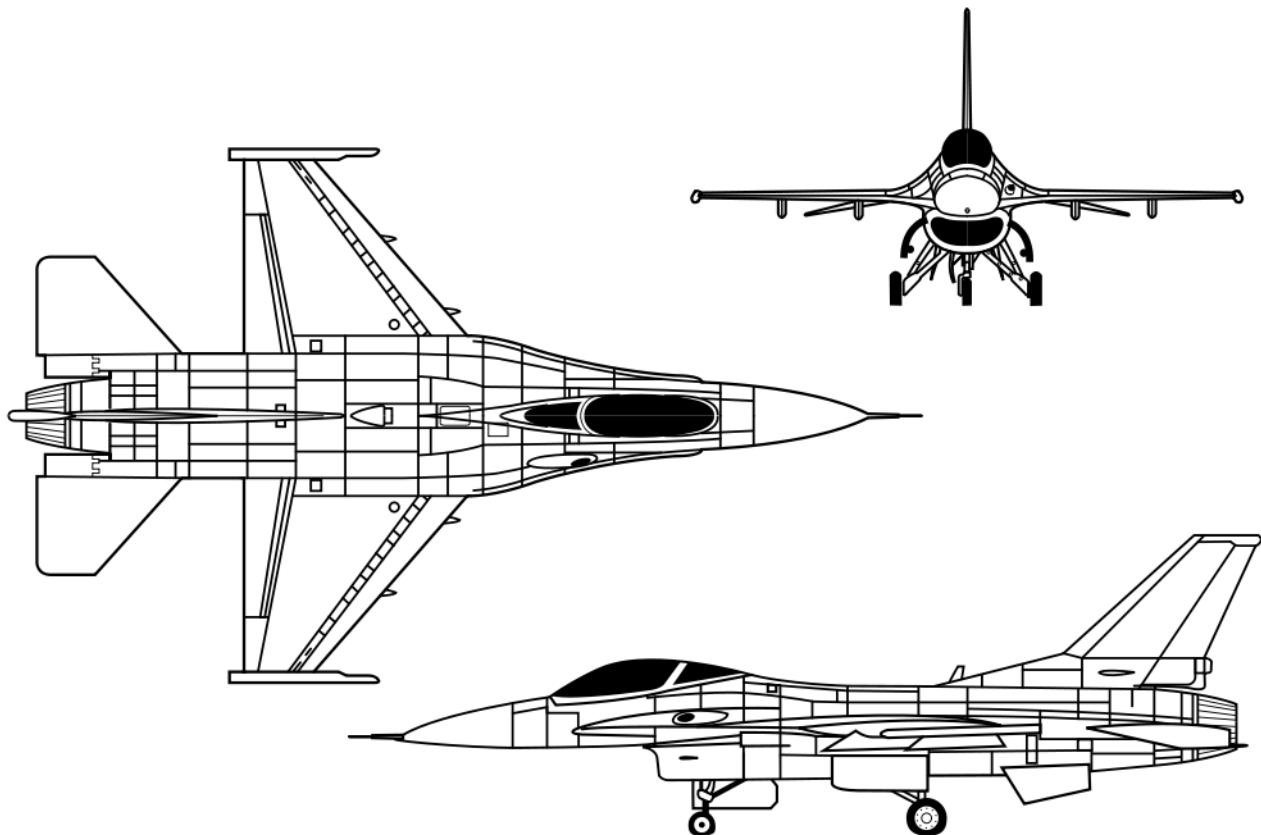


F-16 Fighter Aircraft



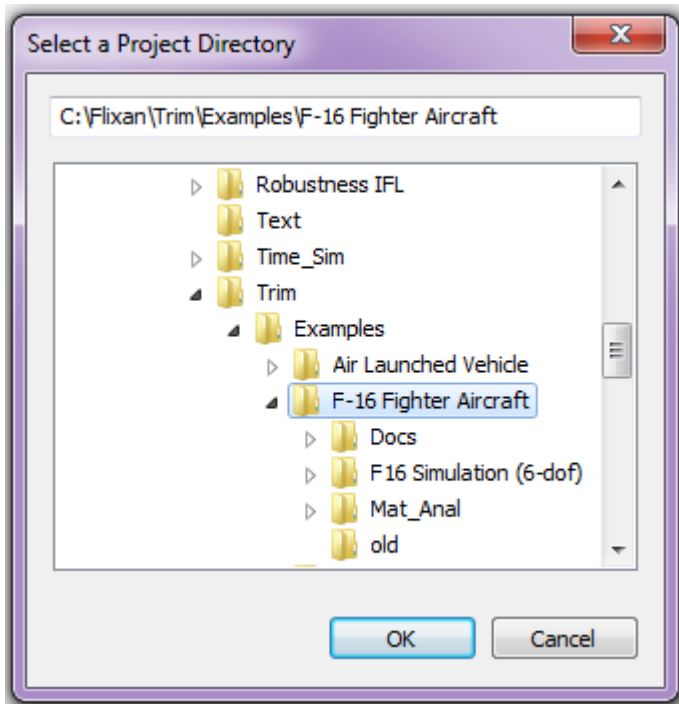
In the following example we will use the Trim program to analyze stability and performance of the F-16 fighter aircraft in various flight conditions along a couple of trajectories from take-off to landing. The aircraft has a single engine with a thrust that can vary from zero to 28,000 (lb). It is controlled by three aero-surfaces: an Elevon, an Aileron and a Rudder. The aerodynamic and mass-properties data were obtained from Brian L. Stevens and Frank L. Lewis book "Aircraft Control and Simulation". The trajectories perform several types of maneuvers in various speeds, angles of attack, and bank angles. We will use the Trim program to evaluate vehicle performance, trim-ability, stability, and maneuverability along two trajectories. We will also use the Flixan vehicle modeling program to create dynamic models in different flight conditions that will be used for flight control system design and analysis. Then we will design state-feedback control laws for a range of angles of attack and dynamic pressures. The analysis will be completed by creating a non-linear 6-dof simulation in Matlab/Simulink, which uses the control laws by interpolating the gains as a function of alpha and dynamic pressure.

The files for the F-16 analysis example have already been created in the proper format and they are saved in directory "C:\Flixan\Trim\Examples\F-16 Fighter Aircraft". There are two trajectory files there. The first trajectory is in "Roll_Pitch_Man.Traj", where the aircraft takes-off, reaches level flight, performs a 180° roll flip, then a 180° pitch maneuver, and it descends to land. The second trajectory is in file "Circle_Man.Traj", where the aircraft takes-off, reaches level flight, banks 40° to the right, maintains a steady and coordinated turn for a few minutes, and then it descends to land. The file "F16.Engn" contains the engine parameters. The engine is defined as throttling with 15,000 (lb) nominal thrust, but it can throttle up and down $\pm 97\%$ from nominal. It is not gimbaling and the thrust direction is perfectly aligned with the vehicle x axis. The engine mass, inertia, and moment arm parameters do not apply in this case because the engine does not gimbal. The aero coefficients for the base vehicle are in file "F16.Aero". The data were created at 3 Mach numbers, 5 angles of sideslip (β), and 51 angles of attack (α). The coefficient increments for the 3 aero-surfaces are in file "F16.Delt". They are created for the same numbers of Mach, alpha, and beta, and for 18 surface deflections from zero. The damping derivatives are in "F16.Damp", and they correspond to the same Mach numbers and alphas as the basic coefficients data. The mass properties are in file "F16.Mass" which contains two sets of data: a heavy set and a light set. The mass properties data should always be in descending weight order. There are no hinge moment and aero uncertainties data in this example.

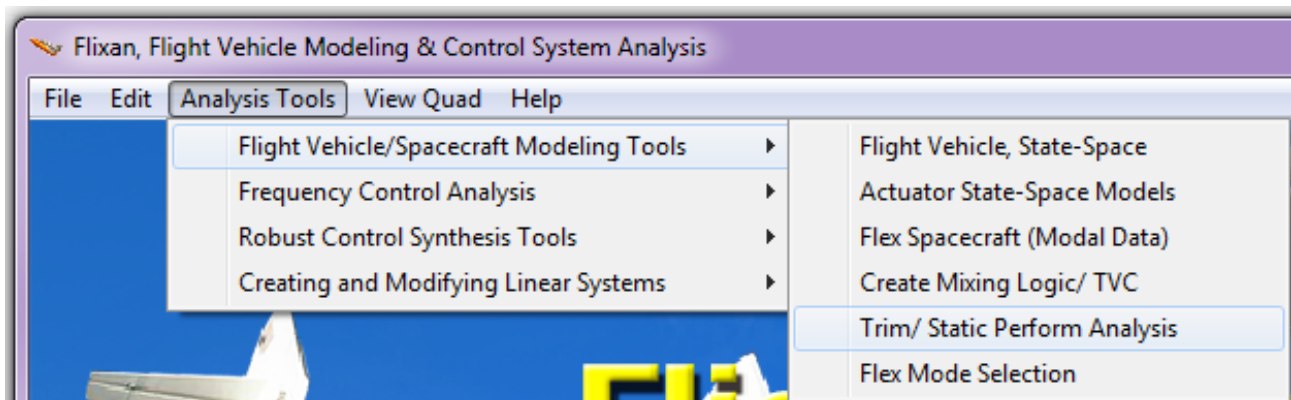


1. Plotting the Aero Data

Let us begin the Flixan program by choosing the project folder that contains the F16 data and selecting the appropriate files, as shown.



From the Flixan main menu select "Analysis Tools" then from the drop-down menu select "Flight Vehicle/ Spacecraft Modeling Tools" and from the menu on the right choose "Trim/ Static Performance Analysis", as shown below. Then from the Trim filename selection menu choose the F16 data files described earlier, and from the (.Inp) and (.Qdr) filename selection menu choose the default files, as shown, because we don't need those yet.



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 F16.Mass	Surface Hinge Moments NO DATA FILE
Trajectory Data Roll_Pitch_Man.Tra	Aero Damping Derivat F16.Damp
Basic Aero Data F16.Aero	Propulsion Data F16.Engn
Contr Surface Aero Coeff F16.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) NewFile.Qdr NewFile.qdr NewFile.Qdr
---	--

Create New Input Set Exit Program Select Files

Main Trim Menu

Select one of the following options

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)

Exit OK

The Trim main menu comes up showing the 12 options available in the Trim program. Select the first option to take a look at the aero data before beginning the analysis to make sure they were properly read. From the following menu select the vehicle mass, Mach number, alpha, and beta, as shown.

Select the following parameters

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

Vehicle Mass (slug)	Mach Number	Angle of Attack (deg)	Angle of Sideslip (deg)
636.86	0.5000	10.0	0.00
823.00	0.2000	2.00	-12.0
636.86	0.5000	3.00	-5.00
	0.8000	4.00	0.00
		5.00	5.00
		6.00	12.0
		7.00	
		8.00	
		9.00	
		10.0	

Select

The menu below shows the various aero-data plotting options in Trim, which are longitudinal aero coefficients and their derivatives versus alpha, lateral aero coefficients and their derivatives versus beta, and aero-surface increment coefficients versus surface deflections, plus their derivatives.

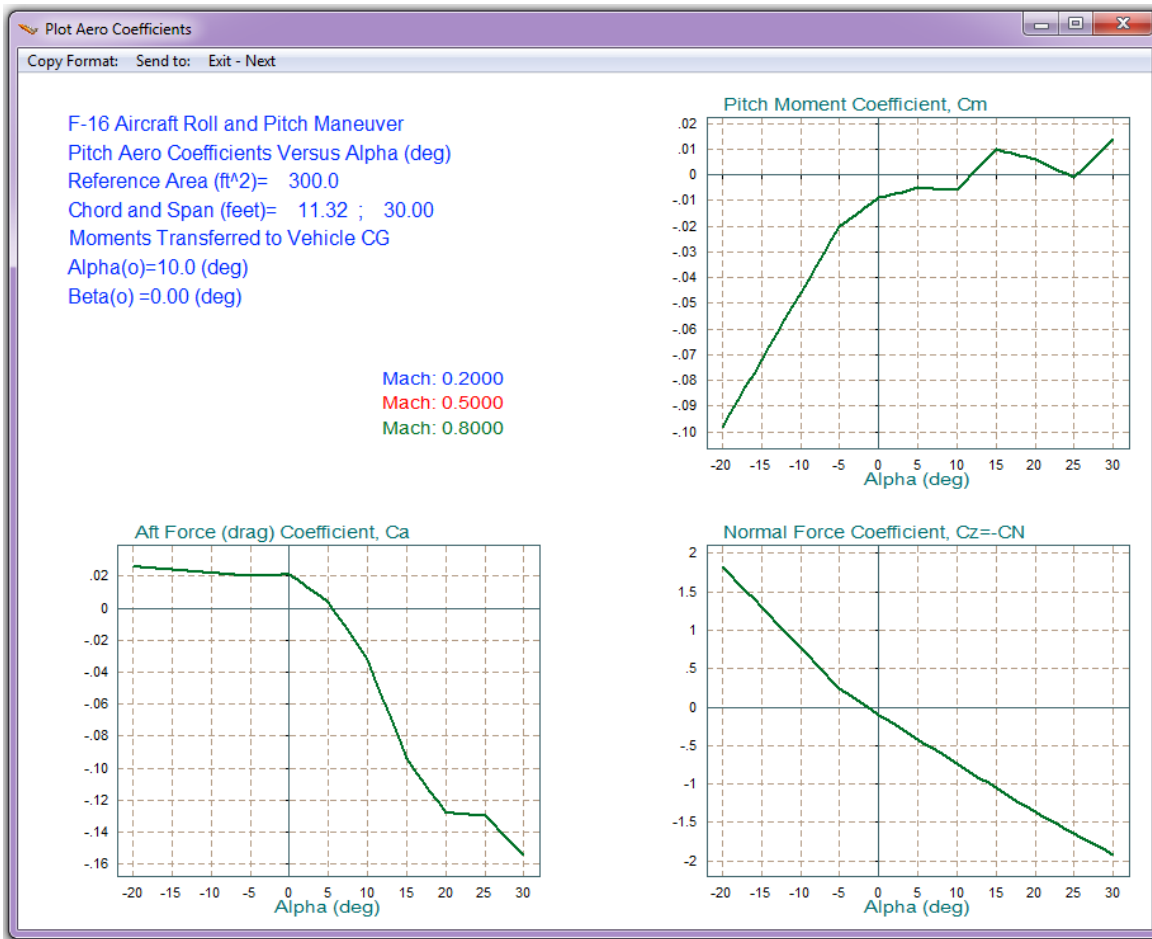
Plot Aero Coefficients and Derivatives

Plot the Pitch or Lateral Aero Coefficients and Derivatives Versus the Angles of Attack, Sideslip, or Surface Deflection in (degrees)

OK Exit

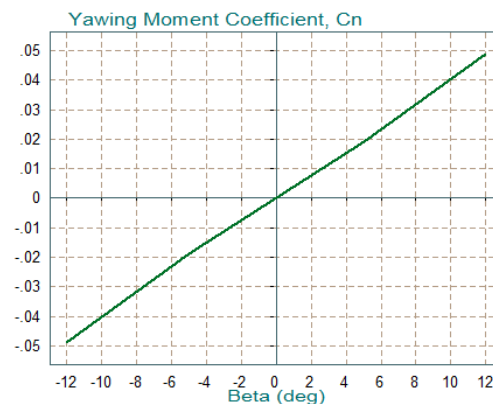
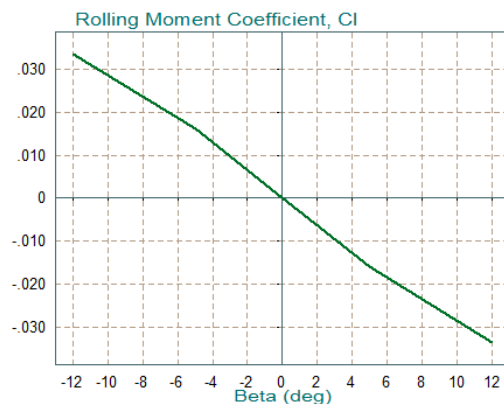
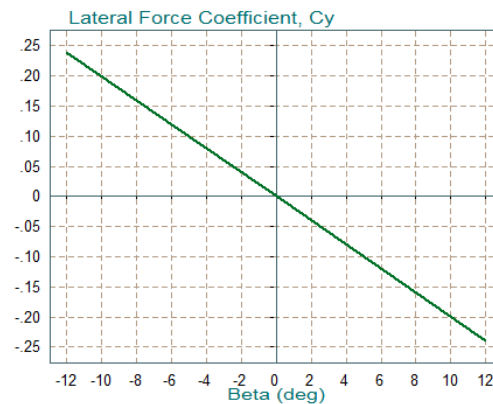
- Basic Pitch Aero Coefficients Versus Alpha
- Basic Lateral Aero Coefficients Versus Beta
- Basic Pitch Aero Derivatives Versus Alpha
- Basic Lateral Aero Derivatives Versus Beta
- Pitch Control Surface Coefficients versus Surface Deflection
- Lateral Control Surface Coefficients versus Surface Deflection
- Pitch Control Surface Derivatives versus Surface Deflection
- Lateral Control Surface Derivatives versus Surface Deflection

The first plot shows the longitudinal aero coefficients of the base vehicle (C_A , C_m , C_z) with the surface deflections at zero. The second plot shows the lateral aero coefficients (C_l , C_y , C_n).

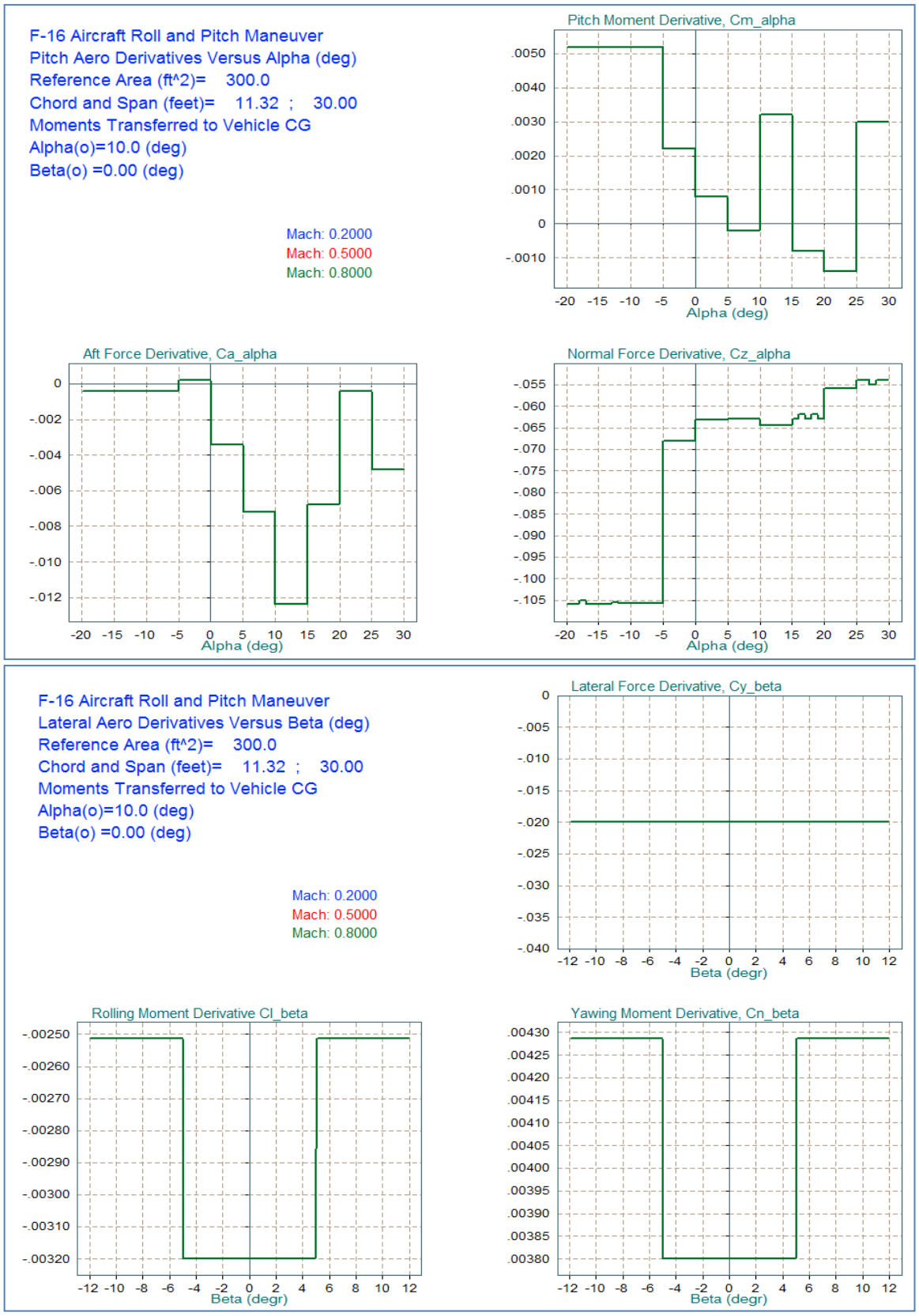


F-16 Aircraft Roll and Pitch Maneuver
 Lateral Aero Coefficients Versus Beta (deg)
 Reference Area (ft²)= 300.0
 Chord and Span (feet)= 11.32 ; 30.00
 Moments Transferred to Vehicle CG
 Alpha(o)=10.0 (deg)
 Beta(o)=0.00 (deg)

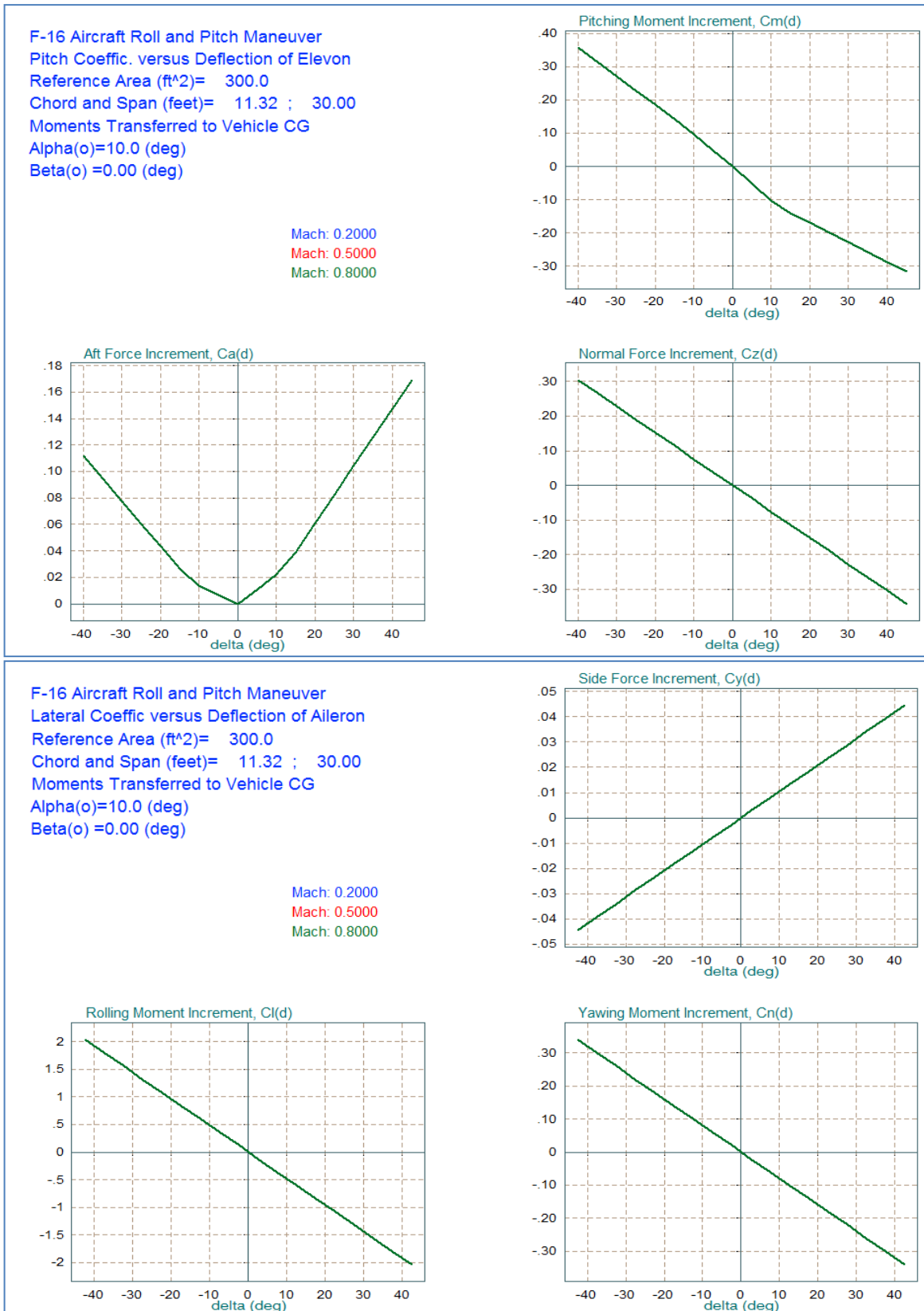
Mach: 0.2000
 Mach: 0.5000
 Mach: 0.8000



The next two plots show the pitch derivatives with respect to alpha versus alpha, and the lateral derivatives with respect to beta versus beta.

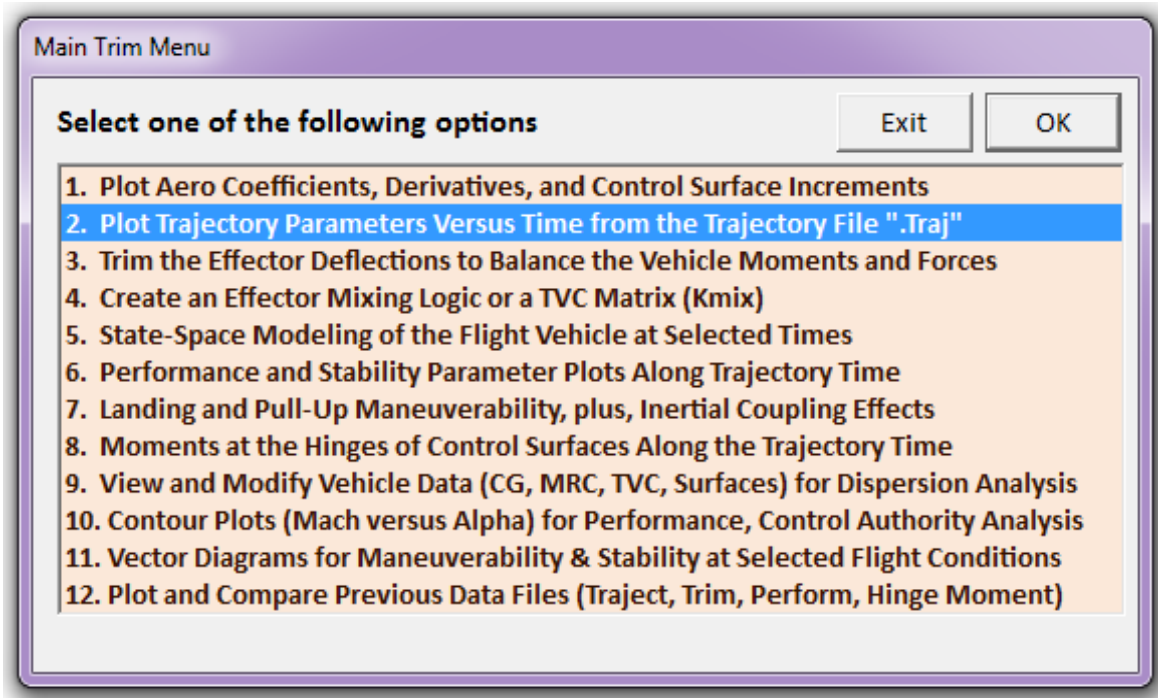


The next two plots show the Elevon and Aileron coefficient increments as a function of surface deflections.



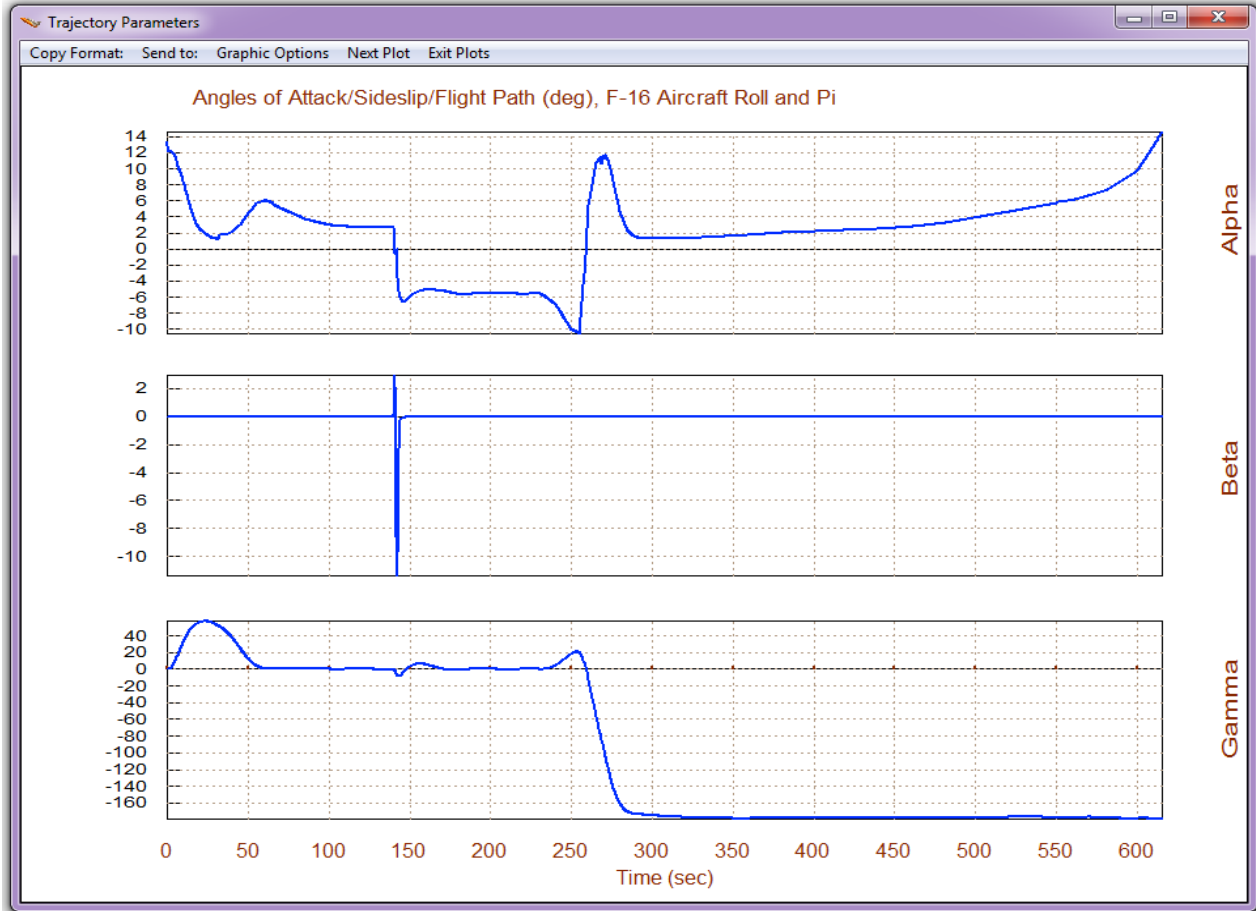
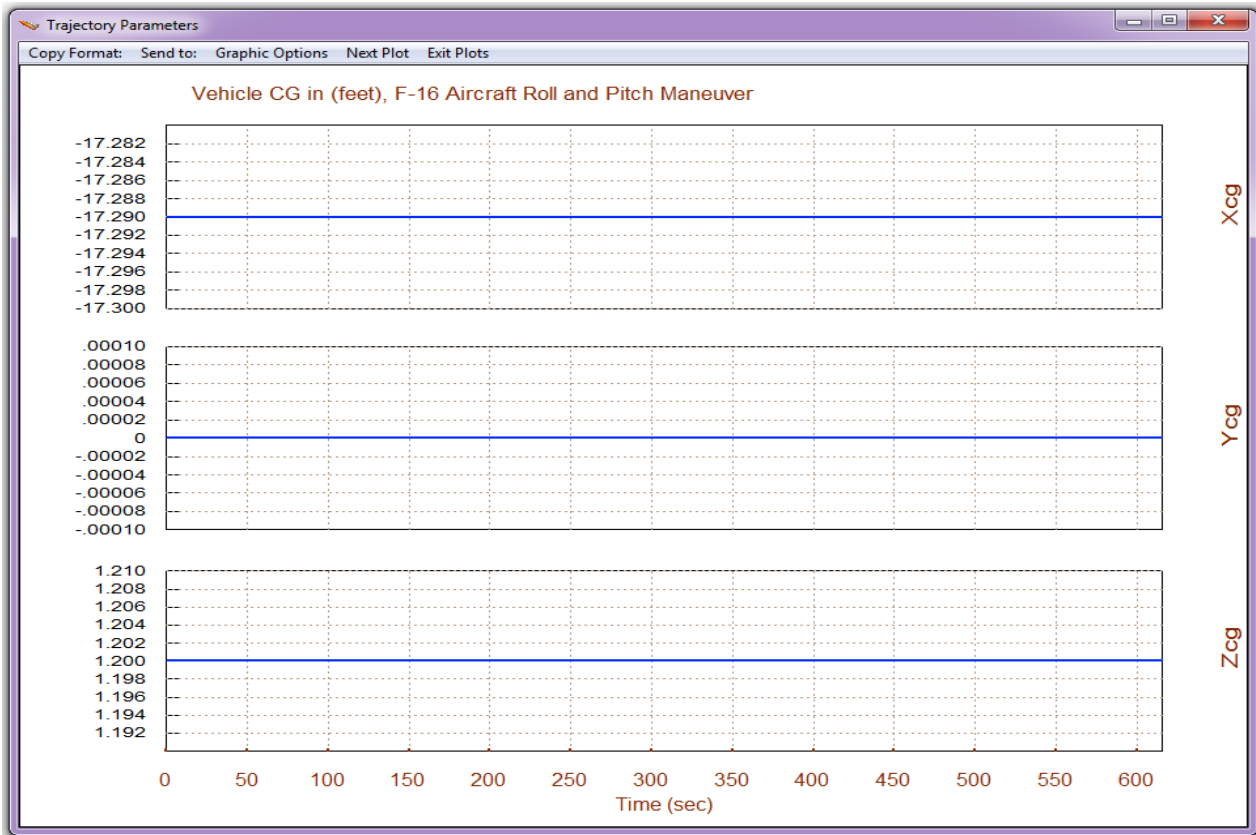
2. Checking the Trajectory Data

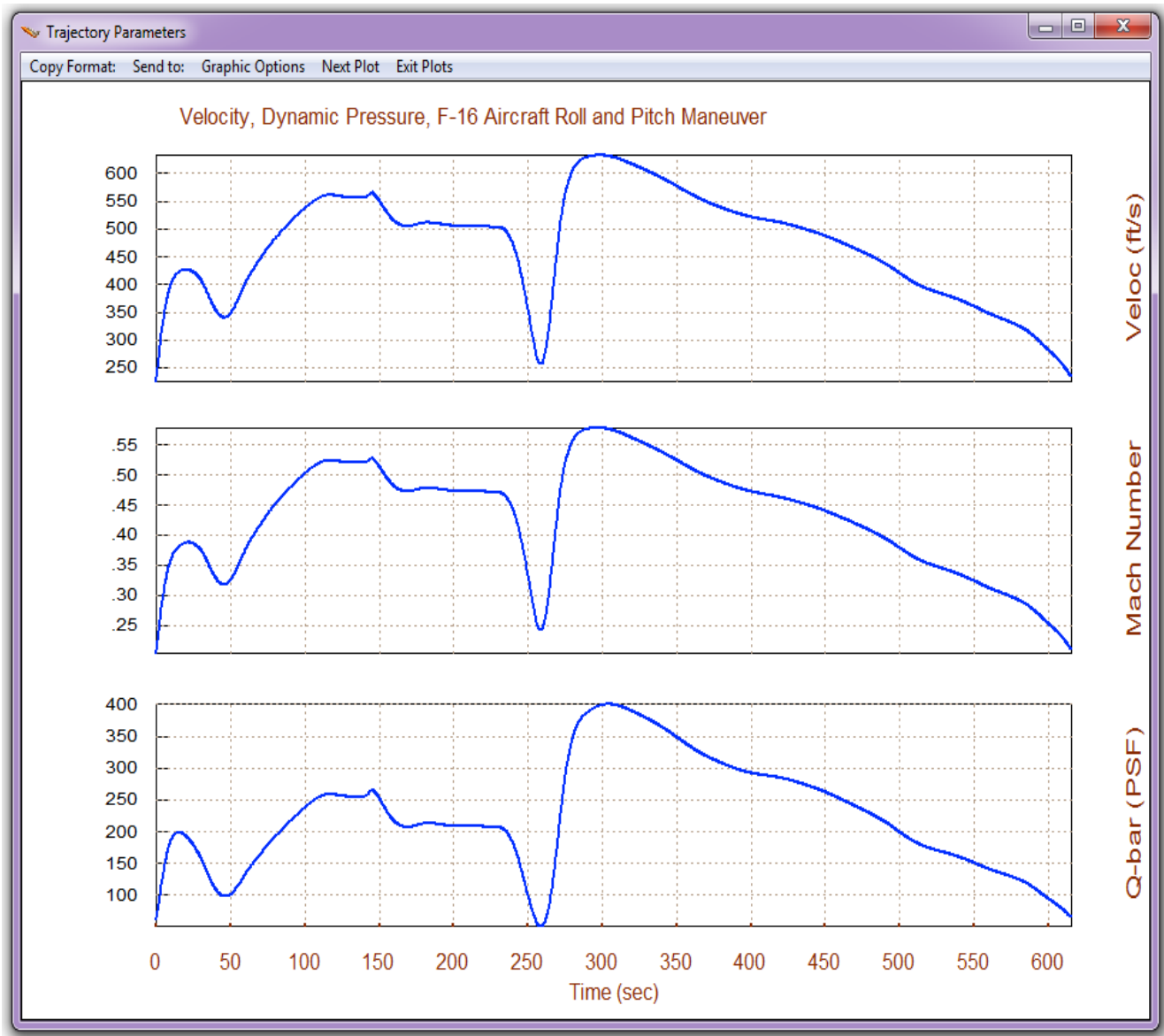
It is also important to take a look at the trajectory data before beginning the analysis. So after returning to the Trim main menu, select the second option which is for "*Plotting the Trajectory Parameters Versus Time*" and click the "OK" button.



The following plots show the trajectory parameters, as a function of time, which are read from the selected trajectory file "*Roll_Pitch_Man.Traj*". The first plot shows the CG location during the flight, which does not vary in this case. The next plot shows α which is initially positive for the aircraft to gain altitude. It changes sign when the aircraft is flying up-side-down in order to maintain level flight. The sideslip β is zero during most of the flight. The short beta transient occurs at 140 sec, during the 180° roll flip. The flight path angle γ is positive while the aircraft is climbing. Then it remains close to zero as the aircraft maintains level flight. The transient at around 140 (sec) is due to the roll flip. During the pitch maneuver, which occurs at 270 sec, the flight path angle rotates 180° and the aircraft is eventually descending with a γ close -178° towards the take-off sight (equivalent to $\gamma=-2^\circ$ in the opposite direction).

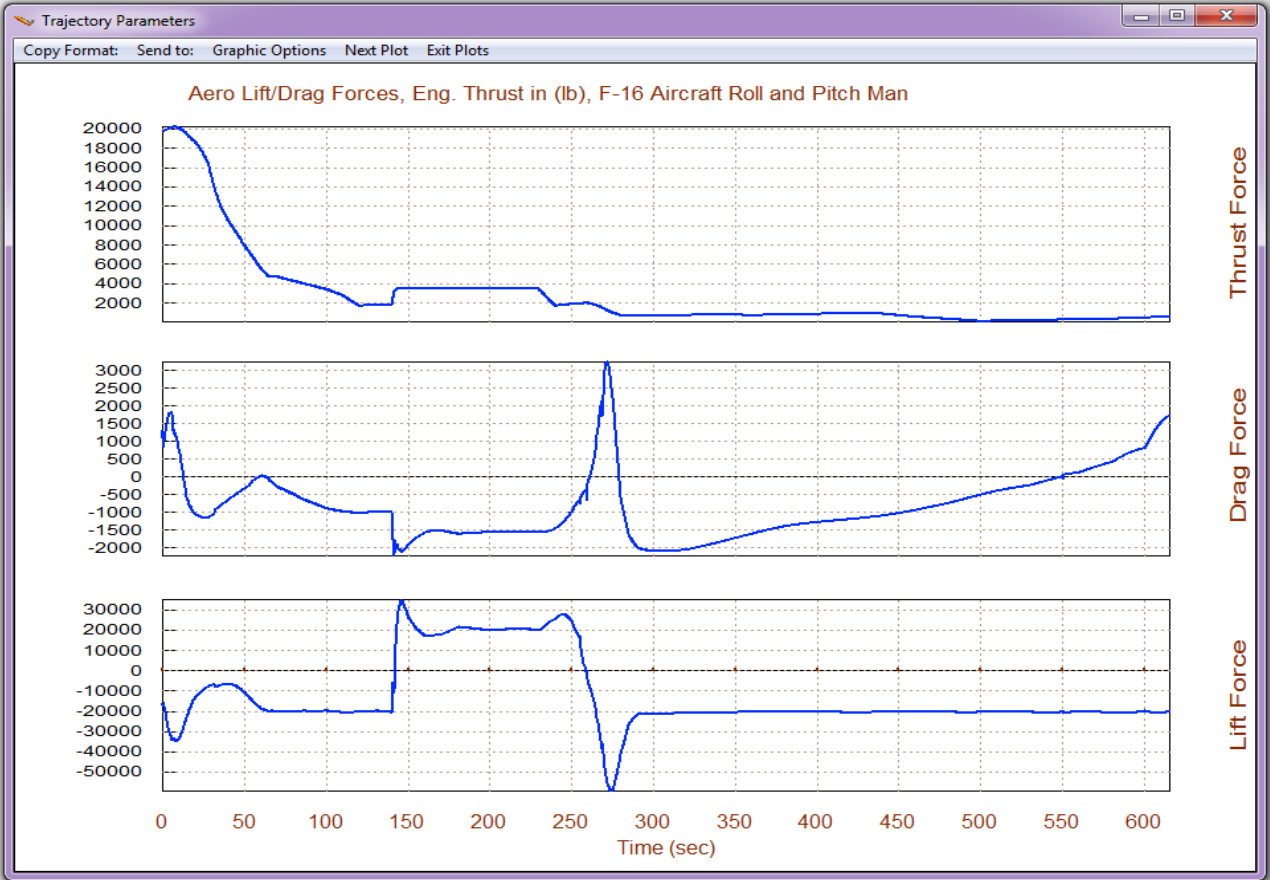
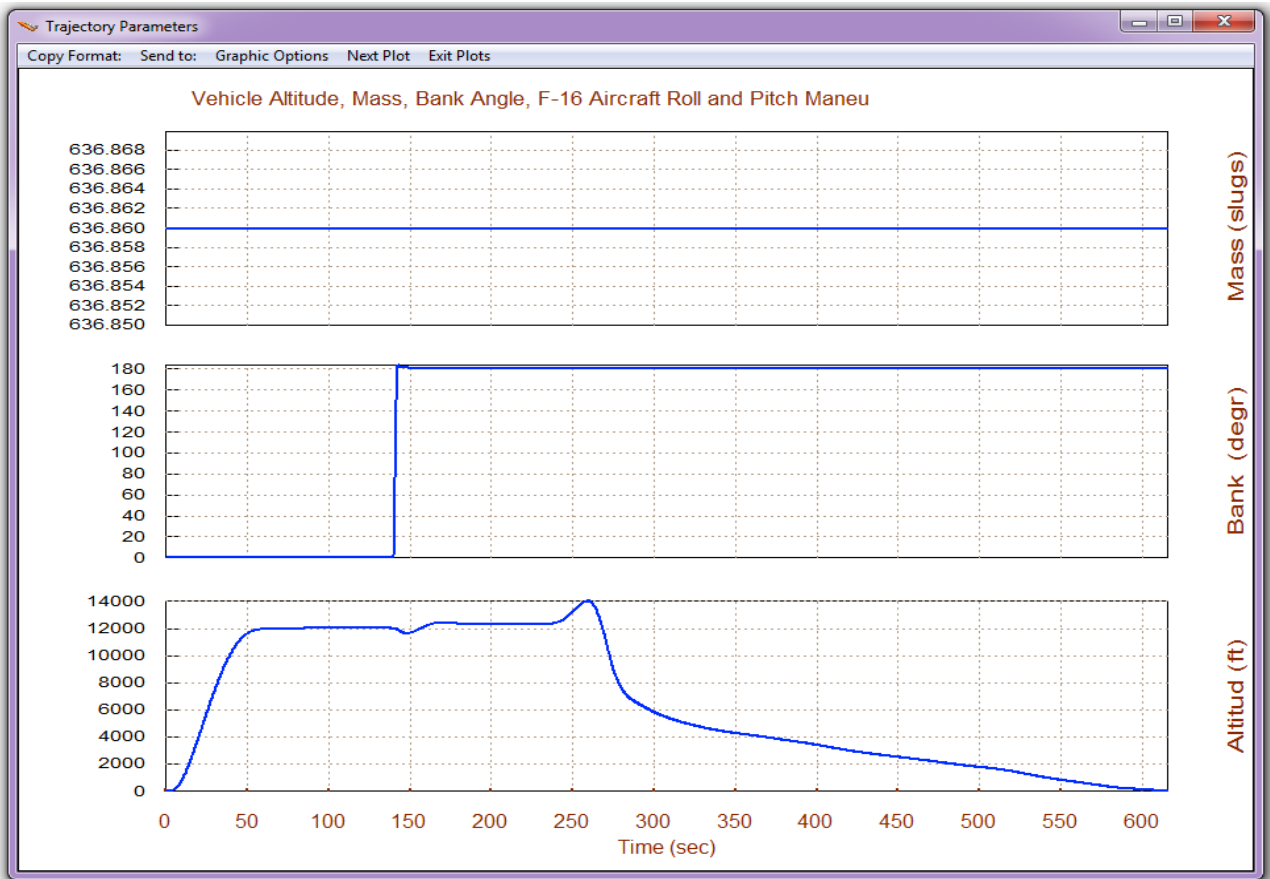
On the top of each plotting window there is a horizontal menu bar that includes several options. If you click on "Next Plot" it will move to the next trajectory data plot. If you click on "Exit Plots" it will go back to the Trim main menu shown above.

