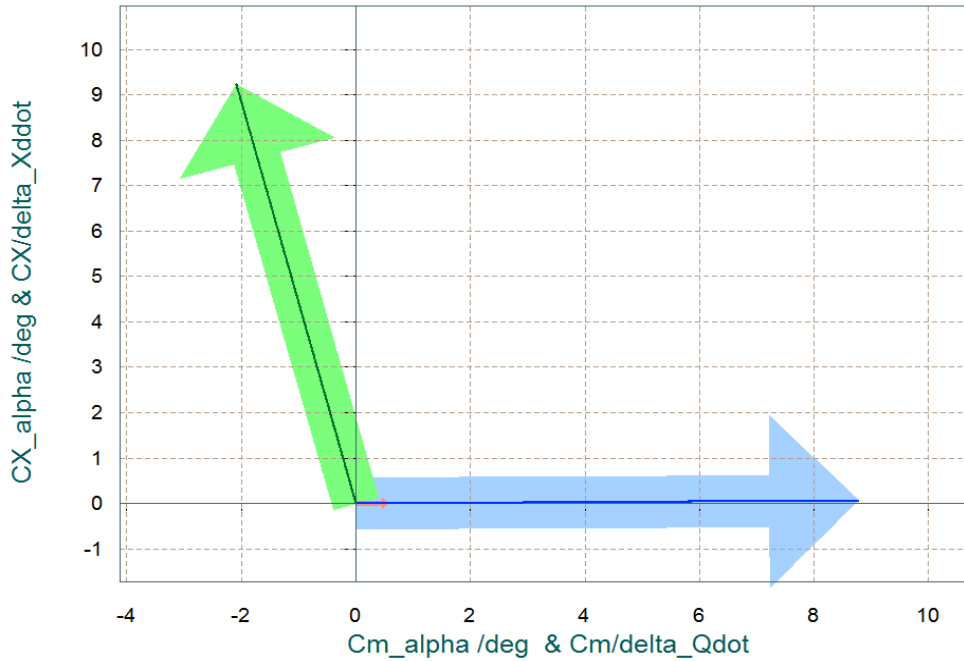
Ratios of Pitch and Axial Accelerations over Corresp Control Acceleration Demands
(Qdot & X_ddot)/Qdot_Demd and (Qdot & X_ddot)/Xddot_Demd, (r/s2)/(r/s2), (g/g)
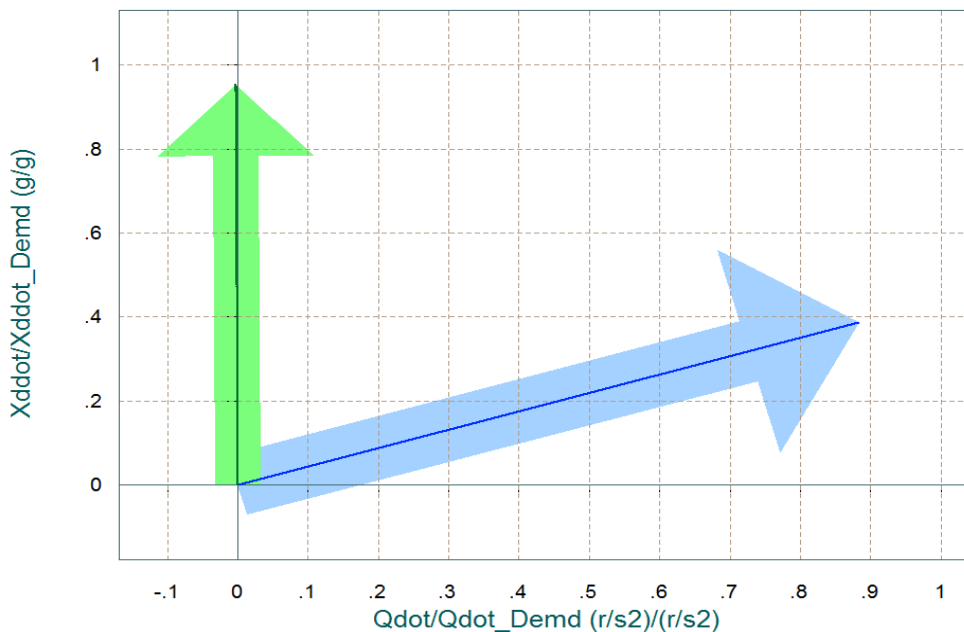
Dynamic Modeling

We will now use the Trim and Flight Vehicle modeling programs to create a linear model of the flight vehicle during first stage without wings, at t=110 (sec) from separation. This model will be used for control design and simulations similar to the previous two phases. Additional pitch and lateral decoupled systems will also be created for control design purposes. So let us begin the Trim program, select the same Trim data files, and also select the Flixan input data file "*Stg1_WOff_T110.Inp*" and the systems file "*Stg1_WOff_T110.Qdr*" in directory "*C:\Flixan\ Trim\Examples\Air Launched Vehicle\Phase C Boost No Wing*".
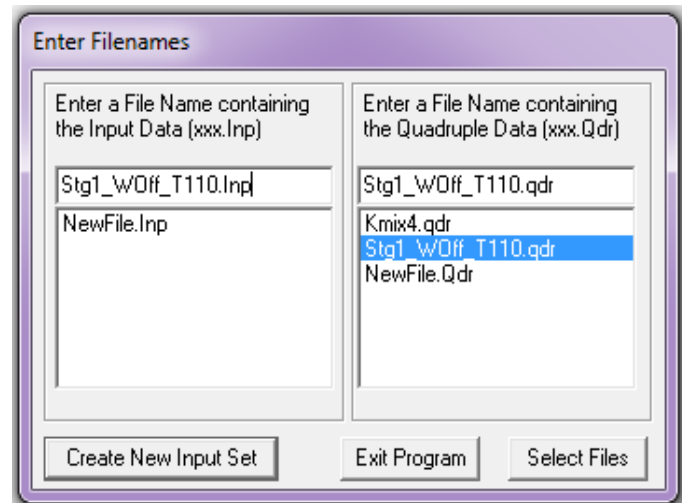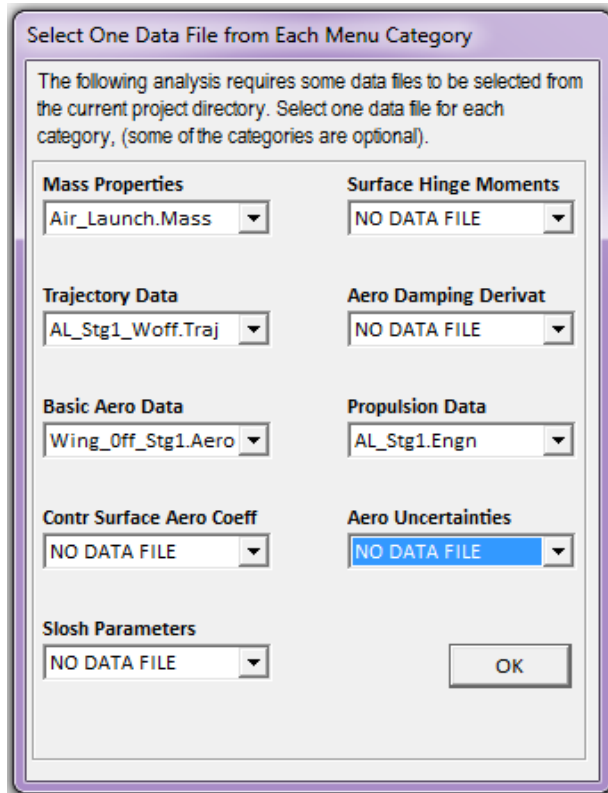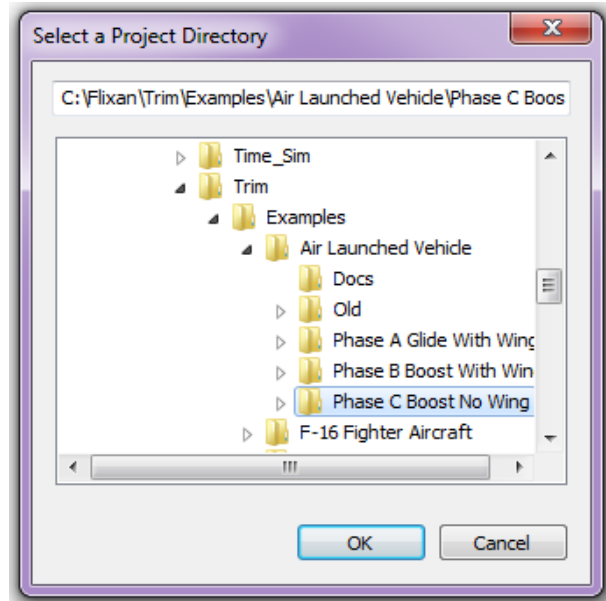
The Trim program will generate the flight vehicle input data in file "*Stg1_WOff_T110.Inp*", and the vehicle dynamic model will be created by the FVMP and it will save it in "*Stg1_WOff_T110.Qdr*". However, in this case this input data file is already prepared, and in addition to the vehicle data it contains also data sets that will be used by Flixan to create reduced and decoupled models for control analysis. The Trim program first generates the vehicle input data in file "*Stg1_WOff_T110.Inp*". The additional data in that file are processed by other Flixan utilities that generate decoupled models and they reformat the systems for Matlab.

From the Trim main menu we select Option (5) which generates vehicle data for the dynamic model. The user is prompted to select a flight time from one of the trajectory plots using the mouse. Go to the top menu bar, click on "*Graphic Options*" and from the vertical drop-down menu click on "*Select Time to Create a State-Space System*".