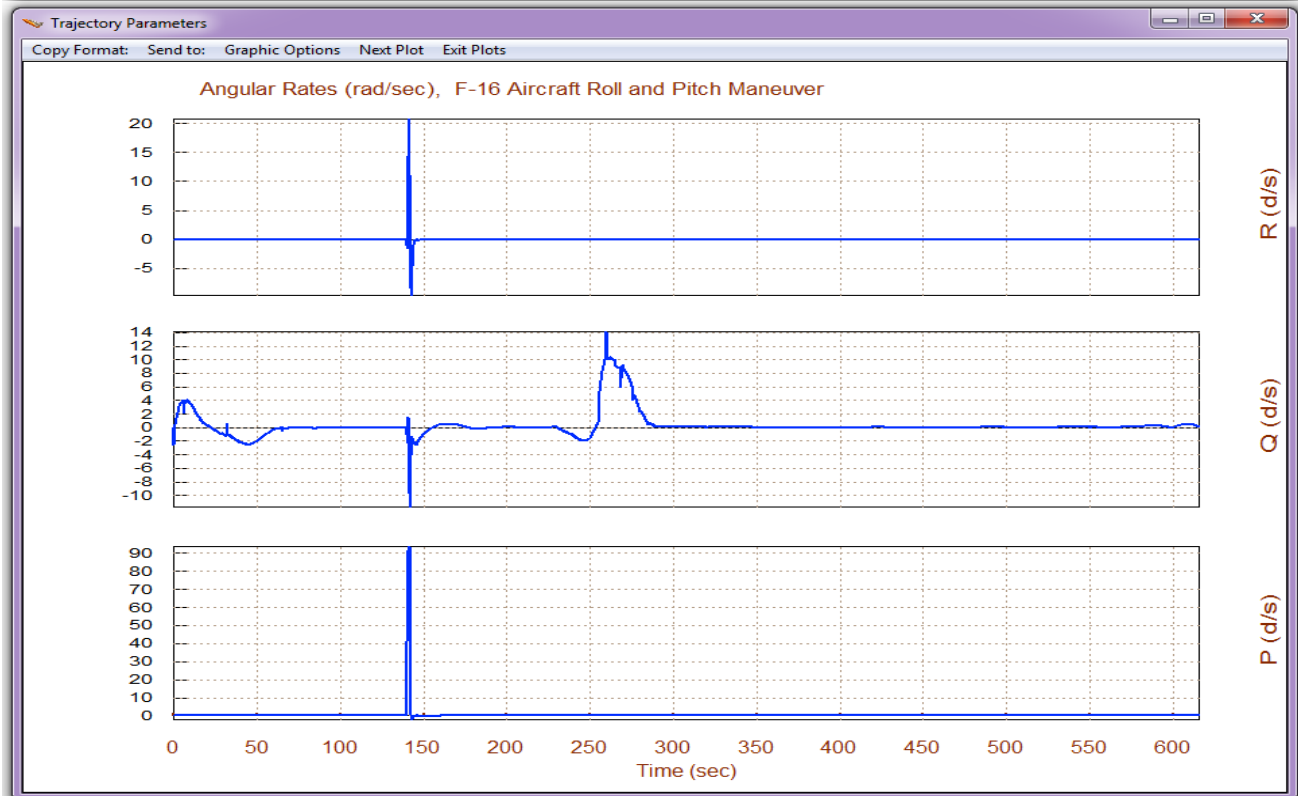
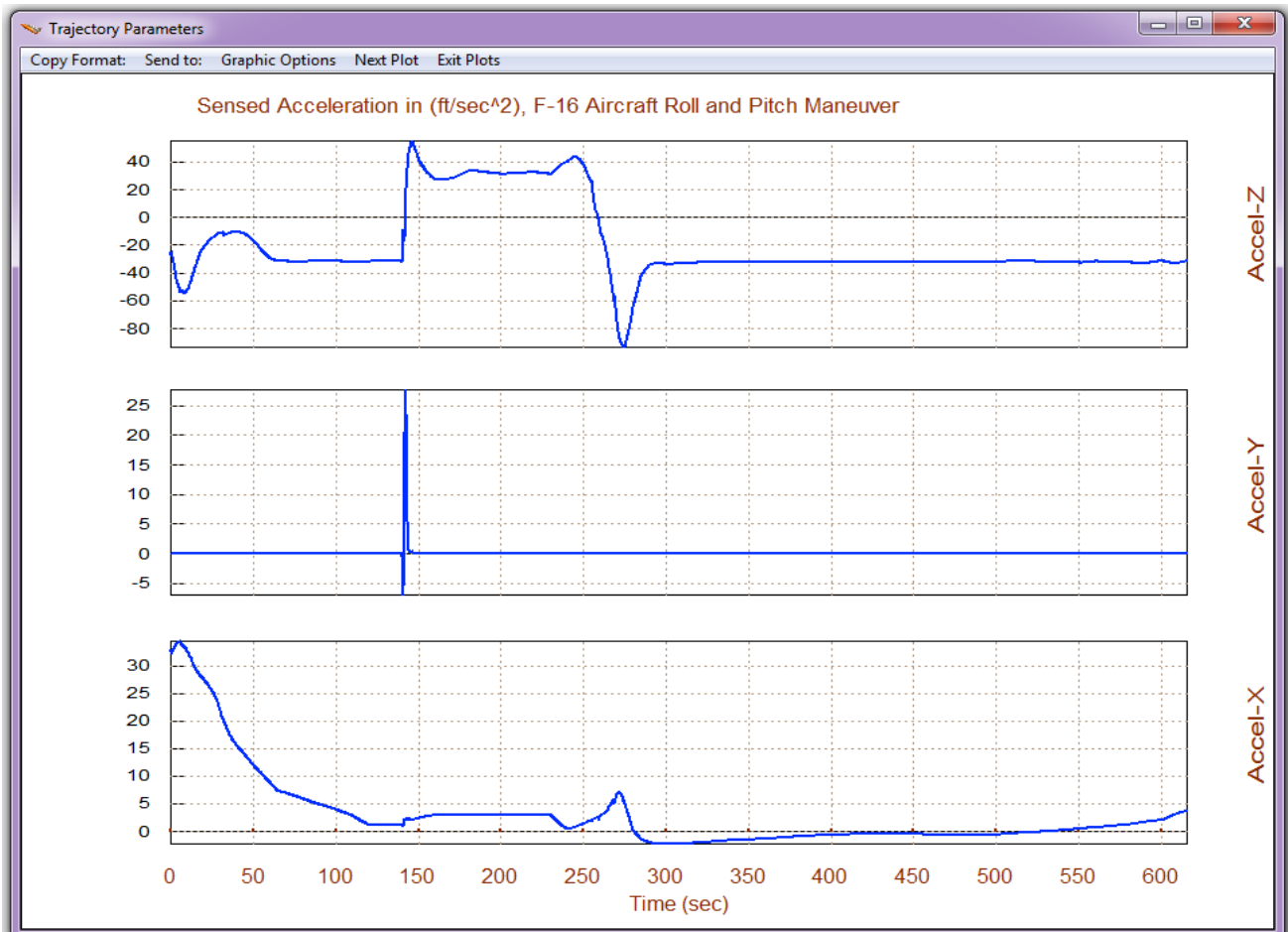




The above plot shows the aircraft velocity, Mach number, and dynamic pressure which follow the same trend. The take-off speed is about 240 (ft/sec). The speed increases to a peak as the aircraft climbs to 12,000 (ft). It drops slightly due to the 180° roll and it maintains a constant speed up-side-down. Then it briefly climbs to 14,000 (ft) causing the speed to dip to 250 (ft/sec) as it performs the 180° pitch maneuver. Then the aircraft loses a lot of altitude causing the speed to peak to 650 (ft/sec). The speed gradually begins to drop as γ gets closer to horizontal and the aircraft descends towards landing. It finally lands at about 240 (ft/sec), same as its take-off speed.

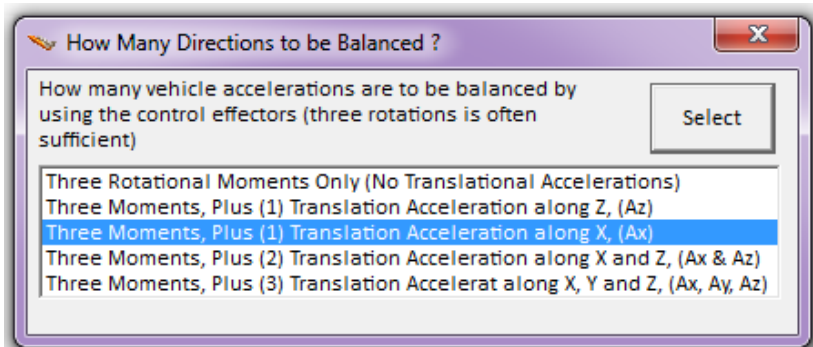
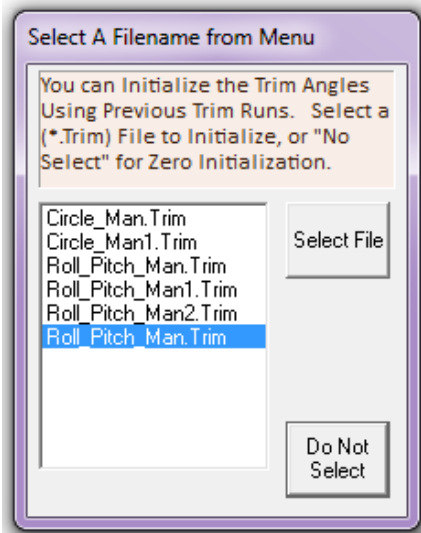
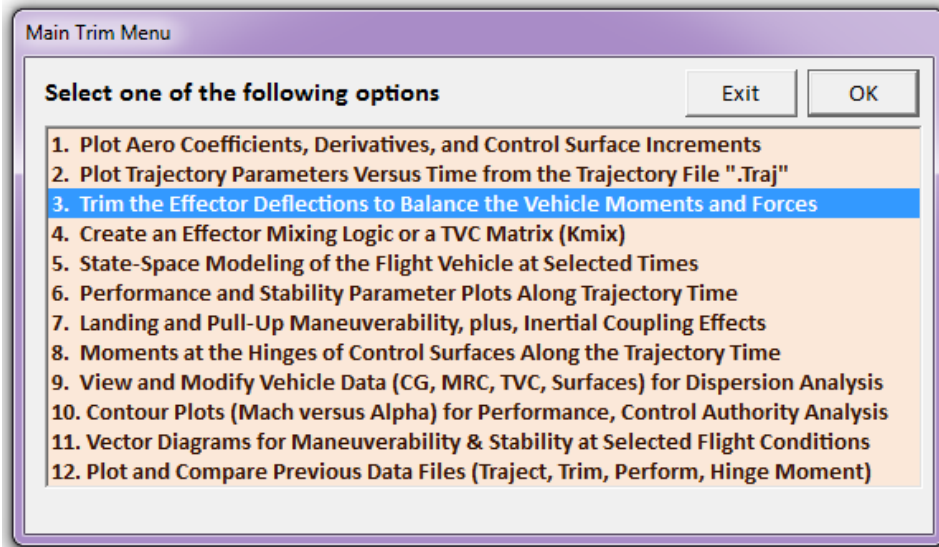
The engine thrust is 20,000 (lb) during take-off. It is reduced significantly during level flight and it is almost zero during landing. The normal acceleration is -1g during level flight or +1g when the aircraft is up-side-down. The side acceleration is zero, except for the yaw transient occurring during the roll flip. The axial acceleration follows the thrust profile. It briefly becomes negative due to drag at high speeds.





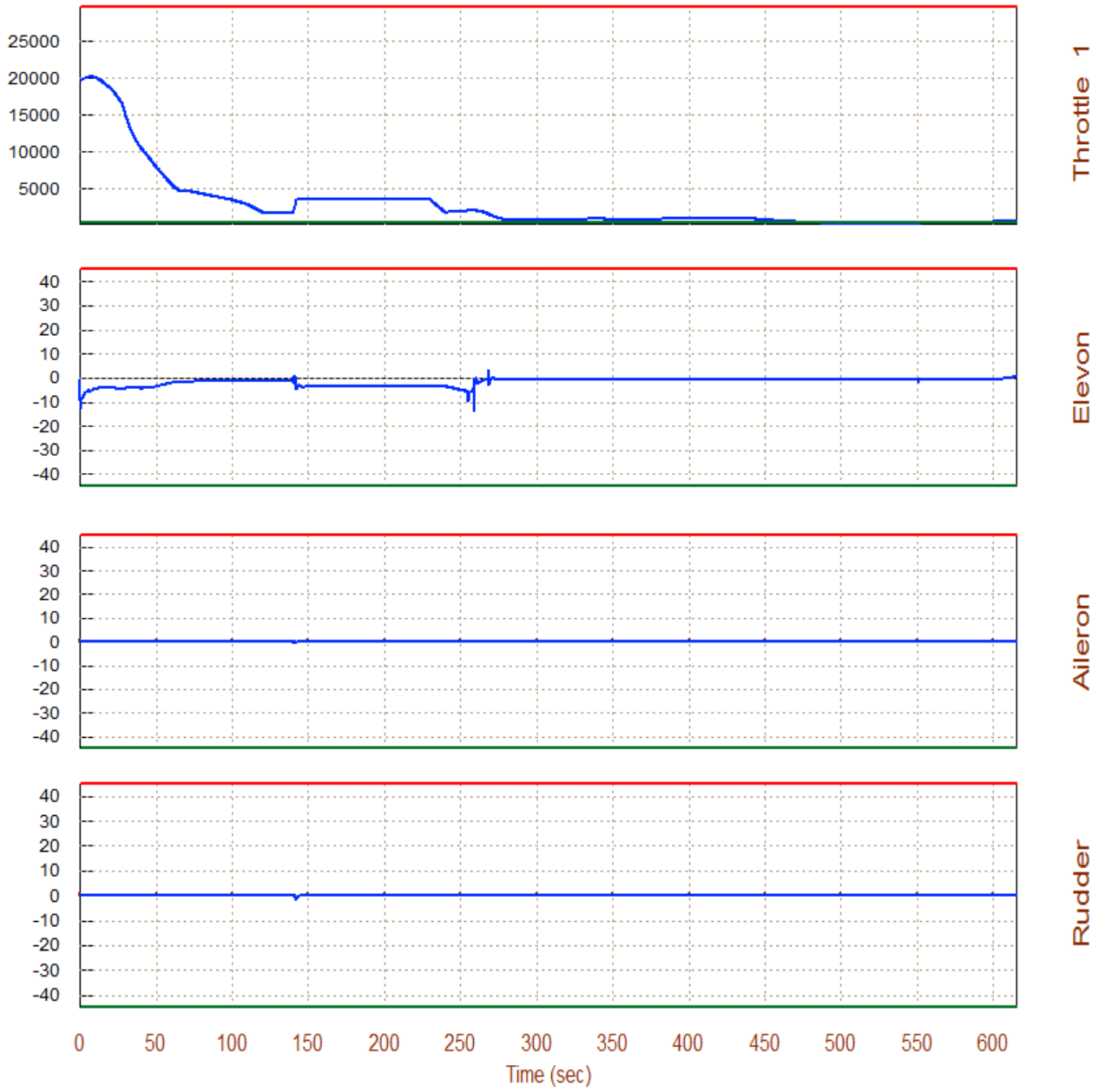
3. Trimming Along The Trajectory

This vehicle has 4 controls: a variable thrust engine and 3 aero-surfaces. We must now trim the controls to match the accelerations defined by the trajectory. After returning to the main menu select option (3) which trims the effectors. In the following menu do not select an initialization file (.Trim) because it is the first time and there aren't any initialization files yet. The next menu is for selecting the degrees-of-freedom to be balanced. In this case we want to balance the three moments plus the axial acceleration.



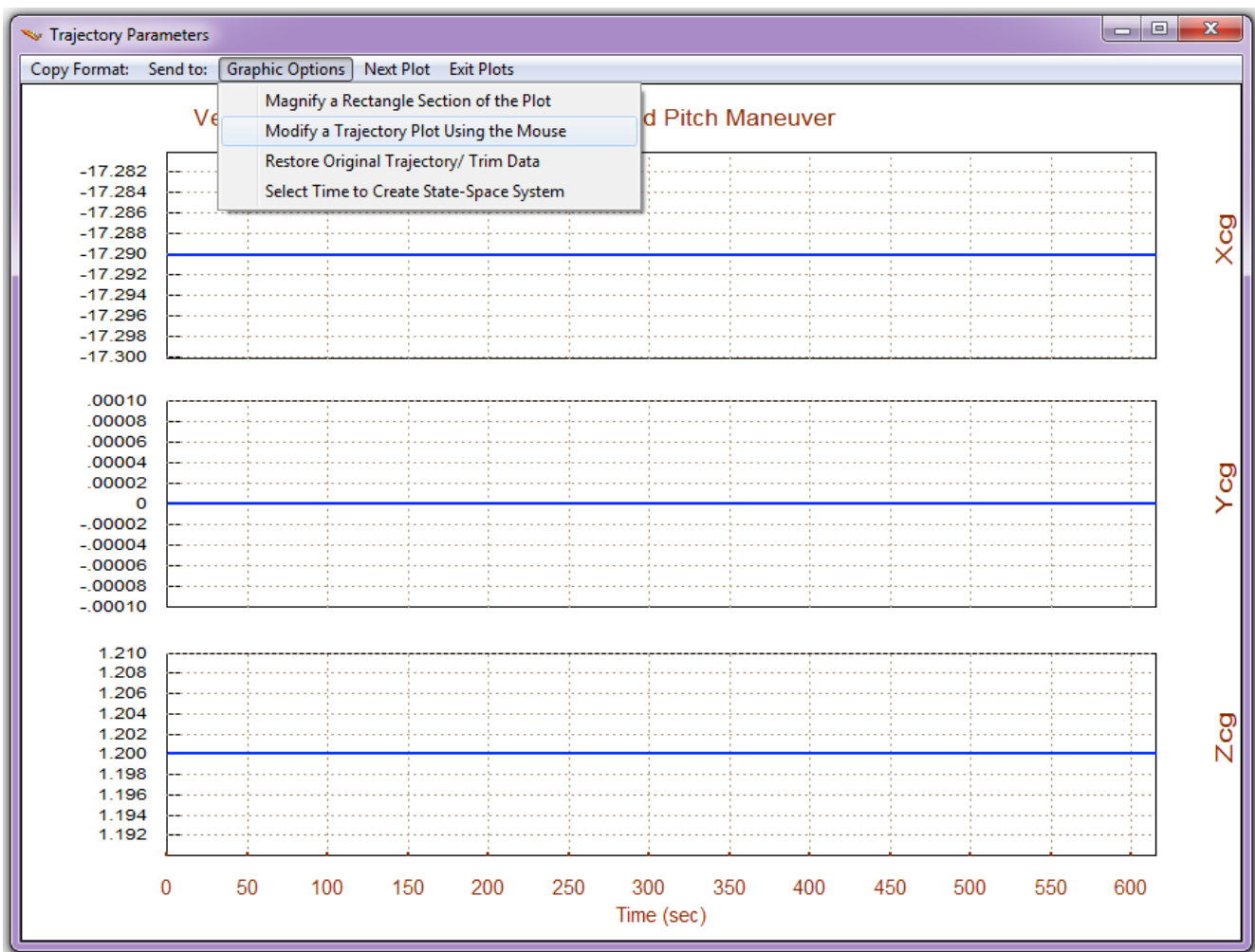
The following plot shows the engine thrust, elevon, aileron, and rudder deflections needed to trim the vehicle along the trajectory. The aileron and rudder deflections are zero because the vehicle has lateral symmetry. The effector deflections and throttle value versus time are saved in file "Roll-Pitch-Man.Trim". This file will be used in the analysis that follows.

Surface & Engine Deflections/ Thrusts, F-16 Aircraft Roll and Pitch Maneuver



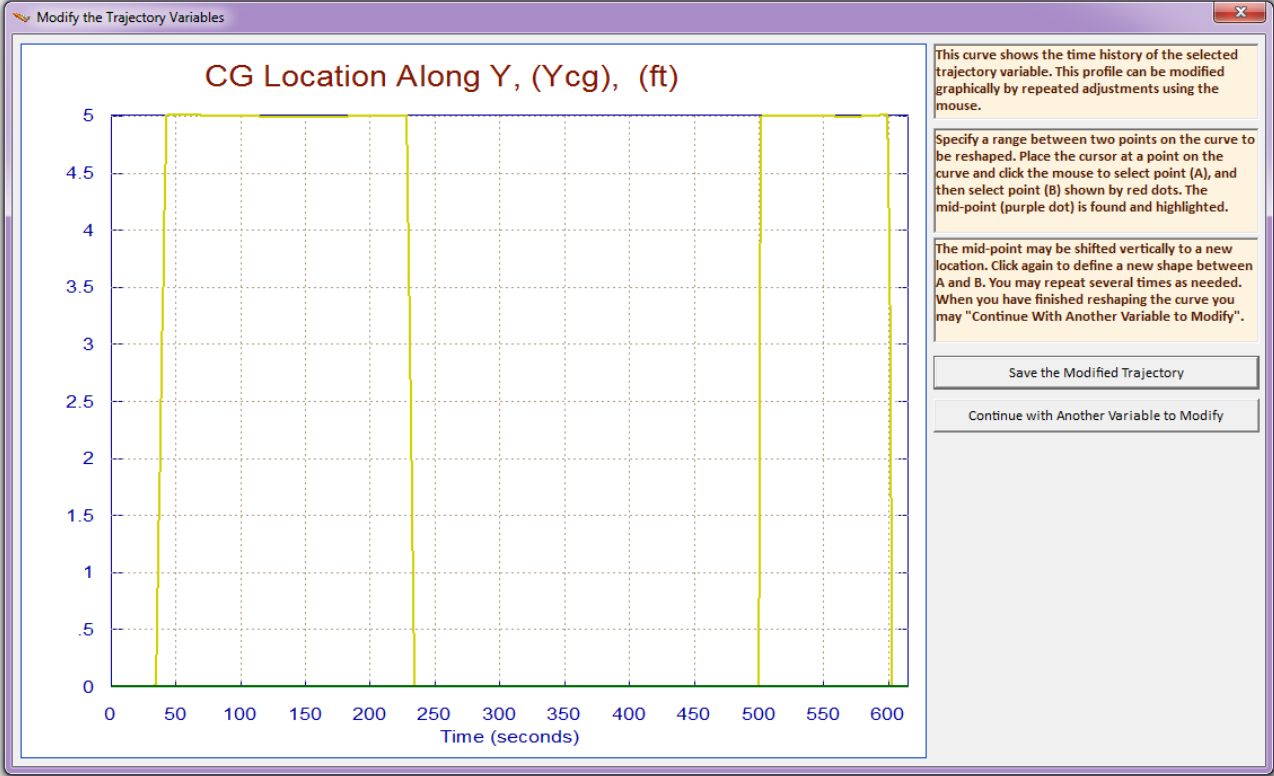
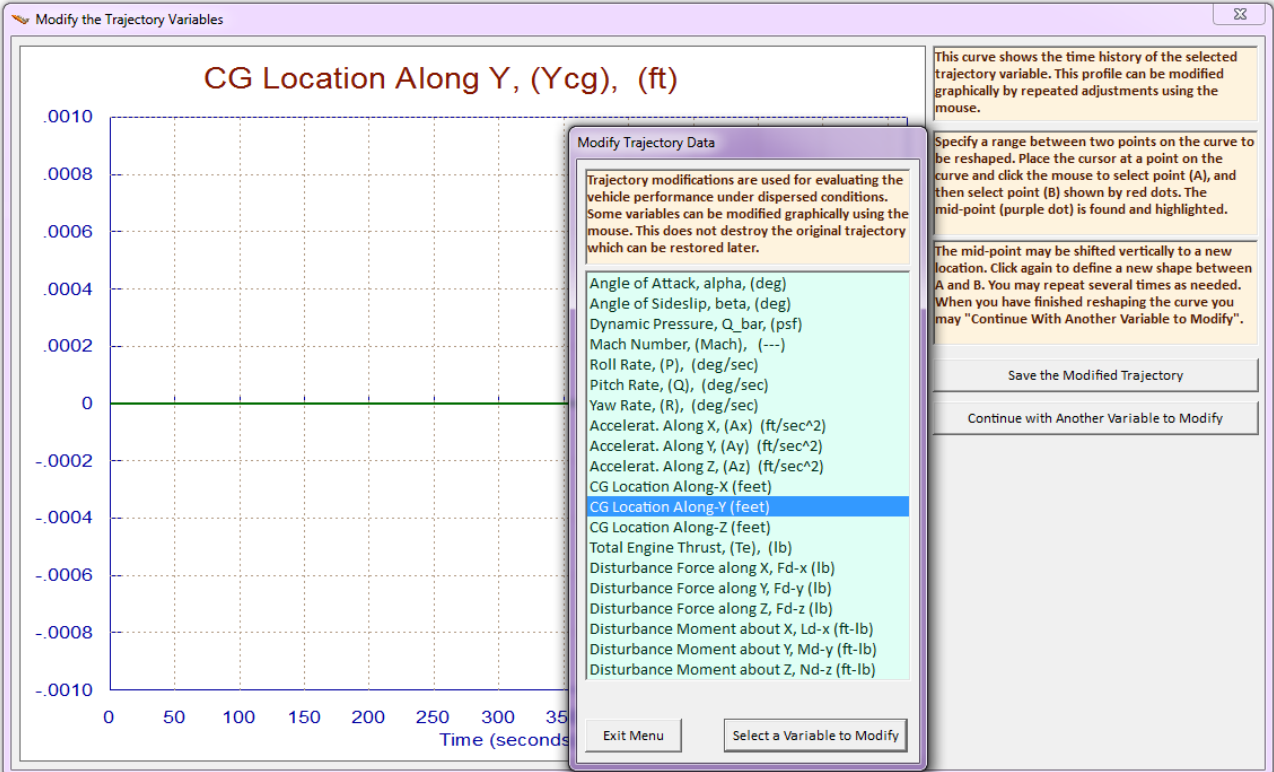
3. Trimming with CG Variations

The Trim program allows the user to modify some of the trajectory parameters in order to evaluate the vehicle's response to parameter dispersions, such as: CG variations, angle of attack or sideslip variations, dynamic pressure, accelerations, Mach number, or to introduce an external disturbance force or moment for analyzing engine misalignments or failures, etc. This can be done graphically by manipulating the trajectory curves directly on the screen by using the mouse. In this case we would like to check if the vehicle has enough control authority to trim with CG variations along the aircraft x and y axes. Return to the Trim main menu and select option (2) again to plot and modify the trajectory. From one of the trajectory plots, go to the horizontal top menu bar and click on "Graphic Options", and then from the vertical pop-up menu select the option "Modify a Trajectory Plot Using the Mouse".

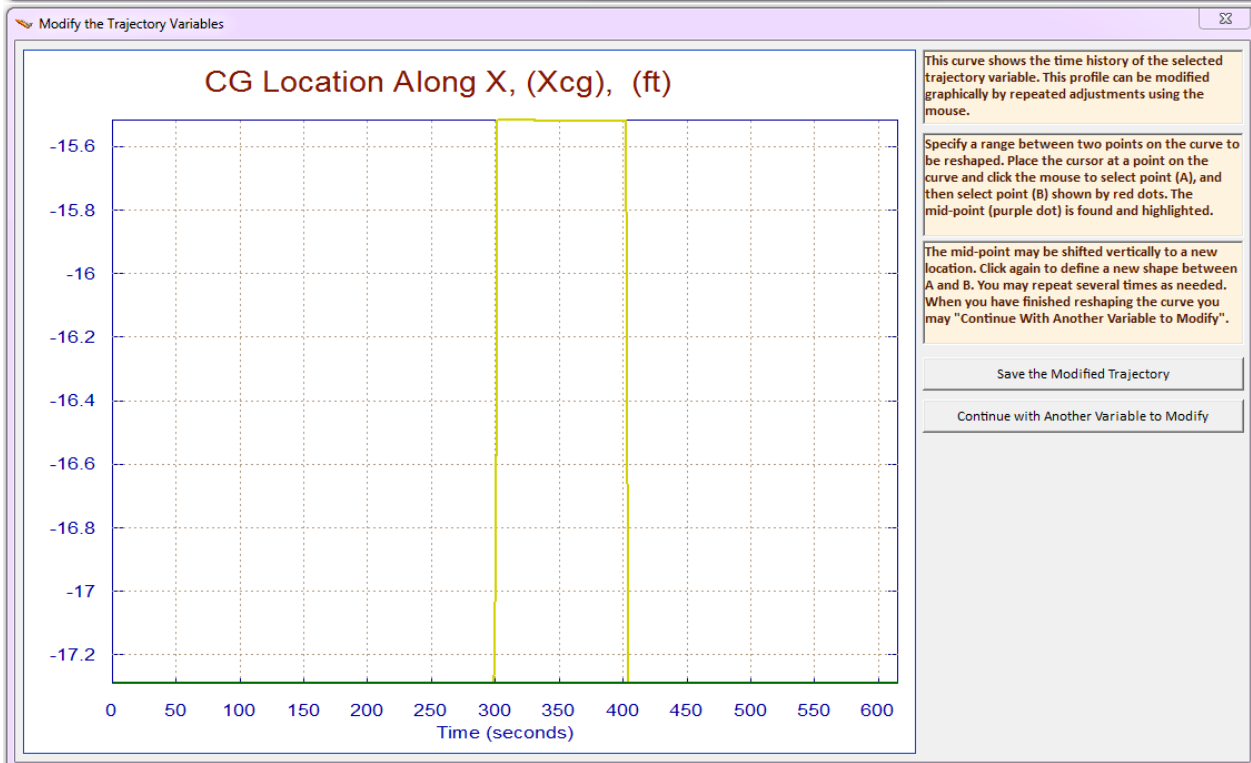
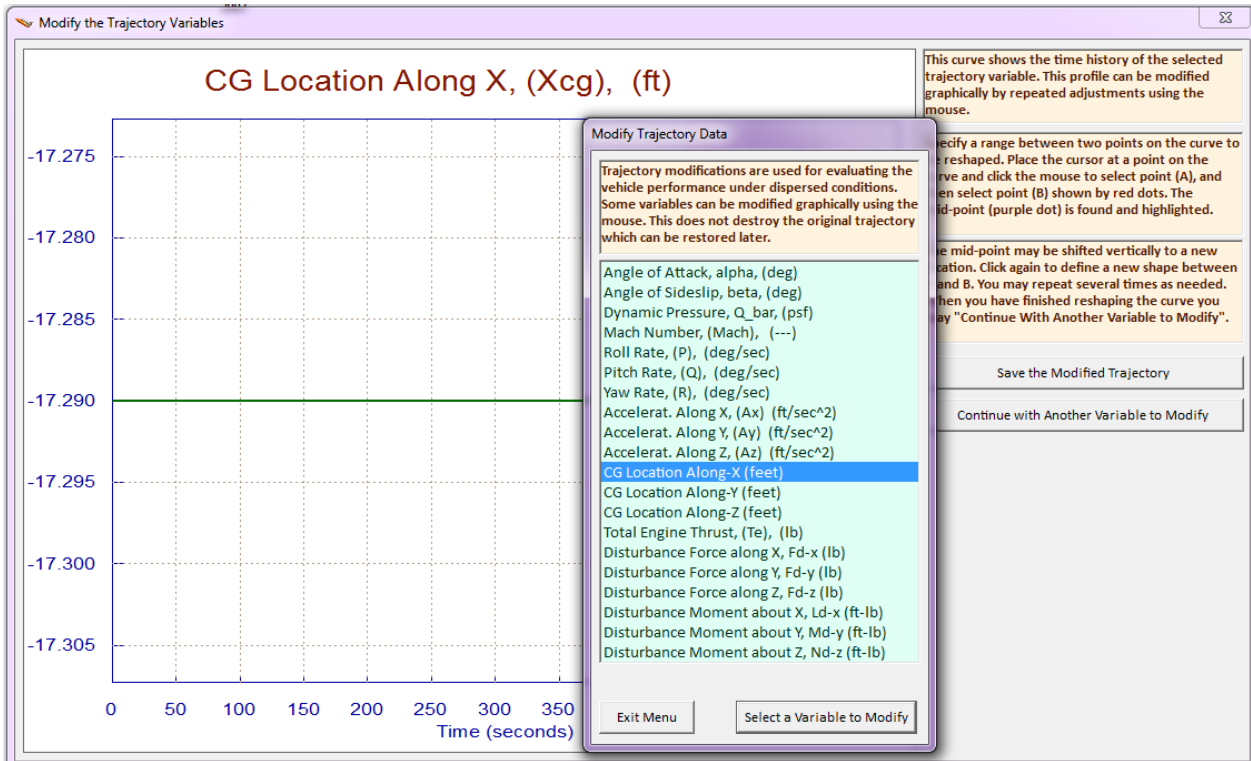


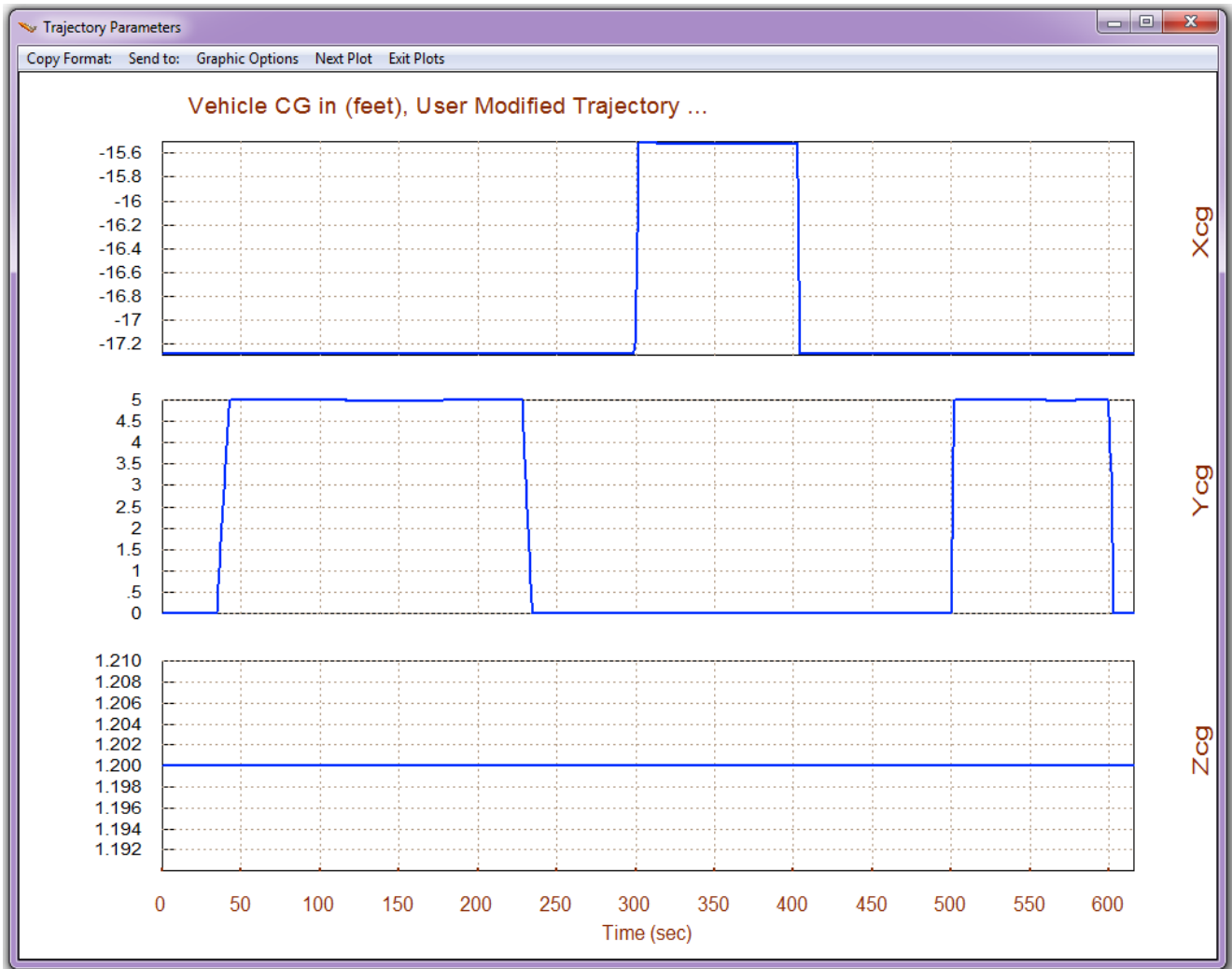
We will now modify two of the trajectory parameters, one parameter at a time. The following menu shows the trajectory parameters that can be modified by the user. Select the CG location along the Y axis and click on "Select a Variable to Modify". A plot of the Y-CG location versus time appears in the window-dialog shown below. The Y-CG travel is shown by the green curve and originally it is zero. We

shall use the mouse to modify it in a couple of time periods and shift the curve five feet towards the right wing. The modified Y-CG travel is shown by the yellow line in the second dialog/plot below. It was modified to 5 (ft) in the time ranges between 30-230 sec, and between 500-600 sec.



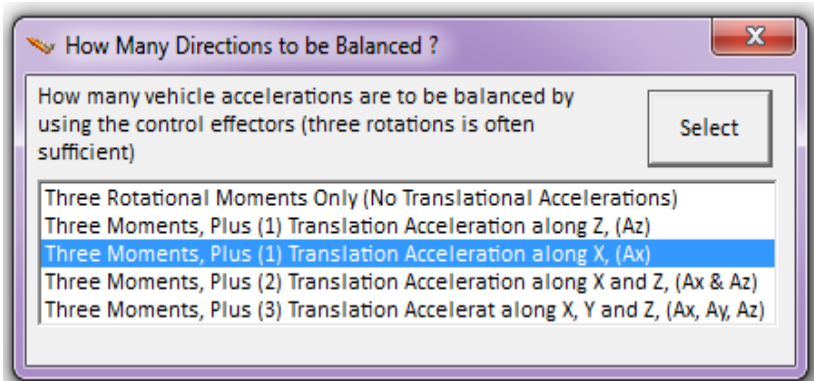
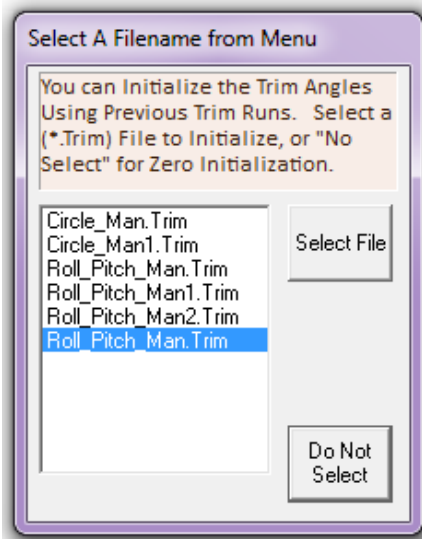
Now click on "Continue with Another Variable to Modify", and from the trajectory parameters menu select the CG location along the X axis. The X-CG location is at -17.29. We will shift it forward a couple of feet to -15.5 in the time period between 300-400 sec, as shown below. Click on "Save the Modified Trajectory" and it will be saved in file "Roll_Pitch_Man1.Traj". It then returns to the trajectory plots.



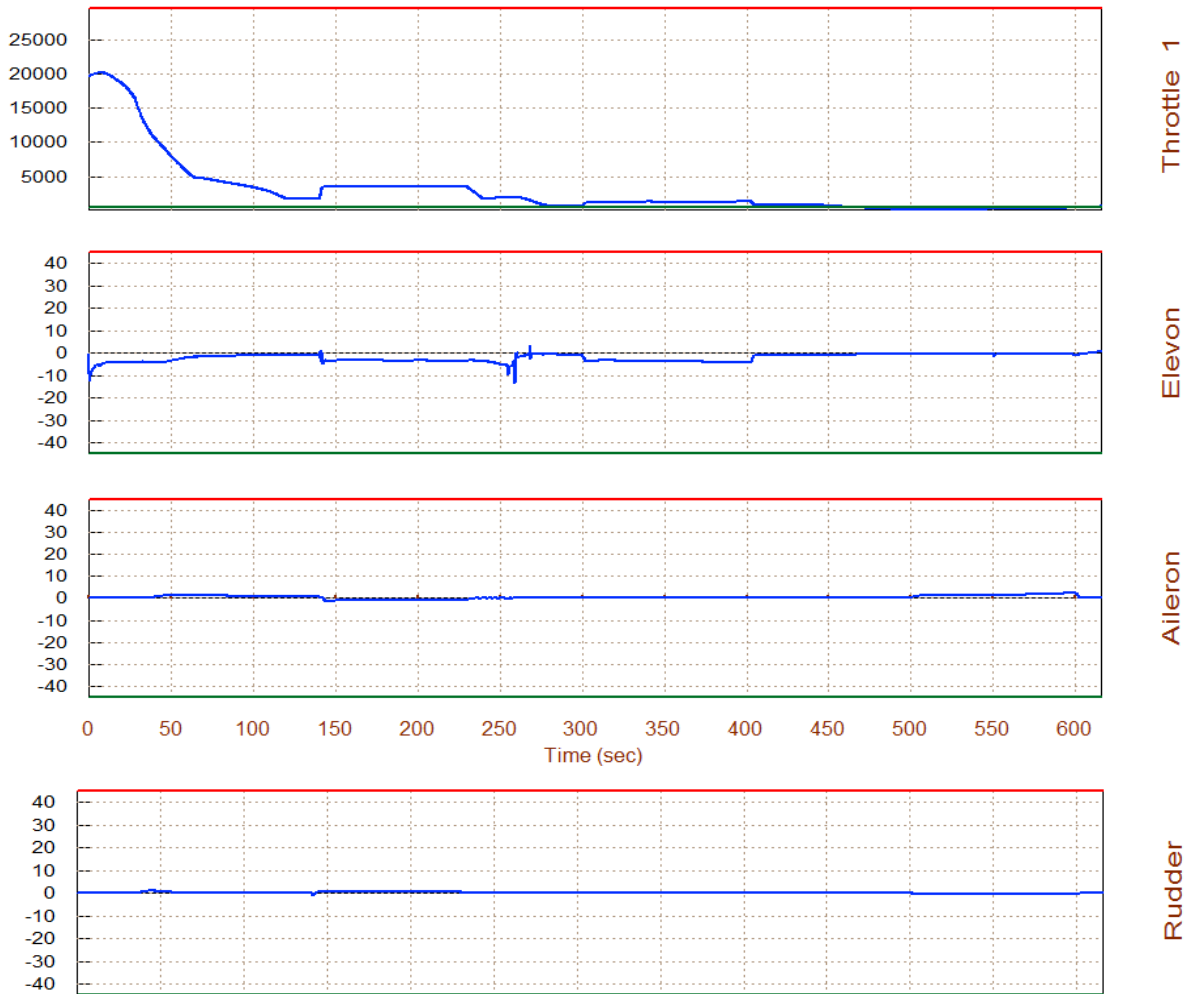


The CG variation of the modified trajectory is shown above. The modified trajectory will remain active in memory for the subsequent analysis until the original trajectory is restored or the program is restarted. It was also saved by the user in file "Roll_Pitch_CGV.Traj" for safety, because it is eventually overwritten by new data.

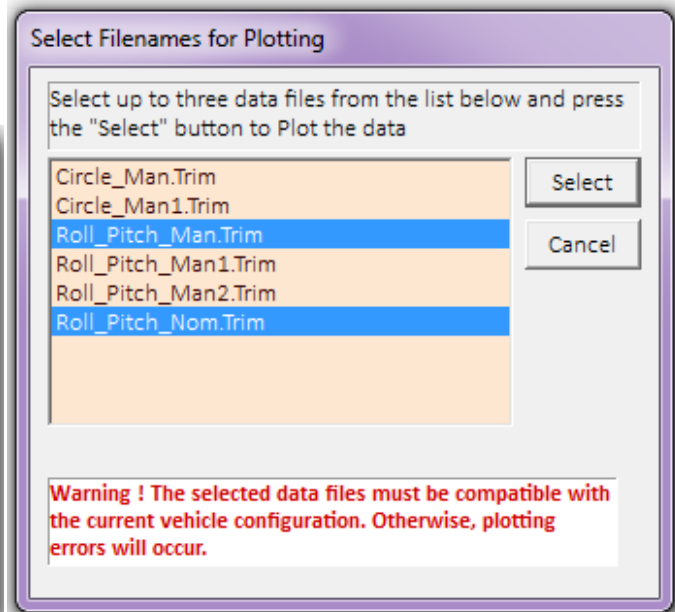
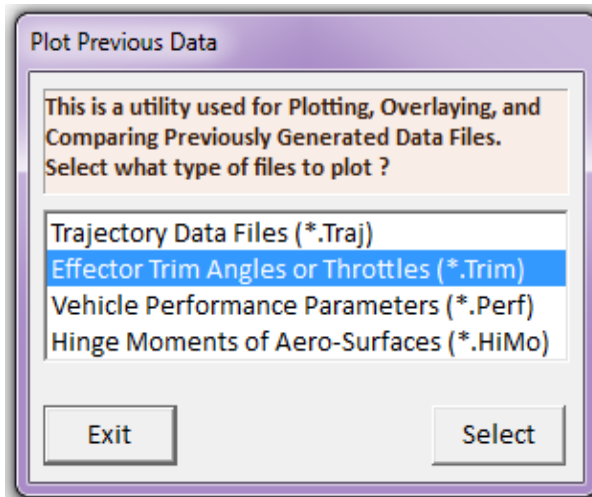
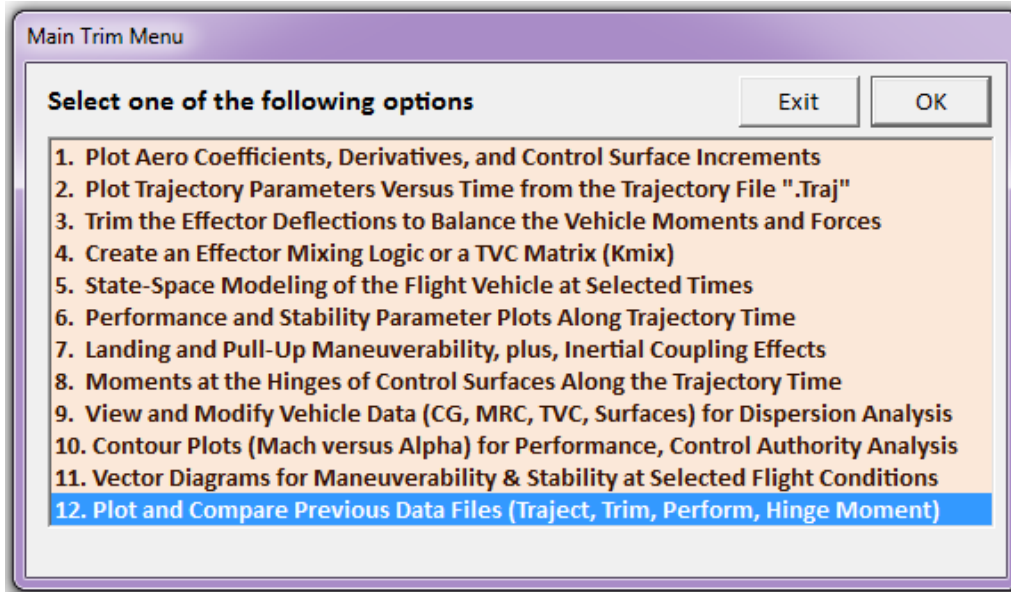
Now click on "Exit Plots", return to the Trim main menu, and select option (3) to trim the effectors as before. In the following menu do not select an initialization (.Trim) file, and from the menu that defines the dofs to be balanced select the three moments plus the axial acceleration, like before. After completing the dispersion analysis the original trajectory can be restored by going back to the "Graphic Options" menu above and clicking on "Restore the Original Trajectory".