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)

Select Time Point   [x]

(i) From the Top Menu of the Trajectory Plots, go to "Graphic Options" and select a Time to create a Linear System

[OK]

Trajectory Parameters

Copy Format: Send to: [Graphic Options]   Next Plot   Exit Plots

　　　　　　　　　　Magnify a Rectangle Section of the Plot
　　　　　　　　　　Modify a Trajectory Plot Using the Mouse　　　　'Flight
　　　　　　　　　　Restore Original Trajectory/ Trim Data
　　　　　　　　　　Select Time to Create State-Space System

8
7
6
5

The program confirms that you have selected the trajectory time 110 sec to create input data for the dynamic model. Click "OK" to continue. The flight vehicle modeling program (FVMP) dialog comes up showing the vehicle data categorized in tabs (extracted from the Trim files).
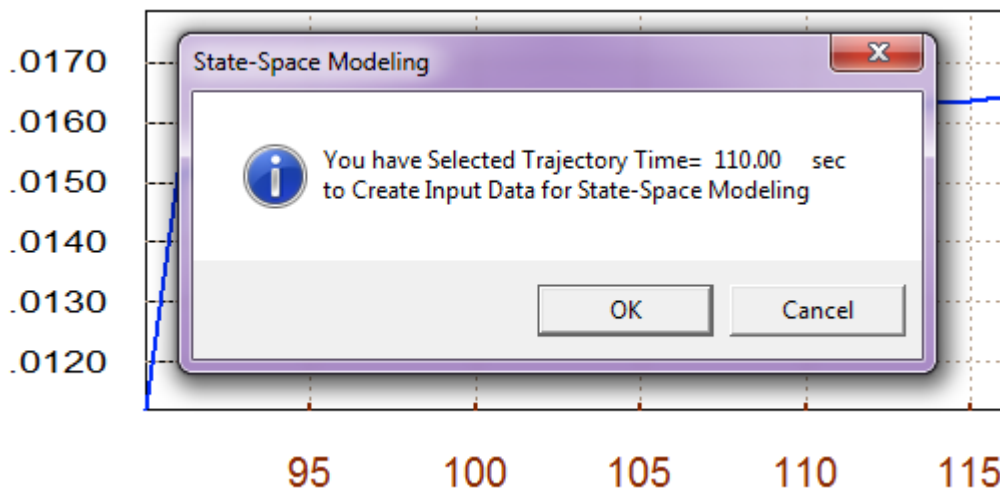
The following dialog allows you edit some of the data or titles in the various fields and tabs. You must click on "*Update Data*" every time you modify a group of data before changing tabs. When you finish editing the dialog click on "*Save in File*" button to save the vehicle data in "*Stg1_WOff_T110.Inp*". You may also edit that file directly by clicking on "*Edit Input File*". Finally you may click on "Run" to generate the state-space system in "*Stg1_WOff_T110.Qdr*". But you are not ready to run it yet before including the remaining of the Flixan data sets for the additional processes described. So click on "Exit" for now, and take a look in the already prepared input file.

The simulation model in file "*Stg1_WOff_T110.Qdr*" includes three throttling engines. There is the main engine (which is also gimbaling) and two RCS jets. Before using the dynamic model in a simulation the user should notice that the throttle inputs to the dynamic model are non-dimensional. They are normalized by the max thrust and the throttle inputs in the dynamic model may vary between zero and ±1. The main engine is defined as having a 400,000 (lb) of nominal thrust which can go up and down ±50% for acceleration control. An input of +1 is equivalent of raising the thrust by +50% which is 600,000 (lb) and an input of -1 is equivalent of lowering the thrust by -50% to 200,000 (lb). A zero input assumes that the thrust is nominal. The two RCS jets are also defined as throttling, and they are not gimbaling. Each input physically represents a pair of back-to-back firing jets. Their nominal thrust is zero in this case and their max thrust is 500 (lb). The throttle inputs may vary between zero and ±1. When the input to the dynamic model is zero it means zero RCS thrust. When the input is +1 it means that the jet force is +500 (lb) and when the input is -1 it means that the jet force is -500 (lb).

The already created input file "*Stg1_WOff_T110*.Inp" includes a number of data sets and each set is processed by a separate Flixan utility. On the top of the file there is a batch set that processes the remaining data-sets together. The first set of data below the batch generates the vehicle model. The next 3 data sets generate reduced order pitch and lateral vehicle subsystems for control design purposes. The last 4 data-sets convert the vehicle models to Matlab m-function format so that they can be loaded into Matlab for control analysis. To process the batch and data-sets from Flixan, go to "*Manage Input Files (*.Inp)*" and then click on "*Process/ Edit Input Data*". The following dialog comes up. From the left menu select the only input file, and then from the right menu select to process the batch set which is the top title in that menu, and then click on "Execute/ View" to run it. Answer "Yes" in the next dialog question. Flixan will generate the vehicle models in file "*Stg1-WOff-T110*.Qdr" and it will also convert them to Matlab format. They are saved in files "vehicle.m", "pitch_des.m", "pitch_ana", and "lateral.m".
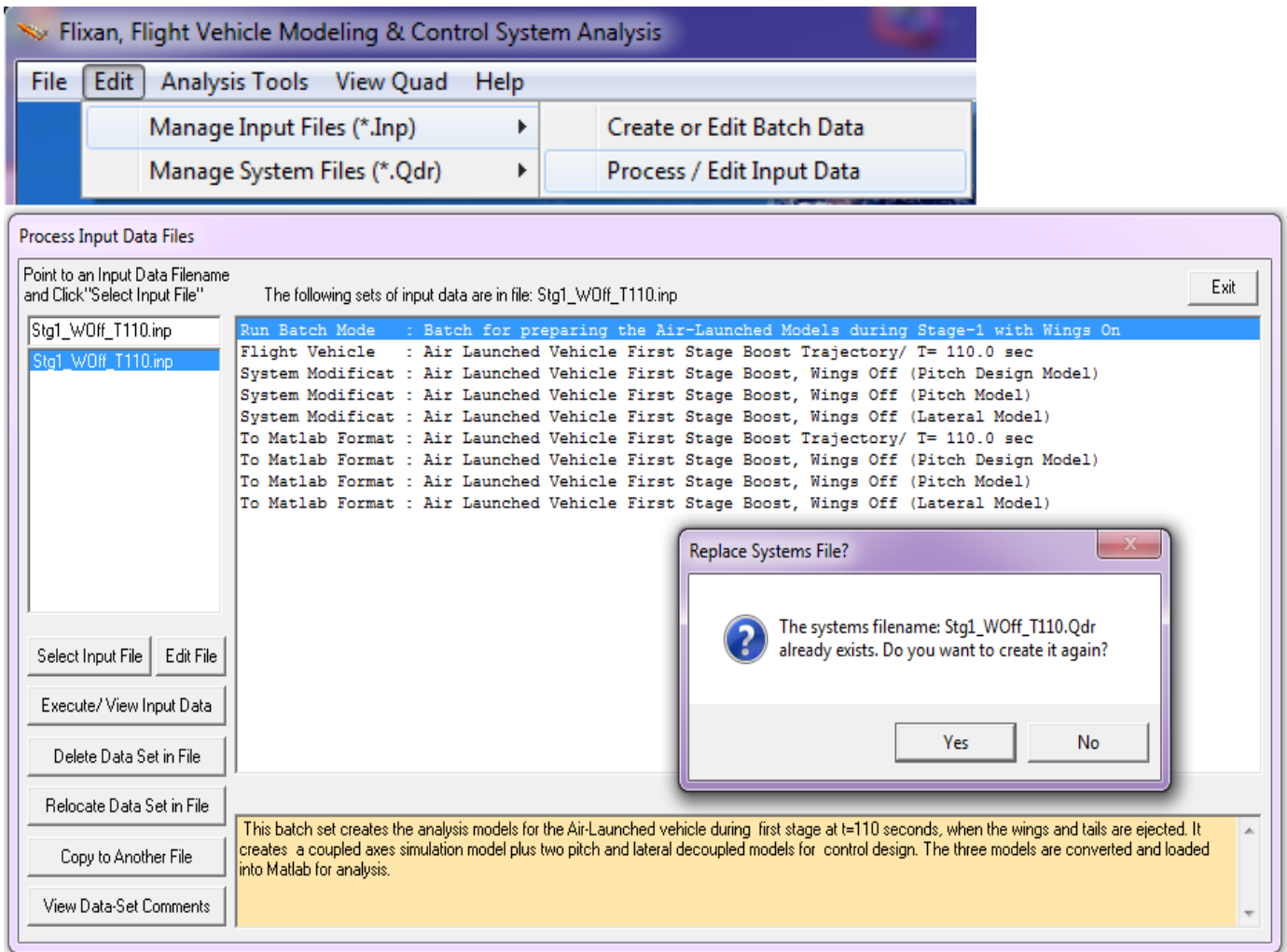
Control Design and Simulation Models

We will now use the models generated in the previous section to perform pitch and lateral control designs and create simulation models in Simulink. This is performed in subdirectory "*C:\Flixan\Trim\ Examples\Air Launched Vehicle\Phase C Boost No Wing\Mat_Anal*". The following script file "run.m" loads the 4 dynamic models and also the effector combination matrix Kmix4c. It also uses the reduced models to design LQR state-feedback gains for pitch and lateral.

```
% Air-Launched Rocket First Stage Analysis Script, No Wings & Tails
d2r=pi/180; r2d=180/pi;
[As, Bs, Cs, Ds] = vehicle;              % Load Big Simulation Model
[Apd,Bpd,Cpd,Dpd]= pitch_des;            % Load Pitch Design Model
[Ap, Bp, Cp, Dp] = pitch_ana;            % Load Pitch Simulation Model
[Al, Bl, Cl, Dl] = lateral;              % Load Lateral Design Model
load Kmix4c -ascii                       % Surfaces Scaling Matrix

% Pitch LQR Design Using
[Ap4,Bp4,Cp4,Dp4]= linmod('Pdes3x');     % 3-state model {thet,q,alfa}
R=5; R=diag(R);                          % Control LQR Weights
Q=[5.0 0.02 6]*5.0; Q=diag(Q);           % State LQR Weights
[Kq,s,e]=lqr(Ap4,Bp4,Q,R)                % Perform LQR design on Jets

% Lateral LQR Design Using
[Al5,Bl5,Cl5,Dl5]= linmod('Ldes5x');     % 5-state model {phi,p,r,bet,betint}
R=[2,1]*20; R=diag(R);                   % LQR Weights R=[3,1]*2
Q=[0.5 0.02 0.1 0.01 0.001]*5.0; Q=diag(Q);  % LQR Weights Q=[0.2 0.1 0.5 0.5 0.04]
[Kpr,s,e]=lqr(Al5,Bl5,Q,R)               % Perform LQR design on Jets
```

In the pitch axis the design model consists of three states (θ, q, and α), and Kq is (1x3) state-feedback matrix. The pitch state-feedback controller was slightly modified and adjusted for gamma tracking. A simple simulation model "*Sim_Pitch.mdl*" in Figure (3.2) is used to evaluate the pitch performance. Its response to a gamma command is expected to be slow because we are analyzing a Max-Q condition where the alpha-feedback loop is acting like a load-relief preventing against big changes in attitude.

The lateral control design is evaluated by means of a simple simulation model "*Sim_Lateral-Simple.Mdl*", shown in Figure (3.3). It is evaluated by its response to perform roll commands. Roll is performed by differential RCS jet throttling. These are analog signals for the time being, in this early evaluation model, rather than "on-off" devices. The reduced vehicle model "*Air Launched Vehicle First Stage Boost, Wings On (Lateral Model)*" from file "*lateral.m*" was used in the lateral control design. Its state-vector originally consisting of (phi, p, r, and β) was augmented by including one additional state, the integral of the sideslip angle (β-integral). This is done by linearizing (linmod) the Simulink model "*Ldes5x.Mdl*". The lateral flight control system is a (2x5) state-feedback matrix Kpr that was designed using the LQR method. This matrix converts the state-vector signals into roll and yaw acceleration demands (dP, dR)$_{FCS}$. The demands are then converted into TVC deflections and throttling commands by the matrix Kmix4c.
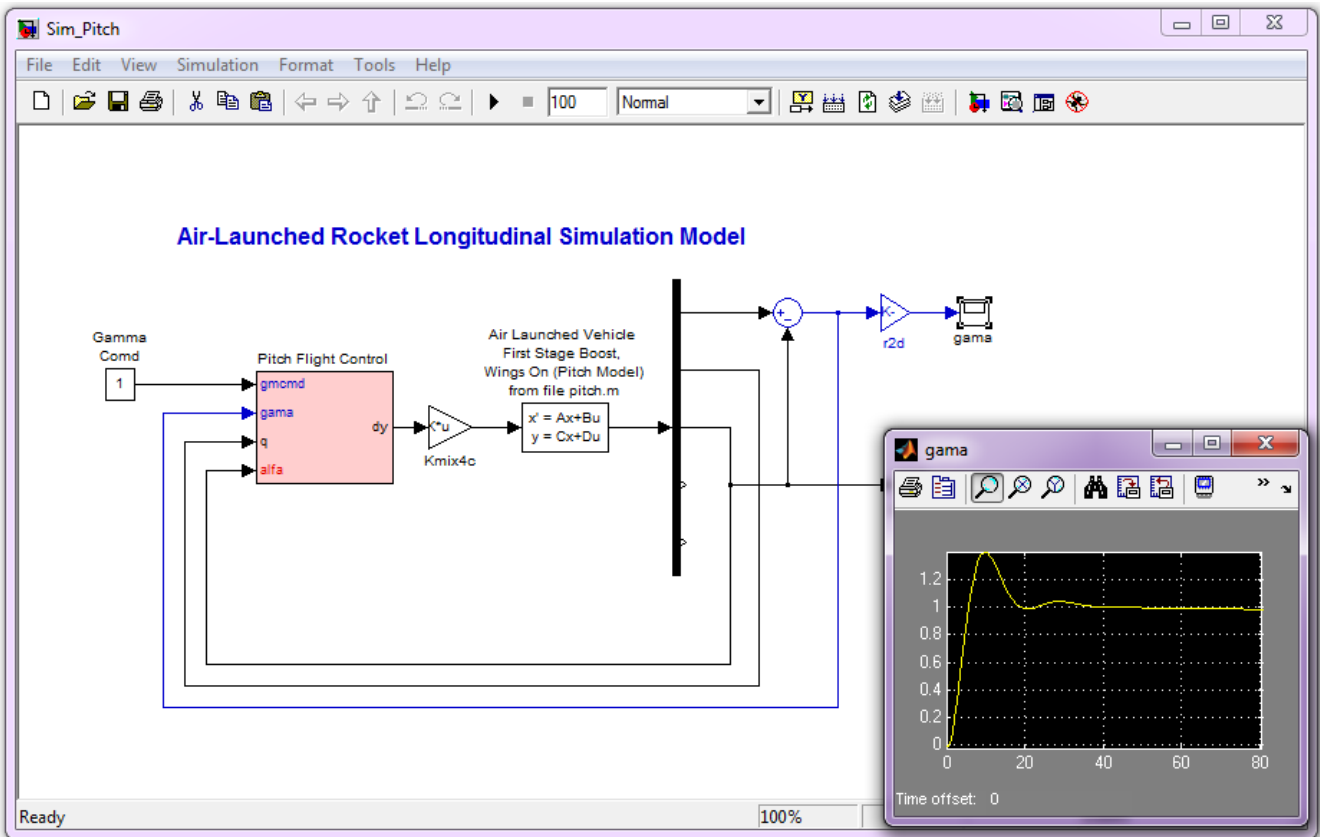
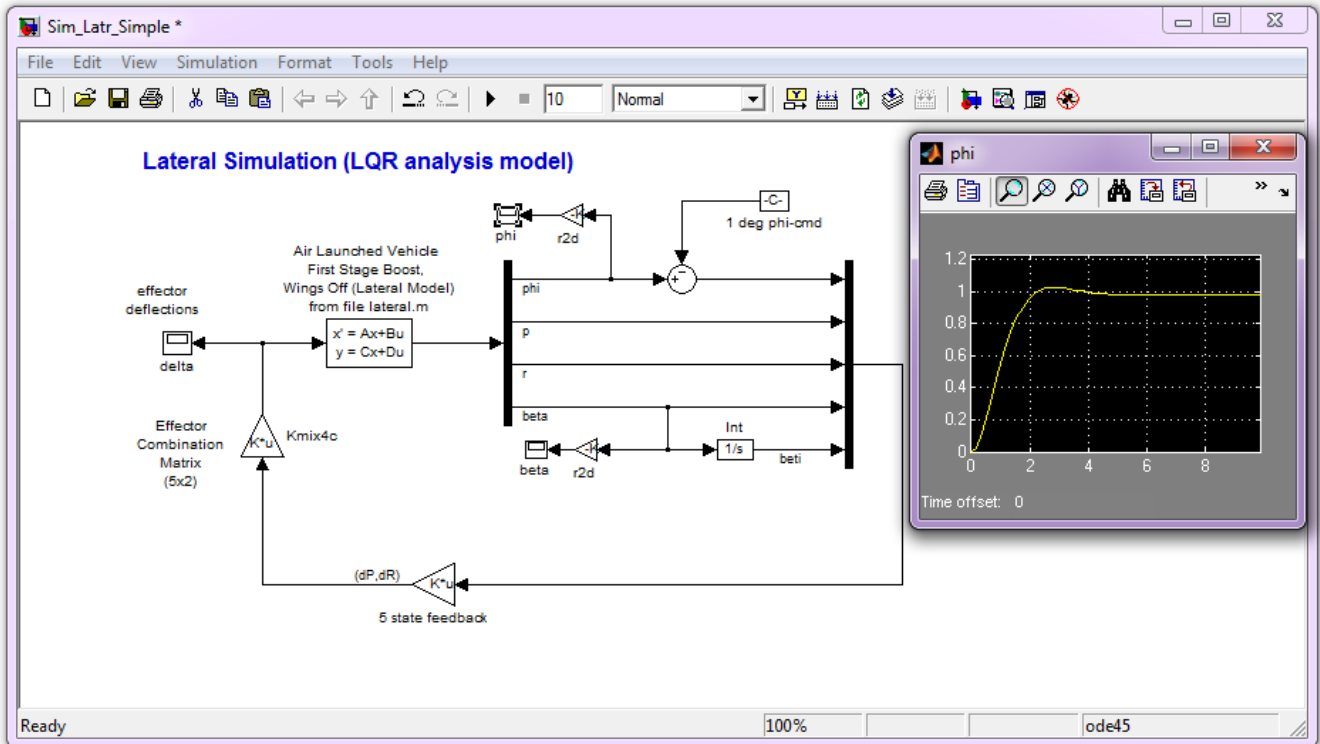**Figure 3.2 Pitch Axis Analysis Model in file "Sim_Pitch.mdl"**

Figure 4.3 Lateral Axis Analysis Model in file "Sim_Latr_Simple.mdl"

3-109

Our main simulation model for this Max-Q case without wings is in file: "*Sim_AL_Wing_Off.Mdl*",
shown in Figure (3.4a) below. It consists of the vehicle dynamics (green block) that is controlled by
three flight control loops: a pitch loop that controls the flight path angle (γ), a lateral control loop that
controls the bank angle (ϕ) and ultimately the cross-range position, and a speed control loop by
throttling the main engine. Simulation plots are generated automatically by the script file "pl.m"
when the execution is complete.

Air-Launched Rocket Simulation (Coupled Model)
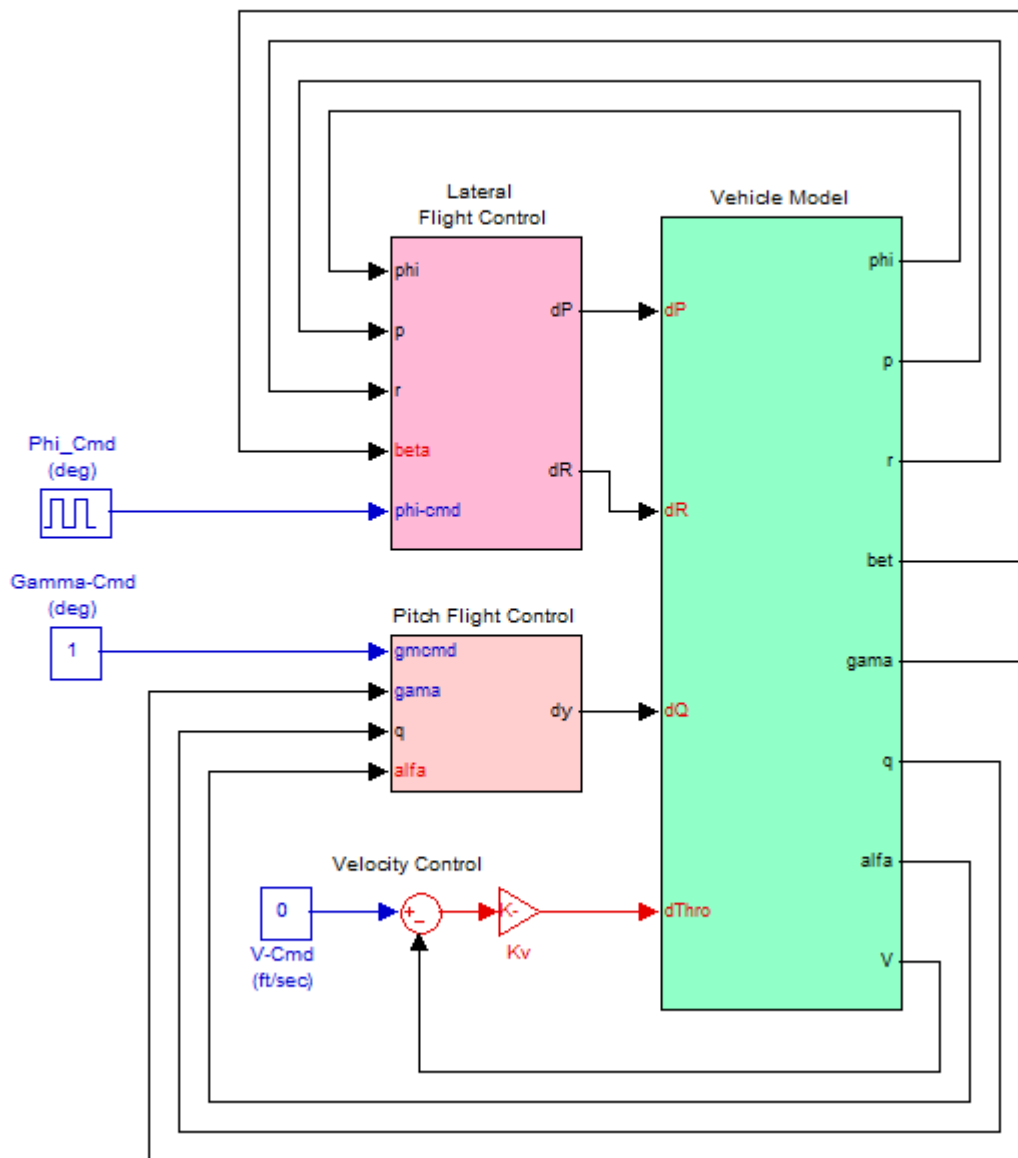
Figure 3.4a Simulation Model for First-Stage Without Wings and Tails, in File: "*Sim_AL_Wing_Off.Mdl*"

Figure (3.4b) shows the vehicle dynamic model. The model is based on the state-space system "*Air
Launched Vehicle First Stage Boost Trajectory/ T= 110.0 sec*" that is loaded from file "*vehicle.m*". The
inputs to the subsystem are roll, pitch, yaw, and axial acceleration demands from the FCS. The matrix
Kmix4c is inserted at its input to convert the FCS demands to effector commands. The effectors in this

phase are: pitch and yaw TVC deflections, throttle control for the main engine, and throttle control for the two RCS jets. There is also a gust input used as a disturbance. The direction of gust was set to excite both pitch and lateral directions and it is defined in the vehicle input data. The pitch control requirement in this vehicle is to track a pre-calculated flight path angle from a table, so the output from the model is gamma which is constructed by combining theta with alpha. The gamma control bandwidth, however, during High-Q is reduced because the vehicle is not expected to maneuver very much in order to avoid undesirable normal loads. The angles of attack and sideslip are not measured directly by the vehicle sensors and they must be estimated from the normal and lateral accelerometers.