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

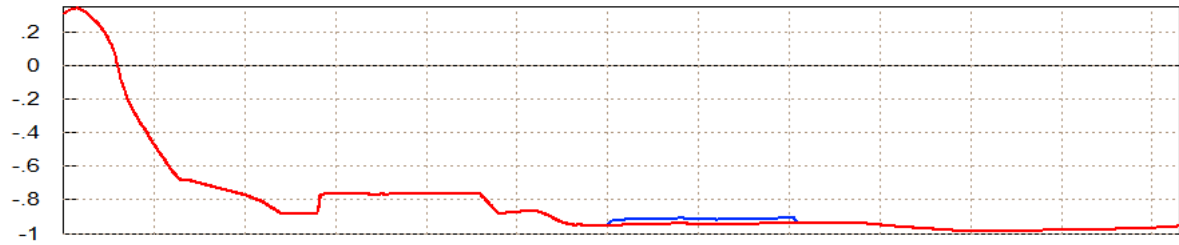


The user may also co-plot the two trim files together (nominal plus CG modified). Return to the Trim main menu and select the last option (12). From the next menu select the ".Trim" type of files and from the third menu select the two trim filenames. The top one is the modified CG trim file "*Roll_Pitch_Man.Trim*" which was just created (blue curve), and the bottom one "*Roll_Pitch_Nom.Trim*" is the trim file that was created using the original trajectory (red curve).



The following plot shows the engine throttle (0 to ± 0.97) and the aero-surface deflections (deg). Zero throttle represents nominal thrust which is 15,000 (lbf). The 2 (ft) X-CG forward shift in the period between 300-400 sec causes an additional -2° elevon deflection. The elevon deflection increases drag and the thrust is slightly increased to compensate for it. The 5 (ft) Y-CG shift towards the right, in the periods between 30-230 sec and between 500-600 sec, causes approx 2° aileron and 1° rudder deflections.

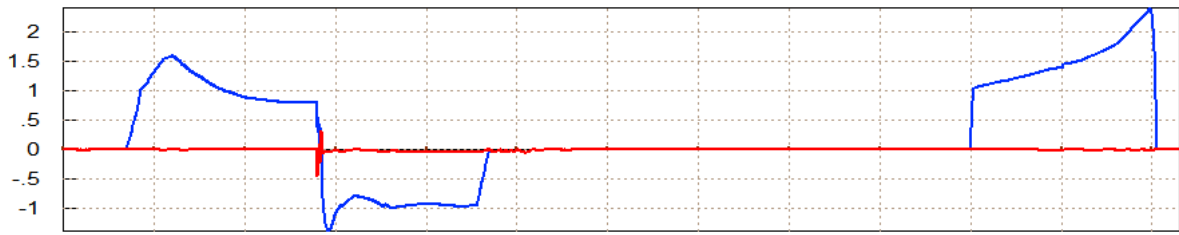
Surface & Engine Deflections/ Throttle, User Modified Trajectory ...



Throttle 1

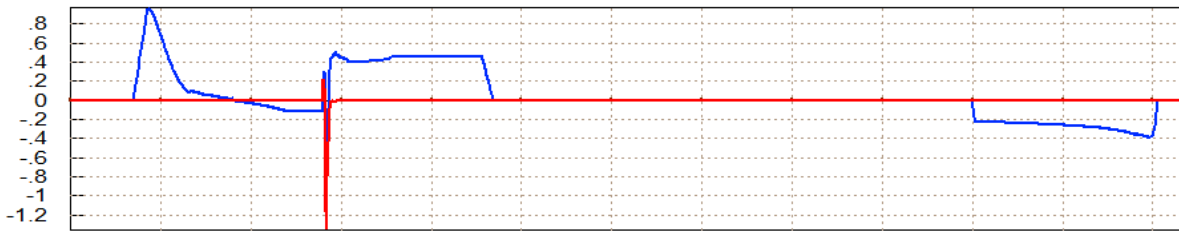


Elevon



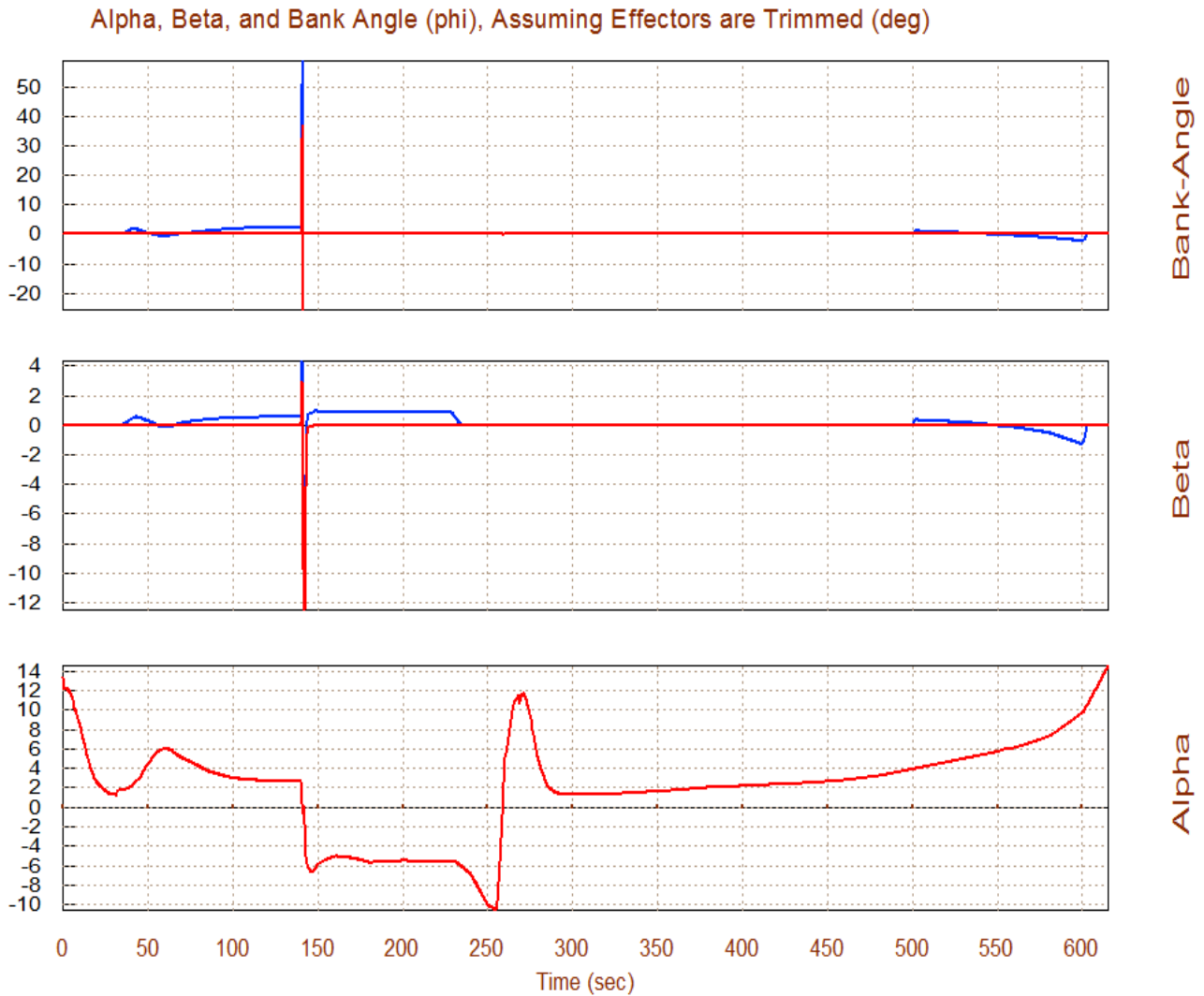
Aileron

Time (sec)



Rudder

Time (sec)

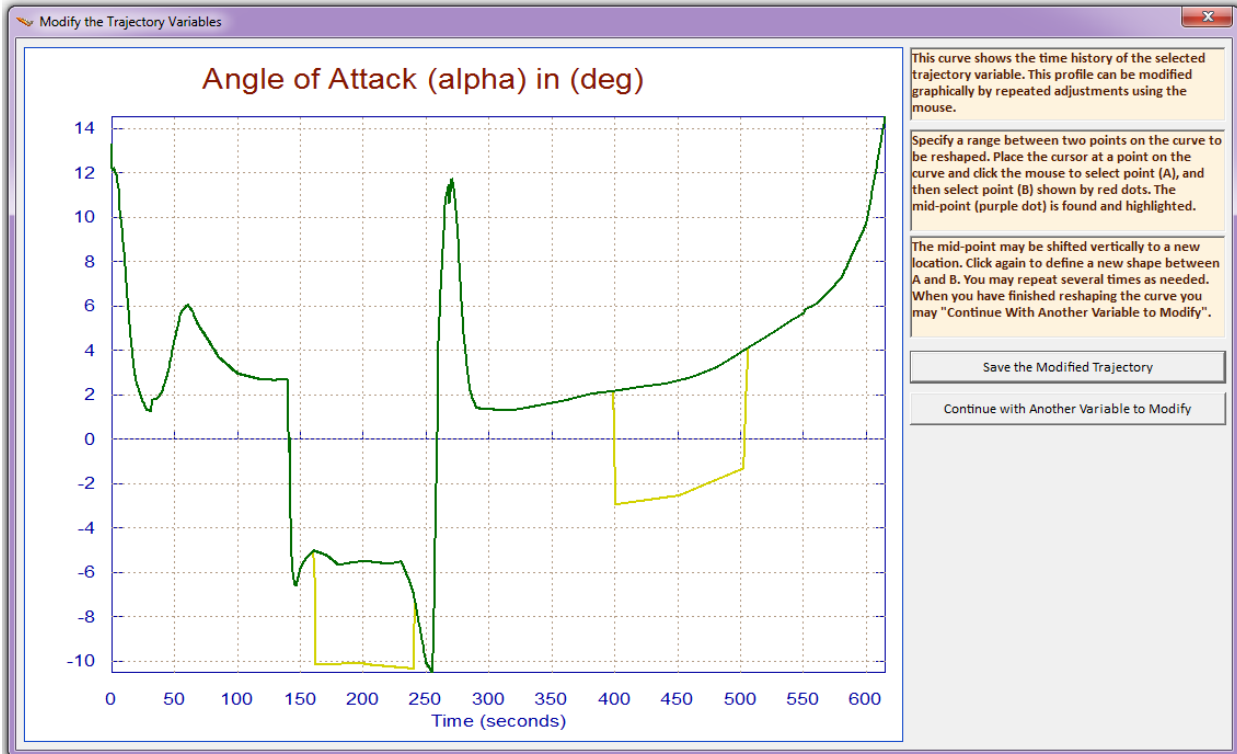
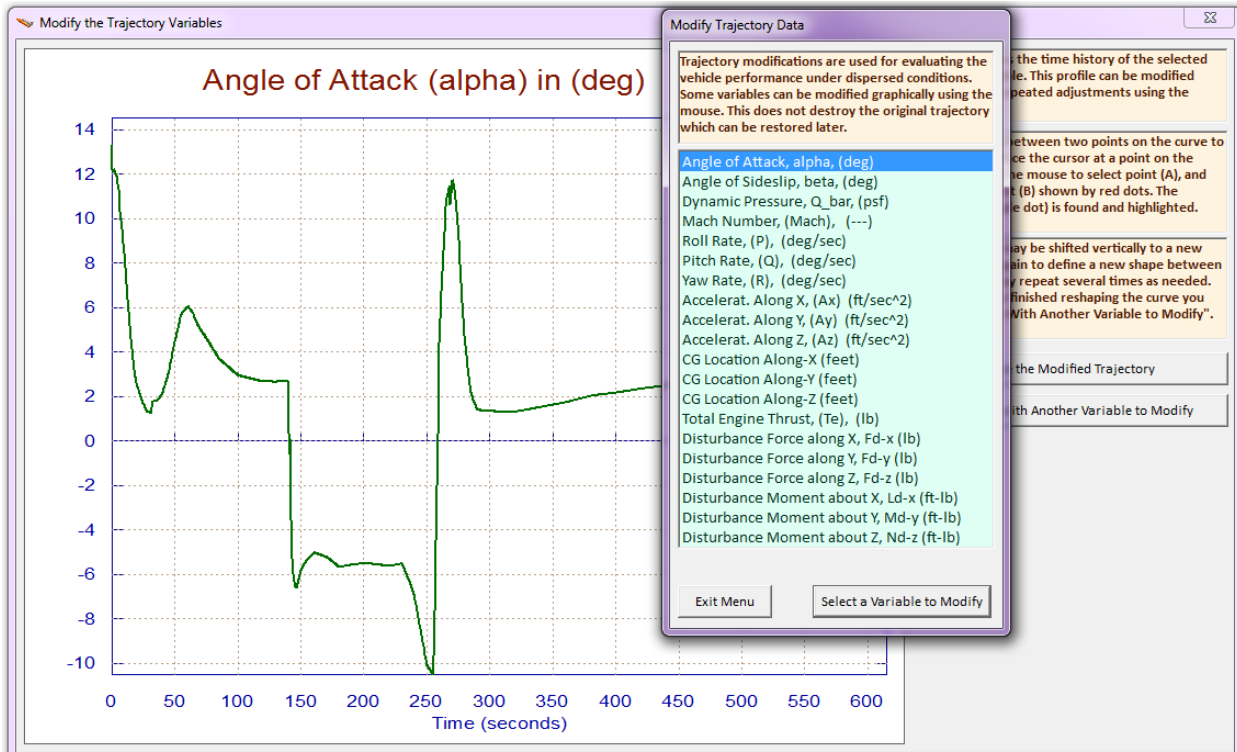


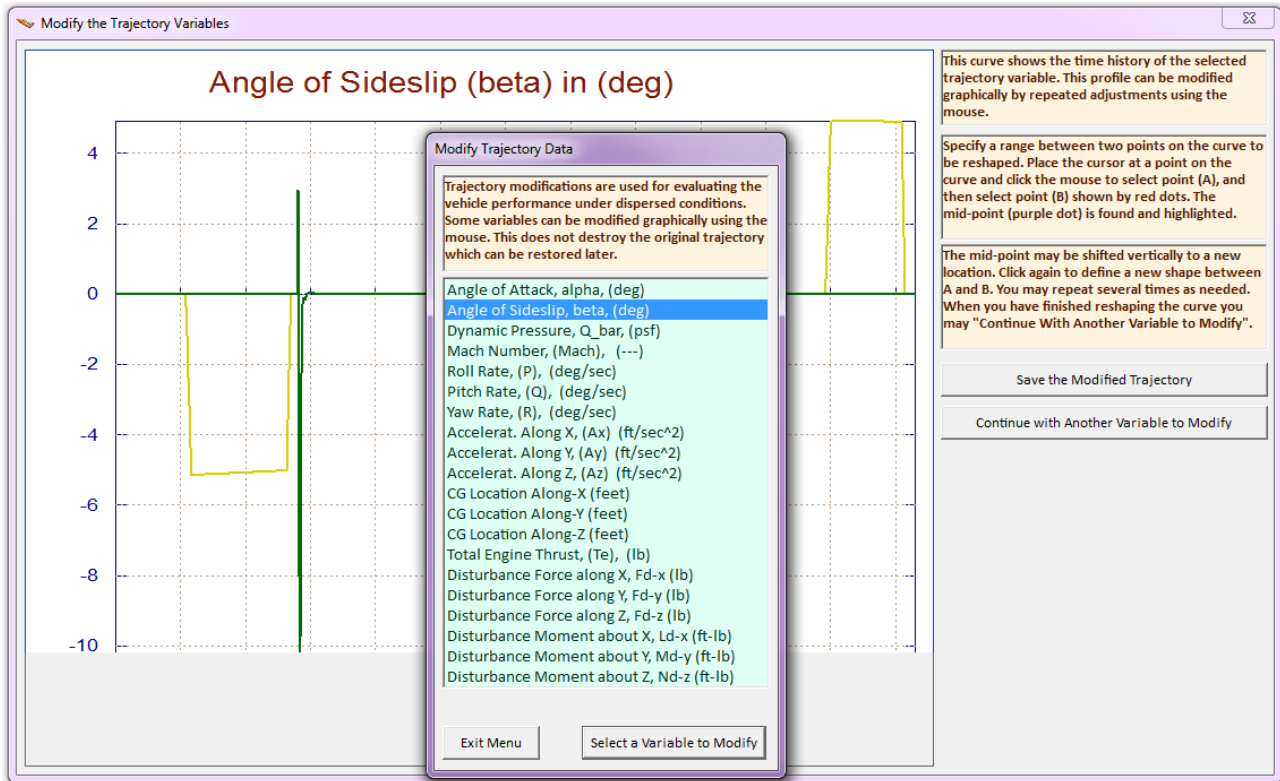
The Y-CG shift also causes approximately 1 (deg) of sideslip beta and a small bank angle (phi).

4. Trimming with Wind-Shear Disturbances

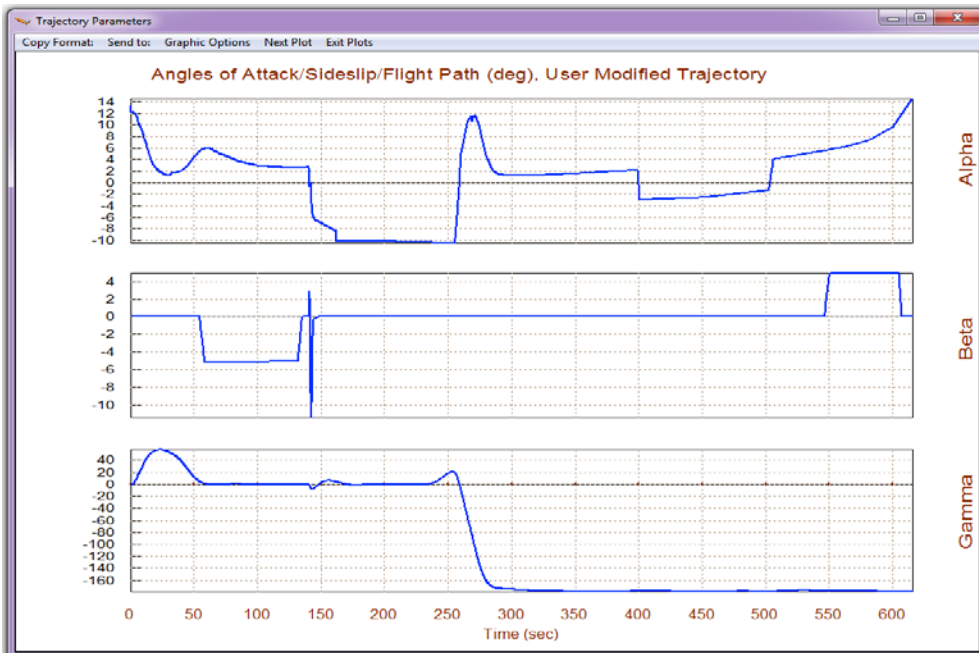
Wind-shear disturbances cause α and β variations from the nominal trajectory and the aircraft must have the control authority required to trim the additional moments and forces along the 4 trim directions. We define the wind-shear in terms of α and β variations from the nominal trajectory values. Wind-shear is introduced by graphically modifying the α and β trajectories from nominal, the same way we modified the CG in Section 3. From the Trim main menu we must select option (2) again to plot and modify the trajectory, but first we must make sure that the original trajectory is restored by going back to the "Graphic Options" menu and clicking on "Restore the Original Trajectory". From one of the trajectory plots, go to the horizontal top menu bar and click on "Graphic Options", and then from the vertical pop-up menu select the option "Modify a Trajectory Plot Using the Mouse". A menu comes up showing the trajectory parameters that can be modified. Select the angle of attack and click on "Select a Variable to Modify". A plot of alpha versus time appears as a green curve in the

window-dialog below. Using the mouse this curve can be modified it in a couple of time periods as shown below. The modified alpha curve is shown by the yellow line below the original trajectory. It was shifted approximately 5°, to represent the effects of a wind-shear, in the time ranges between 180-240 sec, and between 400-500 sec. Now click on "Continue with Another Variable to Modify", and from the trajectory parameters menu select the angle of sideslip.





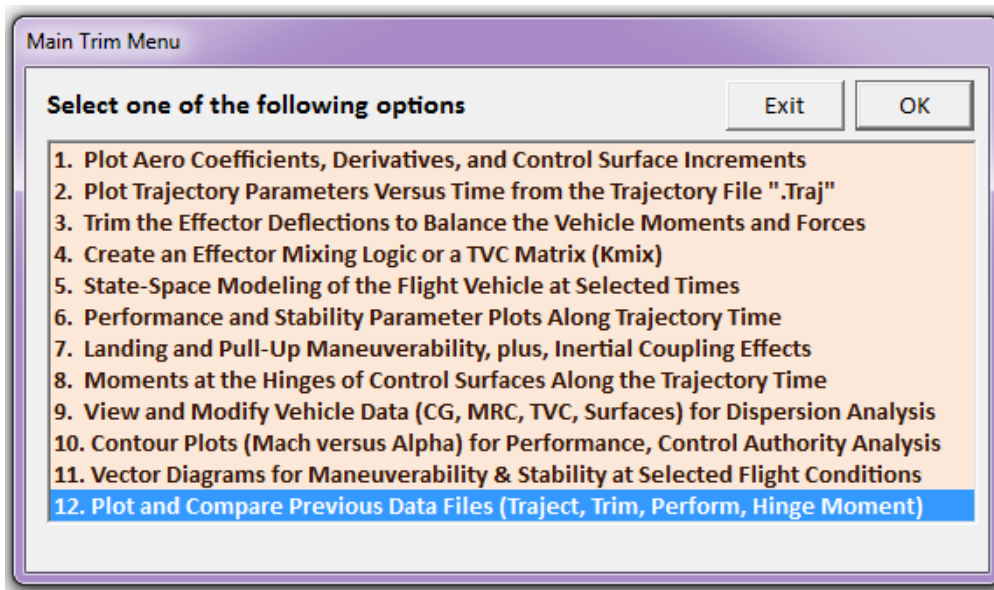
The original angle of sideslip (green) is mostly zero except for the short transient during the roll flip. Using the mouse we modify it in a couple of places by shifting it approximately $\pm 5^\circ$ in the time ranges between 70-130 sec and between 550-600 sec, as shown above by the yellow line. Click on "Save the Modified Trajectory" and it gets saved in file "Roll_Pitch_Man1.Traj" which was renamed "Roll_Pitch_abv.Traj". Click on "Exit Menu" and check the modified trajectory, shown below, and from the top menu bar click on "Exit Plots" to return to the Trim main menu.



From the Trim main menu now select option (3) to trim the effectors as before, but now with the wind-shear trajectory. In the following menu do not select an initialization (.Trim) file, and from the menu that defines the dofs to be balanced select the three moments plus the axial acceleration, like before. The new trim file is saved by the program in "Roll_Pitch_Man.Trim" which was renamed to "Roll_Pitch_abv.Trim".

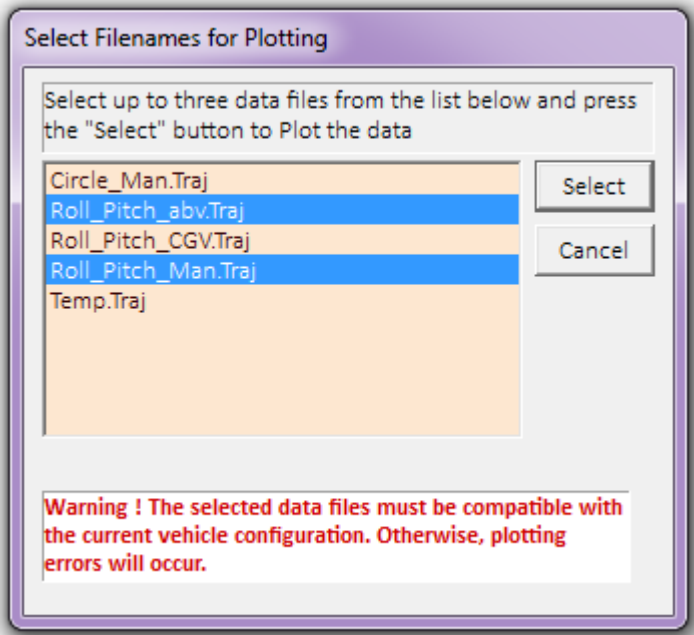
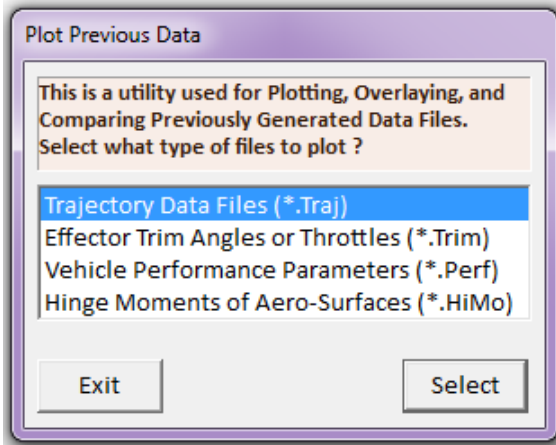


We now return to option (12) to plot and compare the two sets of data created: the two trajectories and the two trim files.



Let us first compare the two trajectory files: the original trajectory in file "*Roll_Pitch_Nom.Traj*" and the (α, β) modified in file "*Roll_Pitch_abv.Traj*". From the data type menu select the trajectory type of files that have an extension (.Traj) and from the filename selection menu select the two trim files. The modified trajectory is shown in blue and the original is red. Their main differences are in the angles of attack and sideslip because of the modification we made.

Return to the menu that plots existing data and now select the trim type of files with extension (.Trim) and from the filename selection menu select the two trim files, i.e. the original trim using the nominal trajectory that was saved in "*Roll_Pitch_Nom.Trim*", and the recently created trim file "*Roll_Pitch_abv.Trim*" that includes the trim effects from the wind-shear disturbances. The 5° beta disturbances cause the vehicle to bank. Near landing the bank angle is about 6° . The aileron and rudder deflect accordingly to balance the rolling and yawing moments. The alpha disturbances cause further elevon deflection which is required to balance the pitching moment. The increased drag due to the elevon deflection is compensated with a slight increase in thrust.



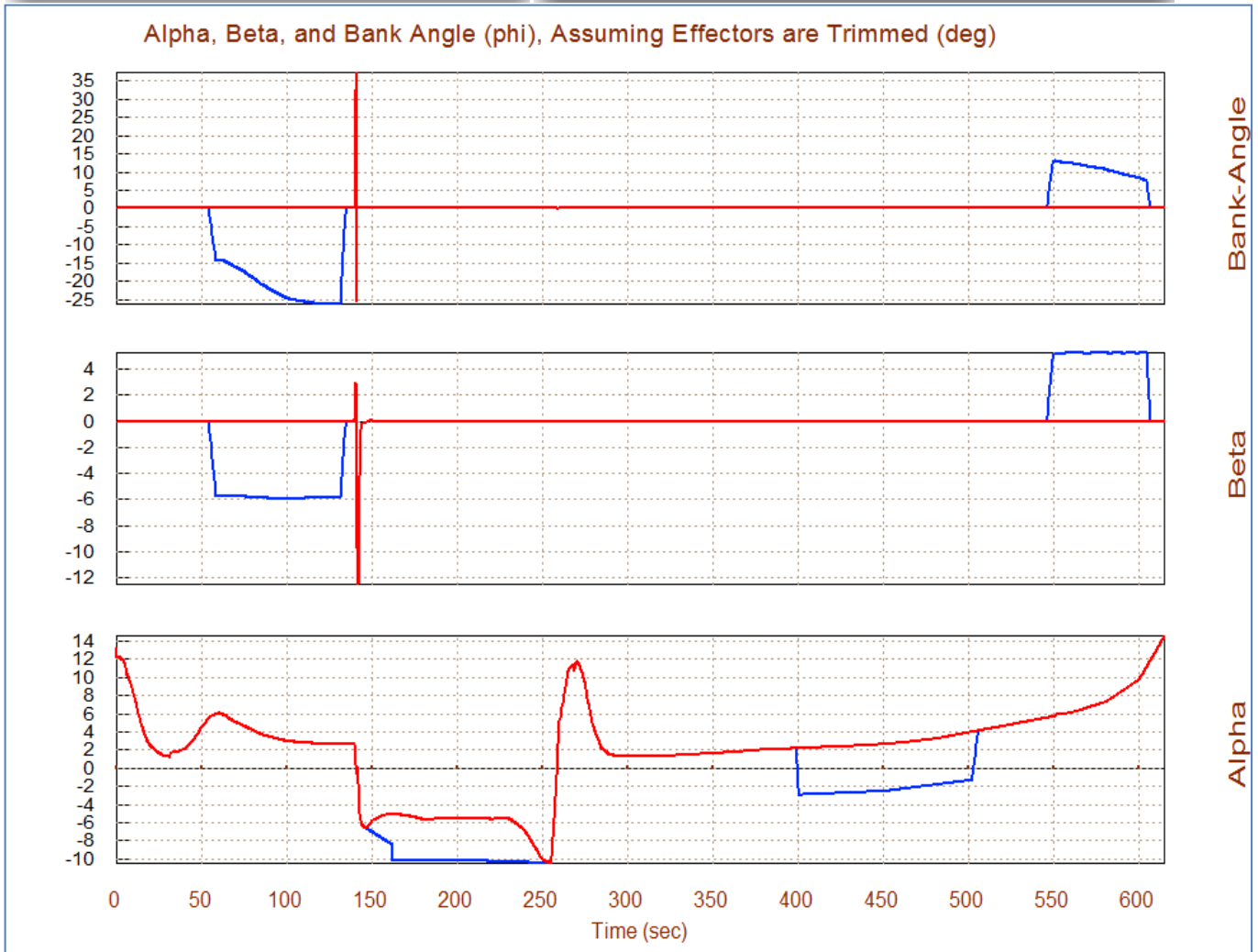
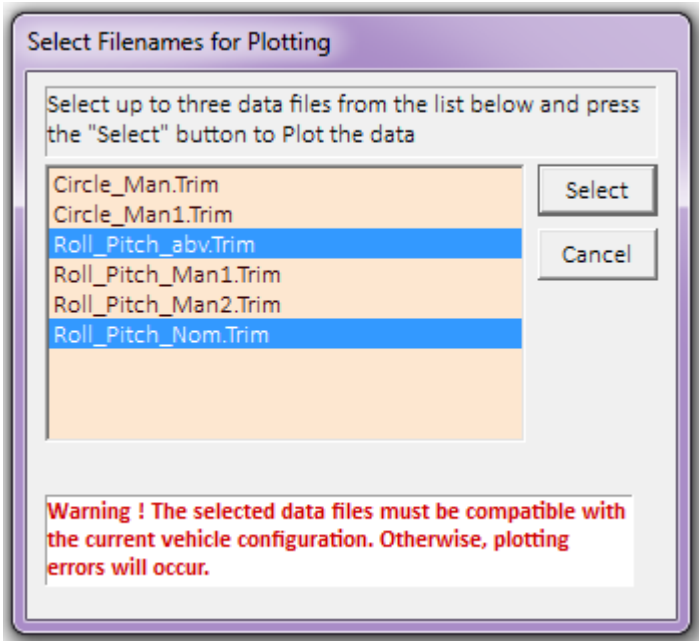
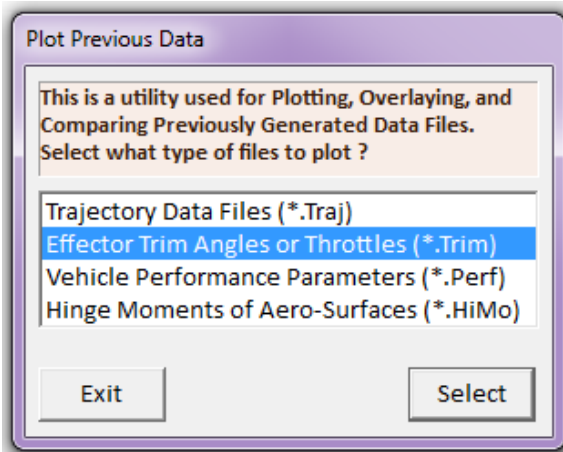
Angles of Attack/Sideslip/Flight Path (deg), User Modified Trajectory



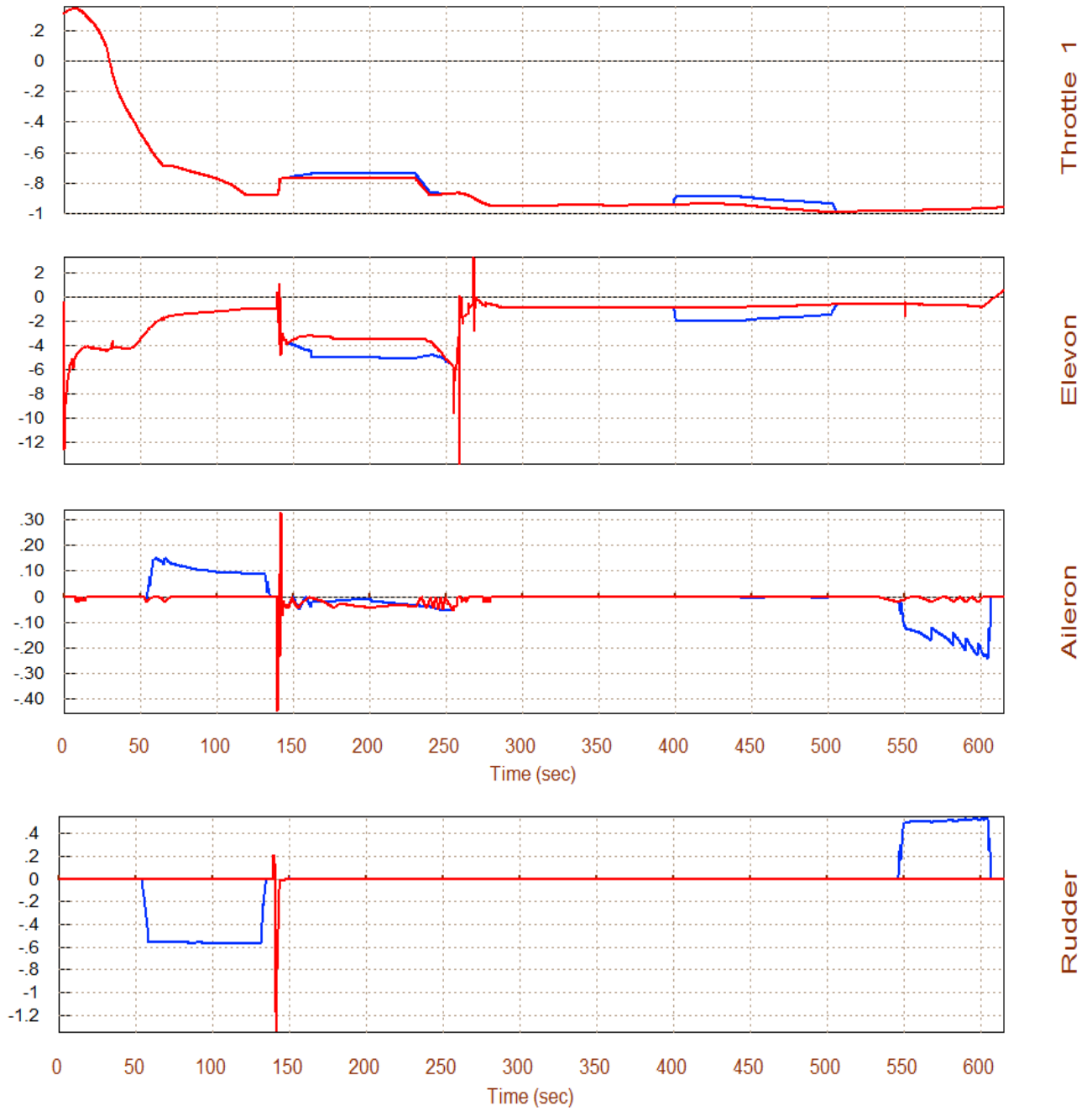
Alpha

Beta

Gamma



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



5. Performance Evaluation Along the Trajectory

In Section (3) we described a number of parameters that define the vehicle performance, stability and maneuverability characteristics. These parameters are calculated along the trajectory from the aircraft data. Before evaluating the performance parameters, however, the Trim program needs to know how the effectors combine together to control various directions. The mixing logic matrix defines the effector allocation along the directions that we are trimming, four in this case. We have already pre-selected a couple of mixing logic matrices for this example and they are located in systems file "*Mix_Logic.Qdr*". The first one *Kmix_500* was created by the mixing-logic option (4) of the Trim program at t=500 sec and it includes coupling between the effectors as it attempts to decouple interaction between the 4 axes. The second mixing matrix *Kmix0* is a straight forward logic and it does not cross-couple the effectors. It simply uses the elevon for pitch, the aileron for roll, the rudder for yaw, and the engine throttle for axial acceleration control. In this analysis we will first use *Kmix0* which does not include cross-coupling. The matrix has 4 inputs for the 4 control demands (3 rotations plus x-acceleration), and 4 outputs for the 4 effectors (the engine throttle control and the 3 aero-surfaces). Notice that the matrix scaling is not important because the control authority parameters are evaluated relative to the effector saturation level.

```
Gain Matrix for ...
Mixing Logic for F-16 Aircraft (No Coupling)
! This Mixing Logic Matrix Ignores the Dynamic Coupling between the 4 directions.
! It uses the Aileron for Roll, the Elevon for Pitch, the Rudder for Yaw, and
! the throttle control for axial acceleration.
Matrix Kmix0          Size = 4 X 4
-----
      1-Roll          2-Pitch          3-Yaw          4-Ax
1-Thr  0.0           0.0           0.0           1.0
2-Row  0.0           -1.0          0.0          -0.0
3-Row -1.0           0.0           0.0           0.0
4-Row  0.0           0.0          -1.0           0.0
-----
Definitions of Matrix Inputs (Columns):      4
P-dot Roll  Accel Demand About X Axis
Q-dot Pitch Accel Demand About Y Axis
R-dot Yaw   Accel Demand About Z Axis
Ax  Forward Accel Demand Along X Axis

Definitions of Matrix Outputs (Rows):      4
Output:  1 Delta(throttle) of Engine
Output:  2 Elevon  Deflection (radians)
Output:  3 Aileron Deflection (radians)
Output:  4 Rudder  Deflection (radians)
-----
```

In order to read the matrix file we must restart the Flixan program and from the Flixan main menu select "*Analysis Tools*", from the drop-down menu select "*Flight Vehicle/ Spacecraft Modeling Tools*" and then "*Trim/ Static Performance Analysis*", as before. From the Trim filename selection menu choose the same F16 data files, and from the (.Inp) and (.Qdr) filename selection menu choose the systems file "*Mix_Logic.Qdr*", as shown. From the Trim main menu select option (6) which calculates the performance parameters as it was described in Section (3).

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 F16.Mass	Surface Hinge Moments NO DATA FILE
Trajectory Data Roll_Pitch_Man.Tra	Aero Damping Derivat F16.Damp
Basic Aero Data F16.Aero	Propulsion Data F16.Engn
Contr Surface Aero Coeff F16.Delt	Aero Uncertainties NO DATA FILE
Slosh Parameters NO DATA FILE	

OK

Enter Filenames

Enter a File Name containing the Input Data (xxx.Inp)	Enter a File Name containing the Quadruple Data (xxx.Qdr)
NewFile.Inp NewFile.Inp	Mix_Logic.qdr Mix_Logic.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)

Notice ...

 A (4 X 4) Mixing Logic Matrix is required

OK

The following dialog is used for defining the source of the mixing logic matrix. We will not let the program calculate one, but we must choose the top option to read an already existing matrix from file "Mix_Logic.Qdr". We click on the second matrix Kmix0, we first take a look at it, and then select it, as shown below. You must also select the maximum expected alpha and beta disturbances.

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: Mix_Logic.qdr, or let the program calculate it

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

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

Select a Mixing Matrix from Systems File

Create a Mixing Matrix Using All Effectors at 100% Participation

Create a Mixing Matrix by Adjusting the Effector Contributions

Select a Gain Matrix

Select one of the following Matrices from the Systems File

KMIX_500	: Mixing Logic for F-16 Aircraft Roll and Pitch Maneuver at Time: 500.00
KMIX0	: Mixing Logic for F-16 Aircraft (No Coupling) , SIZE = 4 X

K Matrix Name

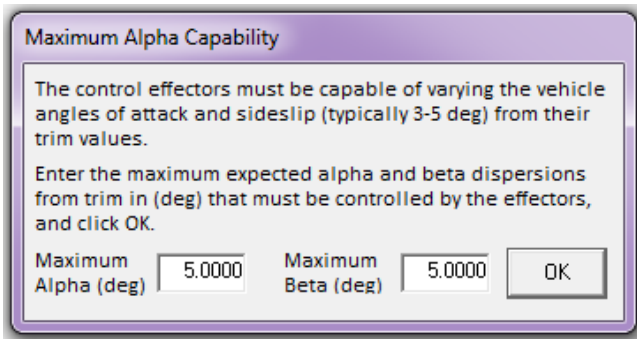
Mixing Logic for F-16 Aircraft (No Coupling)

Inputs | **Outputs** | **Matrix Description**

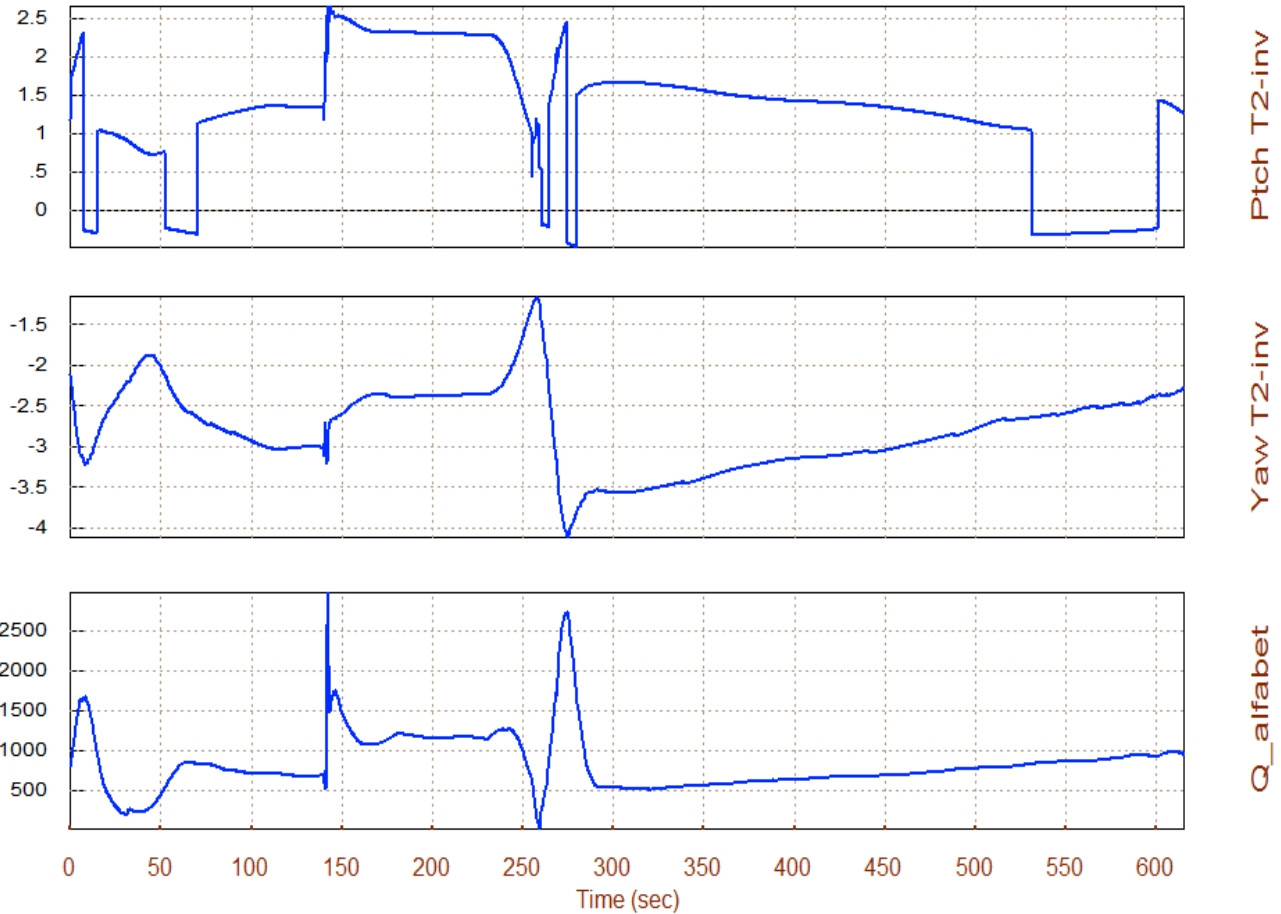
This Mixing Logic Matrix Ignores the Dynamic Coupling between the 4 directions. It uses the Aileron for Roll, the Elevon for Pitch, the Rudder for Yaw, and the throttle control for axial acceleration.