Flight Vehicle Dynamics, Simulation Model
Air Launched Vehicle First Stage Boost Trajectory/ T= 110 sec

Inputs = 6
1 Engine No 1 Pitch Deflect. (rad), Dymax= 8 deg
2 Engine No 1 Yaw Deflect. (rad), Dzmax= 8 deg
3 Main Engine Throttle Input (dTh/Th)
4 Left RCS Throttle Input (dTh/Th)
5 Right RCS Throttle Input (dTh/Th)
6 Wind Gust Azim, Elev Angles=(45 90) (deg)

TVC

Mixing Logic

K*u
Kmix4c

Air Launched Vehicle
First Stage Boost Traject.
T= 110 sec
from file vehicle.m

$x' = Ax+Bu$
$y = Cx+Du$

pwm
In Ou
RCS
RCS

Clock   Time

Roll, Pitch, Yaw &
Axial Accelerat.
FCS Demands

Gust
30 (ft/sec)
0.2 Hz

Gust   Vel Gust (ft/sec)   Gust

Outputs = 14
1 Roll Attitude (phi-123) (radians)
2 Roll Rate   (p-body) (rad/sec)
3 Pitch Attitude (thet-123) (radians)
4 Pitch Rate   (q-body) (rad/sec)
5 Yaw Attitude (psi-123) (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 Accelerom # 1, (along X), (ft/sec^2) Translat. Acceler
13 Accelerom # 2, (along Y), (ft/sec^2) Translat. Acceler
14 Accelerom # 3, (along Z), (ft/sec^2) Translat. Acceler

Figure 3.4b Vehicle Dynamics Subsystem

The two RCS jets in the simulation model are "on-off" devices and they do not provide a continuous thrust. Analog thrusters are a lot more costly to build and "on-off" jets are often preferred. Unlike the simple lateral simulation model which was used to evaluate the control gains design, and it assumes that the RCS signals are analog, in this simulation model the two RCS control signals (left and right) coming out of the mixing-logic matrix are discretized. A pulse-width-modulator device is used to convert the analog signal (varying between -1 and +1) to a PWM signal that triggers jet firing in the

positive or in the negative z-direction. Each input represents a pair of back-to-back firing jets that can be activated via the LQR derived control logic.

Figure (3.4c) shows the PWM block that converts the analog RCS throttle command signals to "on-off" jet firing. By modulating the jets, essentially it produces an average force equal to the commanded force coming out of the mixing-logic matrix. This allows us to use the same LQR state-feedback gains that were developed for a continuous system.
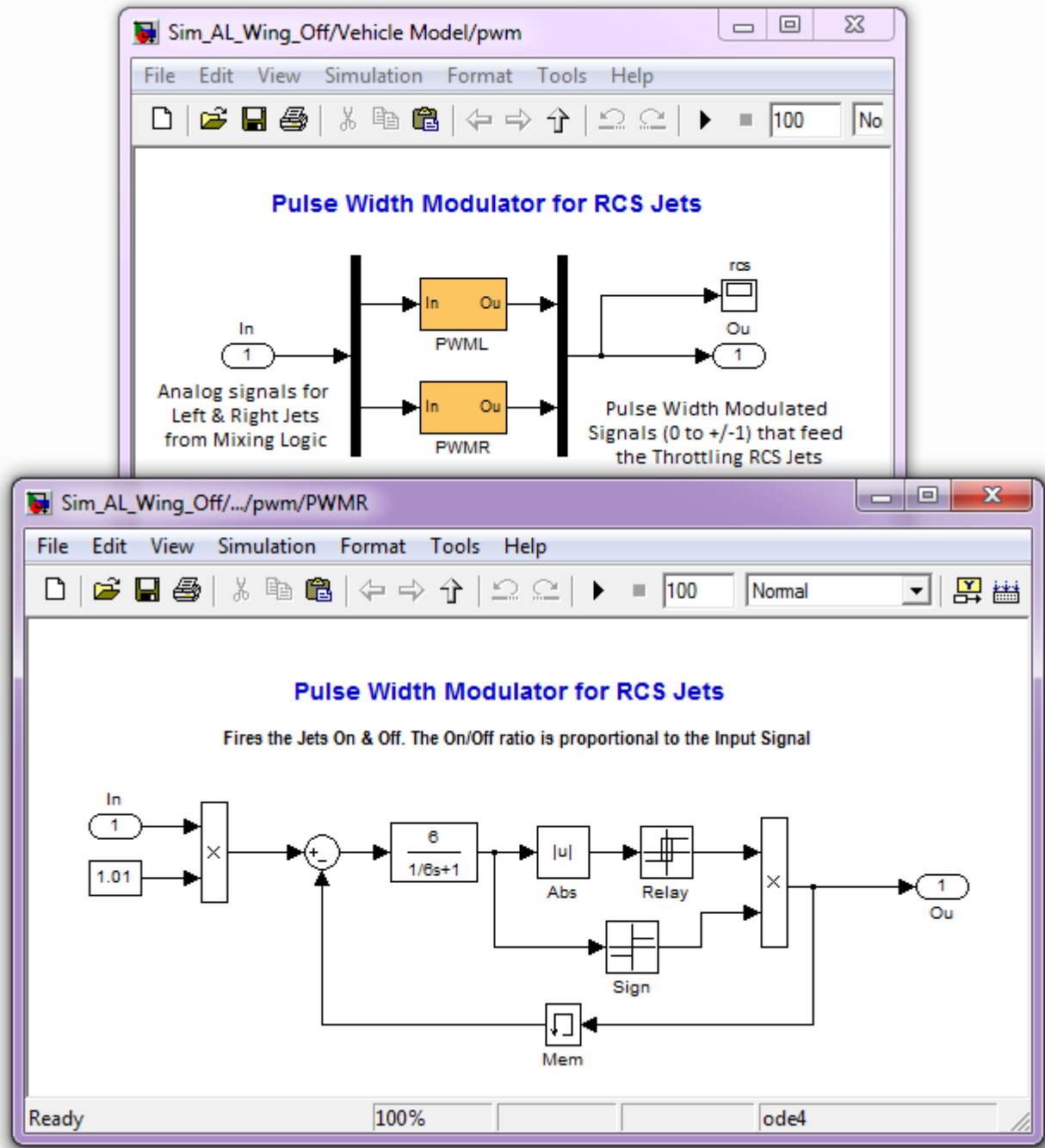

Figure 3.4c PWM Block Produces a Jet Force Equal to the Commanded Force by Modulating the Jet Firings

The next two plots show the lateral and longitudinal flight control systems used in the simulation. They were derived by using the LQR method, as already described.

Lateral Flight Control System
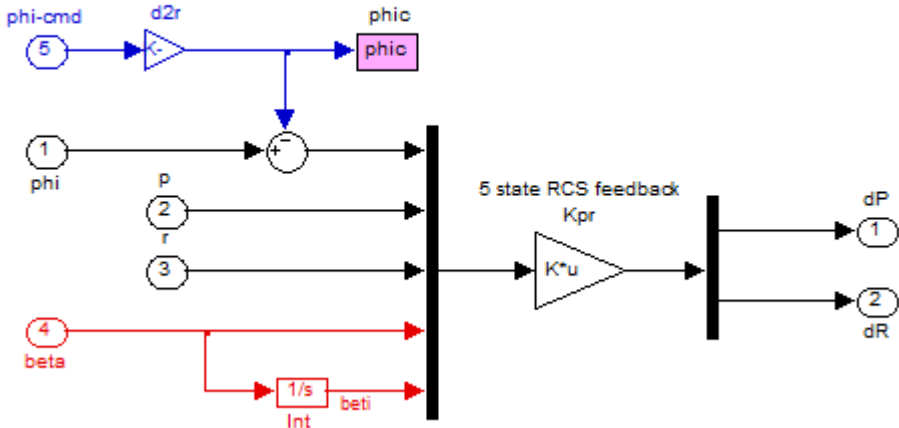
Figure 3.4d Lateral State-Feedback Control System

Flight Path Angle Tracking Dystem
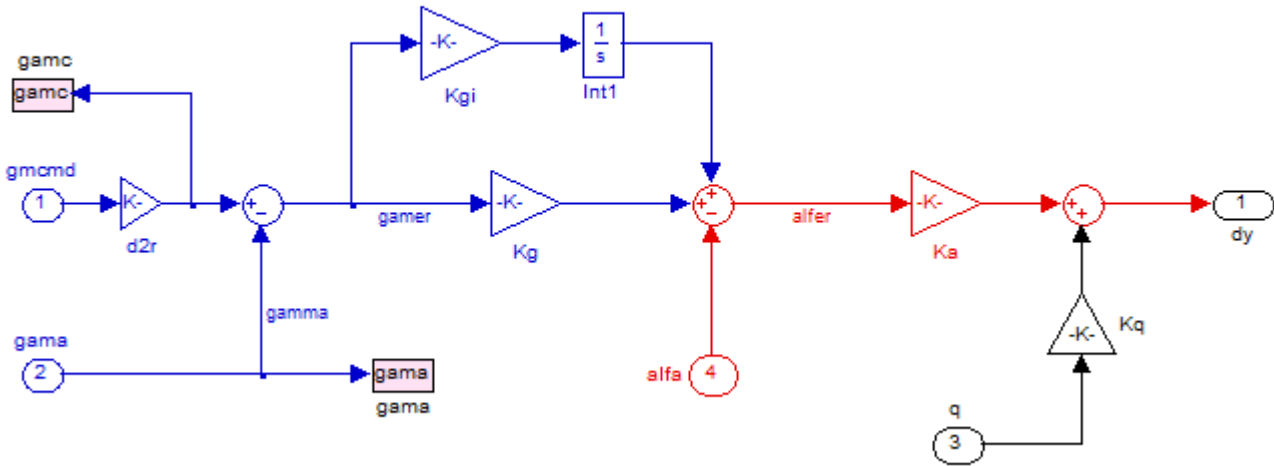
Figure 3.4e Longitudinal Gamma-Tracking Control System

Simulation Results

The simulation model in Figure (3.4) can be excited from guidance command signals. They are step input commands of changes in gamma, phi, and velocity. It can also be excited by wind gusts and turbulence. The wind-gust direction is perpendicular to the vehicle x-axis and skewed at 45° between the +y and +z axes, as it is defined in the vehicle input data file. We will use this Simulink model to calculate the vehicle responses to various types of excitations.