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

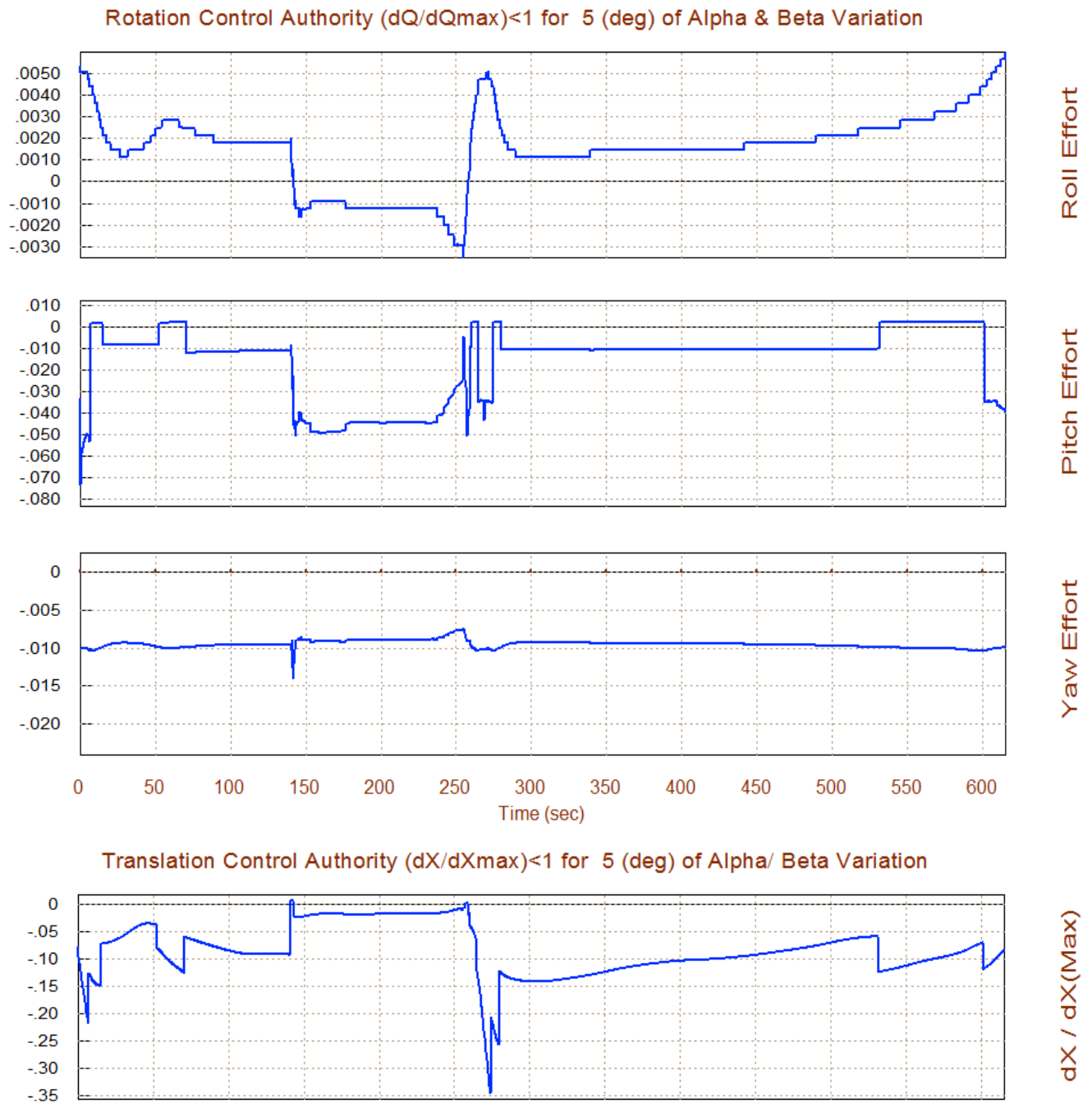
Repeat to change other Inputs, Outputs, or Matrix Elements. Then click on "Save Changes" to save the new values and titles or Exit the dialog.



Short-Period (w) / Time-to-Double-Ampl-Inverse (/sec), $Q_{\alpha\beta}$ (deg-lb/ft²)

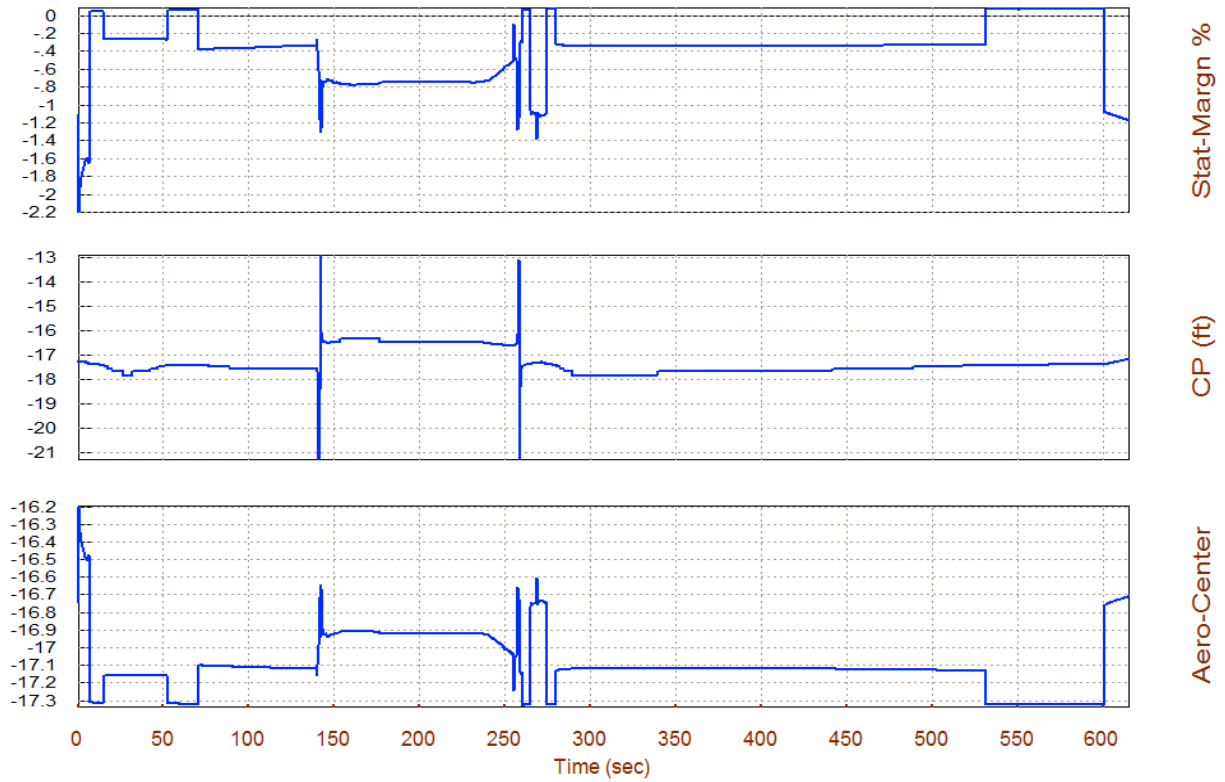


The pitch T2-inverse parameter is mostly positive which indicates that the aircraft is statically unstable in pitch. The peak amplitude is 2.5 which means that the time-to-double amplitude equal to 0.4 sec, which is acceptable. A little instability improves vehicle maneuverability. In the lateral direction, however, the T2-inverse parameter is negative which means that it is statically stable. It has a Dutch-roll resonance varying between 2 to 3.5 (rad/sec). It peaks briefly during the pitch maneuver. The combined (Q_{α} & Q_{β}) normal load due to max alpha and beta peaks to 2,500 (psf-deg), which is also within range.

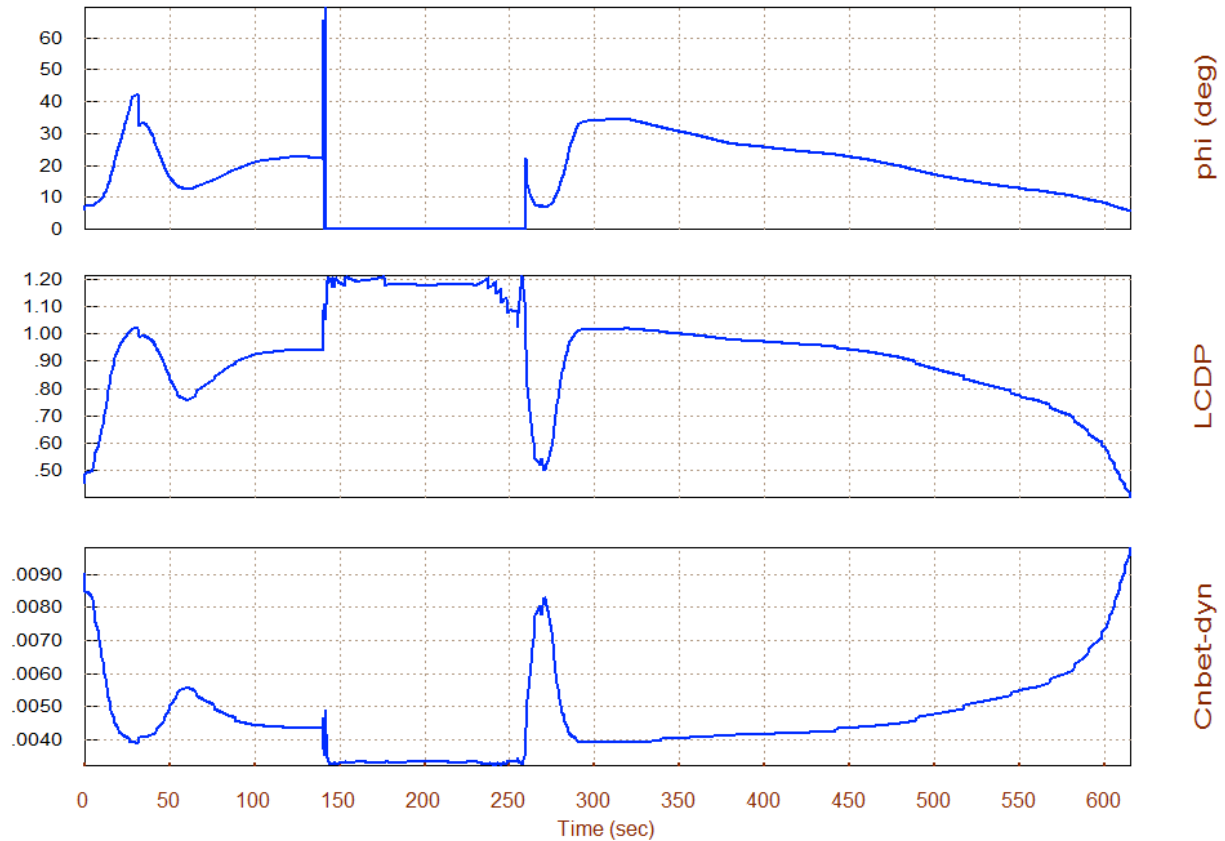


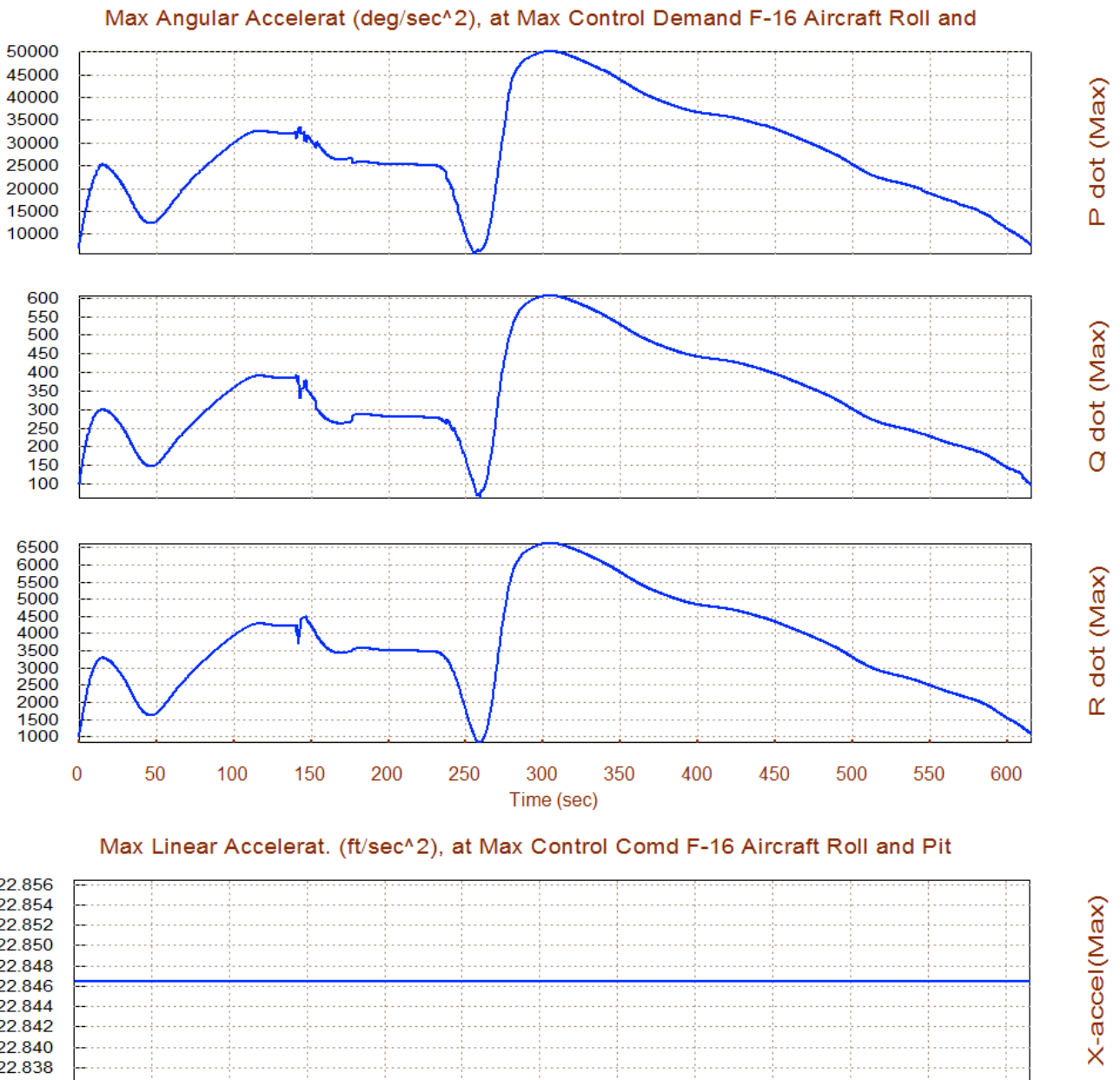
The above plots show the aircraft control authority to react against the max alpha and max beta disturbances as they are defined by equations (3.24) and (3.26). The control authority should be less than 0.5 in all directions. This aircraft has obviously plenty of control authority against the $(\alpha_{max}, \beta_{max})$ disturbances in all 4 directions. The LCDP and the $Cn\beta$ -dynamic they are both very good. The bank angle (ϕ) (with a cross-wind shear of $\beta=5^\circ$) is approximately $\phi=5^\circ$ at landing, which is also fine.

Static Margin, Center of Pressure, Aero-Center (ft), F-16 Aircraft Roll and Pitc



Bank Angle, LCDP Ratio, $C_{n_beta_dynam} / \text{deg}$, F-16 Aircraft Roll and Pitch Maneuve

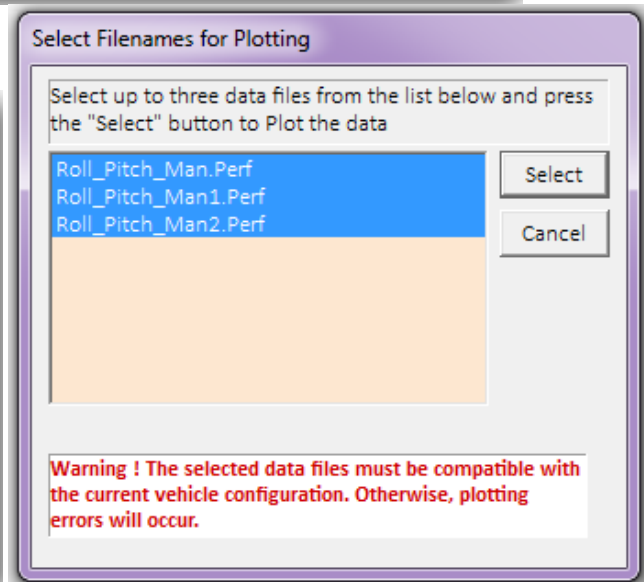
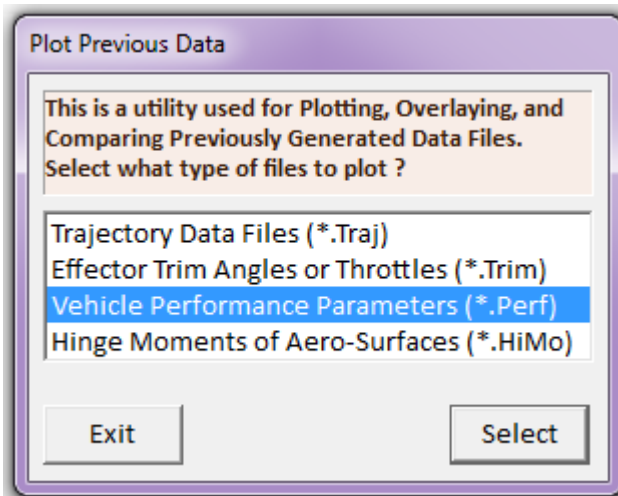
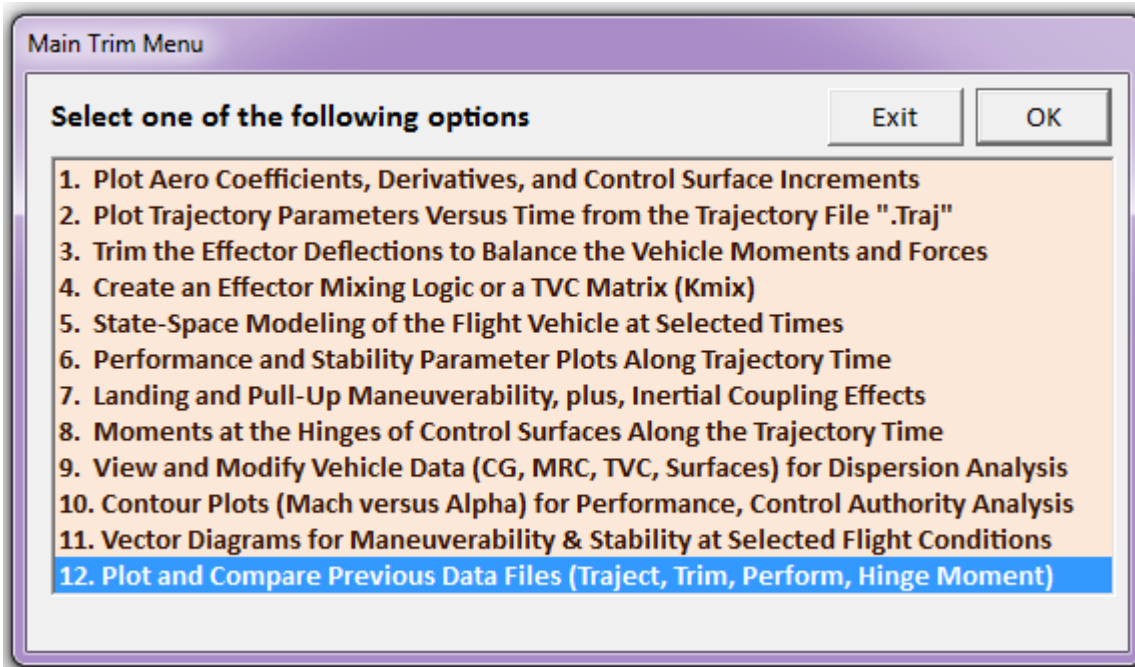


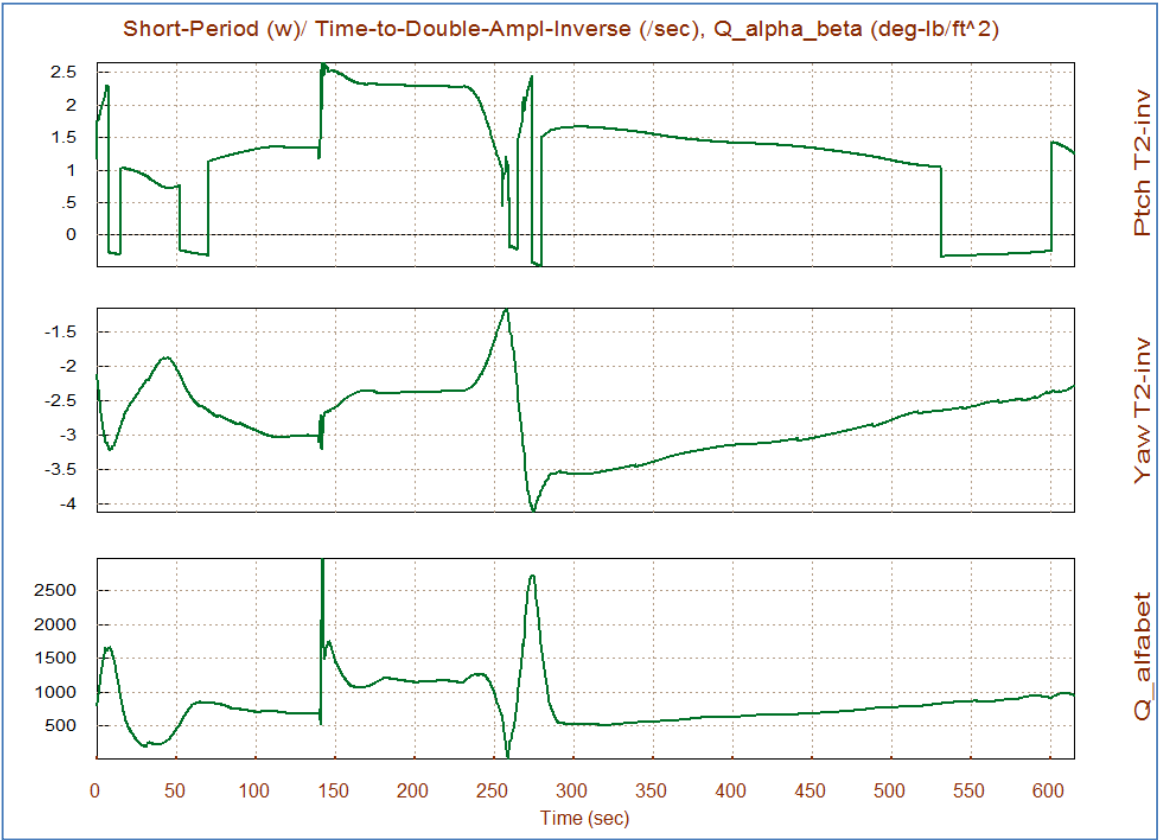


These are the maximum accelerations achieved when the controls are maximized.

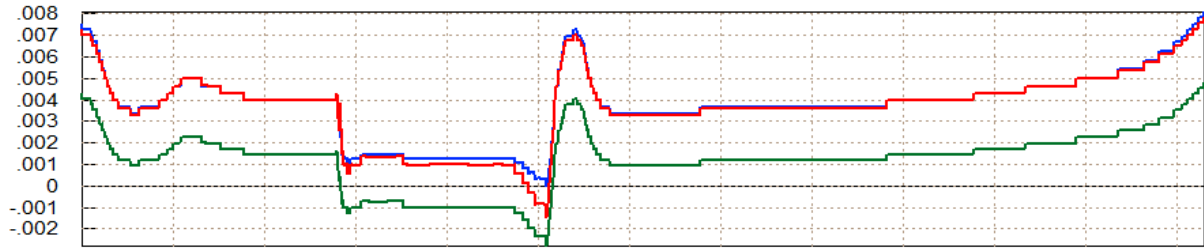
Let us now repeat the performance analysis using two additional mixing-logic matrices and compare the performance results between the three choices. We repeat the same process described in this section 5, but this time we choose the matrix *Kmix_500* from file "*Mix_Logic.Qdr*". This matrix introduces some cross-coupling between the effectors. It was calculated by Flixan at time $t=500$ sec, and it is intended to provide some form of decoupling between axes at this flight condition. In our third selection instead of using a constant mixing logic matrix from file we click on the second option from the mixing-logic selection dialog which allows the program to calculate a matrix at each time step along the trajectory. The performance parameters from the three processes are automatically saved by the program in files (*Roll_Pitch_Man.Perf*, *Roll_Pitch-Man1.Perf*, and *Roll_Pitch_Man2.Perf*).

Return to the Trim menu and select option (12) to plot the data. From the file type selection menu this time select the third option for plotting performance parameters type of data (.Perf). From the filename selection menu on the right select all three files. The top one is the most recently created file where the program calculates a variable mixing matrix (blue curve). The middle file was created with the Kmix_500 matrix that includes effector cross-coupling generated at t=500 sec (red). The bottom file contains the original performance data created with matrix Kmix0 that has zero cross-coupling (green). Some of the performance parameters are not affected by the mixing-logic matrix and they are the same in all 3 cases. The differences between the 3 cases are small but overall the fixed Kmix0 has some advantage in control authority and in the bank angle with cross-wind.

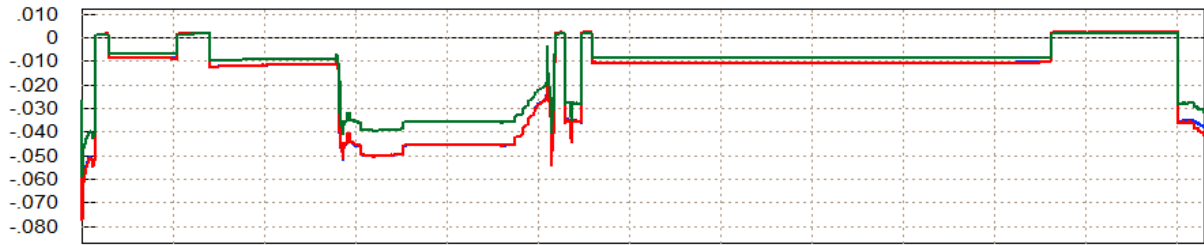




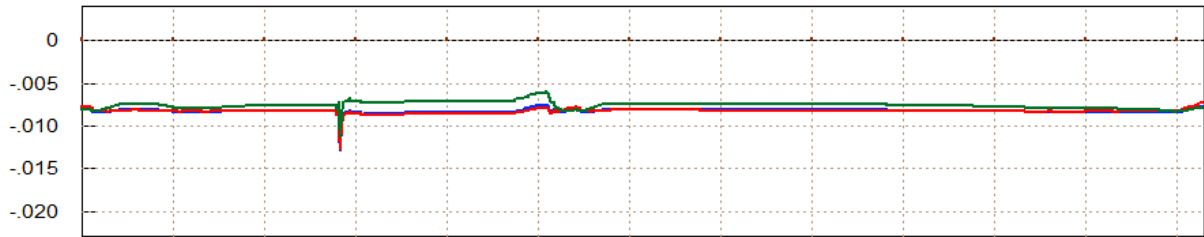
Rotation Control Authority (dQ/dQ_{max}) < 1 for 5 (deg) of Alpha & Beta Variation



Roll Effort



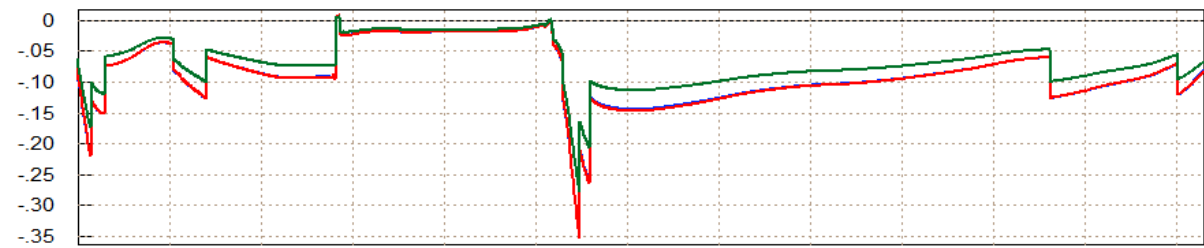
Pitch Effort



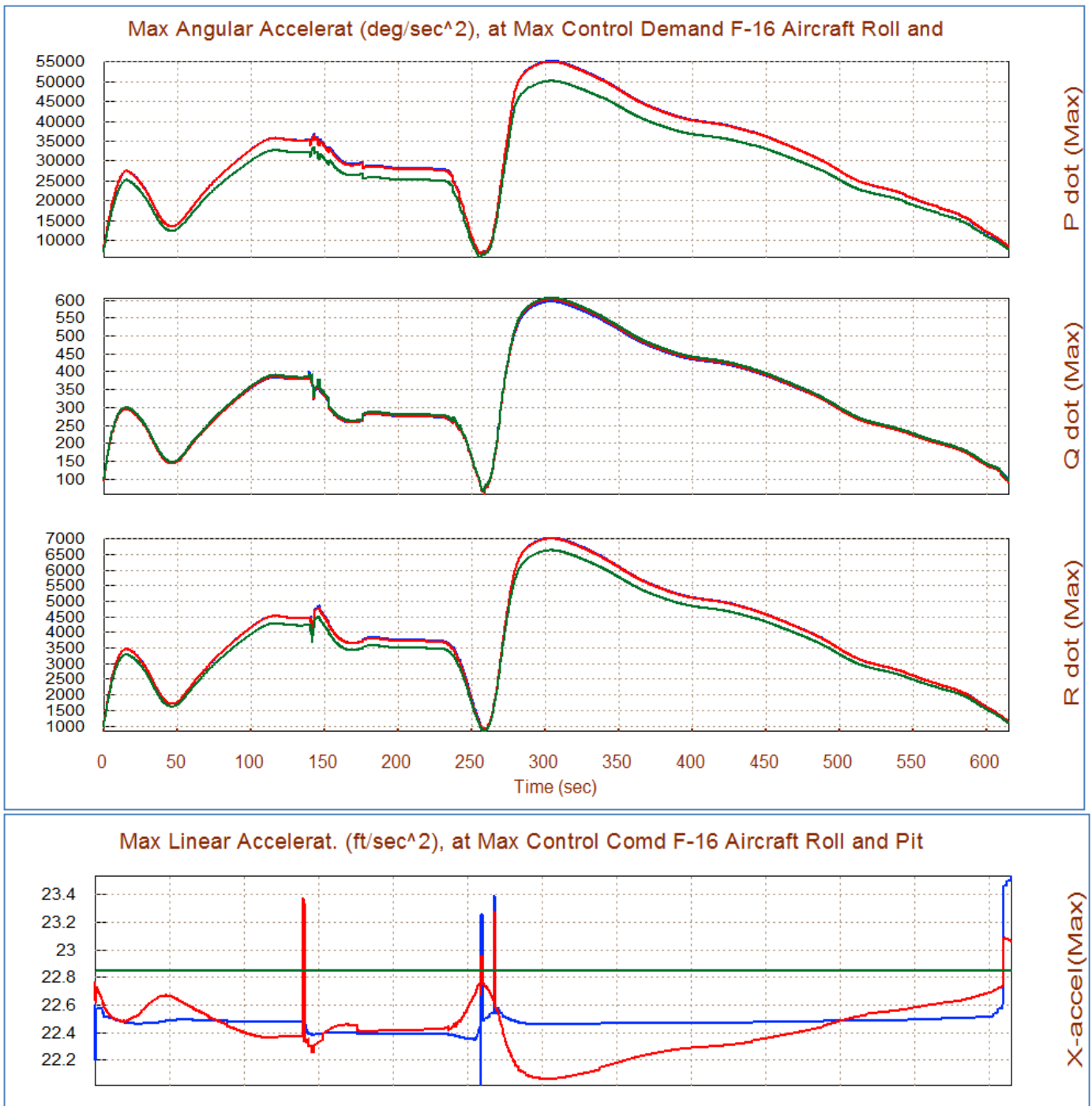
Yaw Effort

Time (sec)

Translation Control Authority (dX/dX_{max}) < 1 for 5 (deg) of Alpha/ Beta Variation



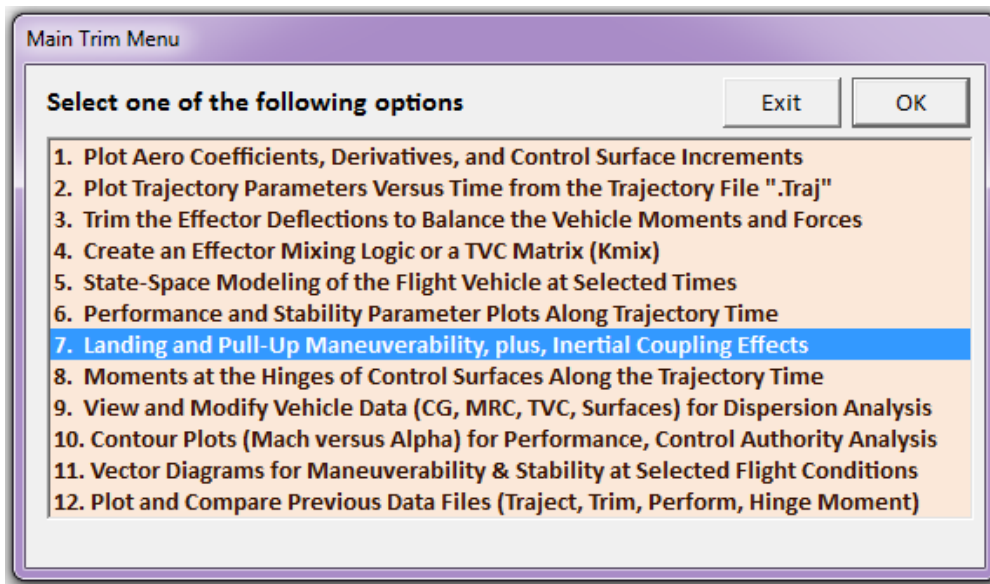
$dX / dX(Max)$



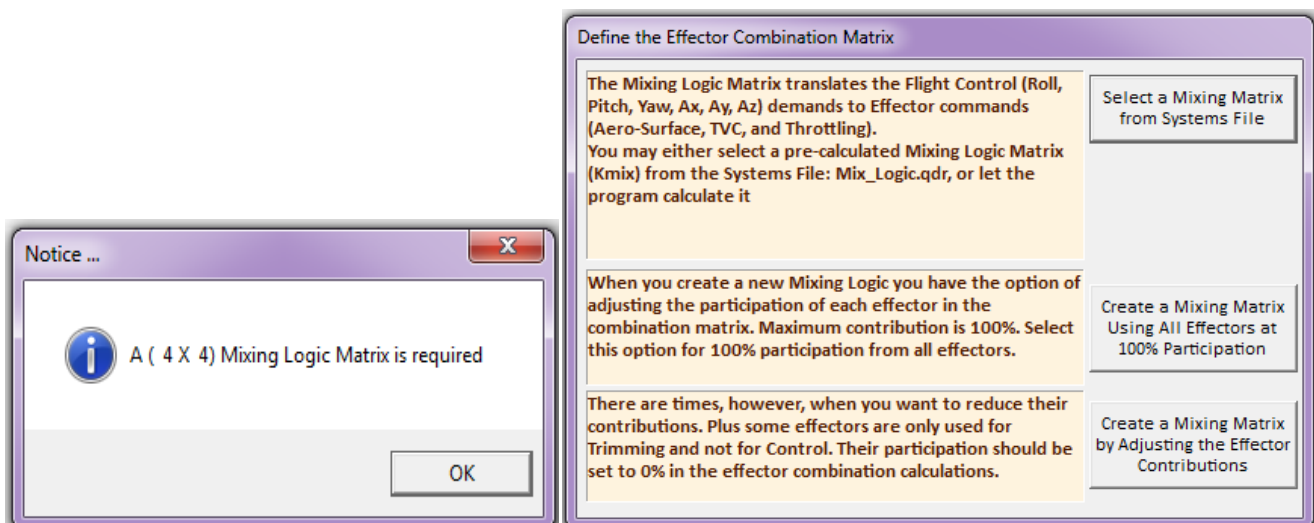
The decoupling matrices generated by the Flixan program (both fixed and variable) provide some additional max acceleration in the roll and yaw directions. Overall, Kmix0 has a little more advantage in performance, although it does not provide axial decoupling.

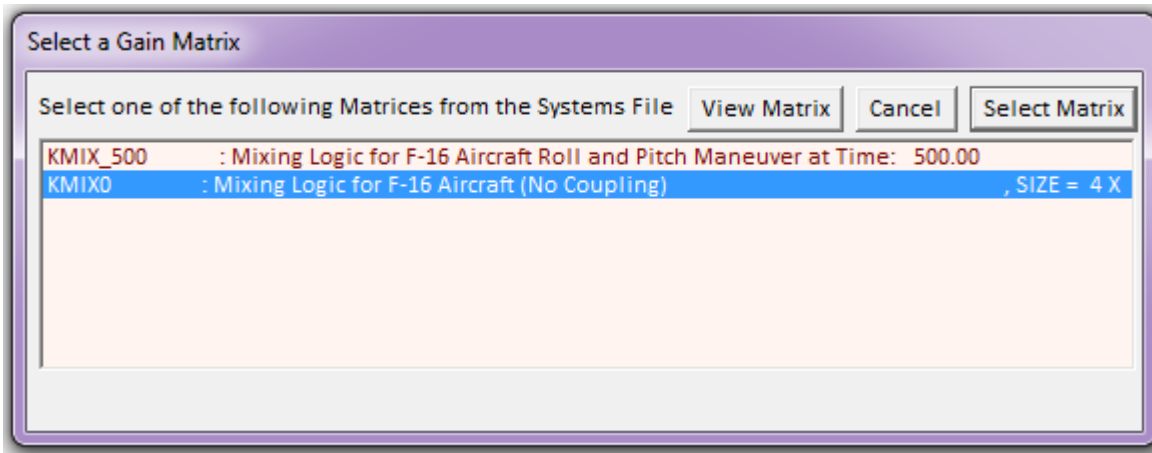
6. Additional Maneuverability Parameters

Option (7) is used for evaluating four additional performance tests which are mainly used for aircraft maneuverability analysis, although the can also be applied to other types of vehicles. The first check analyzes the aircraft maneuverability to perform pull-up maneuvers. The second analyzes the roll and yaw control authority to handle cross-wind during landing and the resulting bank angle. The last two analyze if the vehicle has the control authority required to handle induced pitch and yaw inertial coupling effects due to roll maneuvering. The analysis in this case is performed at specific flight conditions at a selected trajectory time. So from the Trim main menu select option (7) as shown.

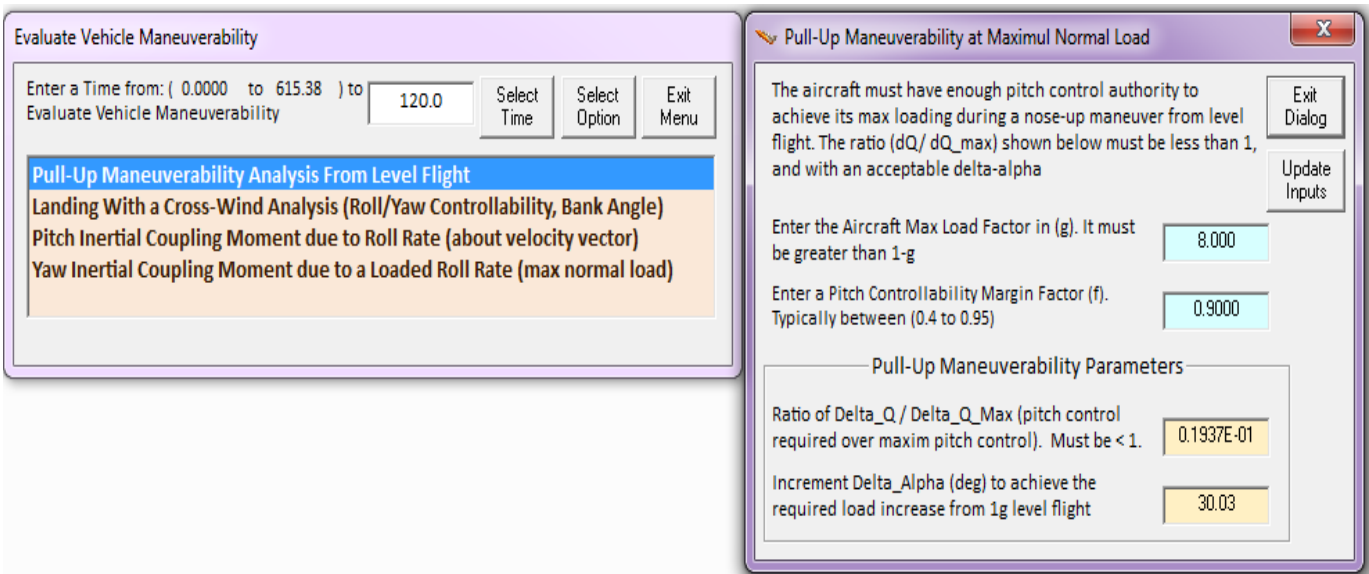


Like before, the effector mixing logic is needed in the performance calculations. We must read the mixing matrix Kmix0 that was used earlier. In the effector mixing logic selection dialog click on the top button "Select a Mixing Matrix from File" to select the matrix Kmix0 from file "Mix_Logic.Qdr", as before.

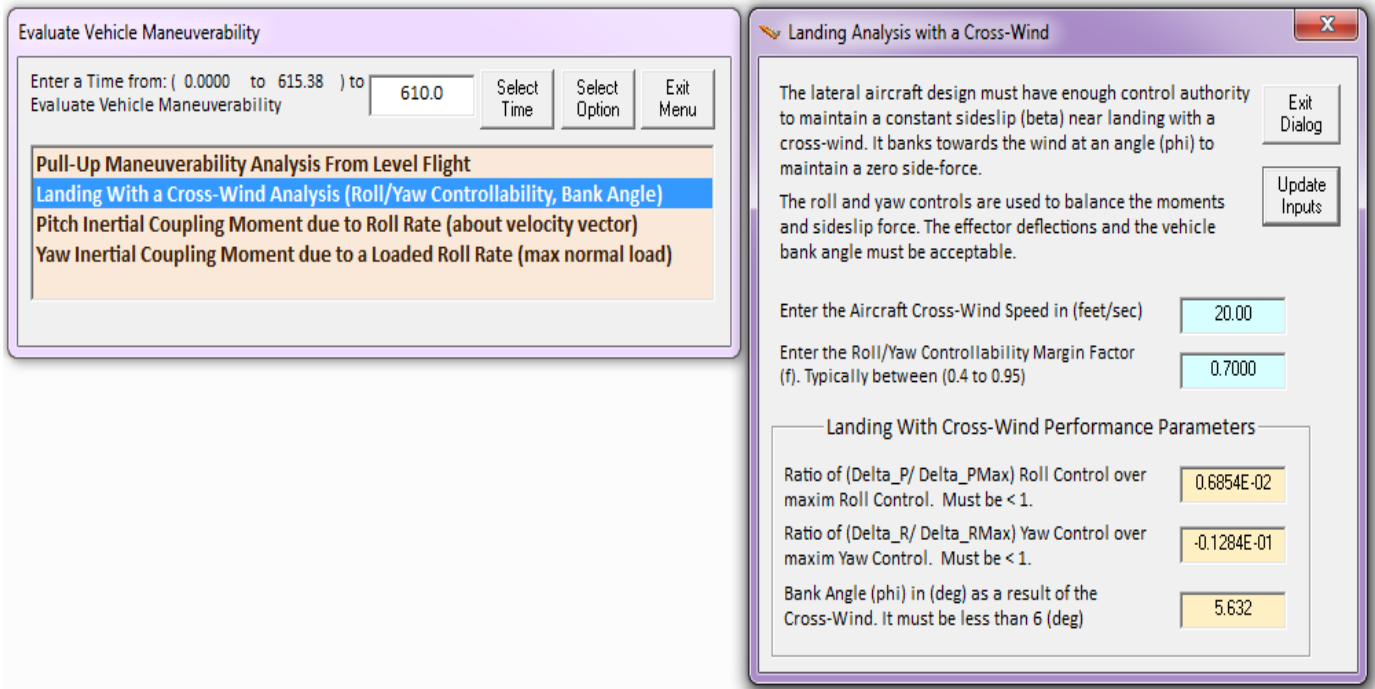




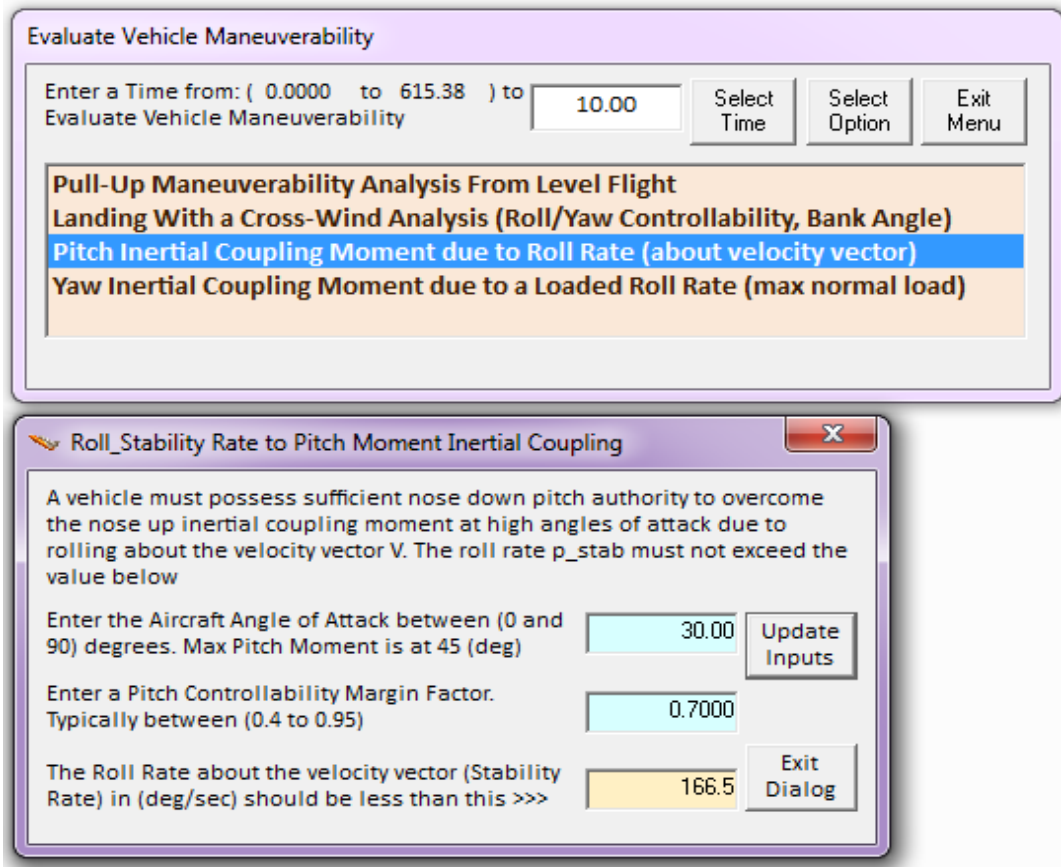
The following menu/dialog shows the four maneuverability analysis options, but you must first enter a time along the trajectory. In this case we enter 120 sec, which corresponds to level flight before the 180° flip, and click on the "Select Time" button. From the menu we select the top option which calculates the control authority required to perform a pull-up maneuver from level flight at the aircraft's max load factor which is 8g, see equation (3.41). In the pull-up maneuverability dialog on the right, we must enter the aircraft load factor and the control allocation factor which in this case it is 0.9, meaning that we don't want to use more than 90% of our max pitch control (δQ_{FCS_max}) for the maneuver, which in this case it is elevon. Click on the "Update Inputs" button and read (in the yellow fields at the bottom) the delta in control authority (from level flight) and the change in alpha ($\delta\alpha$) that is required for the pull-up maneuver at max load. It shows that only 2% of the allocated max pitch control (δQ_{FCS_max}) is required to pull 8g's, and it does it by increasing the angle of attack $\delta\alpha=30^\circ$, see equation (3.42).