Phi-command Simulation

First, a phi$_{-command}$= 4° is applied to the simulation model with all other inputs set to zero. The command is applied for 20 seconds and it is returned to zero, as shown below.

3-114
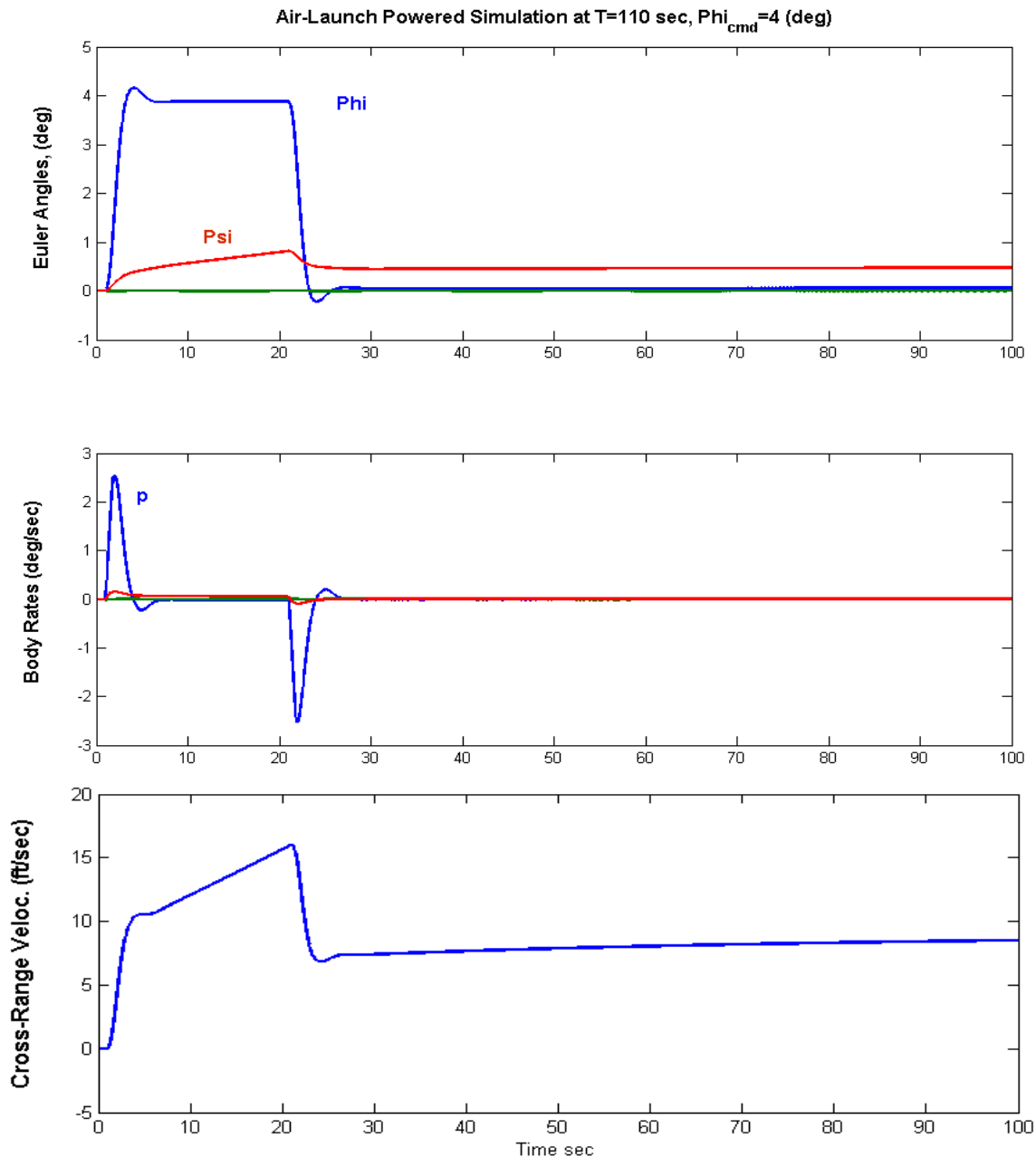
The bank angle responds to the command and the yaw attitude begins to drift due to the steady turn. It stops drifting when the bank angle returns to zero. The cross-range velocity also increases due to banking. Banking is used by guidance as a means to control the flight direction and the cross-range velocity. Notice that the roll controls are not continuous signals. Rolling torque is provided by the two "on-off", left and right RCS thrusters, which are the blue and green pulses respectively. They are firing differentially and the signals are PW modulated to provide an average acceleration equal to the commanded acceleration. The signal amplitudes do not represent their actual thrusts, but the maximum throttling amplitude of the jets, that corresponds to ±500 (lb). Notice that the non-linearity introduces a limit-cycle in roll.
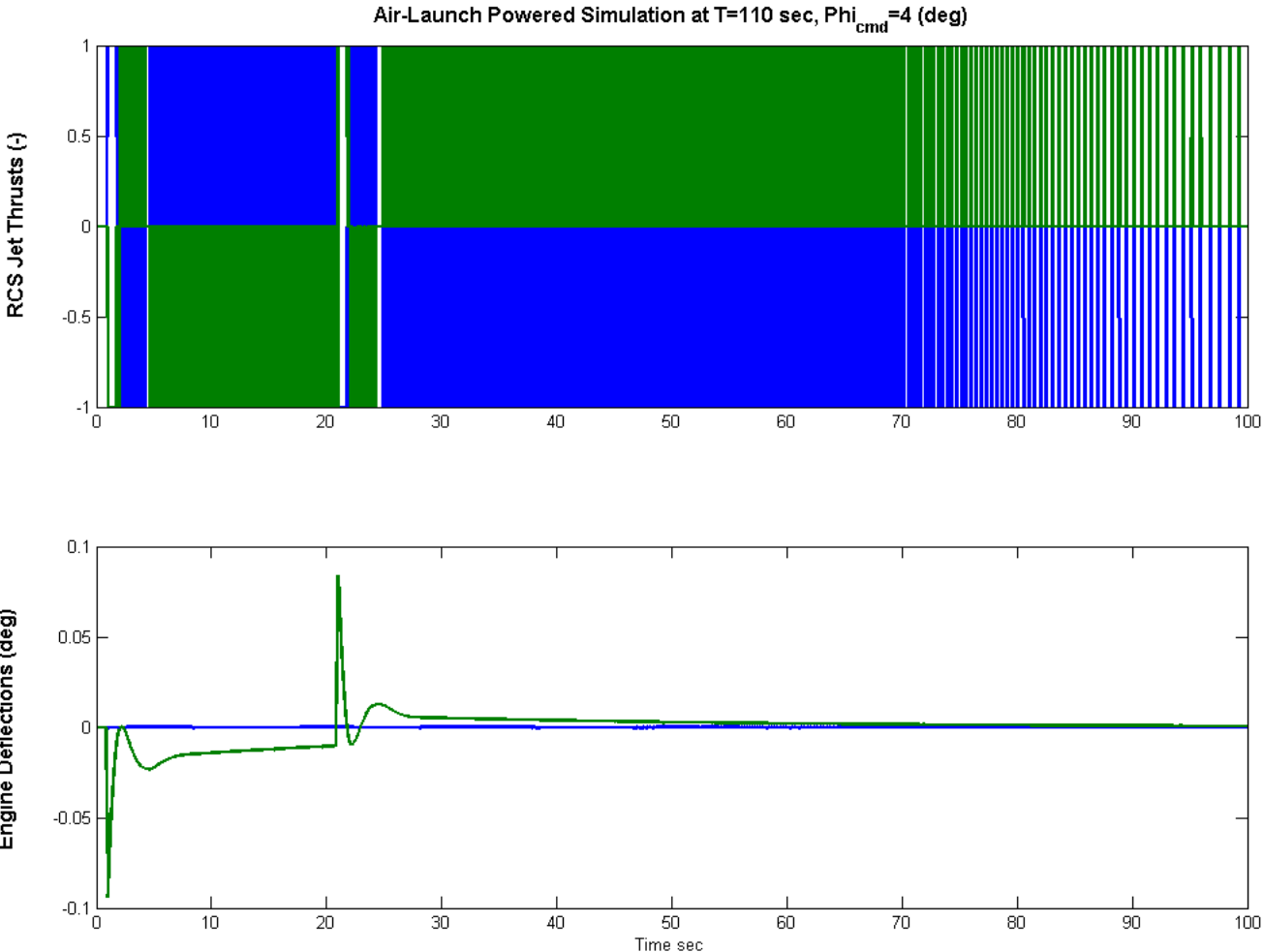
Wind-Gust Simulation

We can study this roll limit-cycle better by introducing a wind-gust disturbance pulse with all other inputs set to zero. The gust velocity amplitude is 45 (ft/sec) skewed to excite all directions.