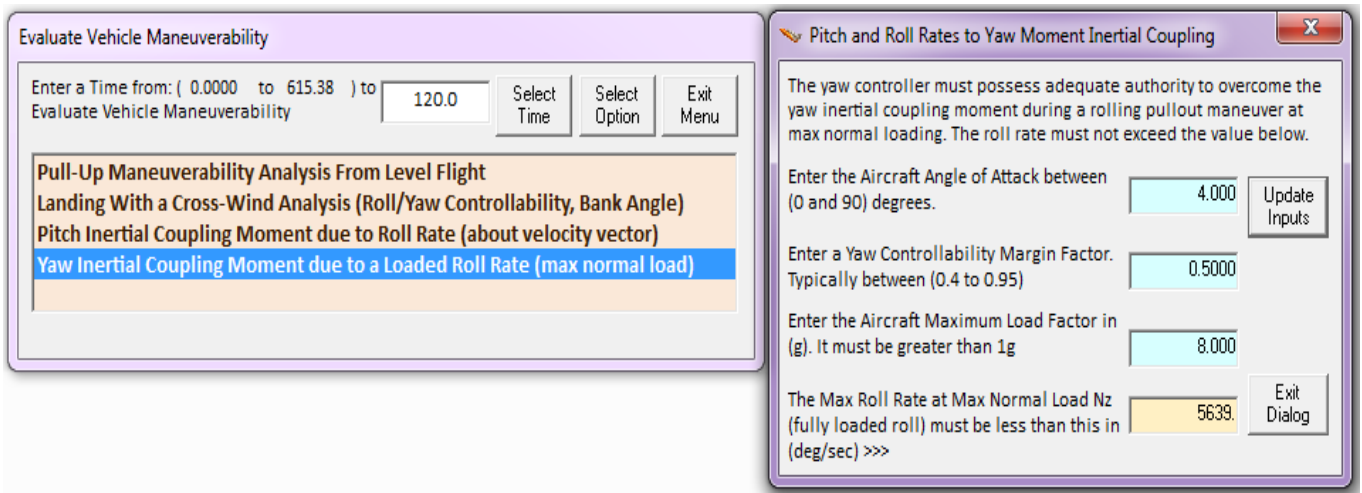
Click on "Exit Dialog" and it returns to the previous 4 options menu. This time we will analyze the vehicle's ability to land with cross-winds. We must first enter a time near landing, 610 sec, and click on "Select Time". Then we must chose the second option "Landing with Cross-Wind" and click on "Select Options". In the dialog on the right, we enter the cross-wind speed, which is 20 (ft/sec) and a controllability margin factor less than one to allow some margin for other functions, and click on "Update Inputs". The yellow fields at the bottom show that the aileron and rudder control efforts to counteract the cross-wind are very small. Orders of magnitude below 1 indicating plenty of margin before it saturates the controls. The bank angle due to the cross-wind is 5.6°, which is acceptable.



The third option analyzes the roll to pitch inertial coupling. When the vehicle is rolling about its velocity vector it produces a pitch torque that has to be taken out by the elevon. Let's choose a different time and in the RHS dialog enter the angle of attack about which the vehicle is rotating $\alpha=35^\circ$, the pitch controllability margin factor (0.7), (meaning that you don't want to allocate more than 70% of pitch control against roll maneuvering), and click on "Update Inputs". The result in the yellow field at the bottom shows that the max roll rate about the velocity vector must be less than 166 (deg/sec). This roll rate can be counteracted with up to 70% of the available pitch control authority (δQ_{FCS_max}).

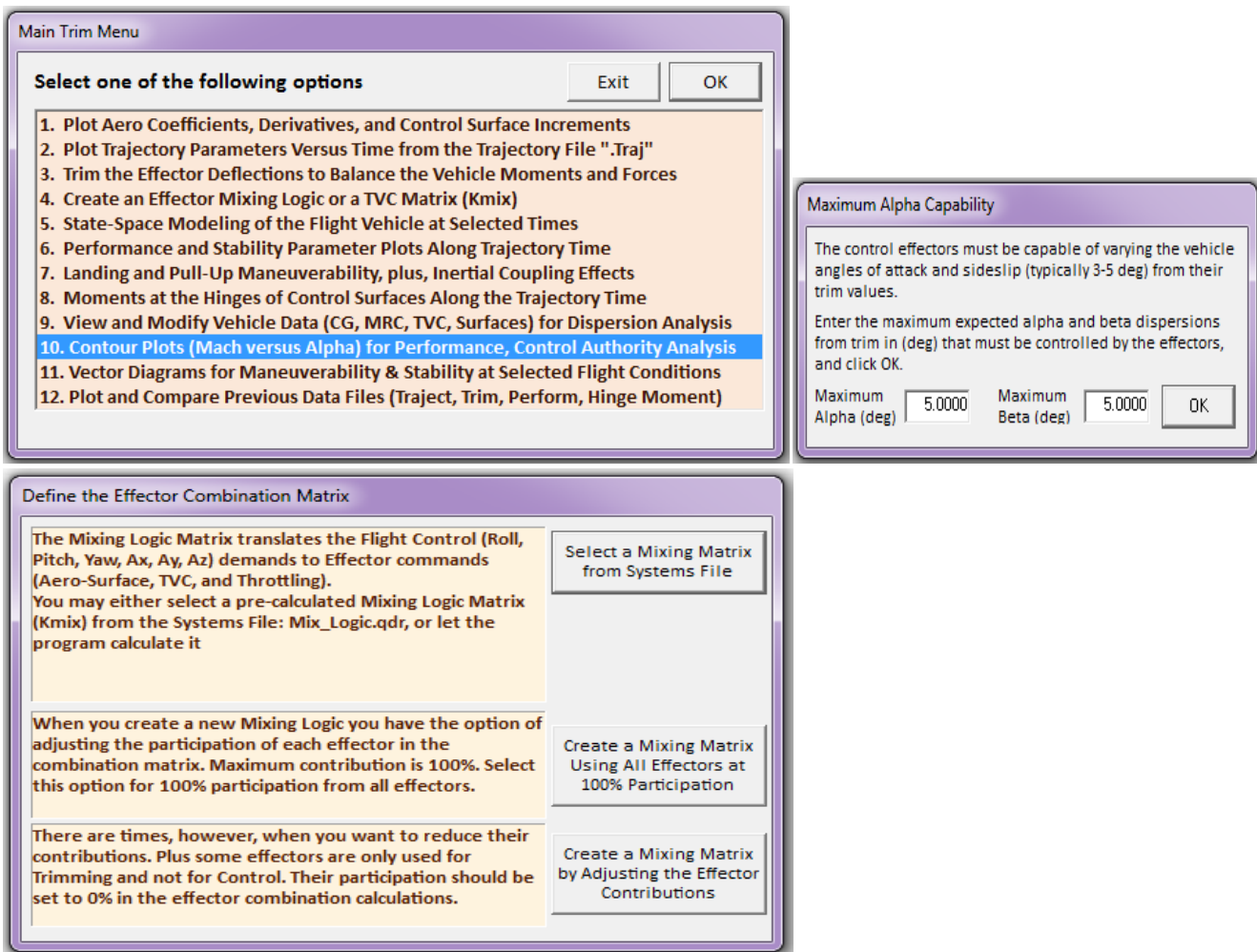


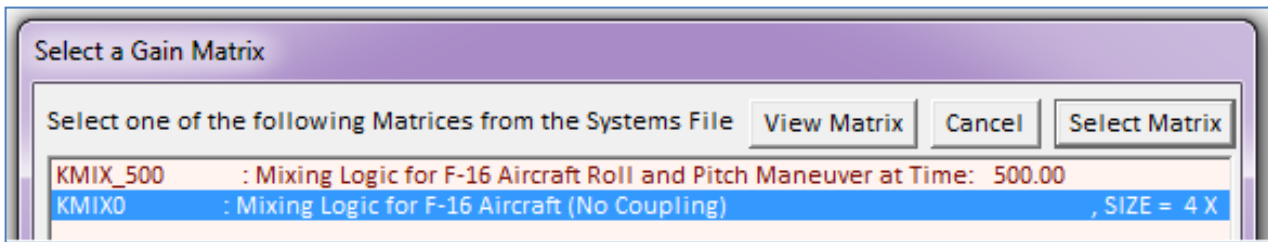
The fourth option analyzes the fighter aircraft capability to roll under maximum normal load. During such a loaded pullout maneuver there is a significant amount of yawing moment generated due to inertial coupling that has to be taken out by the yaw effector which is the rudder. We would like to find out what is the max roll rate under peak normal load that the aircraft is able to achieve within the allocated rudder control authority. Let us initialize from a level flight condition at $t=120$ sec. Choose the fourth option "*Yaw Inertial Coupling due to a Loaded Roll*" and click on "*Select Option*". In the RHS dialog we must enter (in the cyan fields): the angle of attack during the pull-out (4°), the yaw controllability margin factor (0.5), meaning that you don't want to allocate more than 50% of yaw control (δR_{FCS_max}) for this maneuver, which is rudder in this case. You must also enter the aircraft maximum normal load factor, which is (8g). Click on the "*Update Inputs*" button and read (in the yellow field at the bottom) a max roll rate of 5639 (deg/sec). This is the maximum pullout rolling rate under max load that can be achieved without exceeding the allocated rudder authority, which is plenty of roll rate. This completes the additional maneuverability tests.



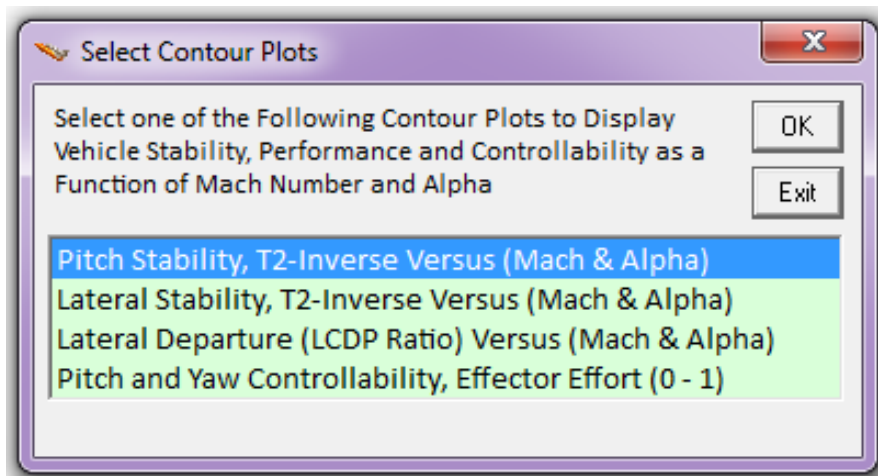
7. Analysis Using Contour Plots

Contour plots are 3-dimensional plots that give us a broader perspective of some important aircraft performance parameters, versus Mach and Alpha, rather than in the vicinity of a trajectory. Occasionally the vehicle may deviate from its target alpha and Mach trajectory or we may want to observe its performance over the entire alpha versus Mach envelope, and to make sure that the envelope does not include any regions of unacceptable performance. It requires the selection of an effector combination logic. In this case we select again the matrix Kmix0 from file "Mix_Logic.Qdr" (discussed earlier), which does not provide any decoupling between the axes. So we have to make sure that this matrix file is selected when starting Flixan. In general, the mixing logic matrix generated by the Flixan algorithm optimizes the control authority of the effector system, but it does not necessarily optimize all vehicle performance parameters and sometimes we may choose a different matrix. Return to the Trim menu, select option (10) which creates the contour plots, and from the dialog that selects an effector combination matrix choose the top option to read a matrix from the systems file, and from the matrix selection menu choose matrix Kmix0, as before. You must also enter the alpha and beta dispersions that define the wind-shear disturbance. Enter 5° for both.

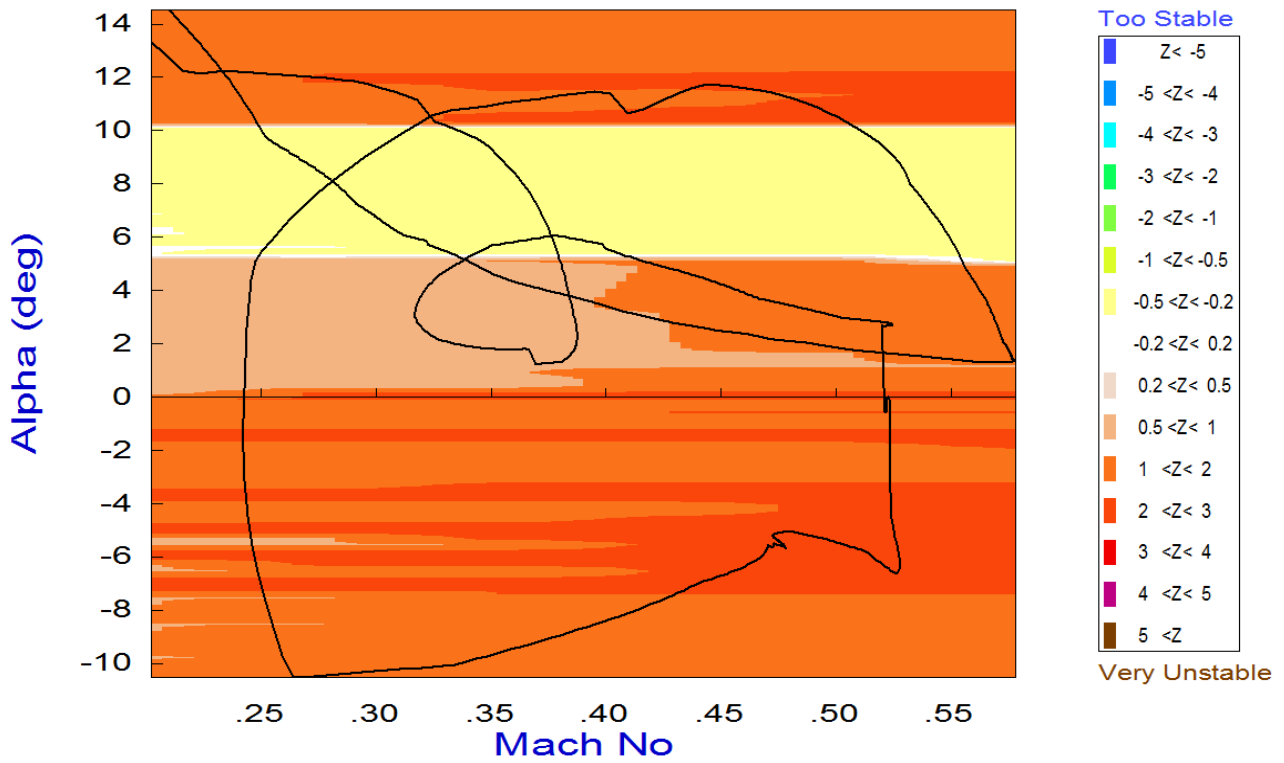




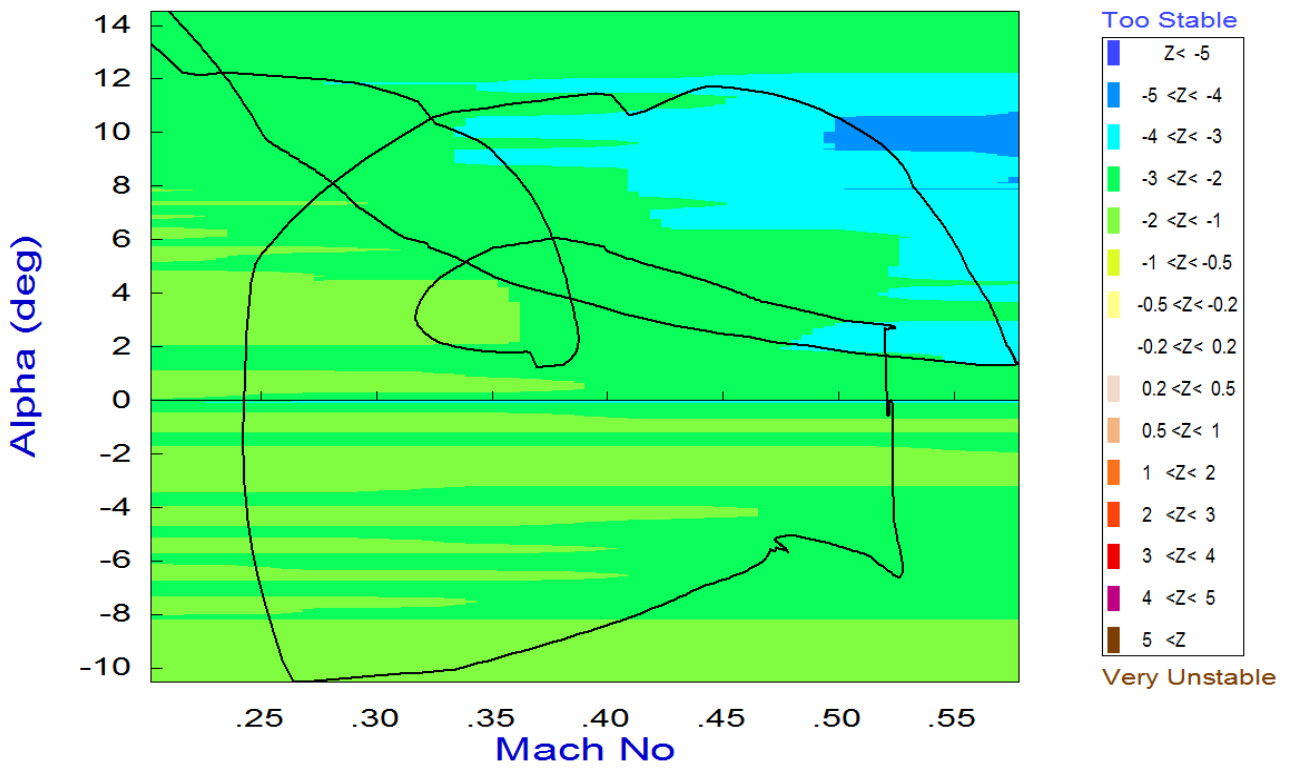
From the contour plots selection menu, shown below, we must select one of the performance parameter that will be presented as a contour plot against Mach and Alpha. The first parameter is the pitch stability parameter that was described in equations (3.14 & 3.15). The trajectory curve is shown by the black line across the Mach versus Alpha field. It starts at T=0 sec in the upper left hand corner where the aircraft takes-off with ($\alpha=13.5^\circ$, Mach=0.2) and it ends at T=615 (sec) also in the upper left hand corner, where it lands with ($\alpha=-14.5^\circ$, Mach=0.2). The pitch stability parameter is the third dimension which is represented by color. The color code is shown on the right. Overall, the aircraft is statically unstable in pitch (maneuverable) with a T2-inverse parameter not exceeding 2.5 sec^{-1} . In the lateral direction the stability parameter is negative (stable) showing the Dutch-roll resonance varying between 2 to 4 (rad/sec). The LCDP ratio is very good, mostly in the yellow and in the white region which is close to one (meaning good roll control and turning capability). The roll control effort is in the white region, meaning that it takes a negligible amount of aileron control to counteract a $\beta=5^\circ$ of wind-shear. The pitch and yaw control efforts are also very small (mostly in the light yellow and the white regions). It means that a wind-shear that causes (α & β)= 5° has a very small impact on the control-surfaces.



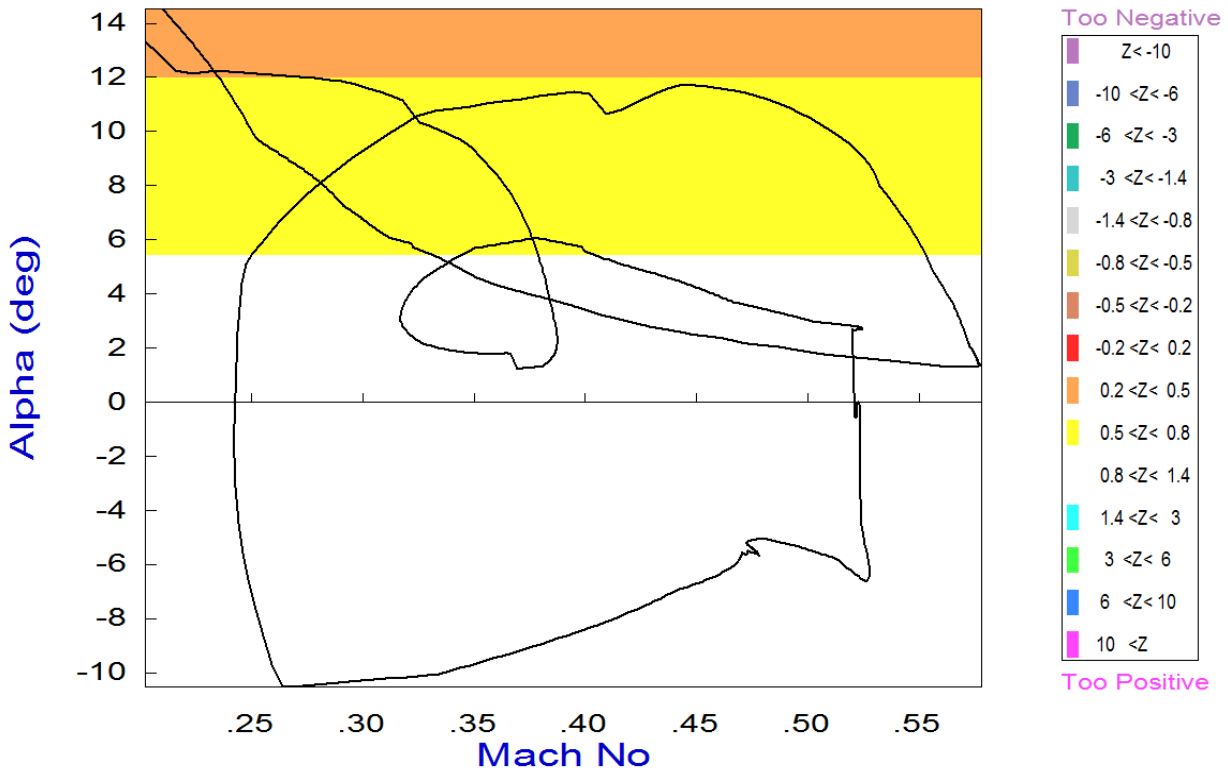
Pitch Stability Contour Plot (Mach vs Alpha)



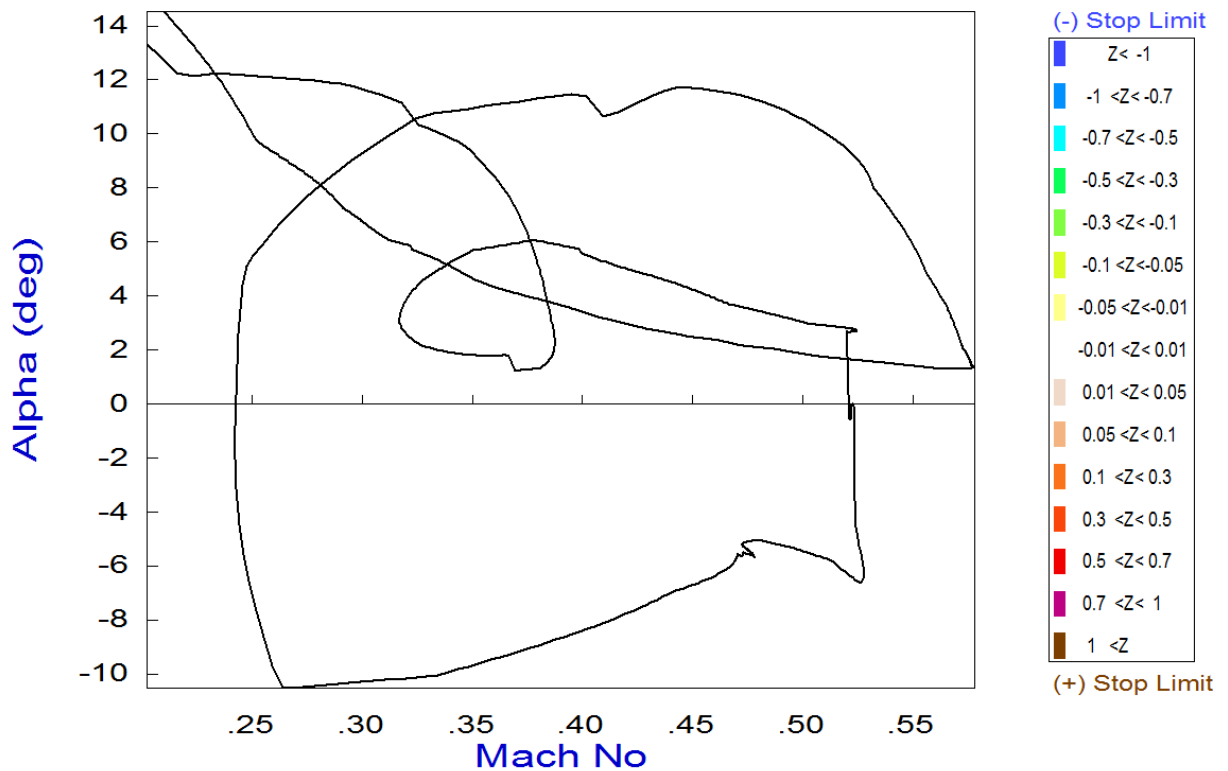
Lateral Stability Contour Plot (Mach vs Alpha)



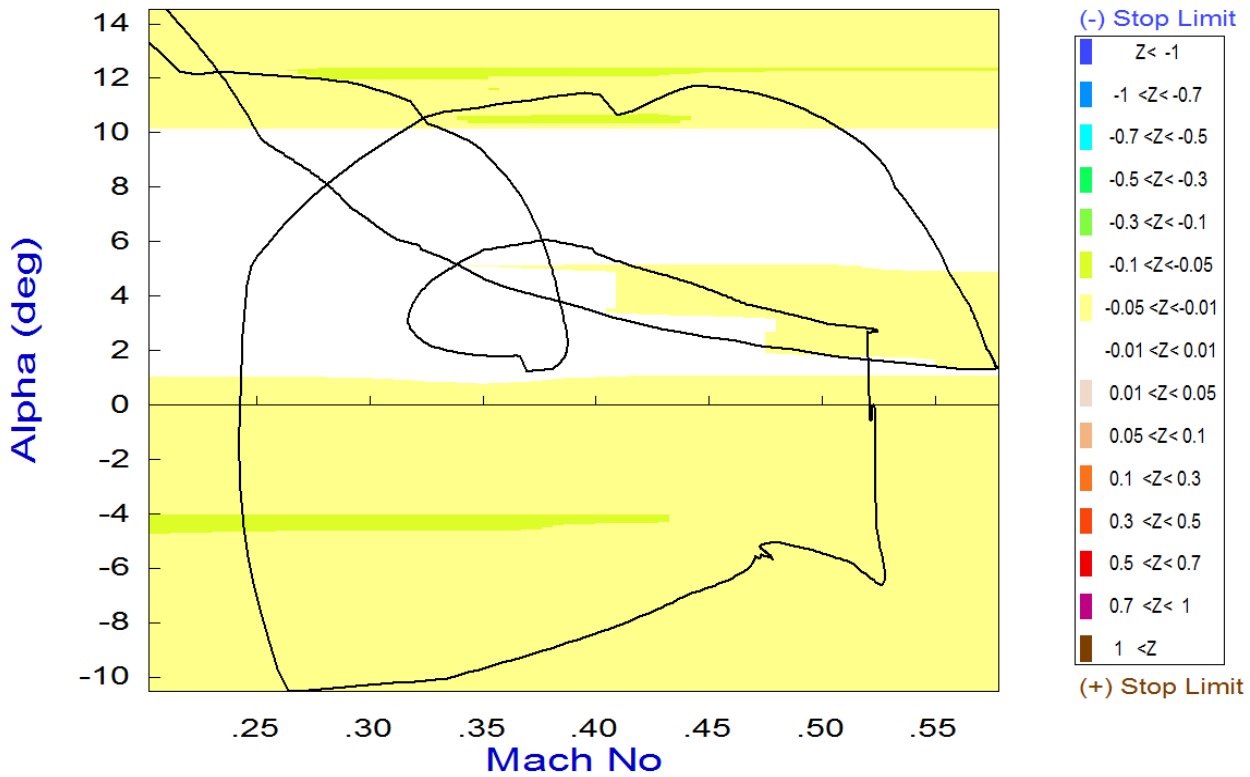
Roll Departure (LCDP) Contour Plot (Mach vs Alpha)



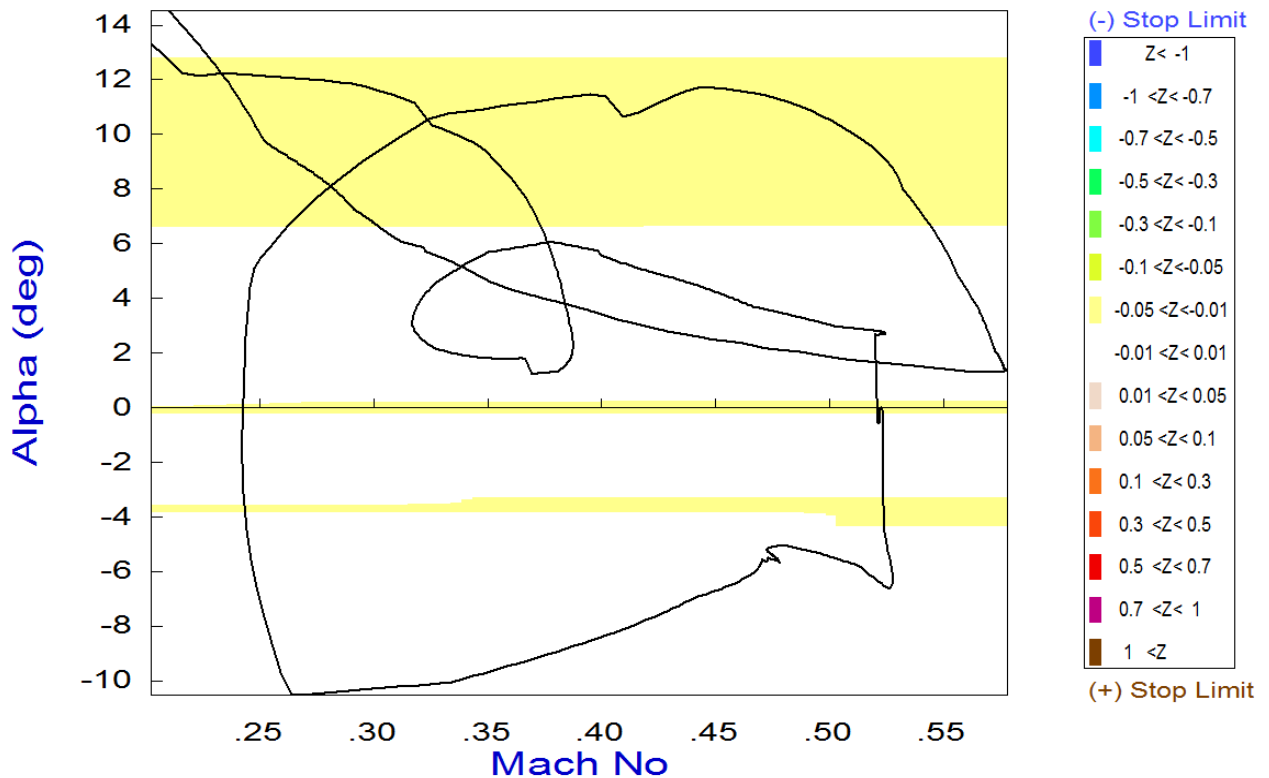
Roll Control Effort Contour Plot (Mach vs Alpha)



Pitch Control Effort Contour Plot (Mach vs Alpha)

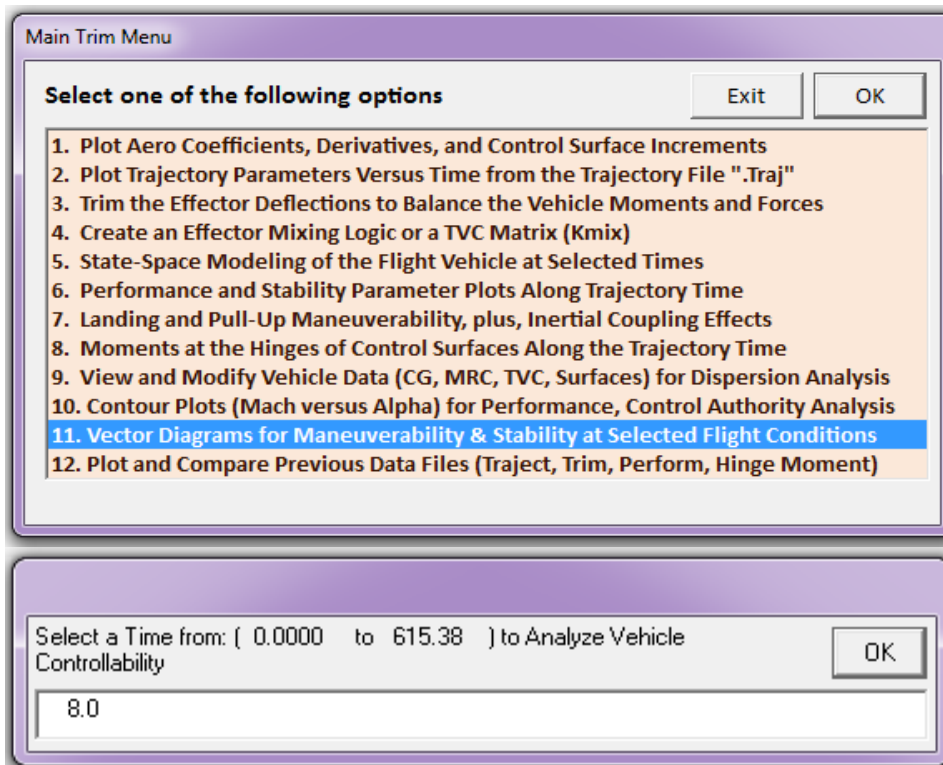


Yaw Control Effort Contour Plot (Mach vs Alpha)



8. Analysis Using Vector Diagrams

Vector diagrams is a graphic method for analyzing vehicle controllability at specific flight conditions, where we visually compare the disturbance effect on the vehicle in 2 directions against our control capability in the same directions and evaluate if the vehicle has sufficient control authority to counteract the disturbance moments and forces. It is not just a magnitude comparison but it also allows us to observe the directions of the controls and disturbances due to winds. They help us evaluate the orthogonality of our control system, the acceleration magnitudes due to the controls and winds, and if the effector system control authority dominates over the disturbances along the control directions. Since our vector plots are limited to 2 directions we typically need several vector diagram plots in order to analyze the control authority in multiple directions. We will analyze a couple of cases along the 180° flip trajectory. The first case is a few seconds after take-off and the second one is just before landing. Return to the Trim main menu and select option (11) for creating Vector Diagrams, and enter a flight time to analyze, 8.0 sec, right after take-off.



The menu/dialog that follows highlights the default aircraft mass (slugs), Mach, alpha, and beta (deg) that correspond to the flight time that was selected. You may keep those parameters or change them to something different. In this case we select the default values and click on "Select". In the following dialog enter the maximum disturbance dispersion angles due to the wind shear (β_{\max} and α_{\max})=10°, and in the effector combination dialog choose the top button to select the (4x4) effector combination matrix Kmix0 from file "Mix_Logic.Qdr", as shown. This matrix converts the 4 acceleration demands to surface deflections and throttle commands. It is not designed to decouple the 4 control axes.

Select the following parameters

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

Vehicle Mass (slug)	Mach Number	Angle of Attack (deg)	Angle of Sideslip (deg)
636.86	0.2000	10.0	0.00
823.00	0.2000	10.0	-12.0
636.86	0.5000	11.0	-5.00
	0.8000	12.0	0.00
		13.0	5.00
		14.0	12.0
		15.0	
		16.0	
		17.0	
		18.0	

Select

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) Maximum Beta (deg) OK

Notice

A (4 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: Mix_Logic.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.

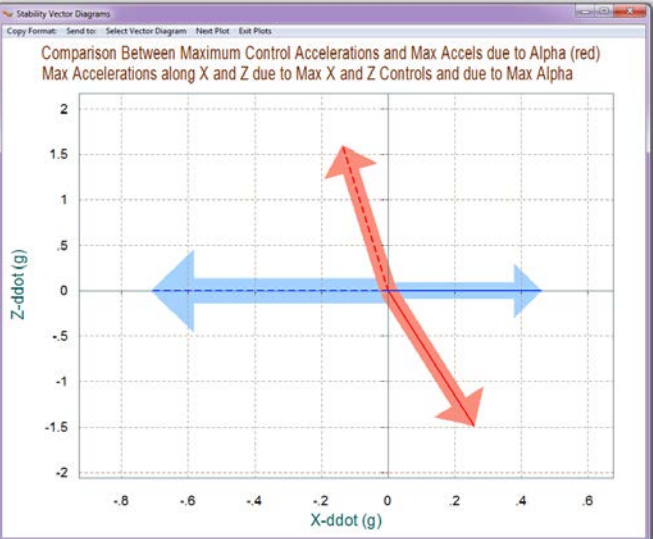
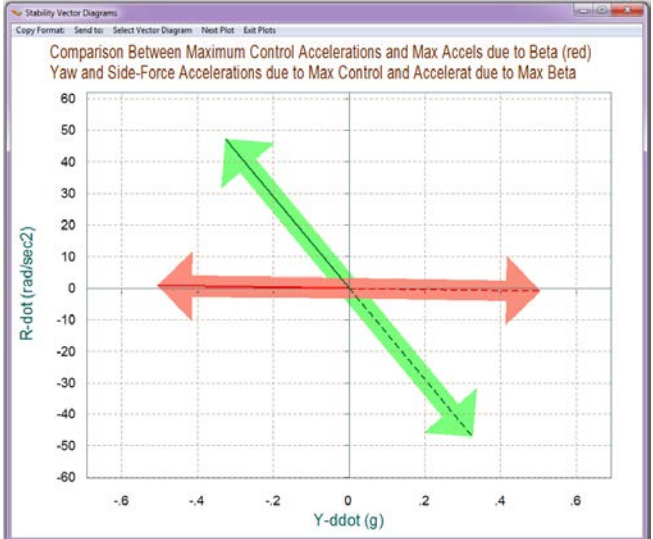
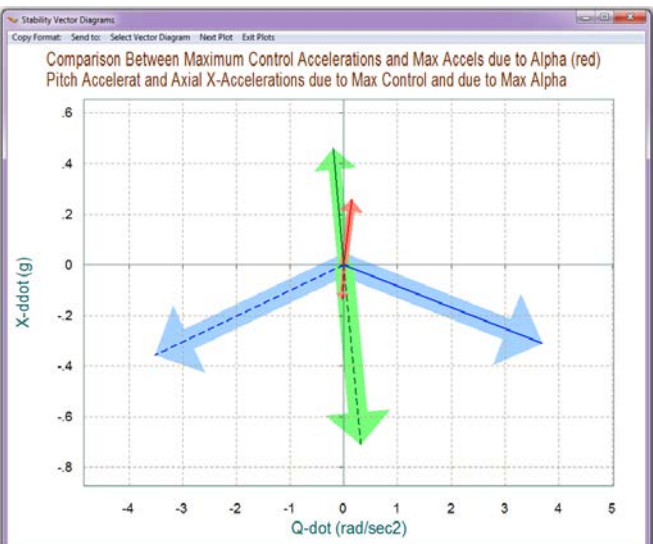
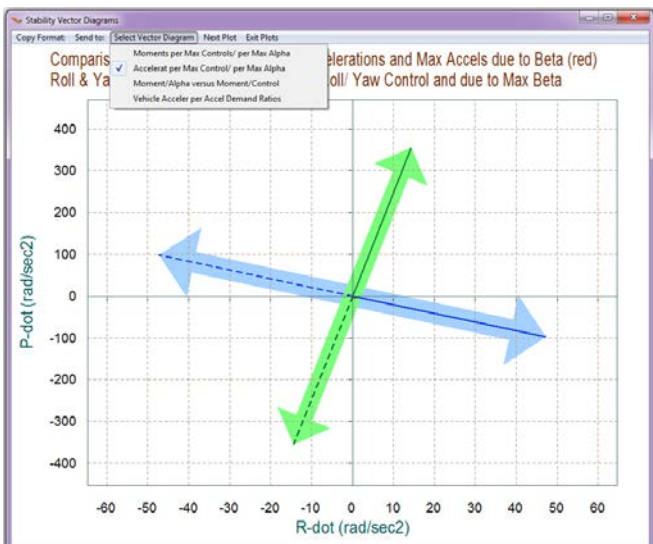
Create a Mixing Matrix by Adjusting the Effector Contributions

Select a Gain Matrix

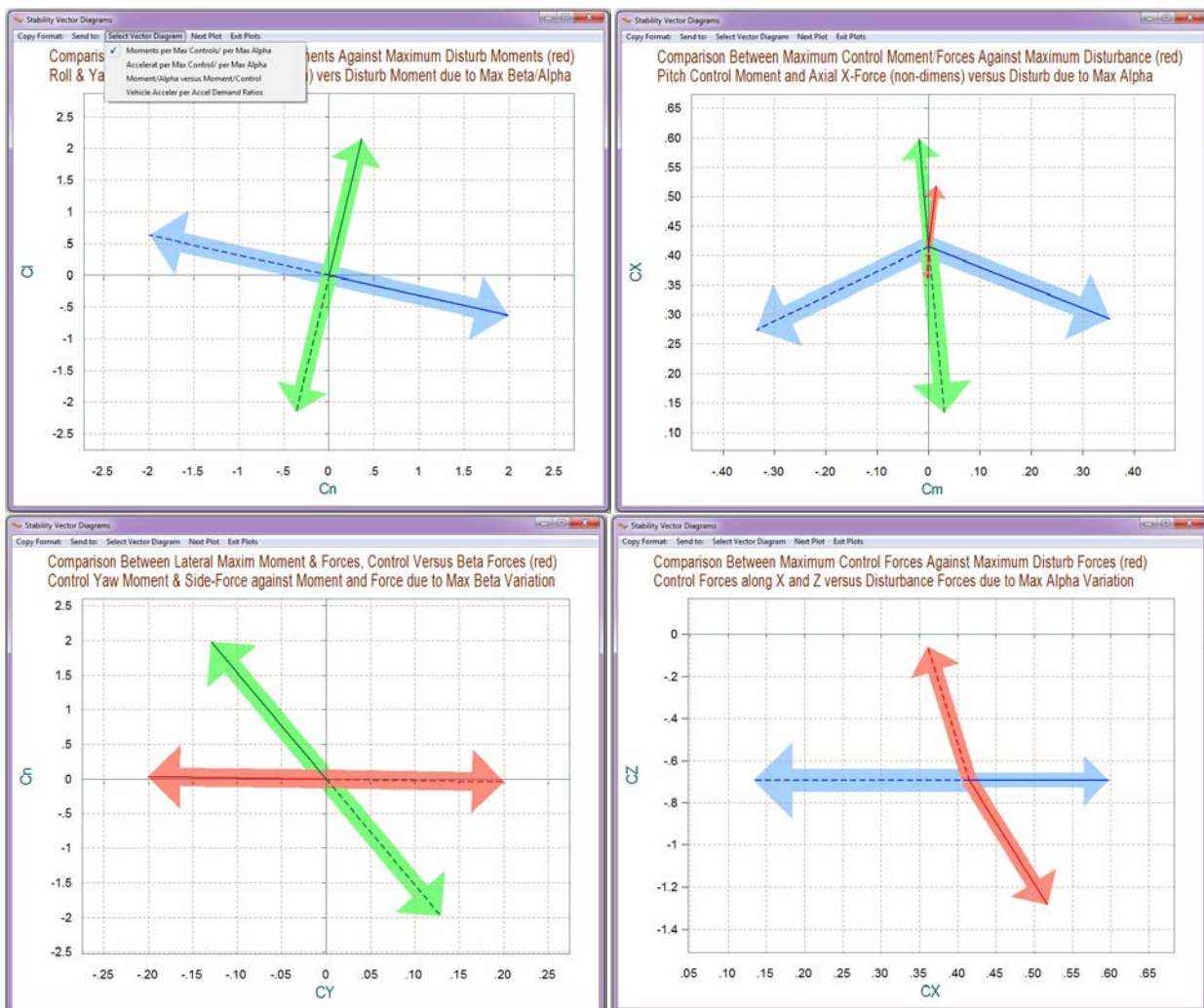
Select one of the following Matrices from the Systems File

KMIX_500	: Mixing Logic for F-16 Aircraft Roll and Pitch Maneuver at Time: 500.00
KMIX0	: Mixing Logic for F-16 Aircraft (No Coupling) , SIZE = 4 X 4

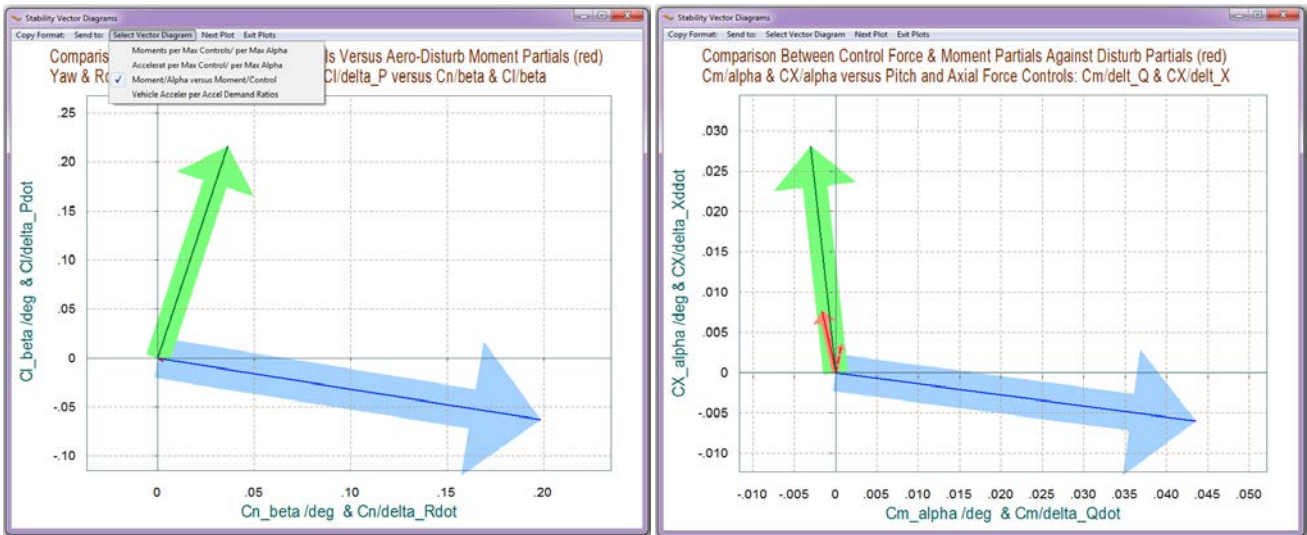
From the vector diagrams top menu bar we may select the type of vector diagrams. Click on "Select Vector Diagrams" and from the vertical pop-up menu select "Accelerations per Max Controls, and Accelerations per Max Alpha/Beta". The first diagram below shows the full roll/ yaw acceleration range achieved from \pm max airon control (green) and also from \pm max rudder control (blue). They are nicely orthogonal to each other showing good controllability in both roll and yaw. The roll and yaw moment vectors due to $(\alpha_{max}$ and $\beta_{max})$ disturbance are not visible because they are too small. The second diagram shows the range in pitch and axial accelerations produced from \pm max elevon control (blue) and also the range in pitch and axial accelerations produced from \pm max throttle control (green). Full throttle from its current level would produce +0.45g acceleration while zero throttle produces 0.7g negative acceleration along the x axis. Also an increase in alpha produces a positive x and pitch delta-accelerations (solid red vector). The third diagram is showing the yaw and side accelerations (\dot{r} and \dot{y}) produced from full \pm max rudder control (green vector), and also the accelerations produced by $(\pm\beta_{max})$ disturbance (red). The fourth diagram shows the axial and normal acceleration changes (\ddot{x} and \ddot{z}) produced from full \pm max throttle control (blue vector), and also the accelerations produced by $(\pm\alpha_{max})$ disturbance (red). An increase in alpha (solid red vector) causes $-\ddot{z}$ and $+\ddot{x}$ acceleration changes.