Air-Launch Powered Simulation at T=110 sec, Wind-Gust=45 (ft/sec)
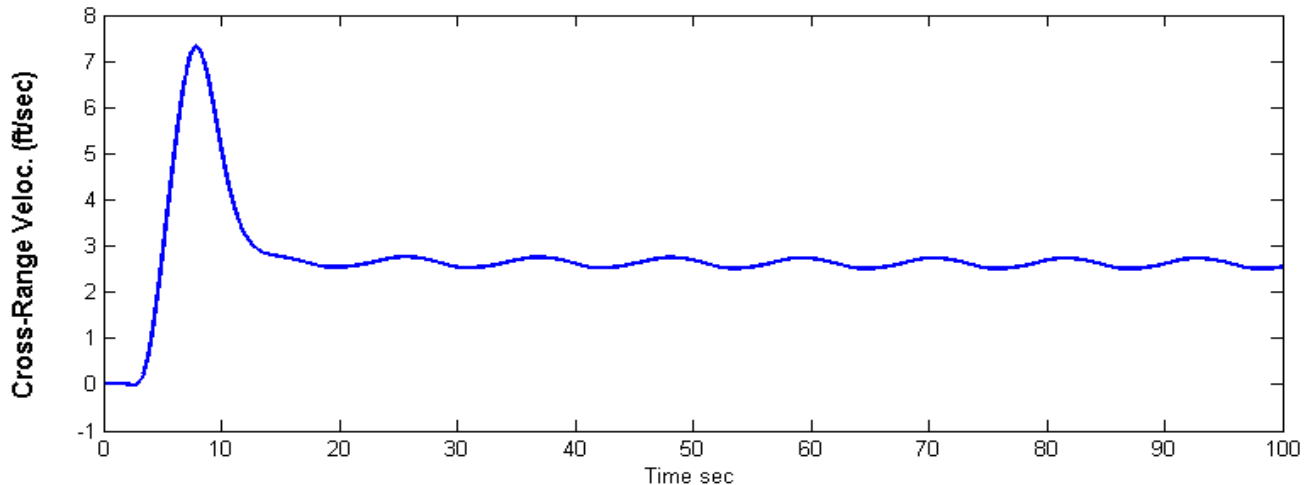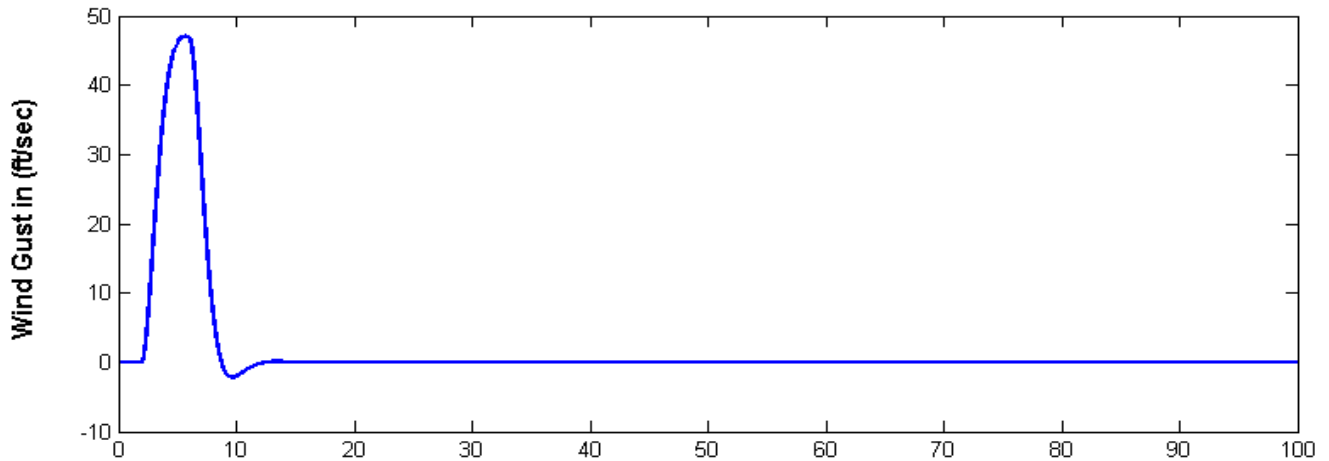
Notice how the RCS jets are throttling differentially to counteract the rolling motion created by the gust-disturbance. Then a roll limit-cycle is excited and it persists, as expected, because of the non-linearity. Its amplitude, however, is reasonably small, only 0.06°. The wind-gust also excites variables in the pitch direction, such as, theta, q, alpha, and NZ. They are attenuated by the pitch FCS using the main engine TVC.

Air-Launch Powered Simulation at T=110 sec, Wind-Gust=45 (ft/sec)

Roll Limit-Cycle= 0.06 (deg)

3-117
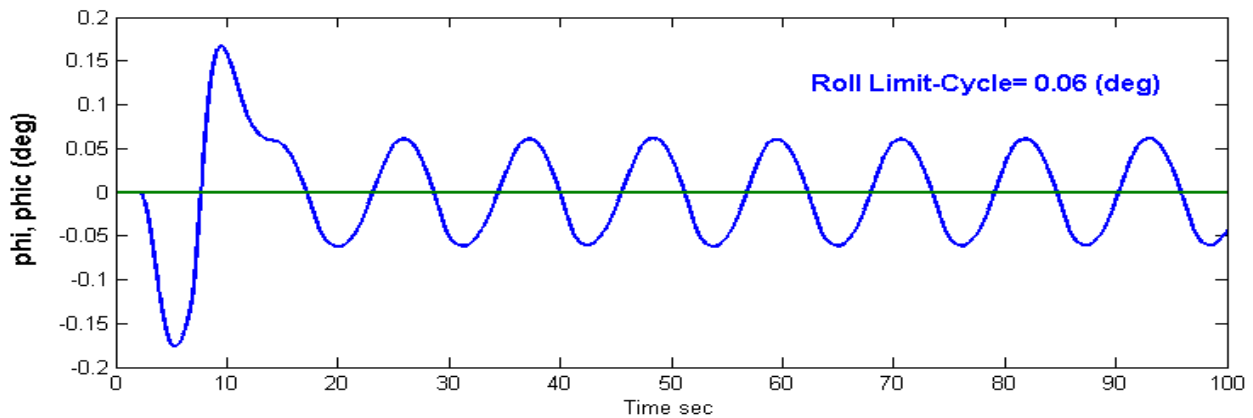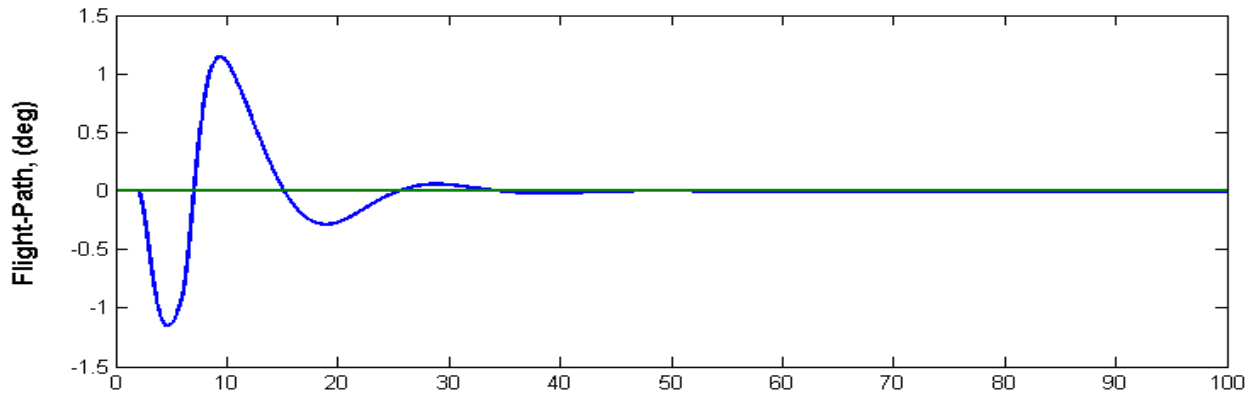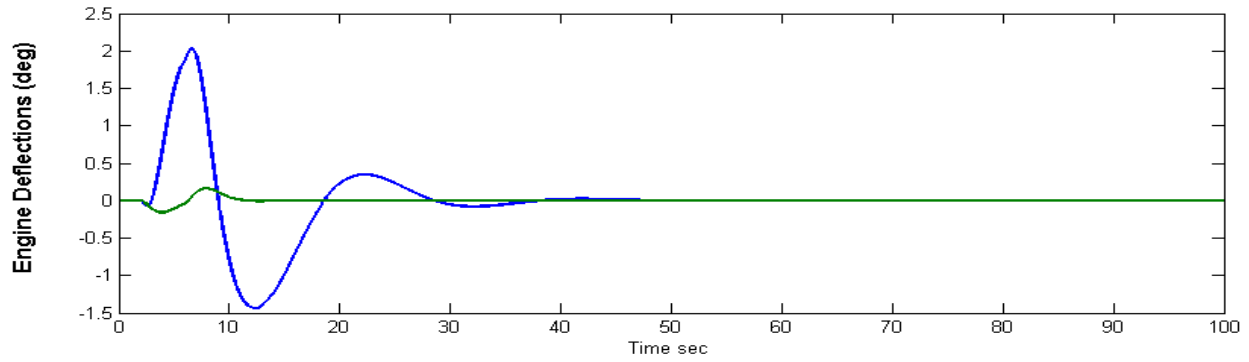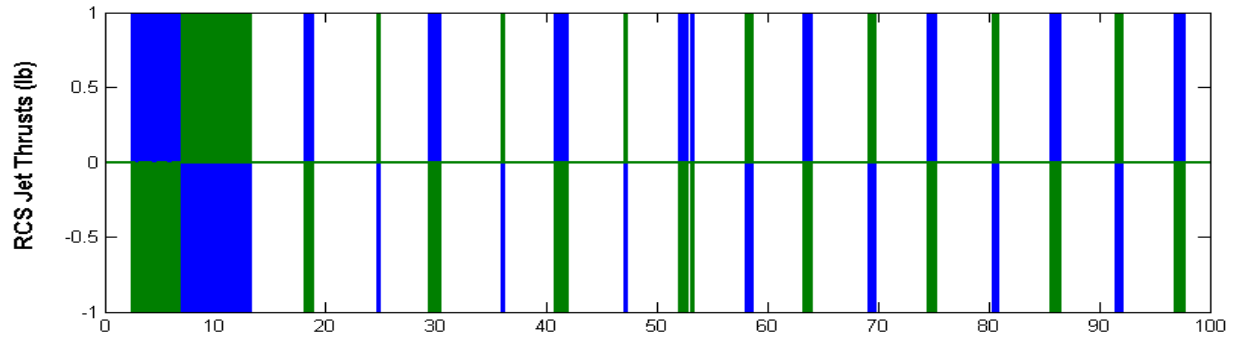
**Air-Launch Powered Simulation at T=110 sec, Wind-Gust=45 (ft/sec)**
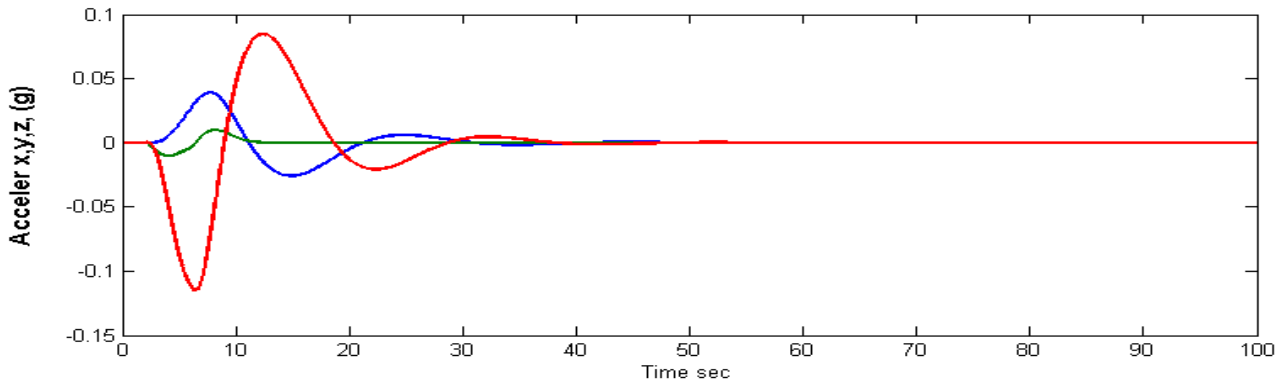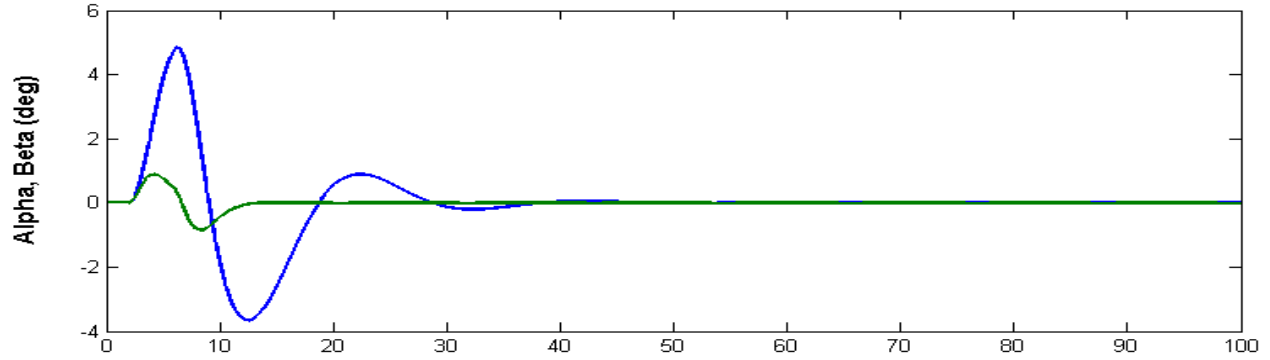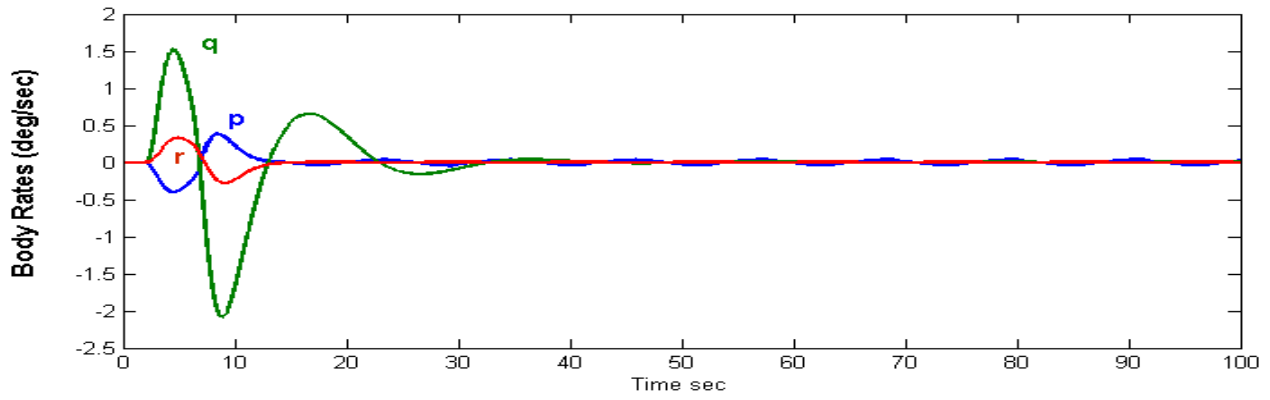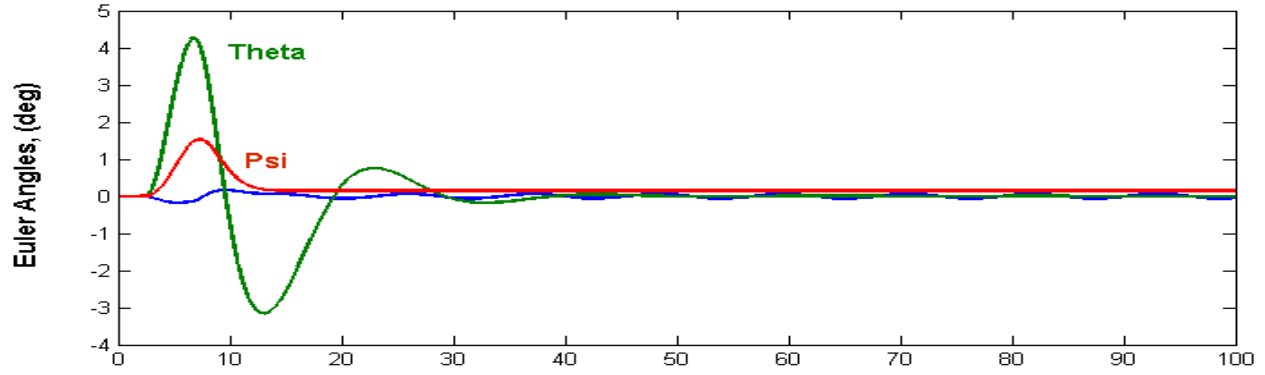
Change in Velocity Simulation