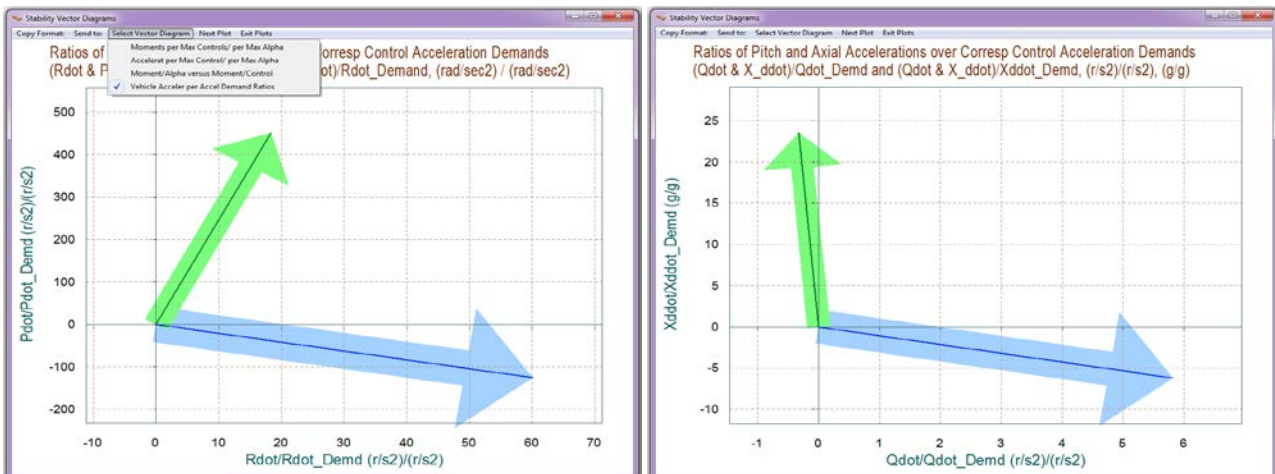
Similarly, the four vector diagrams below show the normalized (non-dimensional) moments and forces. From the vector diagrams top menu bar click on "Select Vector Diagrams" and from the vertical pop-up menu select "Moments/Forces per Max Controls, and Moments/Forces per Max Alpha/Beta". The top diagram shows the full range of roll and yaw control moments produced by maximizing the aileron and rudder deflections from max negative to max positive. The blue vectors correspond to the \pm max rudder and the green vectors to the \pm max aileron deflection. They are orthogonal to each other (which is good). The positive control vectors are represented with solid lines and the negative control vectors are dashed lines. The second diagram shows the axial force coefficient against the pitching moment coefficient (non-dimensional). The blue vectors show the variations due to \pm max elevon deflection, and the green vectors show the variations in the coefficients due to \pm max engine throttle variation. We see that the aircraft is trimmed in pitch because $C_{m0}=0$. The nominal axial force coefficient is $C_{x0}=0.42$. It can be varied by the throttle control from 0.13 to 0.6. The red vectors represent the variations in axial force and pitching moment due to $(\alpha_{max}=\pm 10^\circ)$. The third diagram shows the yawing moment coefficient (C_n) against the side force coefficient (C_Y). The green vector shows the moments and forces produced from full \pm max rudder control. The red curve shows the forces and moments generated by $(\beta_{max}=\pm 10^\circ)$. The fourth diagram shows the normal force coefficient (C_Z) against the axial force coefficient (C_X). The blue vector shows the x-force variation produced from full \pm max engine throttle control. It does not couple in the z direction. The red curve shows the x and z forces generated by $(\alpha_{max}=\pm 10^\circ)$.



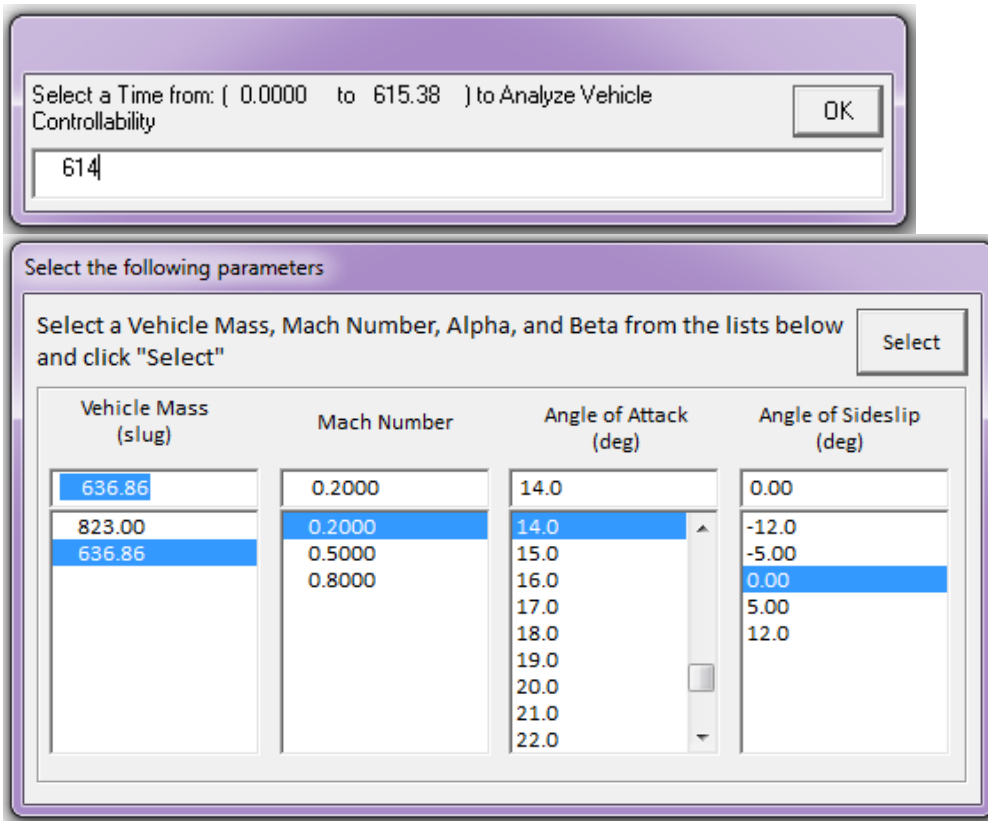
The next 2 vector diagrams show the partials of control moments/forces per flight control acceleration demands. From the vector diagrams selection pop-up menu select "*Moments/Forces per Alpha/Beta, versus Moments/Forces per Control*". The first diagram shows the roll and yaw moment partials per roll and yaw control demands ($\delta_{aileron}$ & δ_{rudder}). The green vector is $(Cl\delta_{ail}, Cn\delta_{ail})$ and the blue vector is $(Cl\delta_{rudd}, Cn\delta_{rudd})$, as defined in equations (8.3 & 8.4). The roll and yaw moment partials per sideslip ($Cl\beta$ & $Cn\beta$) are too small in comparison with the control vectors and they are not visible. The second diagram shows the pitch moment and axial force partials per pitch and axial force control demands (δ_{elevon} & δ_x). The green vector is $(CX\delta_x, Cm\delta_x)$ and the blue vector is $(CX\delta_{elev}, Cm\delta_{elev})$, as defined in equations (8.1 & 8.2). The control partials are nicely decoupled from each other. The red vectors show the partials due to alpha variations ($CX\alpha$, & $Cm\alpha$), which are small.



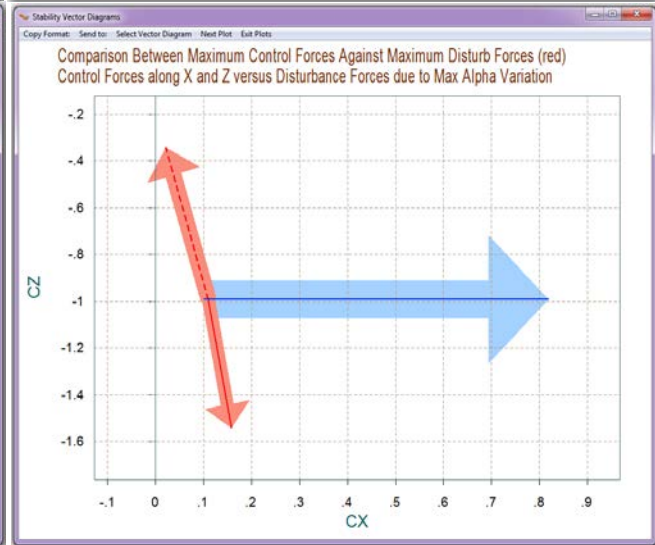
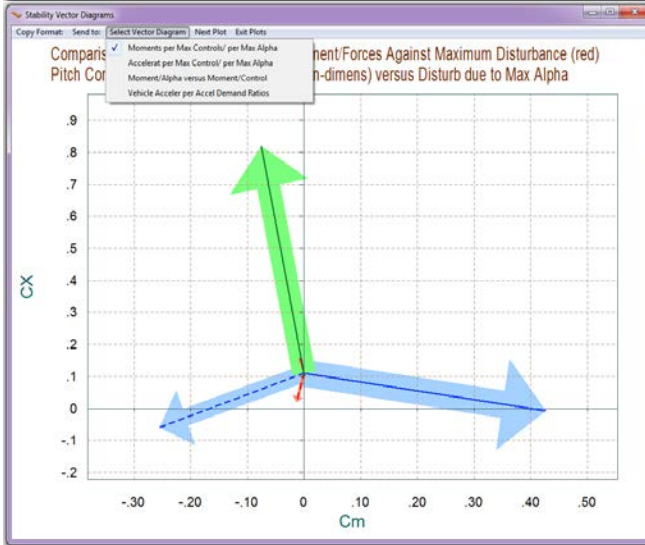
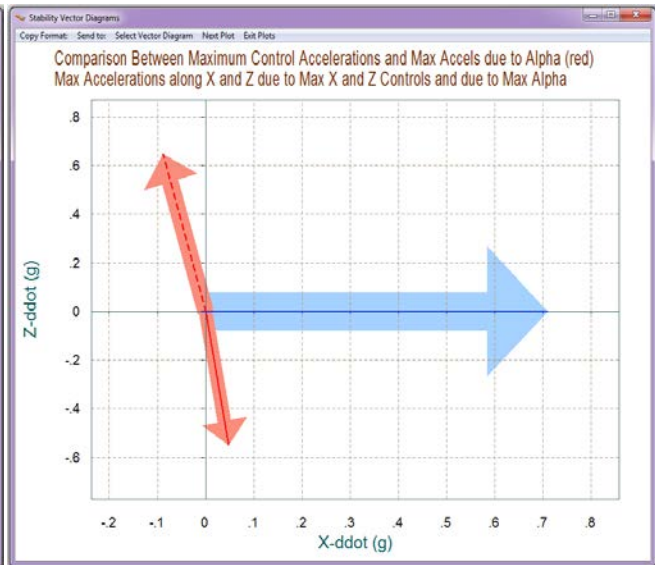
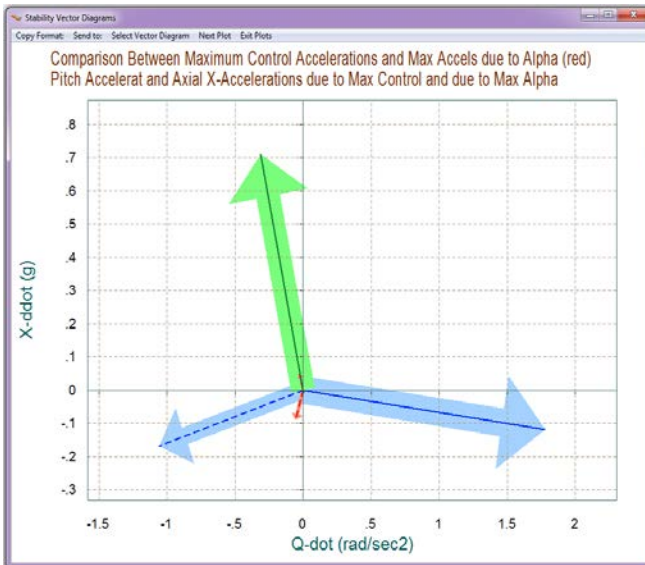
The 2 vector diagrams below are obtained using the 4th vector diagrams type "*Accelerations per Acceleration Demands*". In this example, however, we did not use the mixing logic algorithm to create a decoupling and diagonalizing matrix, as in other examples. The accelerations per acceleration demand partials, therefore, are not unity and vectors and they are not orthogonal to each other as seen in other examples.



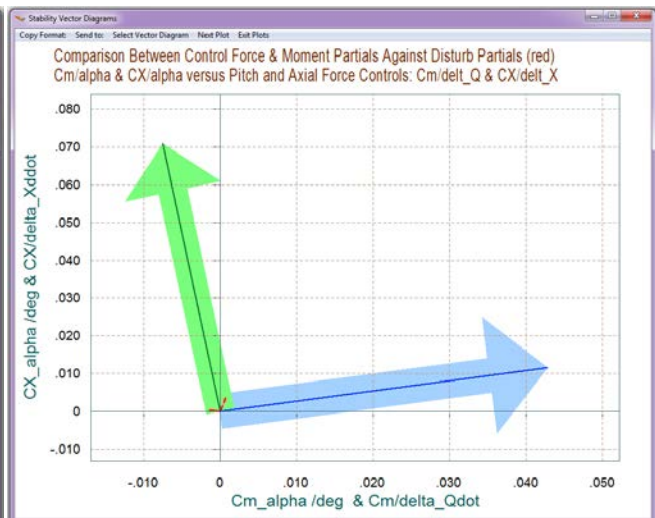
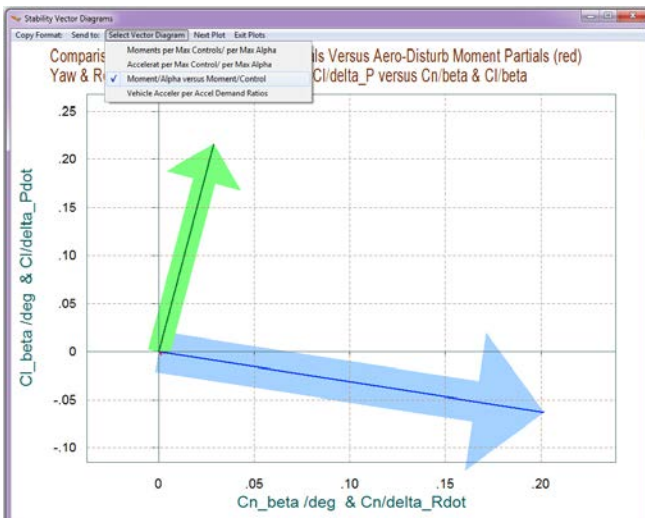
Now let us take a look at a different flight condition near landing at t=614 sec. Return to the main menu, select again option (11), enter the flight time, and the default aircraft mass, Mach, alpha, and beta that correspond to the flight time that was selected.



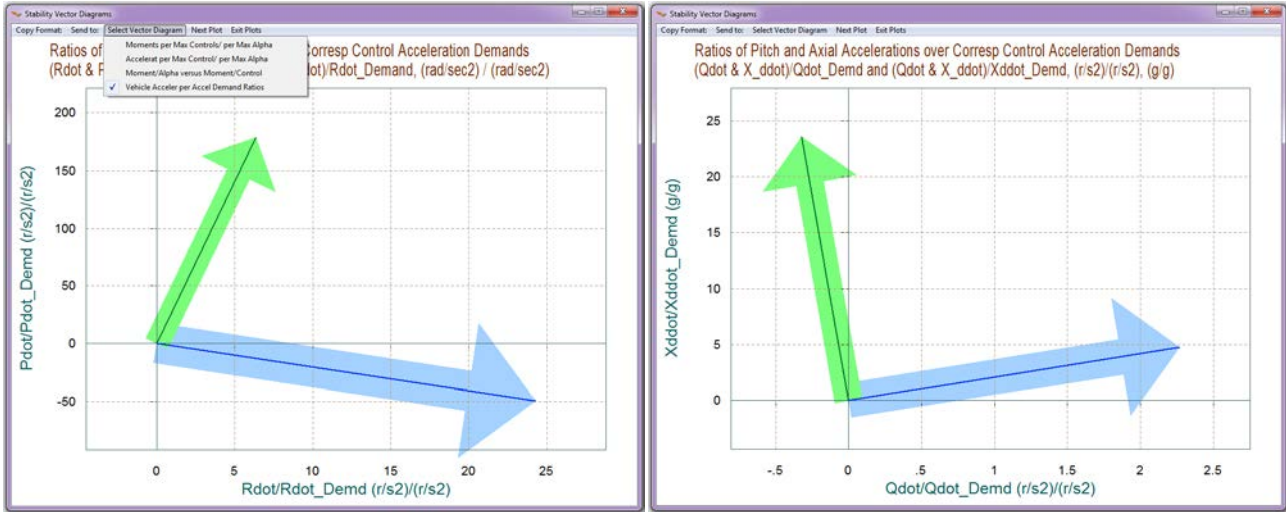
The following diagrams show the maximum variation in pitching moment and angular acceleration, and the maximum variation in x and z forces and in linear accelerations produced by the variation of the two longitudinal controls: \pm max elevon control and \pm max throttle control. The axial force coefficient is $C_{x0}=0.1$ near landing and the throttle control is near zero. So there is only positive throttle control available that can provide 0.7g change in axial acceleration at full throttle. A full positive elevon deflection creates almost twice as much positive moment and angular acceleration than a full negative elevon deflection. Either positive or negative elevon deflections (from nominal) cause an increase in drag (-CX) and negative x-acceleration. Also a decrease in alpha (red dashed vectors) causes a reduction in CX (increase in drag) and an increase in CZ (-normal force).



The next 2 vector diagrams show the partials of control moments/forces per flight control acceleration demands which are similar to those obtained from the take-off flight condition.



The 2 vector diagrams below were obtained using the "Accelerations per Acceleration Demands" vector diagrams type. In this example, however, we did not use the mixing logic algorithm to create a decoupling and diagonalizing mixing matrix, as in other examples. The accelerations per acceleration demand partials, therefore, are not unity and vectors are not orthogonal to each other as seen in other examples.



Now let us repeat the landing analysis by allowing the program to calculate a decoupling mixing logic matrix instead of using Kmix0. Return to the main menu, select option (11) again, the same flight time, and the default aircraft mass, Mach, alpha, and beta that correspond to 614 sec. From the effector combination dialog now select the second option that allows the program to calculate its own mixing matrix at 100% effector participation.

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: Mix_Logic.qdr, or let the program calculate it

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

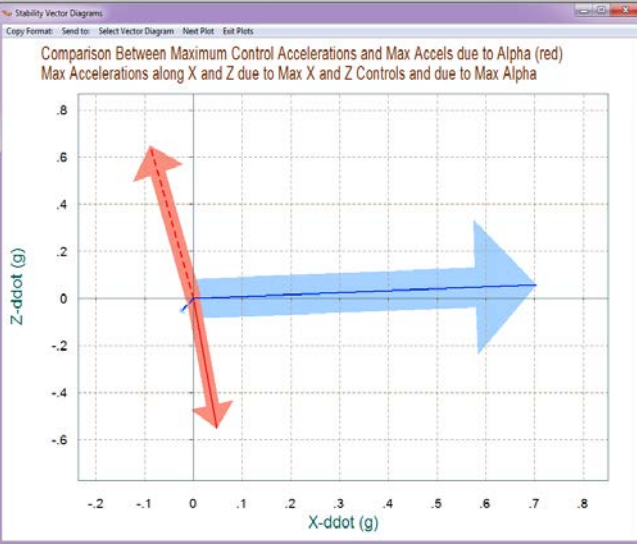
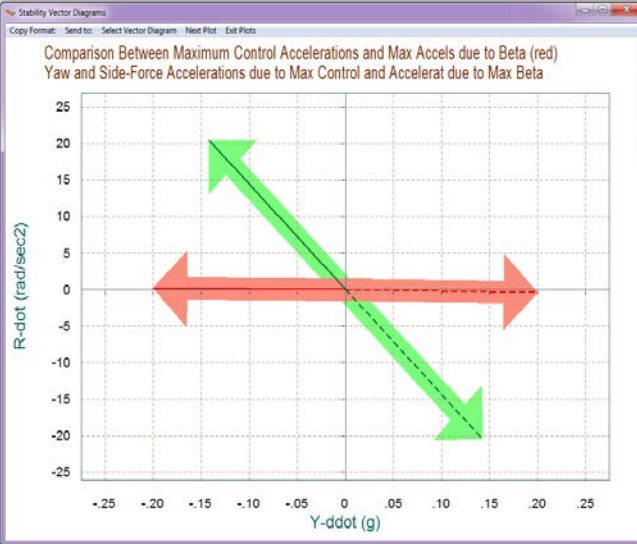
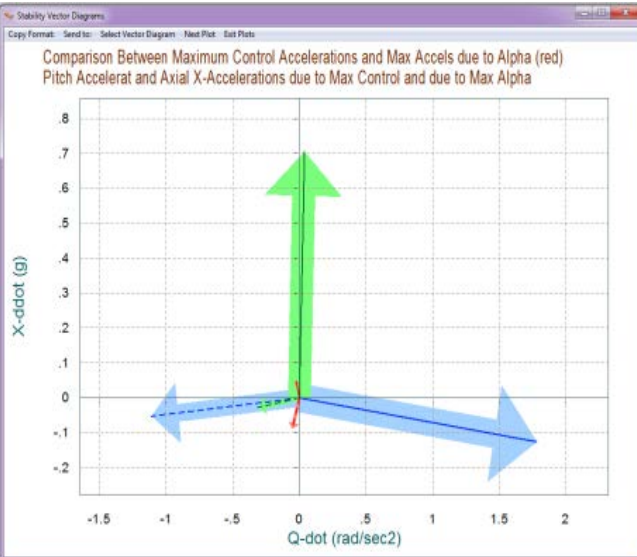
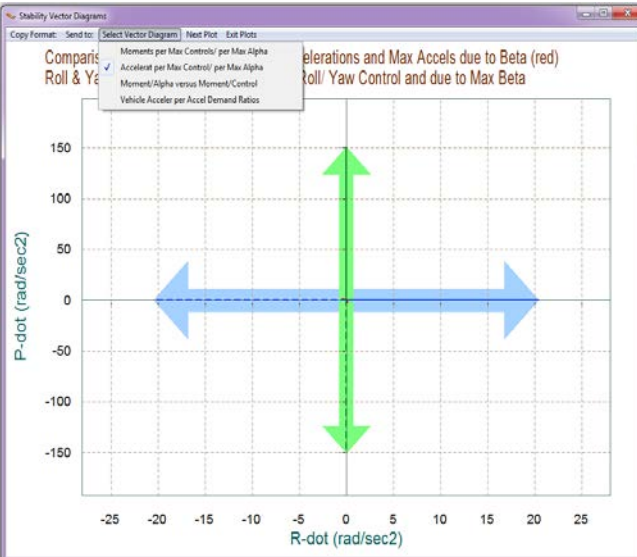
There are times, however, when you want to reduce their contributions. Plus some effectors are only used for Trimming and not for Control. Their participation should be set to 0% in the effector combination calculations.

Select a Mixing Matrix from Systems File

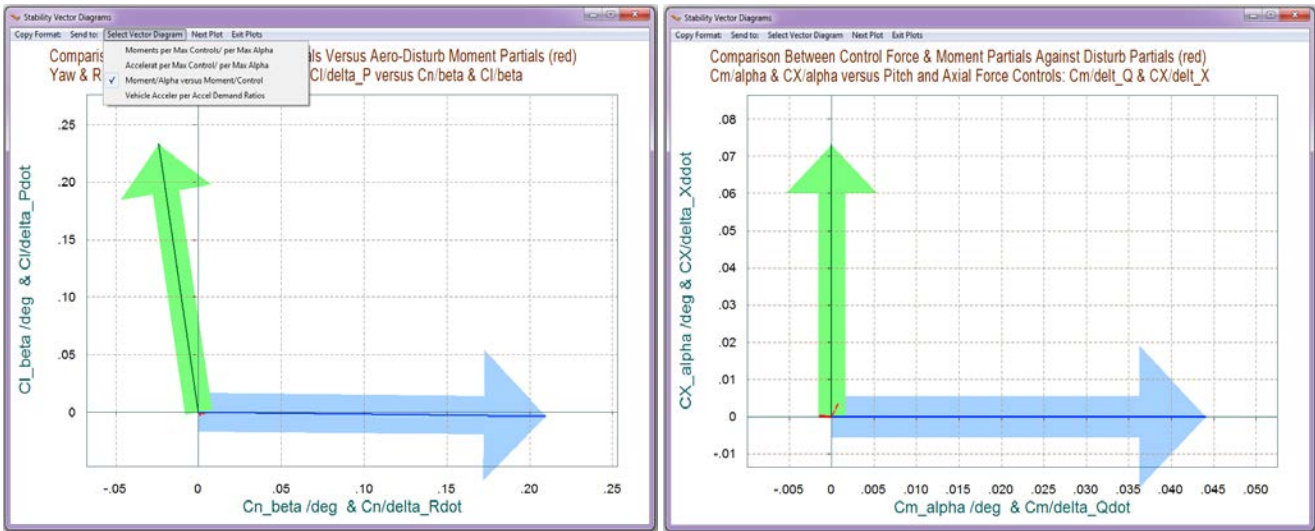
Create a Mixing Matrix Using All Effectors at 100% Participation

Create a Mixing Matrix by Adjusting the Effector Contributions

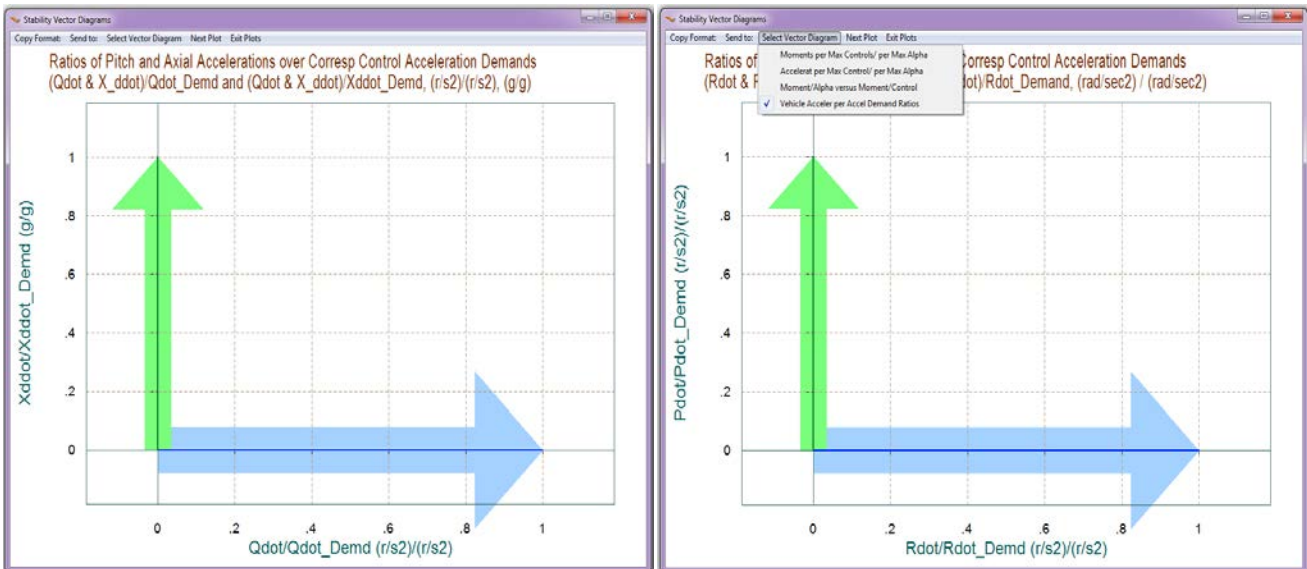
The following plots show the accelerations at max control. Notice how the roll and yaw accelerations due to maximizing the aileron and rudder are now perfectly aligned with the roll and yaw axes. Even the x-acceleration is better aligned with the x-axis.



The moment partials with respect to control demands also look better aligned with the body axes.

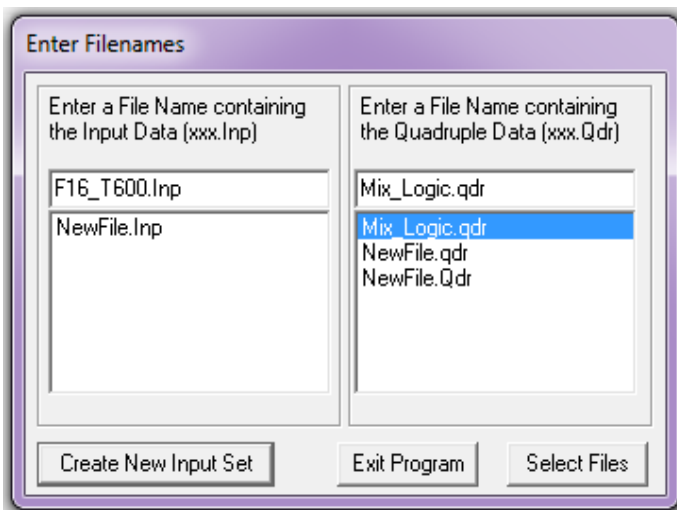


The greatest advantage, however, by allowing the program to calculate the effector combination matrix is in the "Vehicle Accelerations per Acceleration Demand Ratios" vector diagrams. These are ratios of accelerations achieved per accelerations demanded in specific directions. The following two diagrams show acceleration partials per acceleration demands. The first diagram shows the pitch acceleration per pitch acceleration demand perfectly aligned with the horizontal axis and the x-acceleration per x-acceleration demand aligned with the vertical axis. Their magnitudes are one, which means, that the accelerations achieved are equal to the demanded accelerations and they are completely decoupled from each other. The same result is also true in the roll and yaw accelerations per roll and yaw acceleration demands diagram. They are also unity vectors and perfectly decoupled from each other. These diagrams confirm the capability of the effector mixing logic to properly scale and decouple the four control accelerations from each other by counteracting the dynamic coupling inherited in the aircraft mass properties.

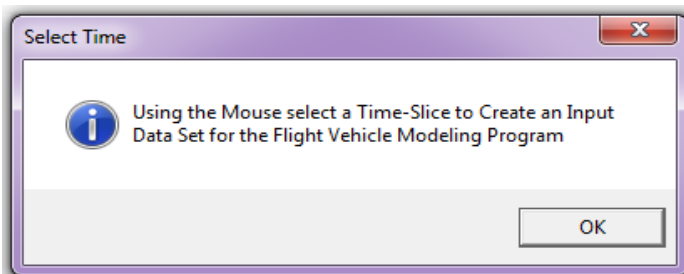
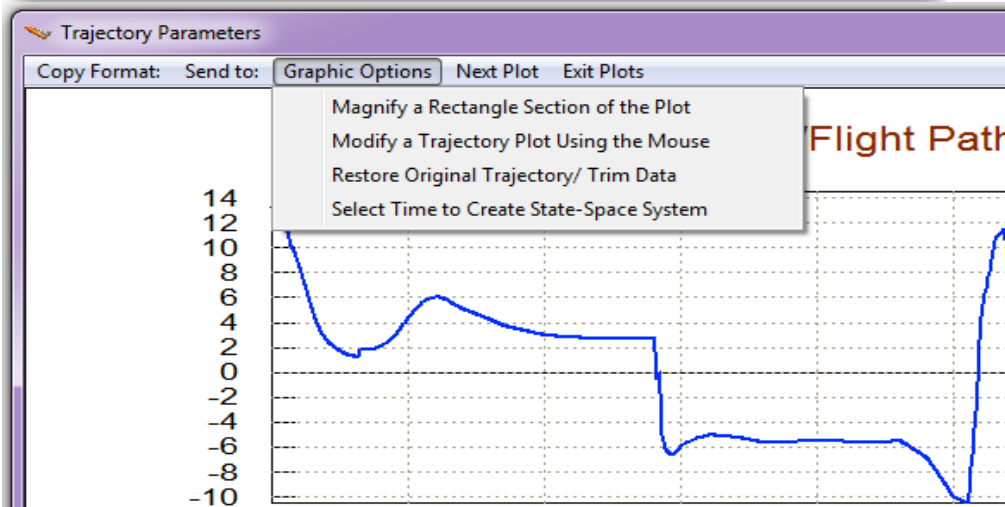
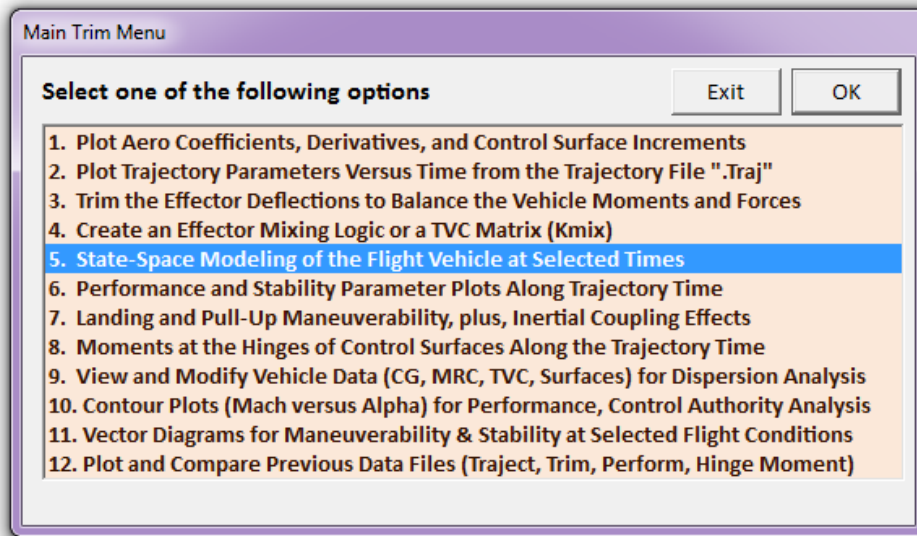


9. Creating Dynamic Models for Control Design

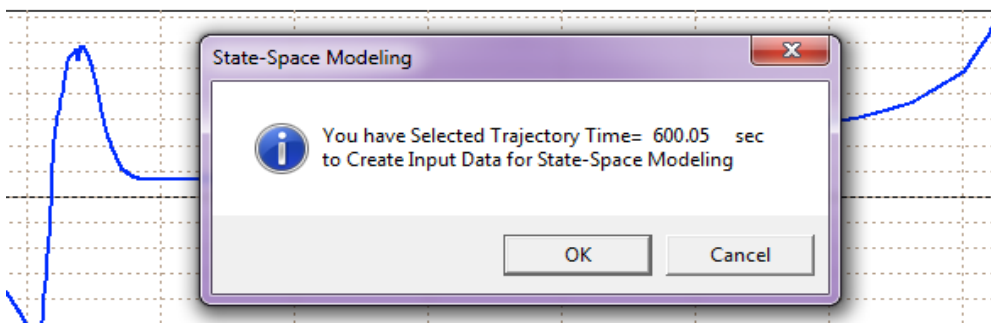
We will now use the Flixan and Trim programs to generate dynamic models for the F16 aircraft at four different flight conditions and in the next two section we will design flight control laws and test them using a non-linear 6-dof Matlab simulation. We selected four flight times that cover a wide range of angles of attack, both positive and negative. The times are: 130, 210, 252, and 600 sec, which correspond to alphas: +3, -5, -10, and +10 (deg). The aircraft uses 4 effectors which are the 3 aero-surfaces and the throttle control. The engine throttle, however, is controlled directly by the pilot and it is not connected to the flight control system. So the engine throttle control input will not be used in the control design and the engine is taken out from the Flixan input data and from the state-space models. So let us resume the analysis by restarting the Trim program. Select the same files as before, and make "F16_T600.Inp" to be the Flixan input data file that will contain the aircraft data, plus other Flixan related model building data. Re-trim the surfaces, if you have not done it already, to make sure that you are using a current trim condition with the proper trajectory.



From the Trim main menu select option (5) to create a state-space dynamic model. A dialog reminds the user how to select a flight time for the dynamic model, click "OK". From one of the trajectory plots go the top menu bar, and choose "*Graphic Options*", and then from the vertical pop-up menu click on "*Select Time to Create State-Space System*". Then using the mouse click at time=600 sec, along the horizontal axis, and confirm that you have selected the correct time by clicking "OK" in the bottom dialog. Otherwise, click "Cancel" and try again.



Path (deg), F-16 Aircraft Roll and Pi



The program is now ready to create a dynamic model at the selected time. The Flixan dialog below displays the flight vehicle parameters prepared by Trim and extracted from the aircraft data files. The data is separated into groups that can be accessed by clicking in the appropriate tabs. It is currently showing the elevon surface data. The user can modify some of the data or titles in this dialog before saving it. You must click on "Update Data" after any modifications. Do not run it yet because there is more work to be done and more data to be included in file F16_T600.inp. Click on "Save in File" and the vehicle data will be saved in file "F16_T600.Inp", under the title "F16 Aircraft Roll and Pitch Maneuver/ T=600 sec". The file "F16_T600.Inp" will be processed by Flixan to generate the dynamic systems for control design and analysis using Matlab/ Simulink. In addition to the vehicle data the input file contains also system interconnection and modification data related to this analysis that will also be processed by Flixan. The systems generated by Flixan will be saved in file "F16_T600.Qdr".

Flight Vehicle Parameters

Vehicle System Title
F-16 Aircraft Roll and Pitch Maneuver/ T= 600 sec

Number of Vehicle Effectors
 Gimbal Engines or Jets. Include Tail-Wags-Dog? **WITH TWD**
 Rotating Control Surfaces. Include Tail-Wags-Dog? **WITH TWD**

Momentum Control Devices
 Reaction Wheels? **Single Gimbal CMGs?** **Include a 3-axes Stabilized Double Gimbal CMG System?**

Number of Sensors
 Gyros
 Acceleromet
 Aero Vanes
 External Torques

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
 Fuel Sloshing:

Reaction Wheels | Single Gimbal CMGs | Double Gimbal CMG System | Slewing Appendages | Gyros | Accelerometer | Aero Sensors | Fuel Slos | 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)
 Largest Positive Deflection from Trim (deg)
 Largest Negative Deflection from Trim (deg)

Surface Location (ft) and Hinge Orientation Angles (deg)
 Xcs
 Ycs Phi_cs
 Zcs Lambda_cs

Control Surface Mass Properties
 Control Surface Mass in (Slugs)
 Moment of Inertia about Hinge (slug-ft²)
 Moment Arm (feet), Surface CG to Hinge
 Control Surface Chord (feet)
 Control Surface Reference Area (ft²)

Aero Force Derivatives
 Ca_delta Ca_delta_dot
 Cy_delta Cy_delta_dot
 Cz_delta Cz_delta_dot
 Control Force Derivatives due to Surface Deflection (1/deg) and Control Force Derivatives due to Surface Rate (1/deg/sec)

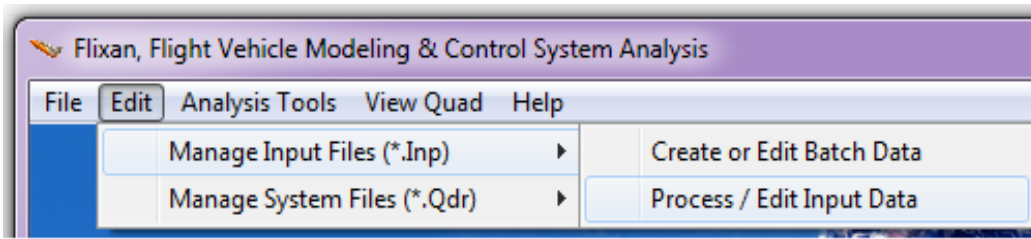
Aero Moment Derivatives
 Cl_delta Cl_delta_dot
 Cm_delta Cm_delta_dot
 Cn_delta Cn_delta_dot
 Control Moment Derivatives due to Surface Deflection (1/deg) and Control Moment Derivatives due to Surface Rate (1/deg/sec)

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

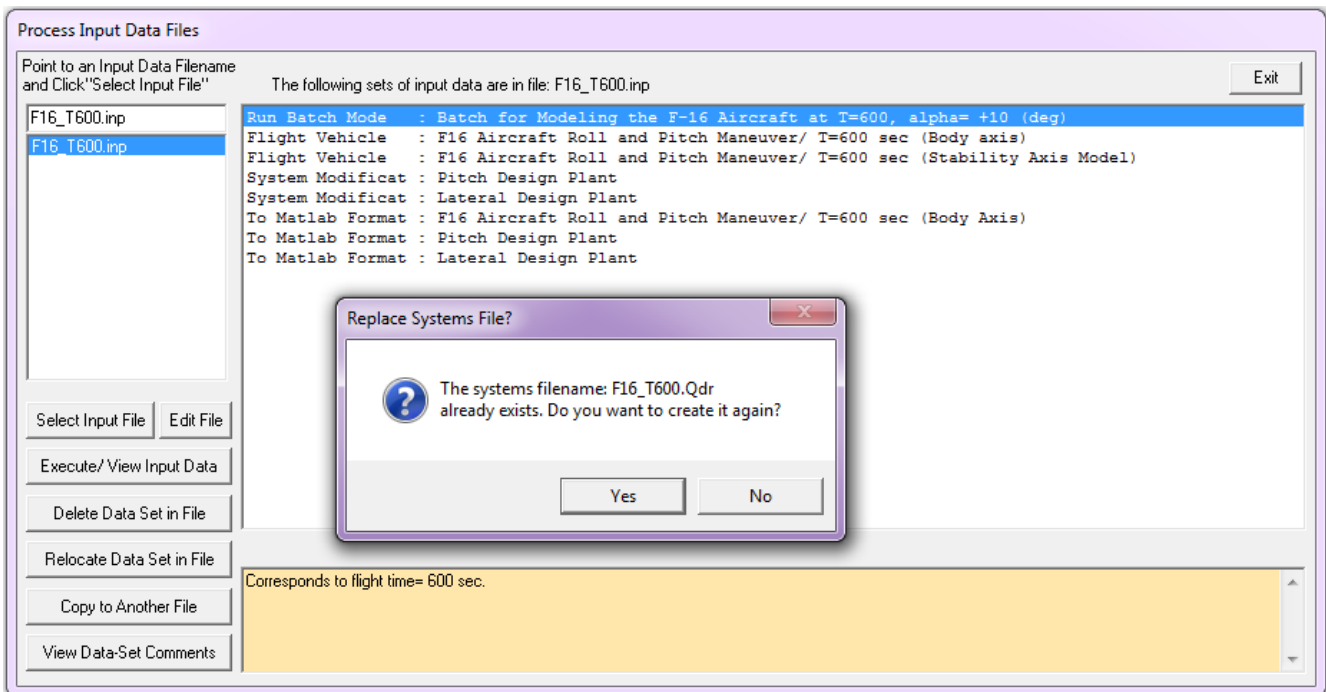
We will skip the full preparation of the input file because it is beyond the scope of this example. Let us now take a look and see what is in file "*F16_T600.Inp*" before processing it in Flixan. The file contains several sets of data and each set corresponds to and it is processed by a Flixan utility. Flixan will create systems and matrices that will be used for control design in the next section using Matlab.