Now the simulation model is commanded to increase its velocity by 10 (ft/sec). This causes a brief positive throttle up, a transient in the acceleration, and a steady increase in altitude.

Air-Launch Stage-1 Simulation at T=110 sec, No Wings, dV_{cmd}=10 (ft/sec)
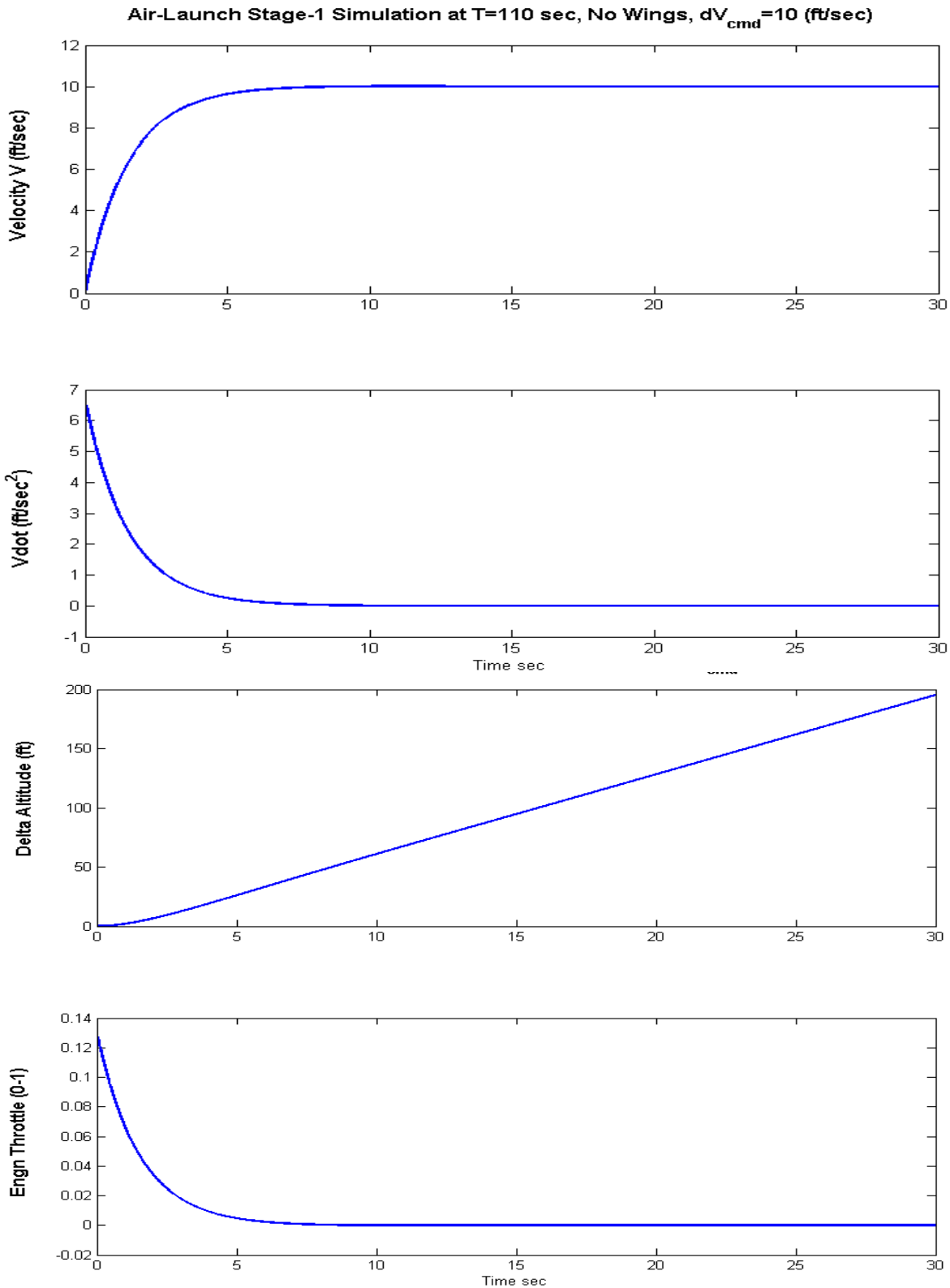
It also causes a drop in alpha in order to prevent an increase in gamma. Notice, the excitation did not affect the lateral axes and the RCS jets.
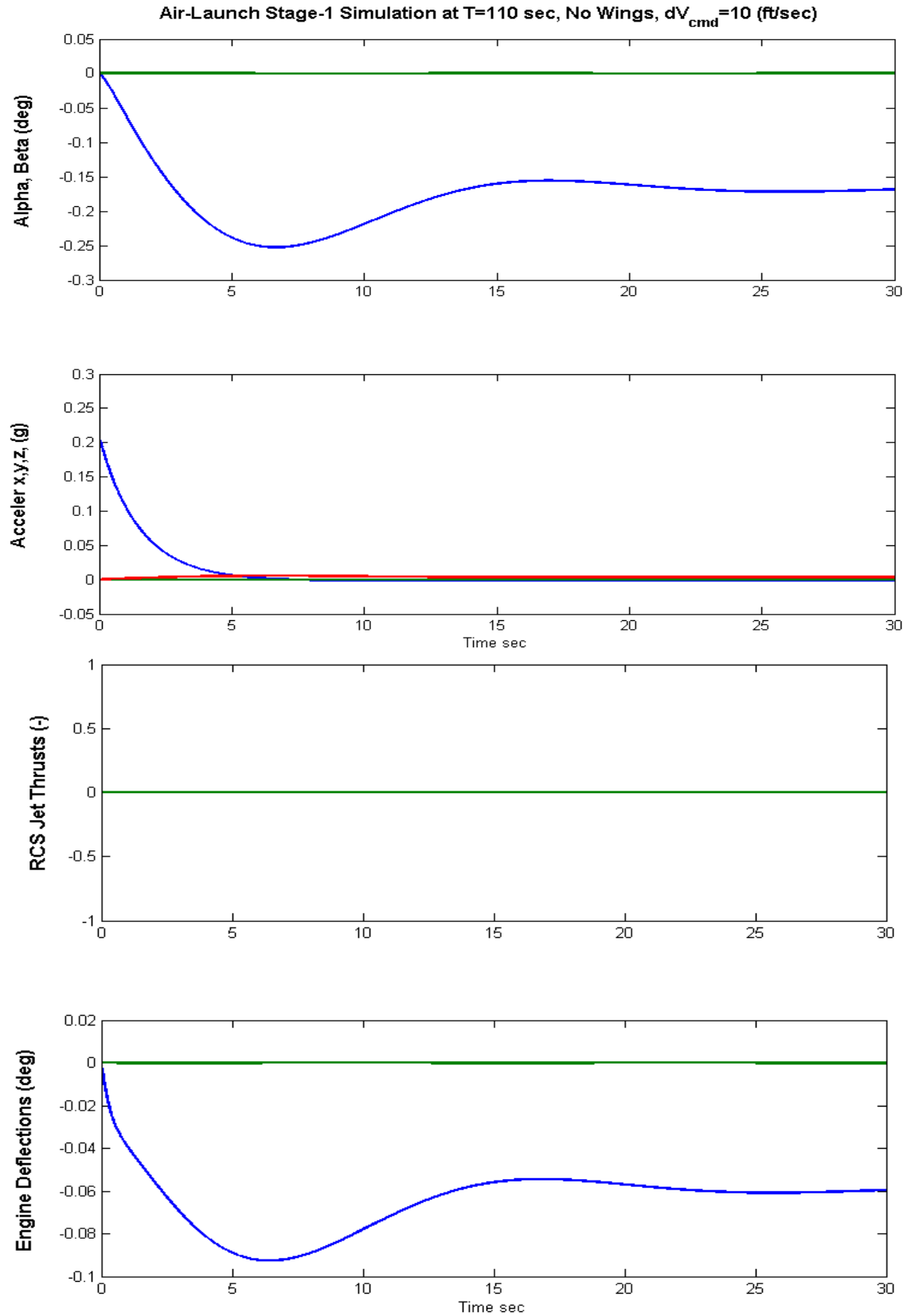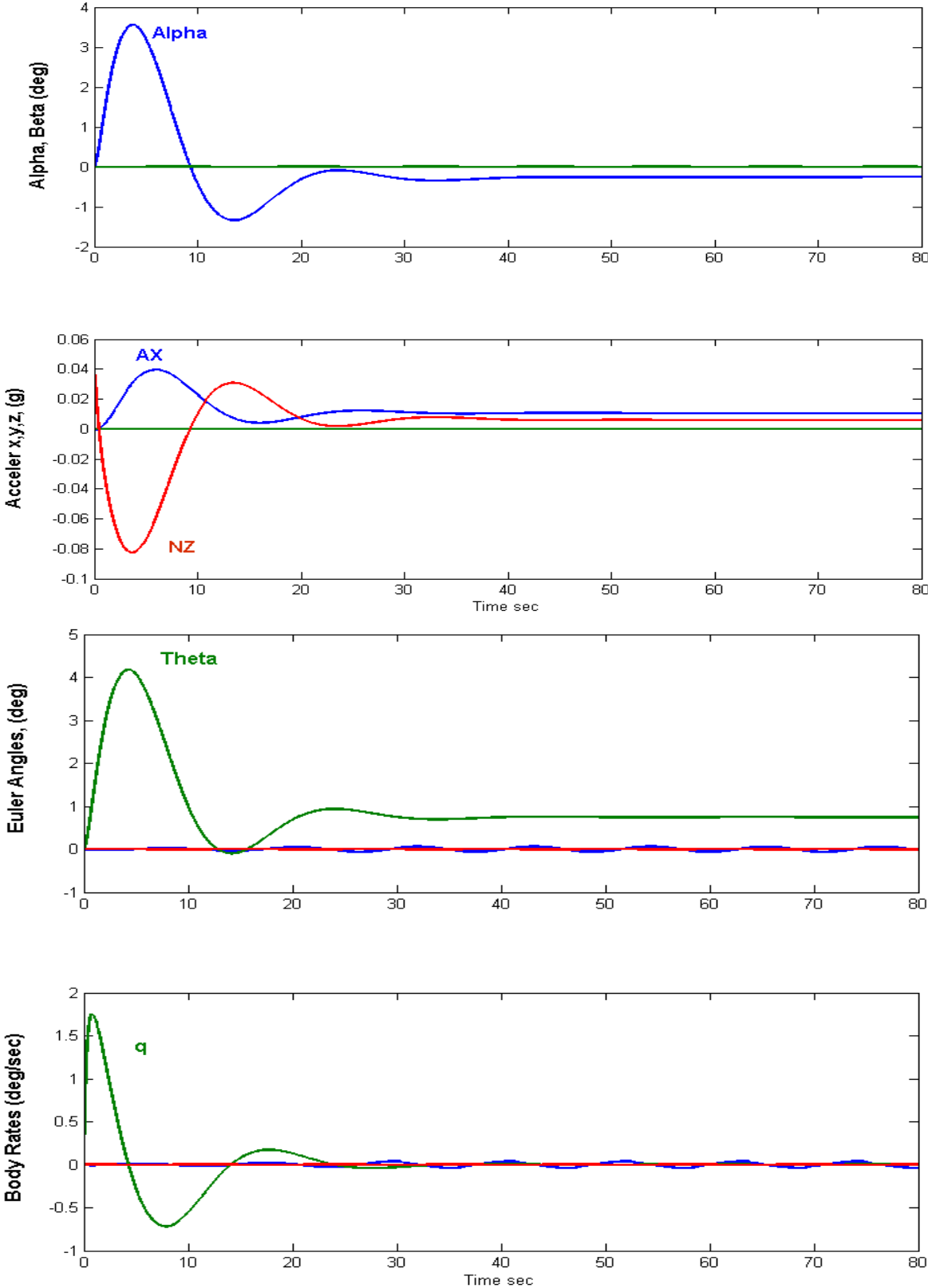
Air-Launch Stage-1 Simulation at T=110 sec, No Wings, dV$_{cmd}$=10 (ft/sec)

Gamma-Command Simulation

In this case the simulation model is commanded to increase its flight-path angle gamma by one degree from steady-state. All other commands and excitations are set to zero. The bandwidth of the gamma control loop is reduced in this case because of the Max-Q. The alpha-feedback is acting like a load-relief and it is slowing the response. The vehicle is not expected to maneuver at Max-Q. Notice how the roll axis is slowly beginning to diverge until the roll RCS thrusters kick-in and they saturate the divergence to a 0.06° limit-cycle.

Air-Launch Stage-1 Simulation at T=110 sec, No Wings, Gamma$_{cmd}$=1 (deg)
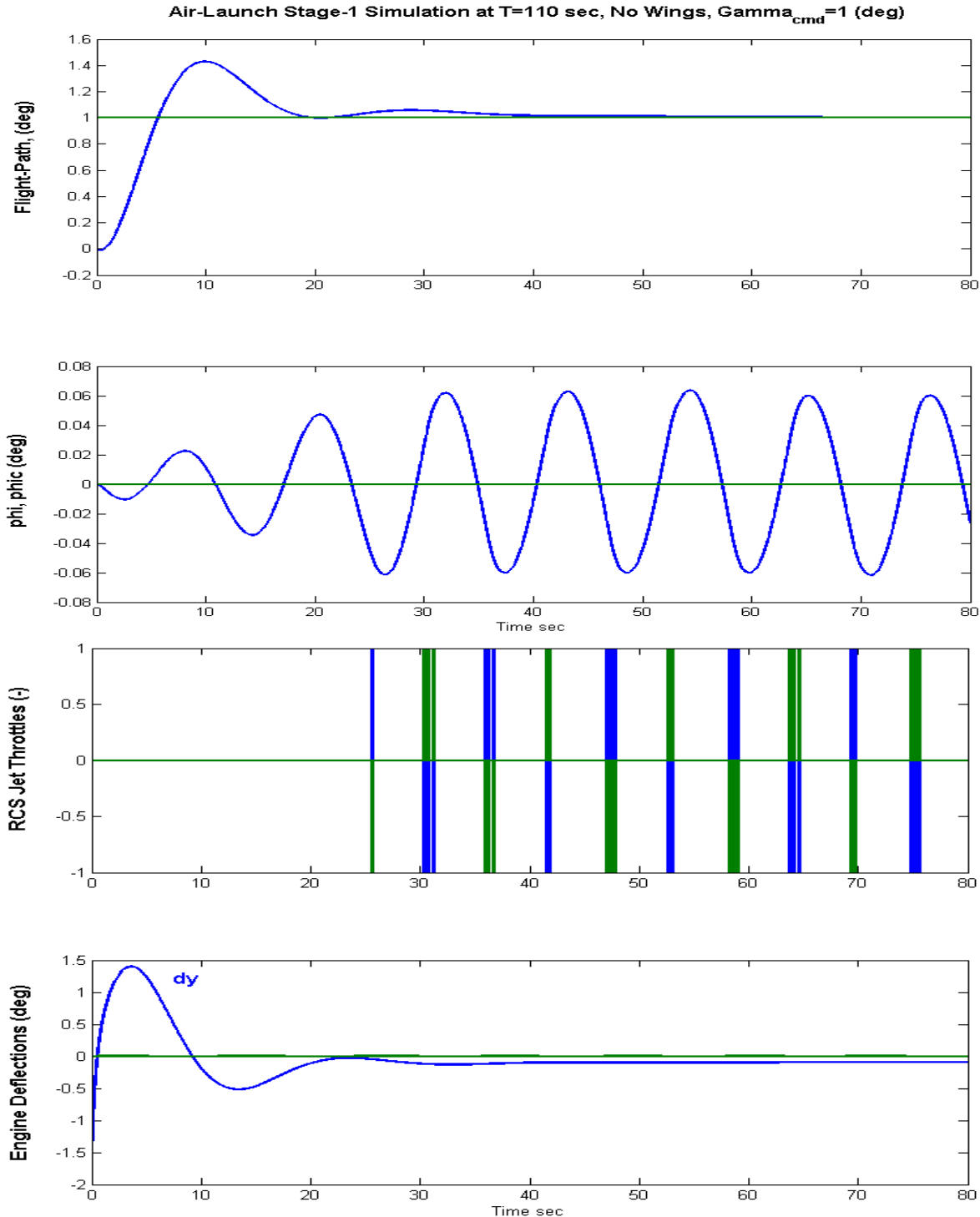
The command also causes a positive alpha, a steady increase in altitude and a drop in velocity that is compensated by throttling up. The TVC briefly deflects in the negative direction to cause the pitch-up, and it gradually decays to its trim position.

Air-Launch Stage-1 Simulation at T=110 sec, No Wings, Gamma$_{cmd}$=1 (deg)

Air-Launch Stage-1 Simulation at T=110 sec, No Wings, Gamma$_{cmd}$=1 (deg)