1. At the top of the file there is a batch set used for processing the data-sets in batch mode. This is faster because it processes them all together, instead of individually. Its title is "*Batch for Modeling the F-16 Aircraft at T=600, alpha= +10 (deg)*".
2. Below the batch there is a flight vehicle data set that corresponds to the flight condition that we have just created. Its title is "*F16 Aircraft Roll and Pitch Maneuver/ T=600 sec (Body axis)*". Its output rates are in body axes and it is used in a linear simulation that evaluates the control gains during the LQR design and helps to adjust the weights.
3. The next set is also flight vehicle data, same flight condition as above, but the output rates (p_s & r_s) are defined in stability axes rather than in body axes. The turn-coordination flag is also turned "on" in this model, which means that the turn-coordination feedback from the bank angle ϕ to the yaw rate (which is software and not physics) is included in the dynamic model. This model is used to create LQR design state-space models that include the turn-coordination feedback. It means that the state-feedback gains generated by the LQR take into consideration that the lateral flight control system the will include a turn-coordination feedback, and the gains are anticipating it. Its title is "*F16 Aircraft Roll and Pitch Maneuver/ T=600 sec (Stability Axis Model)*".
4. The next two system modification sets create the design plants for the LQR method which will be performed in Matlab. They are extracted from the system created in step-3. Their titles are "*Pitch Design Plant*" and "*Lateral Design Plant*".
5. The last three data-sets in the input data file convert the systems created to Matlab function format so they can be loaded into Matlab for further analysis. The body axes model is saved in file "*vehj_sim.m*". The pitch and lateral design plants are saved in "*pitch_plant.m*" and "*lateral_plant.m*".

Now let us process this input file using Flixan. Start the Flixan program and select the project folder "C:\Flixan\Trim\Examples\F-16 Fighter Aircraft\Mat_Design\Alpha+10". Then go to "Edit", "Manage Input Files (.Inp)", and "Process/ Edit Input Data", as shown.



The following dialog is for viewing and processing Flixan input files. The left menu shows the only input file in the project directory, which is "F16_T600.Inp". Select it and click on "Select Input File". The menu on the right side shows the data-sets which are in "F16_T600.Inp". They can be processed individually, but select the batch set on the top to process them all together and click on "Execute/ View". Flixan will process the input file and create the systems in file "F16_T600.Qdr". It will also create the Matlab function files.



We must repeat this process to generate aircraft models for the other three flight conditions related to flight times 130, 210, and 252 sec. The corresponding input data files "F16_T130.Inp", "F16_T210.Inp", and "F16_T252.Inp" must be placed in the appropriate subfolders in "C:\Flixan\Trim\Examples\F-16 Fighter Aircraft\Mat_Design" where the control design will take place and it will be described in the next section.

10. Flight Control Design

The flight control design is based on the Linear Quadratic Regulator method which is solved in Matlab. The design is performed in directory: "C:\Flixan\Trim\Examples\F-16 Fighter Aircraft\Mat_Design". The four Flixan data files (F16_T130.Inp, F16_T210.Inp etc.) that were described in the previous section are placed in the subdirectories: (T130_Alpha+3, T210_Alpha-5, T252_Alpha-10, and T600_Alpha+10). This is where they are processed by Flixan as already described to generate the dynamic models (vehi_sim.m, pitch_plant.m and lateral_plant.m) used in the control design and analysis. The three systems are moved up one directory to be processed one at a time by the Matlab script file "LQR_Design.m" which generates the gains.

```
% LQR Design for the F16 Aircraft
d2r=pi/180; r2d=180/pi;
[As, Bs, Cs, Ds] = vehi_sim;           % Load Augmented Simulation Model
[Avp,Bvp,Cvp,Dvp]= pitch_plant;      % Load Pitch Design Model
[Avl,Bvl,Cvl,Dvl]= lateral_plant;    % Load Lateral Design Model

% Pitch LQR Design Using the 6 Aero-Surfaces
[Ap4,Bp4,Cp4,Dp4]= linmod('Pdes3x'); % 4-state model {q, alfa, alf_integr}
R=0.5;                                % LQR Weights R=
Q=[0.15 6 3.0]*10; Q=diag(Q);         % LQR Weights {q,alfa,alfint}
[Kq,s,e]=lqr(Ap4,Bp4,Q,R)             % Kq =[0.05 0.5 0.3]*3
save Kq_an5_Q400.mat Kq -ascii

% Convert Lateral State Vector from Body to Stability Axes, Outputs=States
[Ap2,Bp2,Cp2,Dp2]= linmod('Ldes5x'); % Add the Phi-Integral State
Al2= Cp2*Ap2*inv(Cp2); B12= Cp2*Bp2; % Transform State-Vector to (p,r)_stability
Cl2= Cp2*inv(Cp2); D12= Dp2;

% Lateral LQR Design                    % States: {phi,p,r,beta,phint}
R=[2,1.5]*10; R=diag(R);               % LQR Weights R=[1,1]
Q=[2 0.01 0.01 0.001 0.1]; Q=diag(Q); % LQR Weights Q=[1 1 1 0.04 0.04]*0.4
[Kpr,s,e]=lqr(Al2,B12,Q,R)             % Perform Lateral LQR design
save Kpr_an5_Q400.mat Kpr -ascii

% Body to Stability Transform Parameters
ge=32.174; V0=400; alfa=10; Thet0=10;
calfa=cosd(alfa); salfa=sind(alfa);
```

The pitch state-space plant has only one input, the elevon. The original model consists of two short-period states (q & α), and it is augmented in the Simulink file "Pdes3x.Mdl" to include α -integral. Similarly the lateral state-space plant which originally consisted of 4 states (ϕ , p_s , r_s , & β) it is augmented in the Simulink file "Ldes5x.Mdl" to include ϕ -integral. It has two control inputs: the aileron and the rudder. Notice that the lateral design plant, although its output rates are in the stability axes, its states are still in the body axes. The states are easily transformed to stability before applying the LQR algorithm, and the output matrix C becomes unity.

The selection of the positive-definite weight matrices Q & R is an iterative process requiring a few trials and adjustments. A simple linear simulation model "LQR_Sim.mdl" is used to evaluate the state-feedback gains and to make sure that they are neither too high, resulting in a high bandwidth system and requiring very big surface deflections, nor too small where the system response becomes sluggish. This Simulink model is shown in Figure (1) and it includes the pitch and lateral plants

uncoupled (from files "pitch_plant.m" and "lateral_plant.m") with their state-feedback loops closed. In the simulation model the pitch system is commanded with an $\alpha_{cmd}=1$ radian, and the lateral system is commanded with a $\phi_{cmd}=1$ radian. This was an initial test, uncoupled, and it does not include all the states because the phugoid mode is missing, plus the rate measurements come in the body axis and not in the stability axis. So we need a better gain evaluation model.

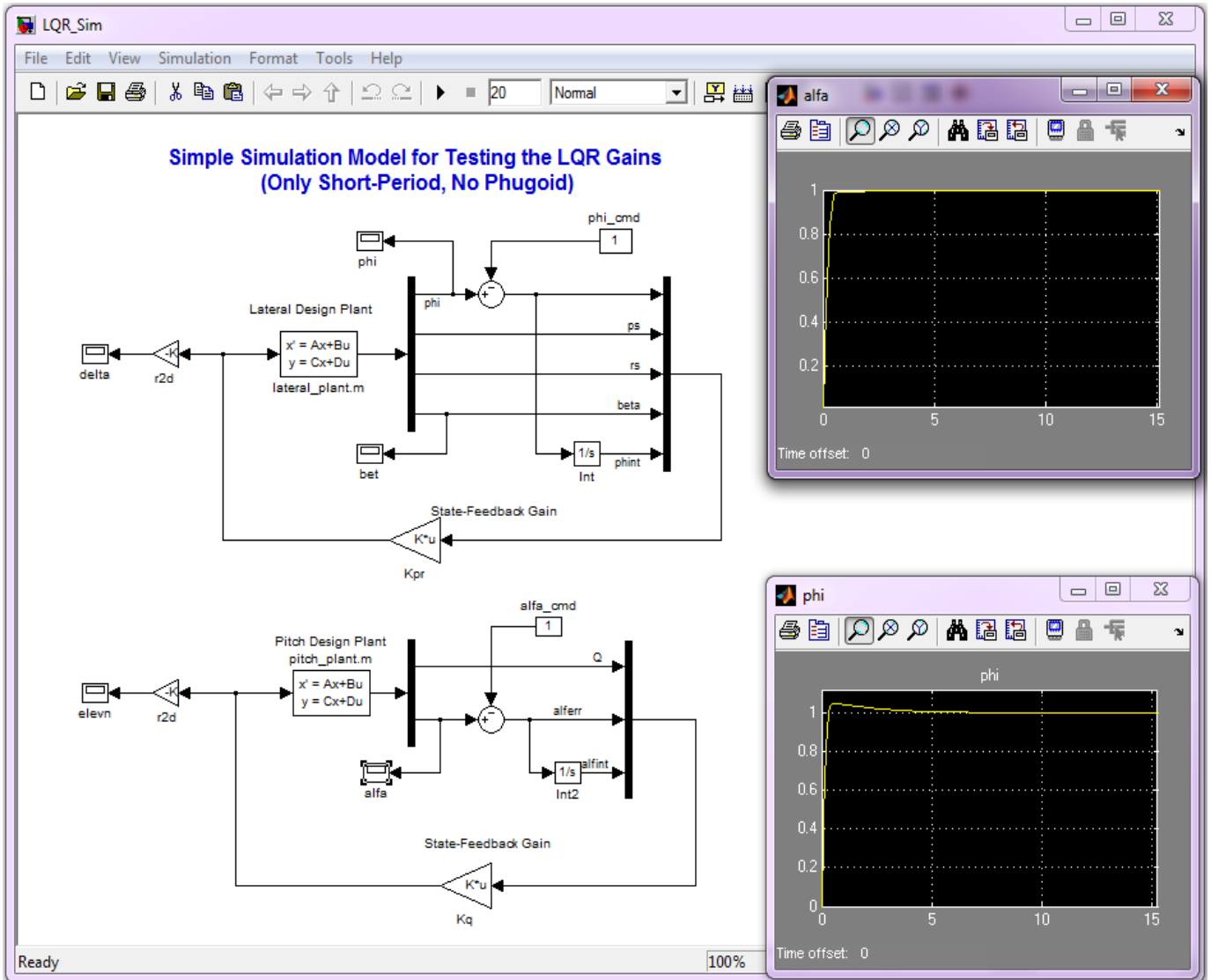


Figure 1 Simple Simulation Model "LQR_Sim.mdl" for an Initial Evaluation of the State-Feedback Gains

The linear Simulink model in file "LQR_Sim2.mdl", shown in Figure (2) is more efficient in analyzing the system's response to the roll and pitch commands. It uses the coupled pitch and lateral dynamics from file "vehi_sim.m" where the output rates are in the body axis, plus it includes also the phugoid states (δV & δh). The rates must, therefore, be transformed to stability axis because the state-feedback expects stability rates. The transformation block is shown in Figure (3). It includes also the turn coordination feedback terms which are functions of the bank angle (ϕ).

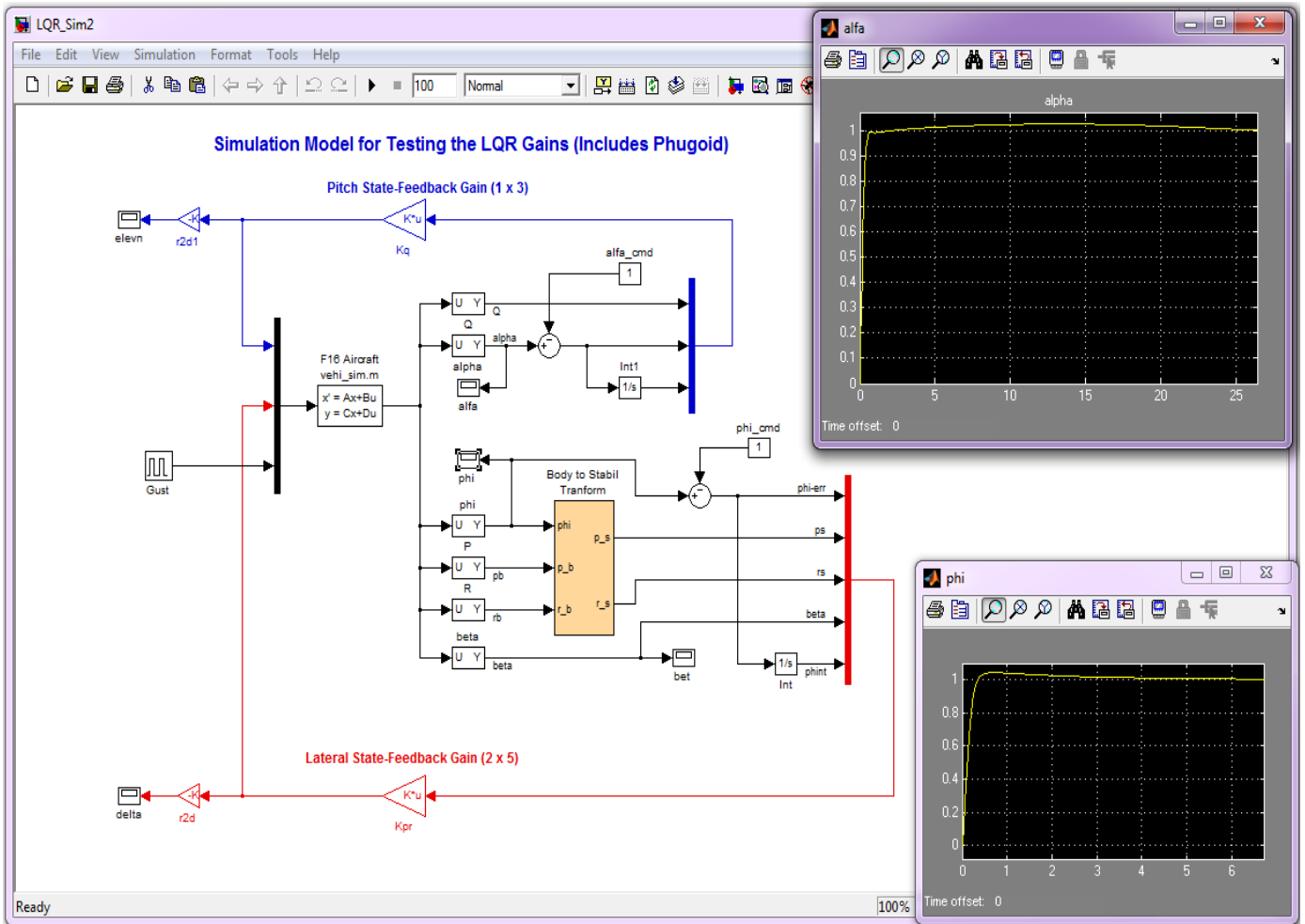


Figure 2 Linear Simulation Model "LQR_Sim2.mdl" for a Better Evaluation of the State-Feedback Gains

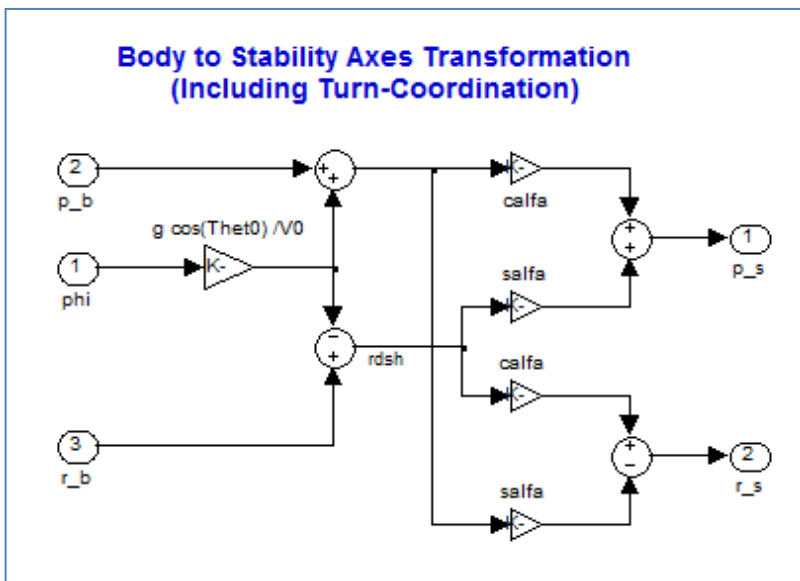


Figure 3 Body to Stability Axis Transformation Including also Turn Coordination

Dynamic models and state-feedback control gains were generated by the "*LQR_Design.m*" file at four different alphas: -10, -5, +3, +10 (deg), and also at 3 separate dynamic pressure/ velocity pairs: (100, 250, 400 psf) / (200, 400, 600 ft/sec). A total of 12 sets of (1x3) pitch gain matrices (Kq) and 12 sets of (2x5) lateral gain matrices (Kpr) were obtained. The separate matrix files are placed in subdirectory "*Mat_Design\Gains*" where they are combined into 4-dimensional matrices: Kq(1:4:3:4) and Kp(2:5:3:4) by the Matlab script file "*FCS_mat.m*", show below. The first two subscripts correspond to the matrix row and column subscripts. The third subscript corresponds to the 3 dynamic pressures, and the fourth to the 4 angles of attack. These gain matrices will be used and interpolated in the non-linear 6-dof simulation that will be described in detail in the following section.

```
% Combines the separate pitch and lateral matrices Kq_ and Kpr_
% into single four-dimensional matrices Kq(:, :, :, :) and Kpr(:, :, :, :)
% as a function of dynamic pressure and alpha, and saves them in FCS_Gains.mat
clear all
load Kq_ap10_Q100 -ascii; load Kpr_ap10_Q100 -ascii
load Kq_an10_Q100 -ascii; load Kpr_an10_Q100 -ascii
load Kq_ap3_Q100 -ascii; load Kpr_ap3_Q100 -ascii
load Kq_an5_Q100 -ascii; load Kpr_an5_Q100 -ascii

load Kq_ap10_Q250 -ascii; load Kpr_ap10_Q250 -ascii
load Kq_an10_Q250 -ascii; load Kpr_an10_Q250 -ascii
load Kq_ap3_Q250 -ascii; load Kpr_ap3_Q250 -ascii
load Kq_an5_Q250 -ascii; load Kpr_an5_Q250 -ascii

load Kq_ap10_Q400 -ascii; load Kpr_ap10_Q400 -ascii
load Kq_an10_Q400 -ascii; load Kpr_an10_Q400 -ascii
load Kq_ap3_Q400 -ascii; load Kpr_ap3_Q400 -ascii
load Kq_an5_Q400 -ascii; load Kpr_an5_Q400 -ascii

Kq(:, :, 1, 1)=Kq_an10_Q100(:, :); Kpr(:, :, 1, 1)=Kpr_an10_Q100(:, :);
Kq(:, :, 1, 2)=Kq_an5_Q100(:, :); Kpr(:, :, 1, 2)=Kpr_an5_Q100(:, :);
Kq(:, :, 1, 3)=Kq_ap3_Q100(:, :); Kpr(:, :, 1, 3)=Kpr_ap3_Q100(:, :);
Kq(:, :, 1, 4)=Kq_ap10_Q100(:, :); Kpr(:, :, 1, 4)=Kpr_ap10_Q100(:, :);

Kq(:, :, 2, 1)=Kq_an10_Q250(:, :); Kpr(:, :, 2, 1)=Kpr_an10_Q250(:, :);
Kq(:, :, 2, 2)=Kq_an5_Q250(:, :); Kpr(:, :, 2, 2)=Kpr_an5_Q250(:, :);
Kq(:, :, 2, 3)=Kq_ap3_Q250(:, :); Kpr(:, :, 2, 3)=Kpr_ap3_Q250(:, :);
Kq(:, :, 2, 4)=Kq_ap10_Q250(:, :); Kpr(:, :, 2, 4)=Kpr_ap10_Q250(:, :);

Kq(:, :, 3, 1)=Kq_an10_Q400(:, :); Kpr(:, :, 3, 1)=Kpr_an10_Q400(:, :);
Kq(:, :, 3, 2)=Kq_an5_Q400(:, :); Kpr(:, :, 3, 2)=Kpr_an5_Q400(:, :);
Kq(:, :, 3, 3)=Kq_ap3_Q400(:, :); Kpr(:, :, 3, 3)=Kpr_ap3_Q400(:, :);
Kq(:, :, 3, 4)=Kq_ap10_Q400(:, :); Kpr(:, :, 3, 4)=Kpr_ap10_Q400(:, :);

save FCS_Gains.mat Kpr Kq
```

11. Non-Linear 6-dof Simulation for the F-16

The F-16 simulation model described here is implemented using the Matlab program and the Aerospace Block-Set/ Simulink toolbox. The aerodynamic and mass-properties data were obtained from Brian L. Stevens and Frank L. Lewis book "Aircraft Control and Simulation". The flight control system used is a simple state-feedback derived by the LQR method. The aircraft design models were obtained from Flixan, as already described in sections (9 & 10). The simulation model is set up to perform two separate maneuvers: (a) a take-off to level flight, followed with a 180° roll, then a 180° pitch maneuver, and then descent and landing, and (b) a take-off to level flight, followed by a steady 40° coordinated turn, descent and landing. The maneuvers are controlled by 3 built-in command signals representing the pilot controls, which are: alpha-command, roll-command, and throttle-command, see Figure (4). There are two sets of signal generator commands for the two maneuvers.

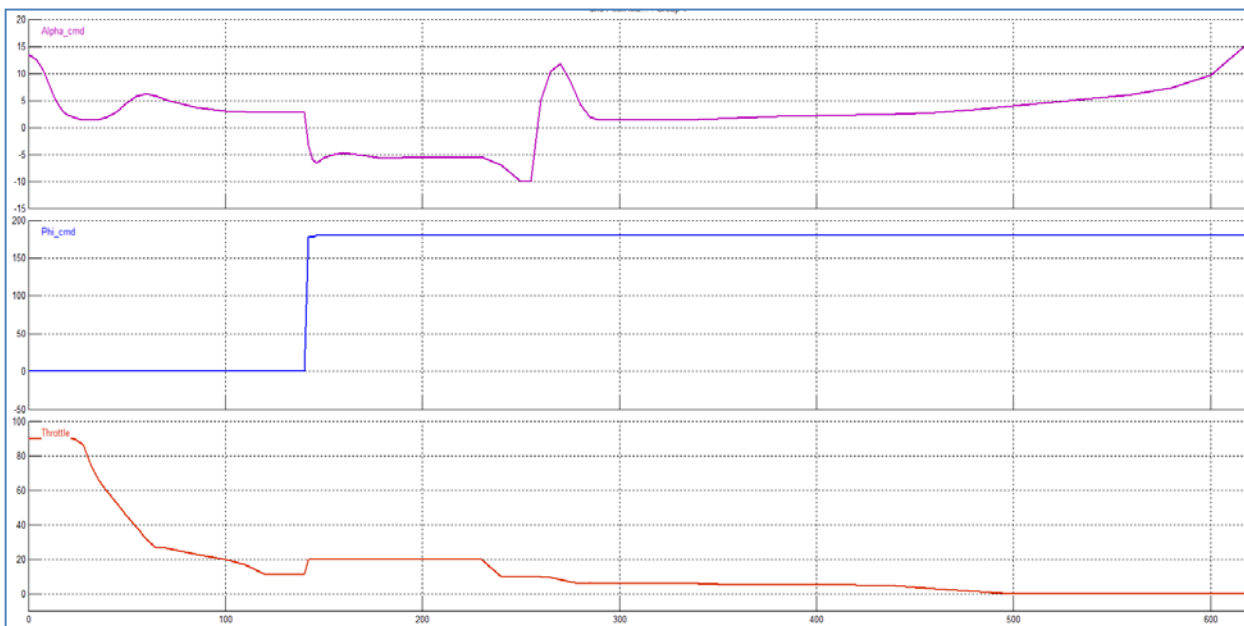


Figure 4 Pilot Commands for the 180° Roll and Pitch Maneuver

The F-16 simulation files are in folder "C:\Flixan\Trim\Examples\F-16 Fighter Aircraft\F16 Simulation (6-dof)". The Simulink model is in file "F16_6dof_Sim.Mdl" shown in Figure (5). A lot of the simulation subsystems are "off-the-shelf" Simulink models. It is initialized by the m-file "init.m" which initializes the speed, angle of attack, mass-properties, aero-parameters, thrust models, and the flight control gains. When the simulation is complete the file "pl.m" plots the simulation results.

F-16 Aircraft 6-dof Non-Linear Simulation

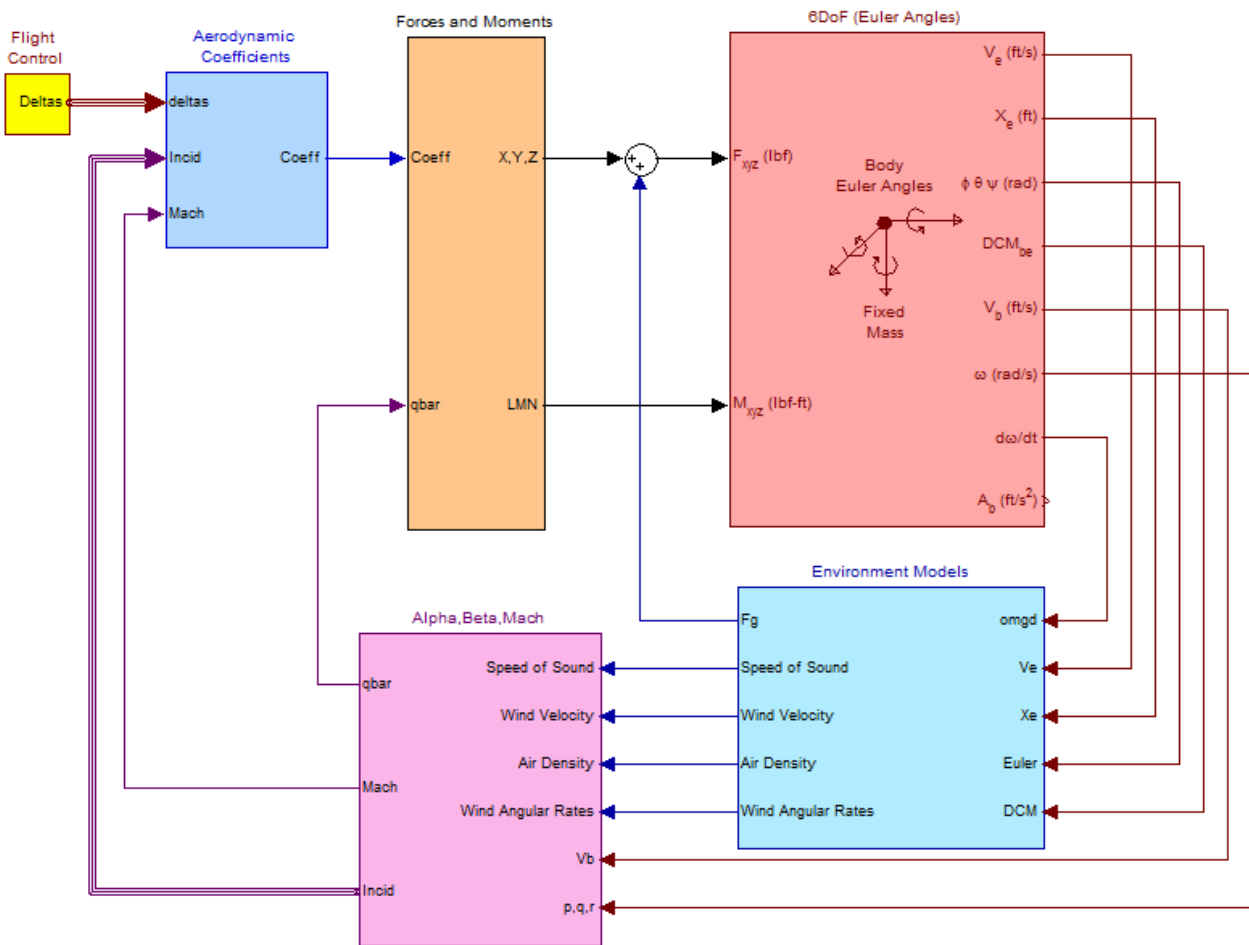


Figure 5 F-16 Simulation Model in File: "F16_6dof_Sim.Mdl"

Figure (6) shows the calculation of the environment variables in detail. Figure (7) shows the calculation of the engine and aerodynamic forces and moments which are applied to the vehicle. The aero moments depend also on the CG location relative to the location of the MRC. Figure (8) shows the calculation of: alpha, beta, velocity, dynamic pressure and Mach number. Figure (9) shows how the aerodynamic coefficients are calculated as a function of: Mach, alpha, beta, and surface deflections. The coefficients consist of two parts: (a) the aero coefficients of the base vehicle (blue block) plus (b) the increments from the aero-surfaces as a function of their deflections from zero (yellow block). The yellow block in fig. (9) is shown in detail in fig. (11) consisting of three aero-surfaces (elevon, aileron, and rudder). It calculates the increments in the base coefficients (C_A , C_Y , C_Z , C_l , C_m , C_n), as a function of: Mach #, alpha, beta, and surface deflections. Figure (12) shows the calculation of the Elevon increments in detail. The aerodynamic coefficients for the base vehicle (at zero deflections) are loaded from file "*Base_Aero_Coeff.m*". The coefficient increments due to surface deflections are loaded from files "*Elevon.m*", "*Aileron.m*", and "*Rudder.m*".

Environment

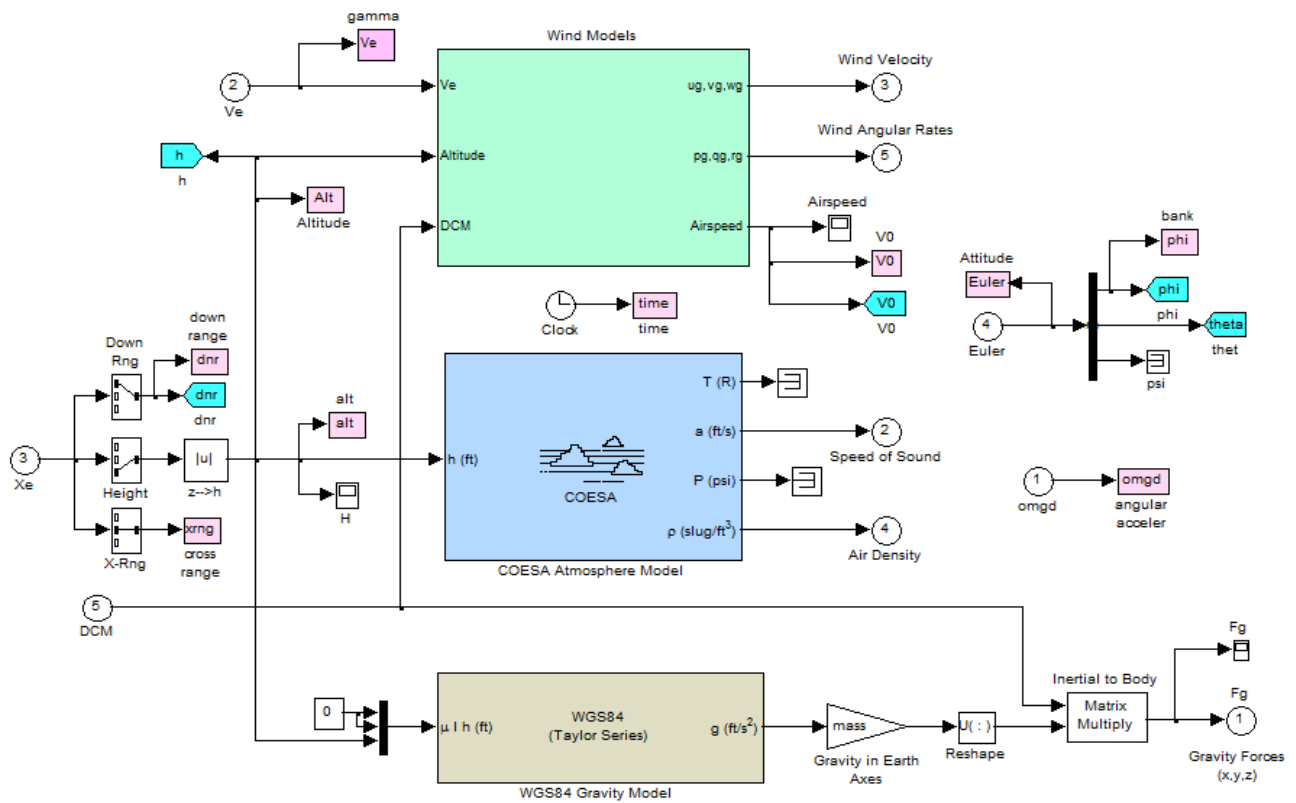


Figure 6 Environment Model

Moments and Forces due to Aero and Engine Thrust

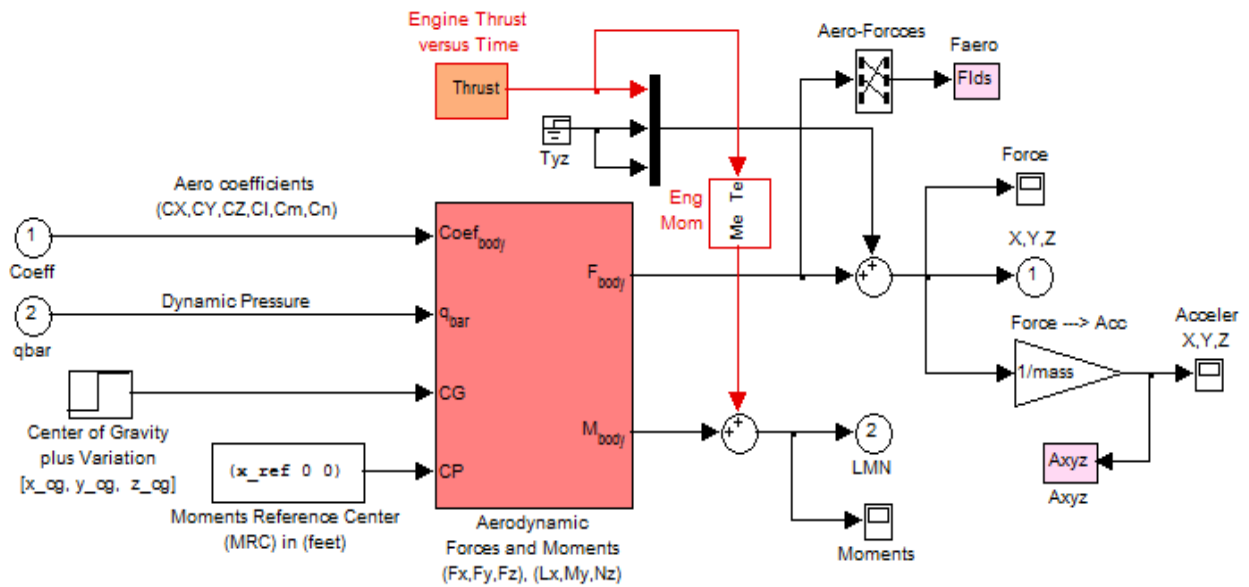


Figure 7 Moments and Forces due to Aero and the Engine Thrust

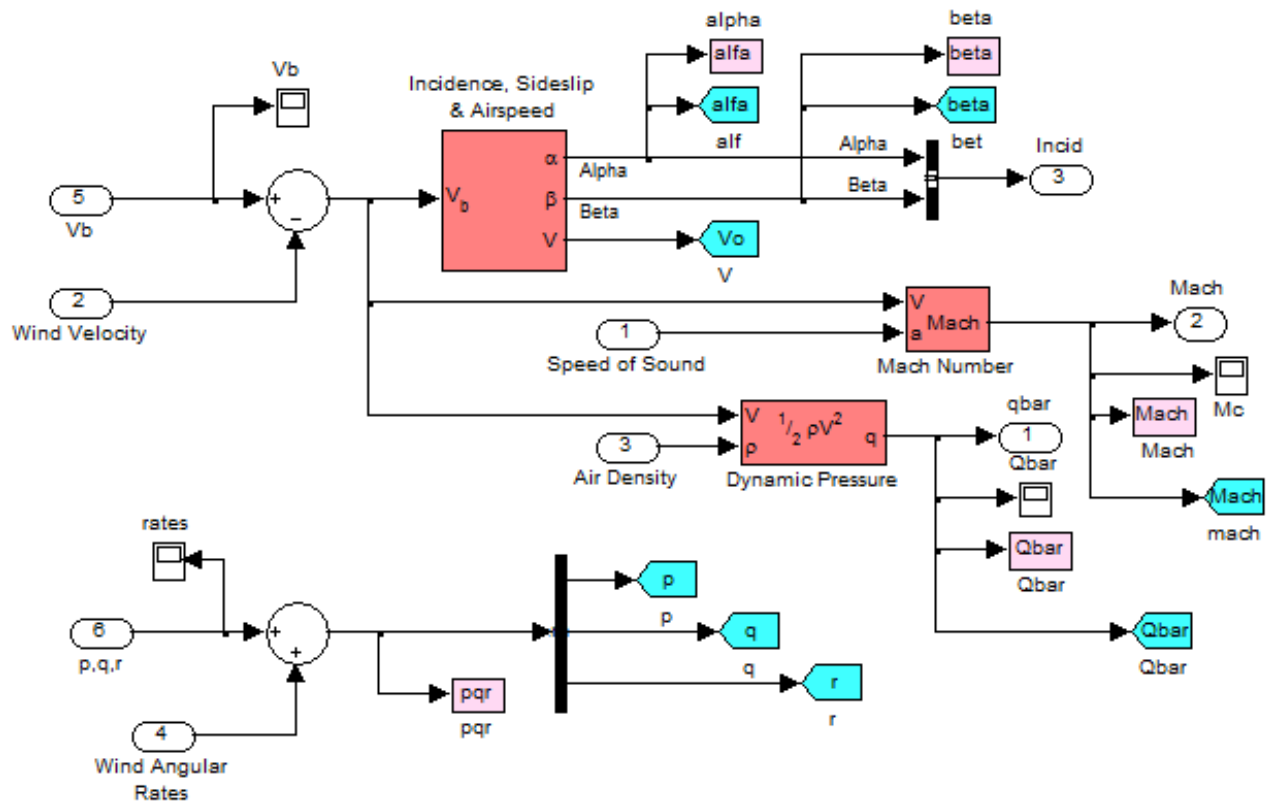


Figure 8 Alpha, Beta, Speed, Mach, and Dynamic Pressure Calculation

Aero Coefficients funct. of: Alpha, Beta, Mach#

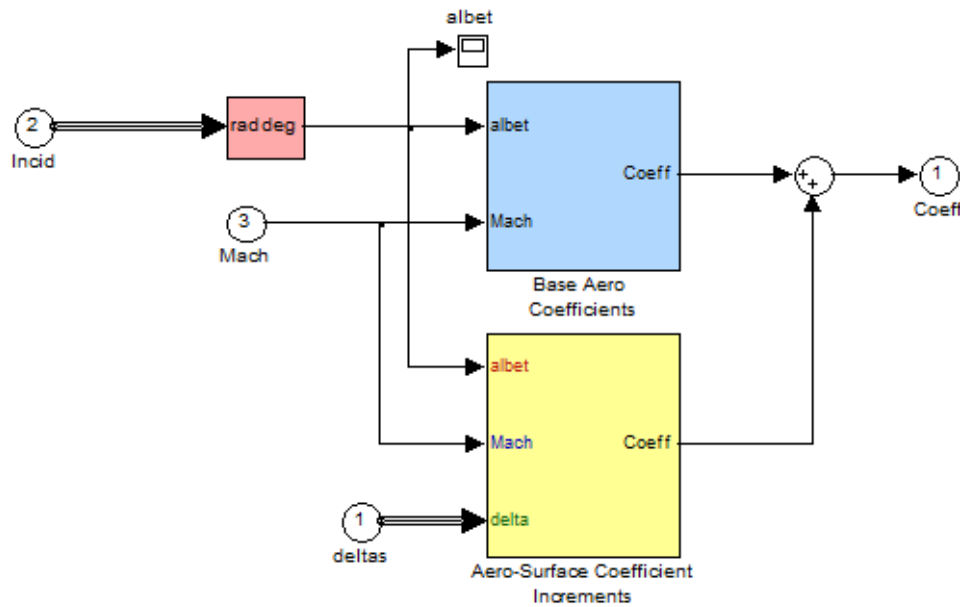


Figure 9 Aero Coefficients Calculation as a Function of: Alpha, Beta, and Mach Number

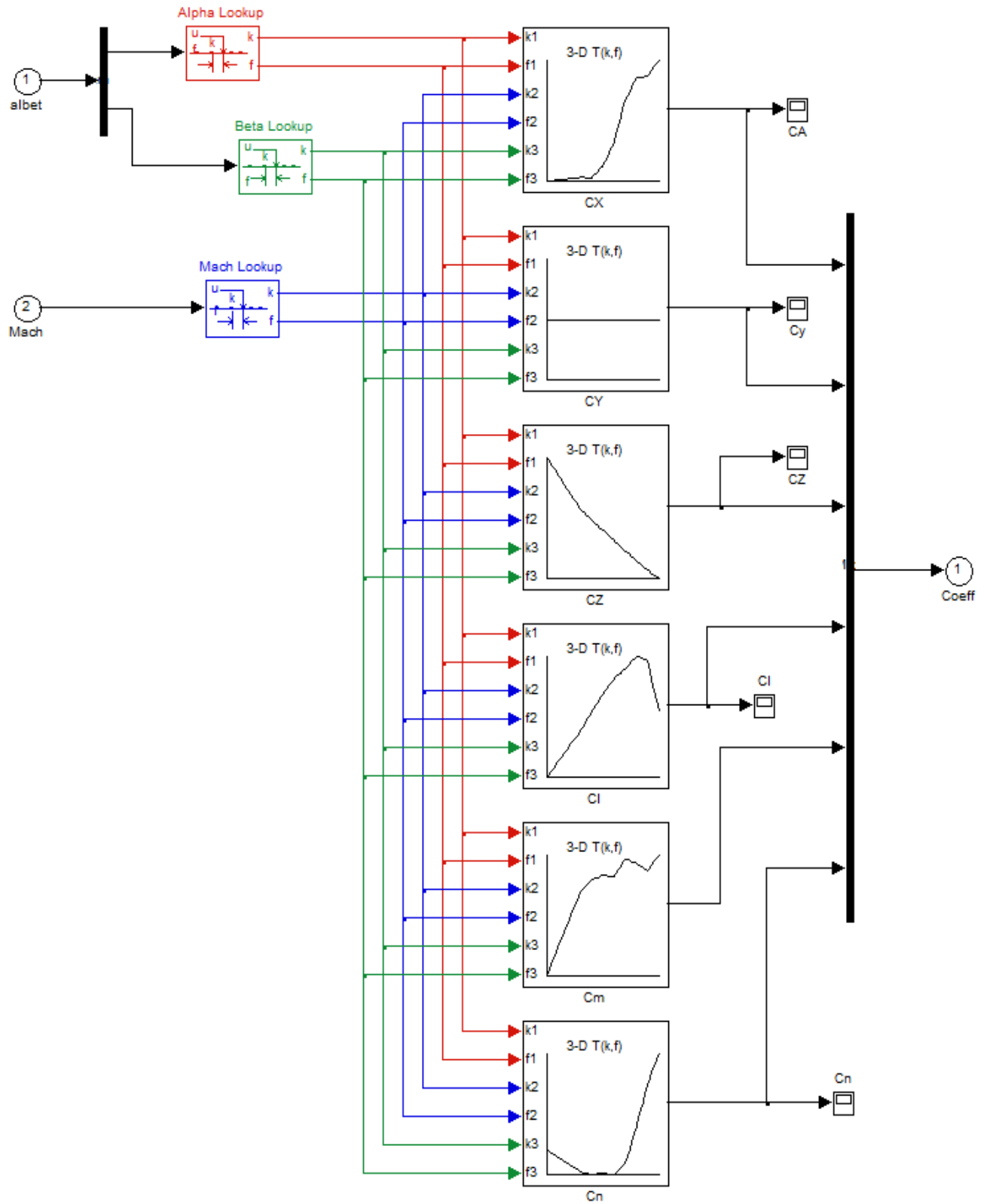


Figure 10 Base Aero Coefficients {CA, CY, CZ, CI, Cm, Cn} Calculation as a Function of: Alpha, Beta, and Mach Number

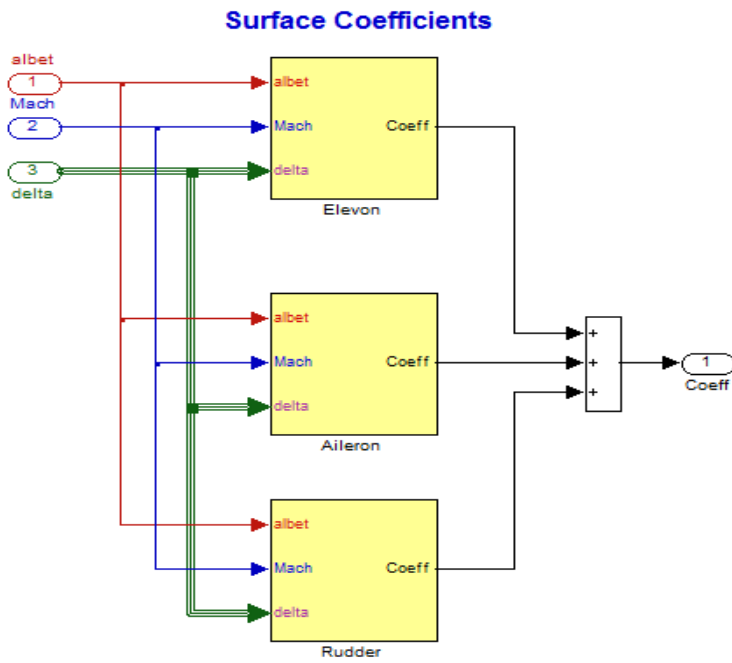


Figure 11 Control Surface Increment Coefficients for the Elevon, Aileron, and Rudder

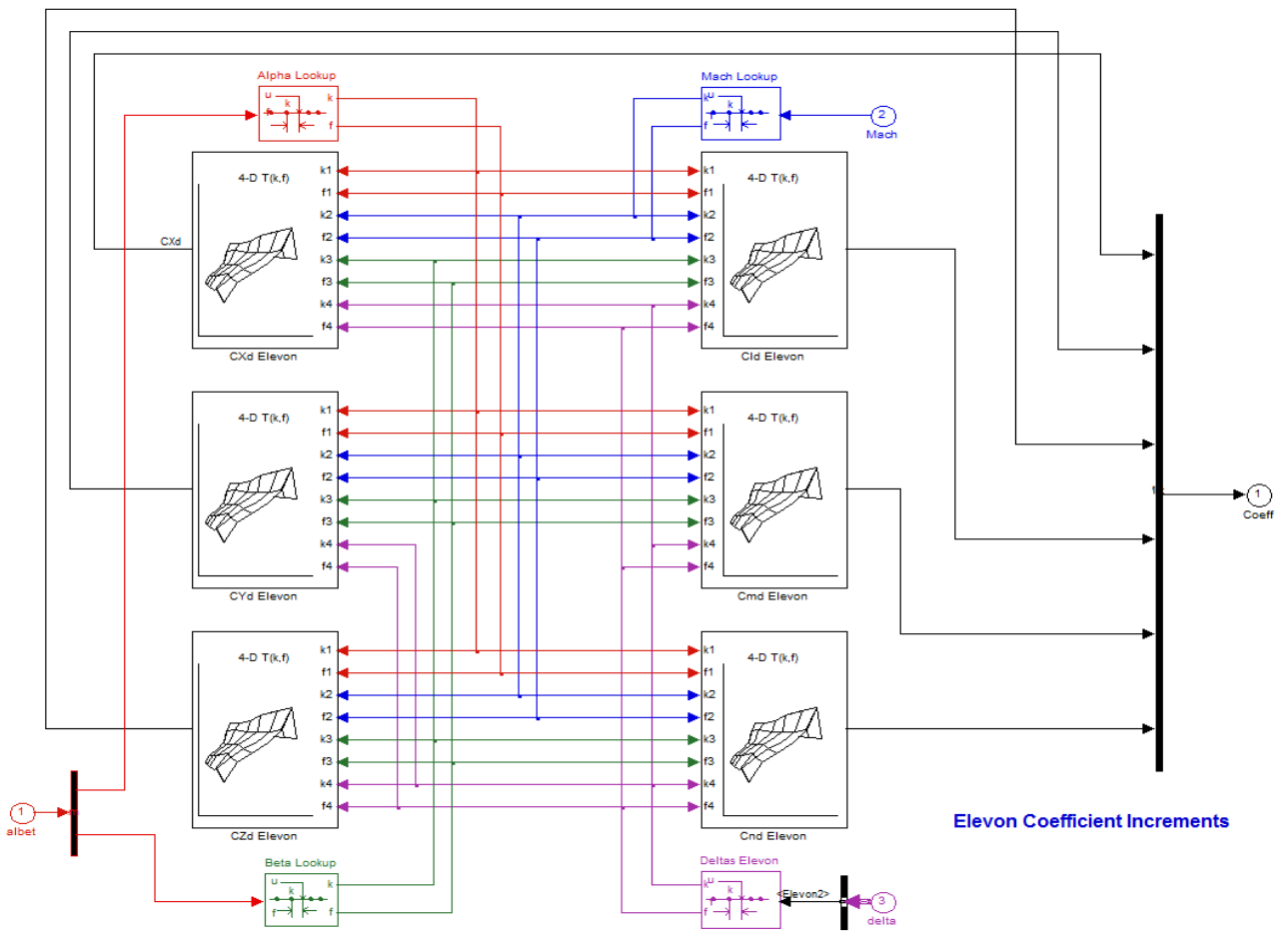


Figure 12 Elevon Increments Calculated as a Function of: Alpha, Beta, Mach #, and Surface Deflection

Flight Control System

The flight control system is shown in detail in Figure (10). It consists of two state-feedback loops, (a) the pitch state-feedback that uses pitch rate, alpha-error, and integral of alpha-error, and (b) the lateral state-feedback that uses roll error, roll and yaw stability axes rates, beta, and integral of roll error. The rates are measured in the body axes and they are converted to stability axes as a function of the angle of attack, see Fig. (11). This reduces beta and the side loads when the vehicle performs roll maneuvers.

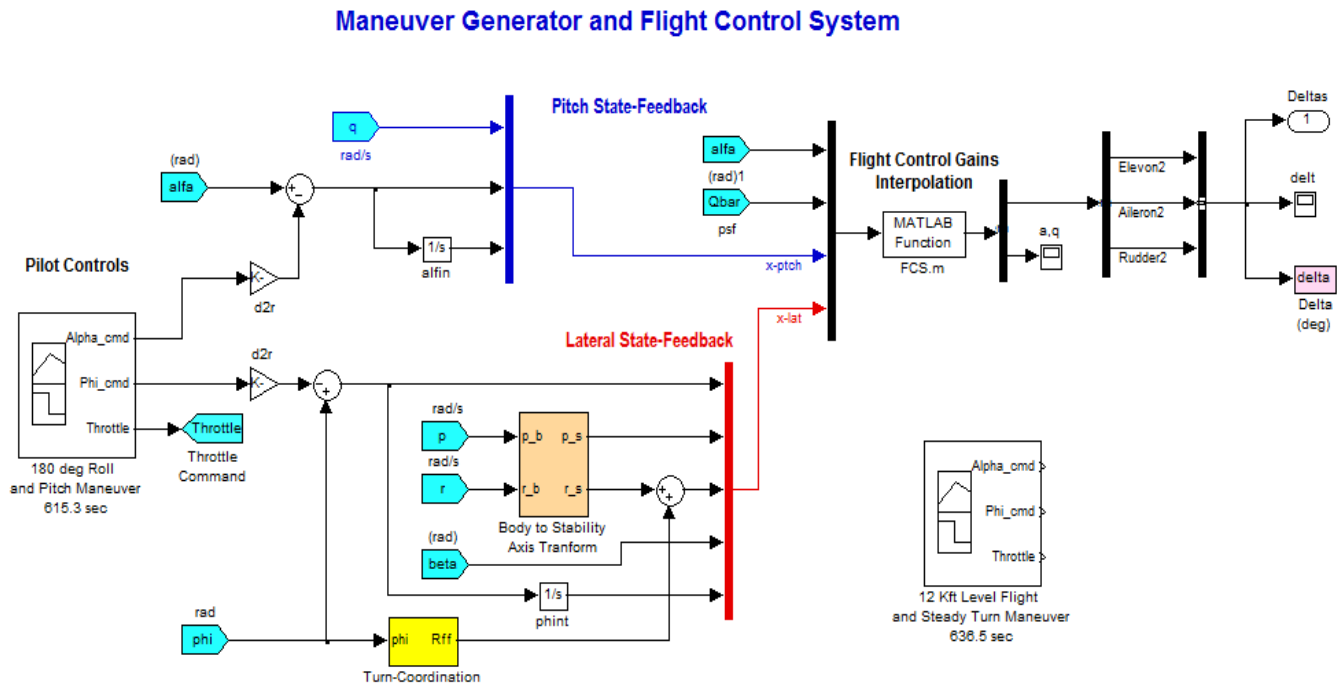


Figure 13 Simple Flight Control System Including Pilot Maneuvering Commands

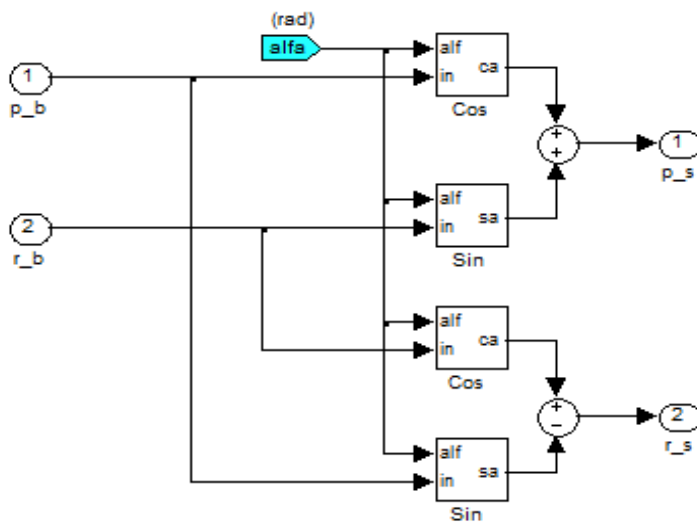
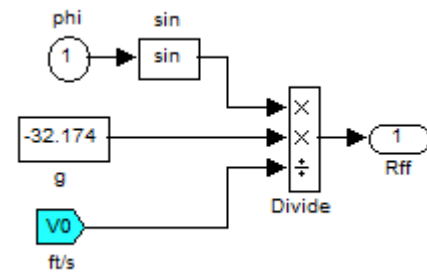


Figure 14 Body to Stability Axes Transformation

The lateral state-feedback gains were designed using lateral design models that have output rates defined in stability axis and they also include turn-coordination feedback logic, as it was already described in Section (10). The figure shows the turn-coordination block. It commands a yaw rate as a function of the bank angle ϕ according to the equation: $R_{ff} = \frac{g}{V_0} \sin \phi$. It uses a gravity component to counteract the centripetal side-force due to turning.



The control law gains were calculated based on Flixan models that were generated in section (9) at different angles of attack and dynamic pressures. A matrix of pitch and lateral gains were created in section (10) for the following range of alphas: [-10, -5, +3, +10] and for the following range of dynamic pressures [100, 250, 400]. The pitch and lateral multi-dimensional gain matrices (Kq) and (Kpr) respectively are loaded from file "FCS_Gains.Mat" during initialization. These matrices were created in the control design section 10. In the simulation the control gains are interpolated as a function of alpha and dynamic pressure. The interpolation is implemented in the Matlab function "FCS.m", shown below.

```
function Dqpr= FCS(Alfa,Qbar, u1,u2)
% Implements State-Feedback Control Laws
% u1 is the pitch state-feedback variables [q,alfa,alfa-integr]
% u2 is the lateral state-feedback variables [phi,p,r,beta,phi-integr]
global Kq Kpr

% Design Alphas: [-10, -5, +3, +10]
if (Alfa< -5) Ia=int8(1); Ia2=Ia; a=1; da=0;
elseif (Alfa>=-5) & (Alfa<0) Ia=int8(2); Ia2=int8(3); a=2; da=(Alfa-5)/5;
elseif (Alfa>= 0) & (Alfa<5) Ia=int8(3); Ia2=int8(4); a=3; da=(5-Alfa)/5;
elseif (Alfa>= 5) Ia=int8(4); Ia2=Ia; a=4; da=0; end

% Design Qbars: [100, 250, 400]
if (Qbar< 150) Iq=int8(1); q=1; dQb=0; Iq2=Iq;
elseif (Qbar>=150) & (Qbar<300) Iq=int8(2); q=2; dQb=(Qbar-225)/75;
if (dQb>=0) Iq2=int8(3); else Iq2= int8(1); end
elseif (Qbar>=300) Iq=int8(3); q=3; dQb=0; Iq2=Iq; end

dq1= Kq(:,:,Iq,Ia)*u1; dq2= Kq(:,:,Iq,Ia2)*u1; dq3= Kq(:,:,Iq2,Ia)*u1;
dpr1=Kpr(:,:,Iq,Ia)*u2; dpr2=Kpr(:,:,Iq,Ia2)*u2; dpr3=Kpr(:,:,Iq2,Ia)*u2;

dq= dq1 + (dq2 - dq1)*da + (dq3 - dq1)*dQb*sign(dQb);
dpr=dpr1 + (dpr2-dpr1)*da + (dpr3-dpr1)*dQb*sign(dQb);
Dqpr=[-dq*180/pi; -dpr*180/pi; a;q];
```

The Matlab function "*Thrust.m*" calculates the engine thrust as a function of the throttle command from the pilot. The thrust is also function of the vehicle altitude, and the Mach number, as defined in the Stevens and Lewis book "Aircraft Control and Simulation".

Simulations

We will now show the results from the two simulation maneuvers. The first one is mainly in the pitch plane. The aircraft takes off at a speed of 155 mph and 13.5 (deg) of alpha, and almost at full power. It climbs to 12,000 (ft) and flies at constant altitude for a while. At $t=140$ sec, it performs a 180° flip in roll and it flies at constant altitude, up-side-down, with a negative alpha for about a minute. Then it pitches up by increasing its negative alpha to gain altitude and when the speed drops it reverses alpha to positive, and it performs a 180° pitch maneuver as it loses altitude and reverses its direction. Then it stabilizes its descent rate $\gamma=-2$ (deg/sec) approximately and lands not very far from its take-off site. The pilot commands for this maneuver are shown in Figure (4).

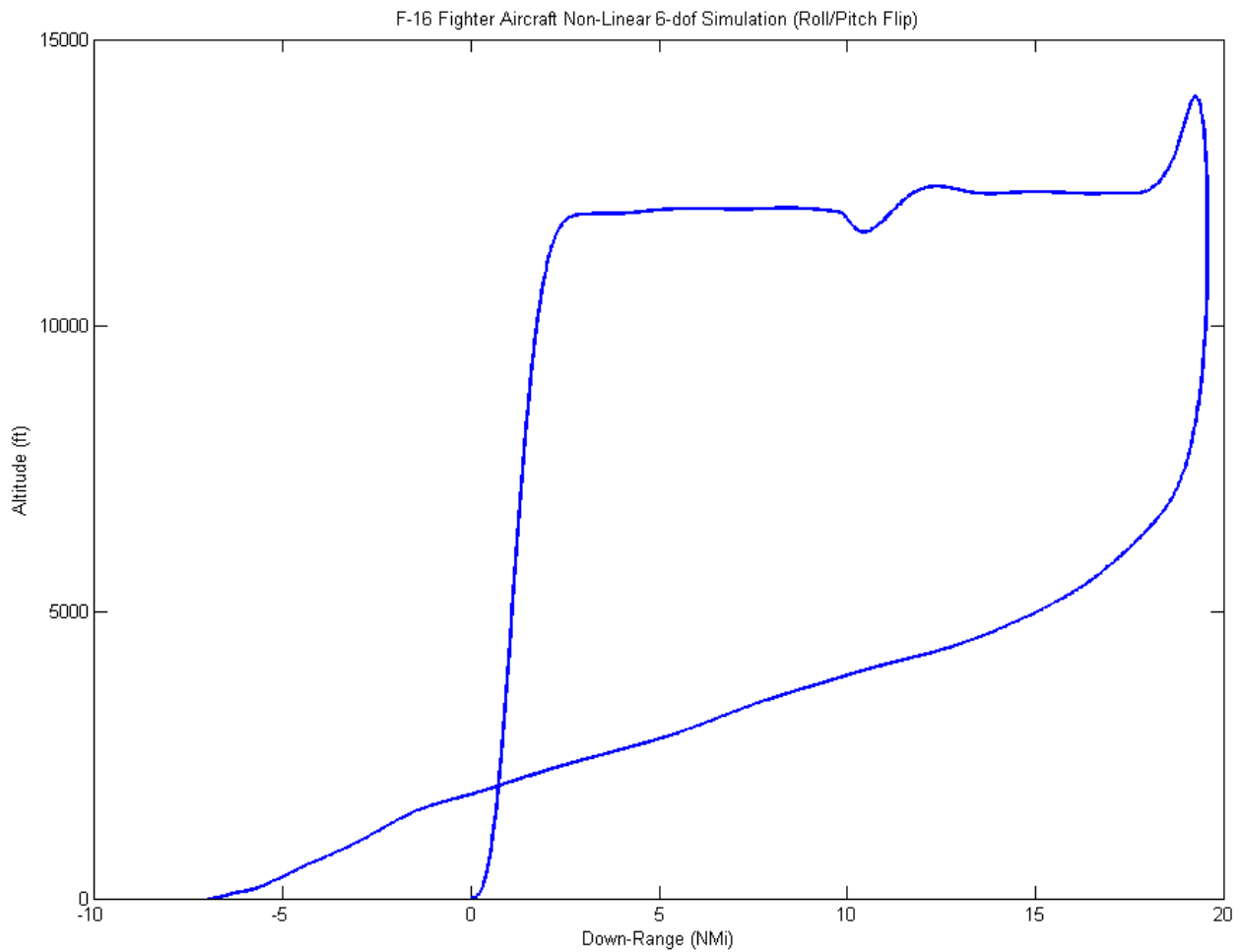


Figure 15.1 Altitude Versus Down-Range from Take-Off to Landing

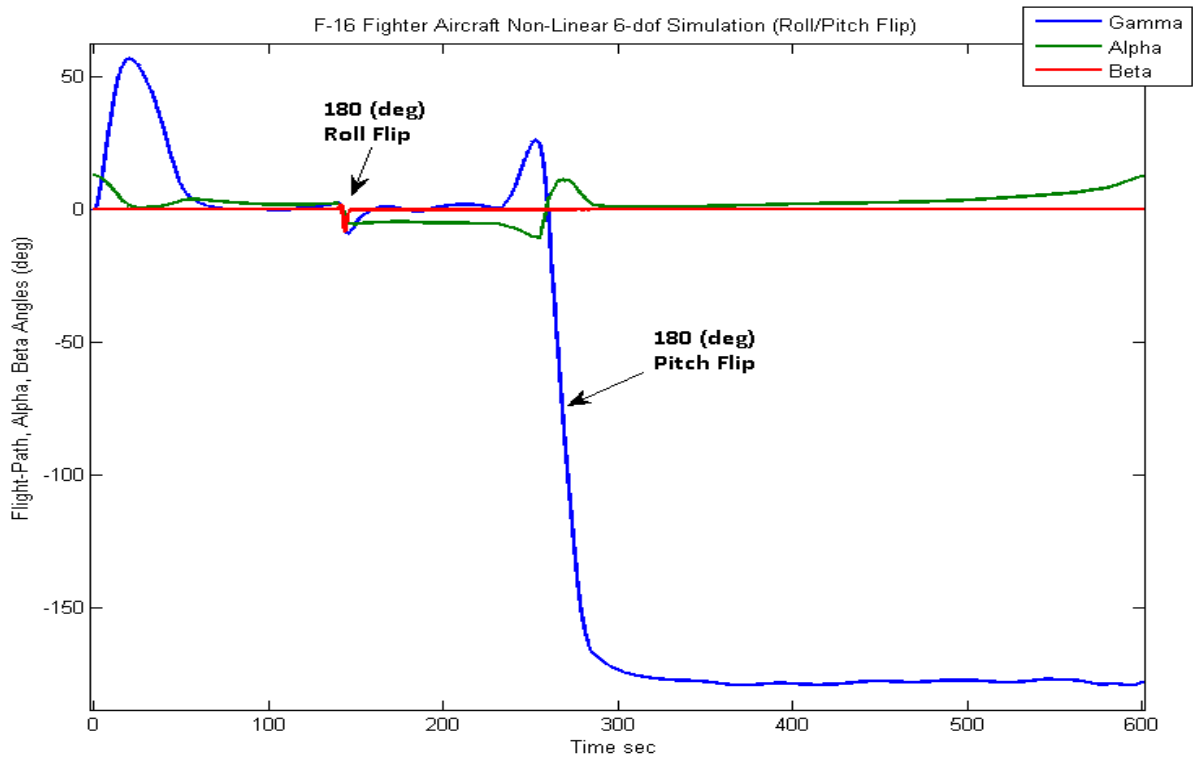


Figure 15.2 Flight-Path Angle (blue), and Angles of Attack and Sideslip (deg). It shows the climb, the roll-reversal, the pitch maneuver, and the slow descent at $\gamma = -178^\circ$

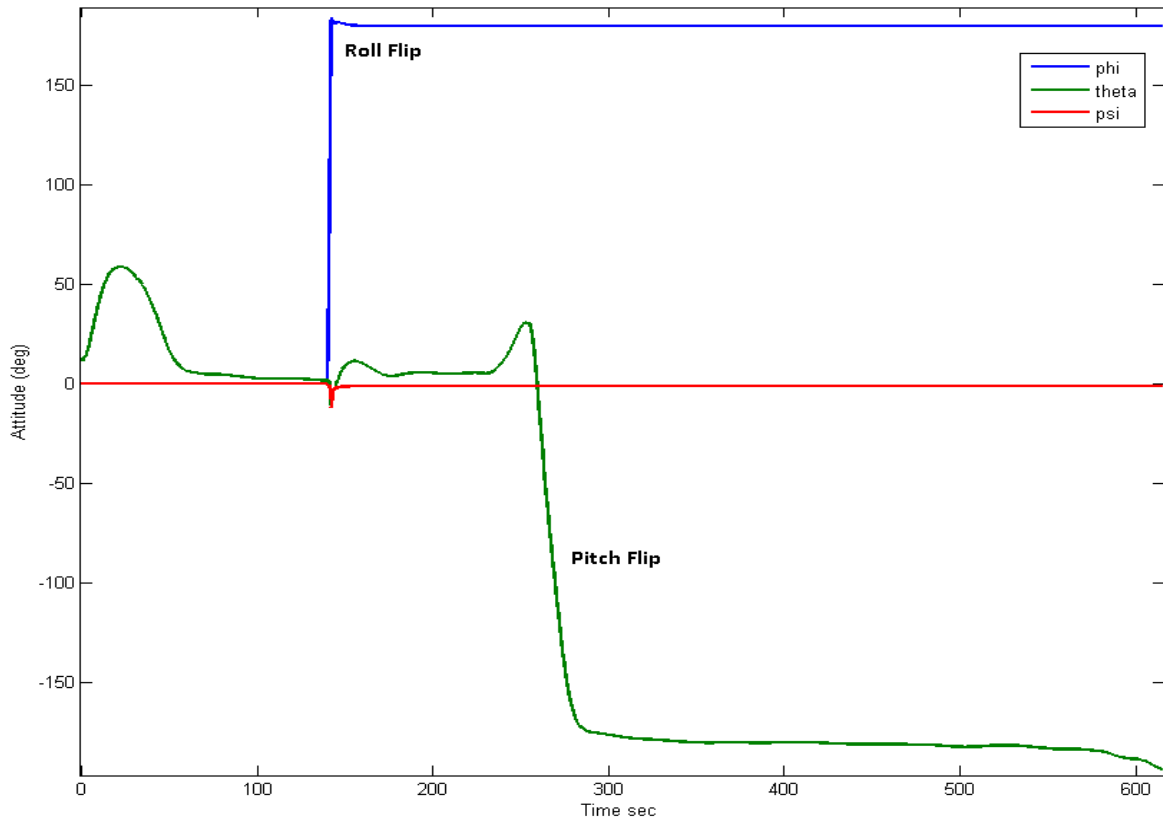


Figure 15.3 Euler Angles Showing the Roll and Pitch Maneuvers

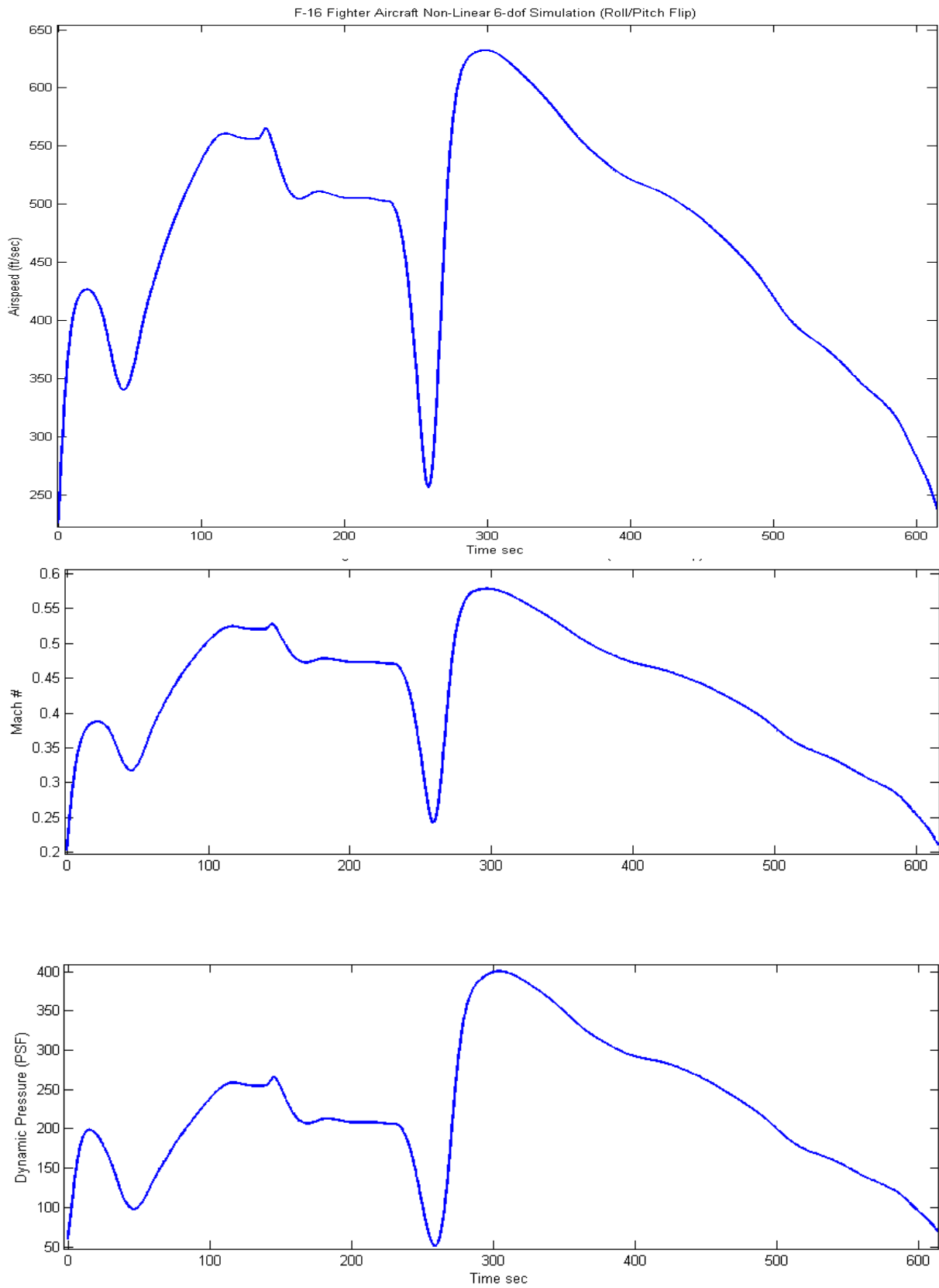


Figure 15.4 Figure shows how the airspeed is reduced prior to the 180° pitch maneuver and direction reversal. The speed is also reduced prior to landing.

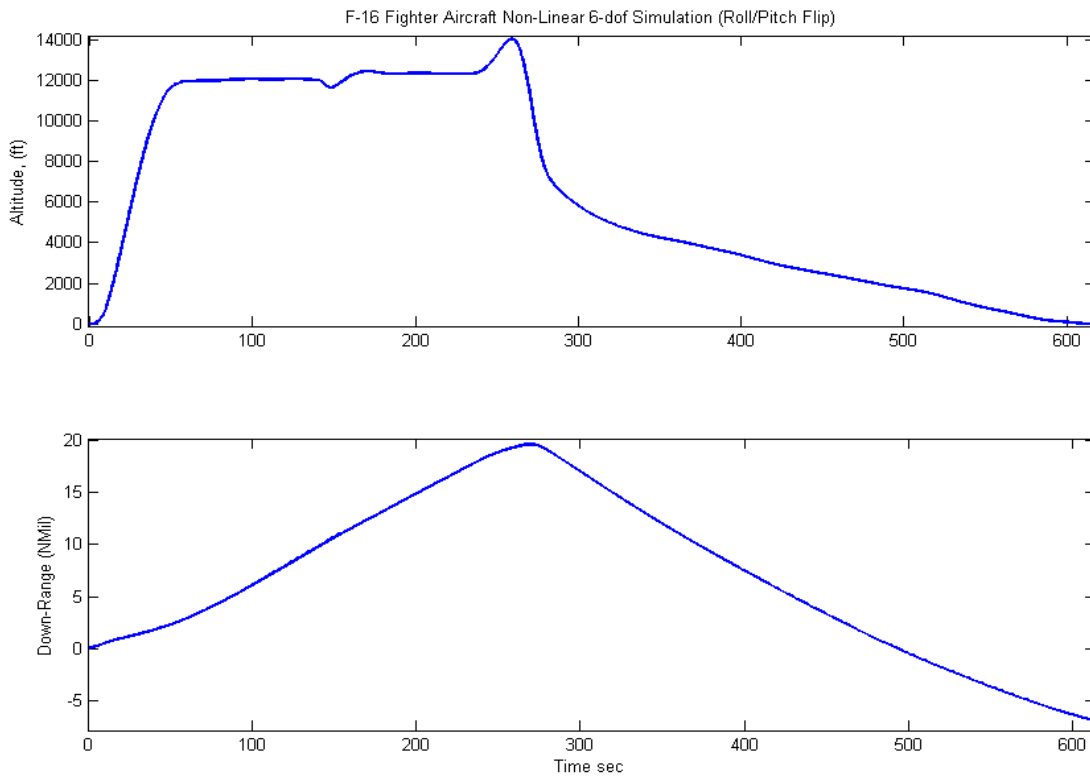


Figure 15.5 Altitude and the Downrange versus Time. The altitude drops slightly during the roll flip but it is regained by adjusting the negative alpha. It drops fast during the pitch maneuver but the rate of descent is stabilized and further reduced prior to landing. The downrange reaches 20 (NMI) prior to the pitch reversal and then it reduces as the vehicle returns towards its landing site.

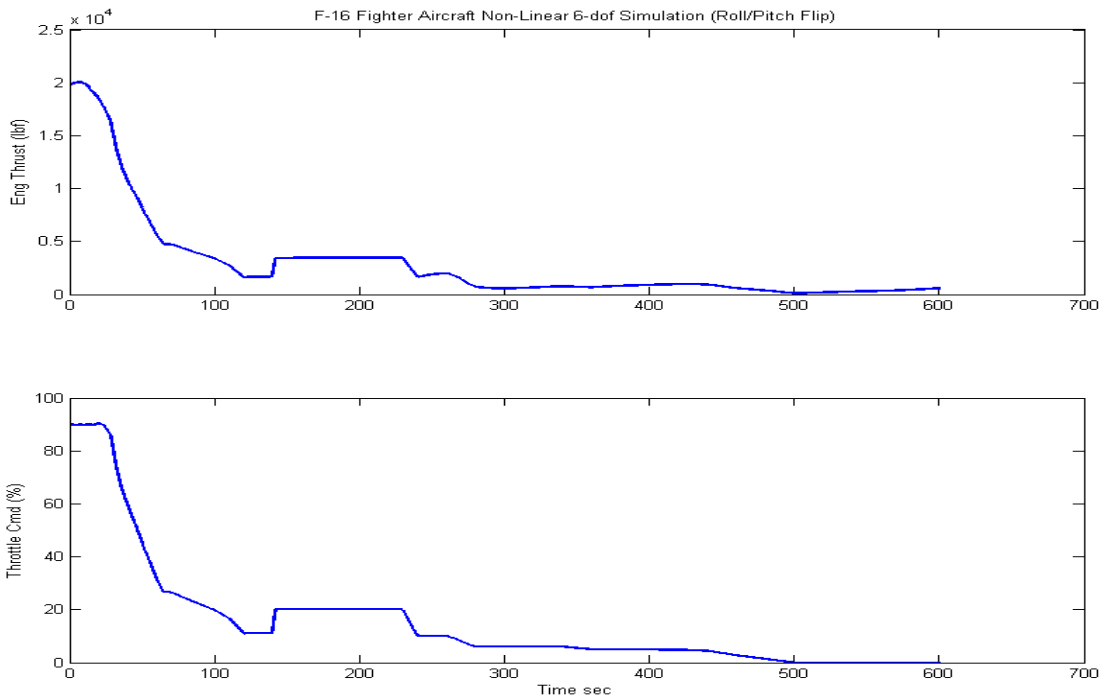


Figure 15.6 Throttle Control and Actual Engine Thrust versus Time. The engine thrust is calculated as a function of Altitude and Mach #, and it is implemented in Matlab function Thrust.m.

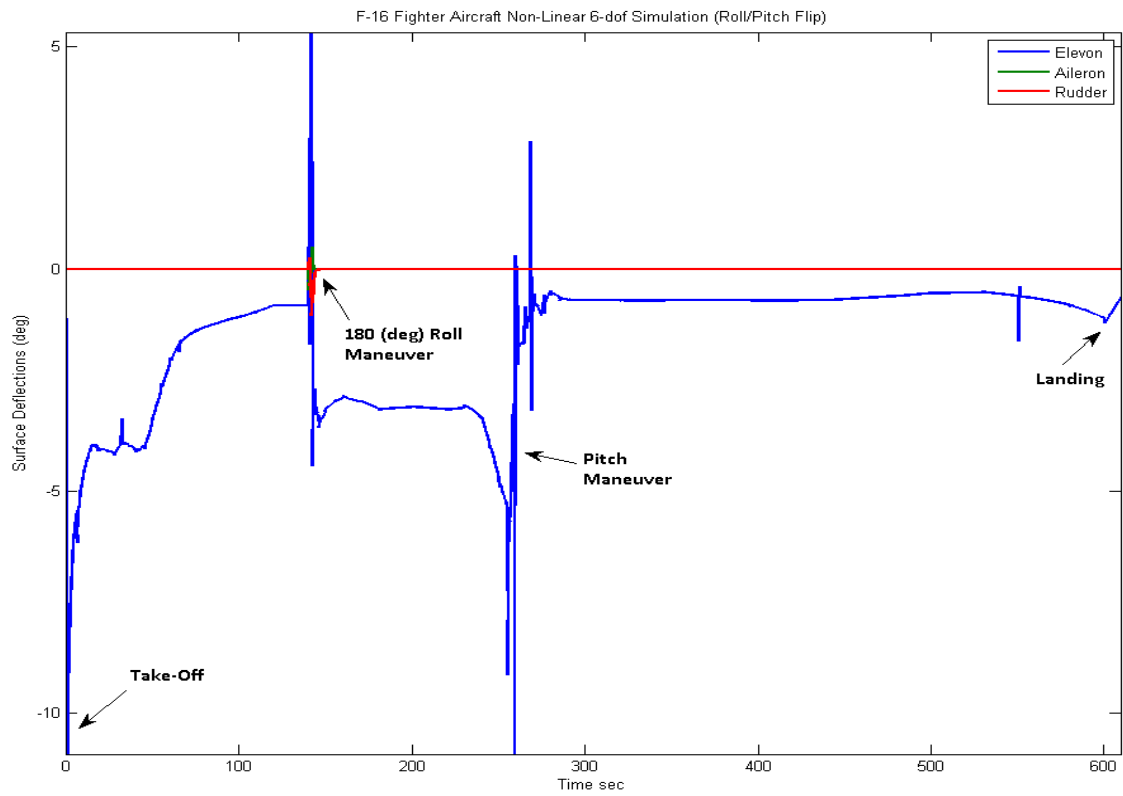


Figure 15.7 Surface Deflections are Mainly in the Elevon. The Aileron and Rudder deflect during the Roll Maneuver.

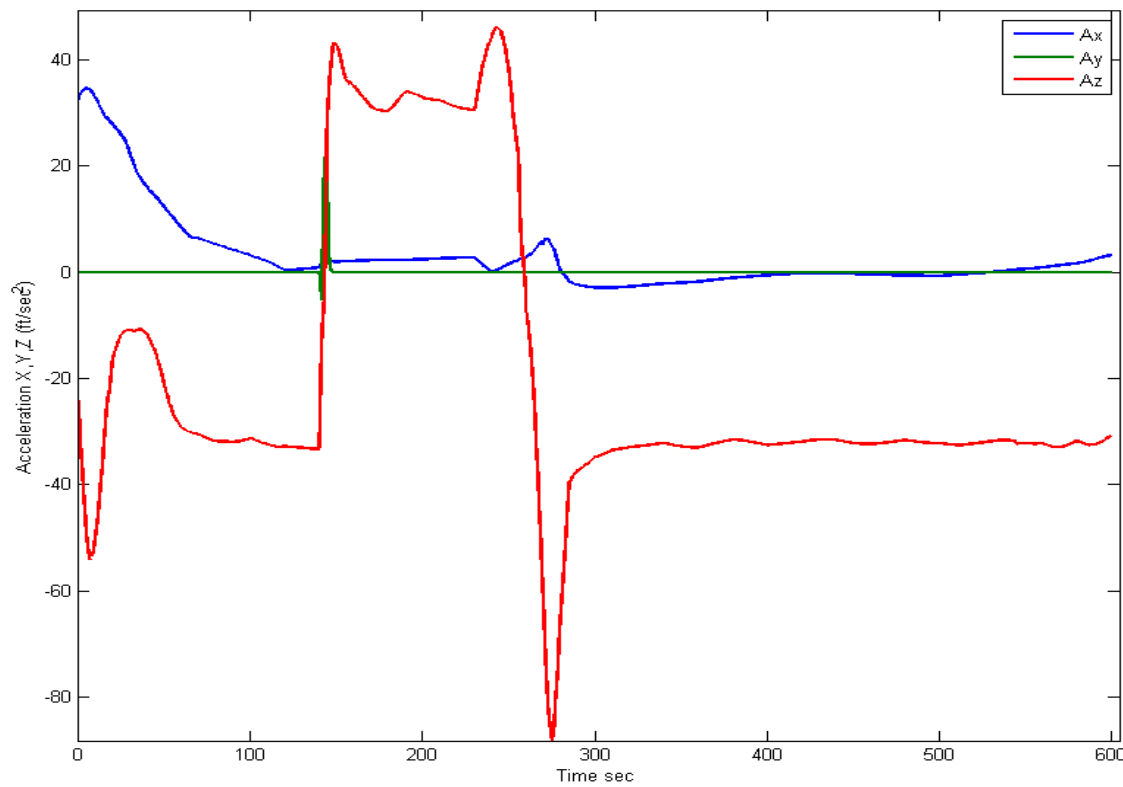


Figure 15.8 The Axial Acceleration results from the Engine Thrust. The Normal Acceleration during level flight is -32.2 or +32.2 when the vehicle is up-side-down.

The second simulation is obtained using another signal generator function "*12 (Kft) Level Flight and Steady Turn Maneuver*", see Fig. 13. The beginning part of the maneuver is very similar to the first one. From level flight it banks 20 (deg) to the right and performs steady turns at level flight. Then it returns to zero bank, descends and lands at a different site.

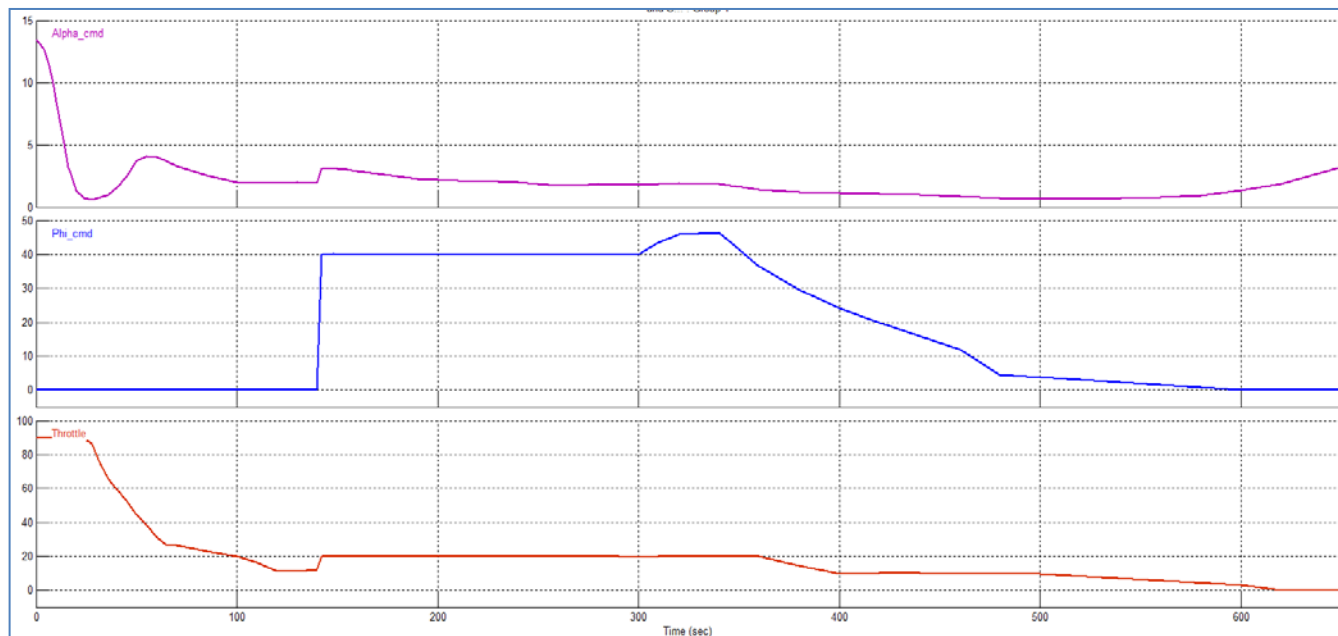


Figure 16.1 Pilot Commands for the Steady Turns Maneuver

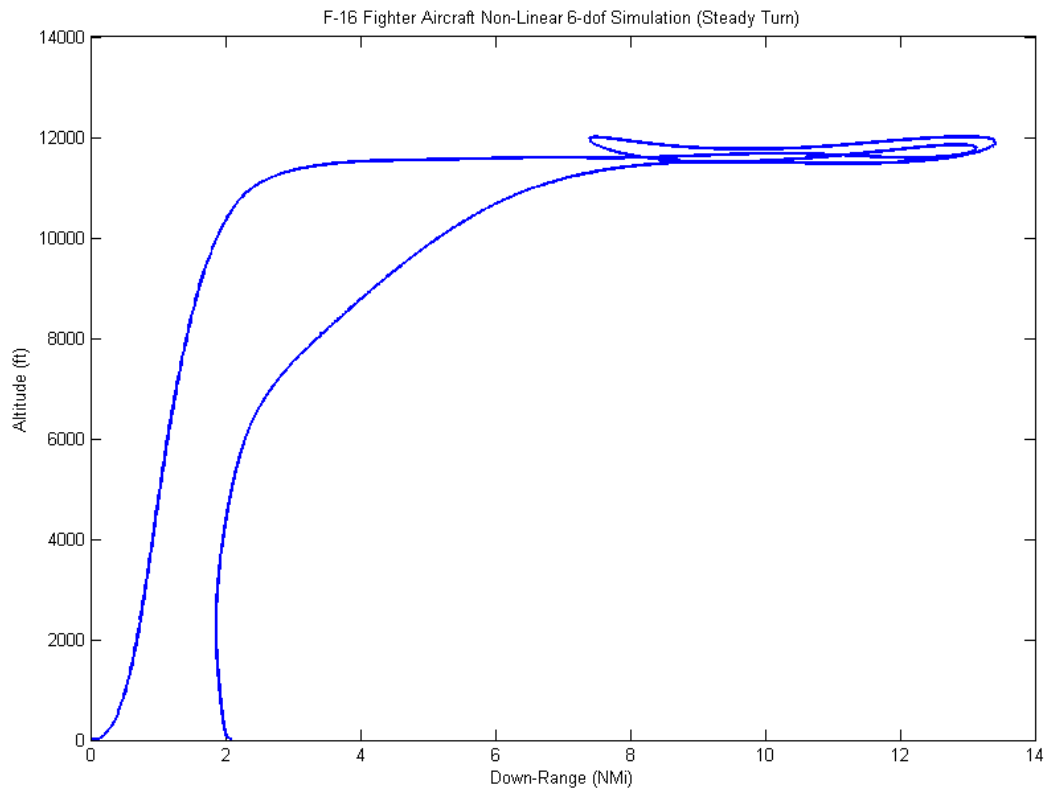


Figure 16.2 Altitude Versus Down-Range from Take-Off to Landing

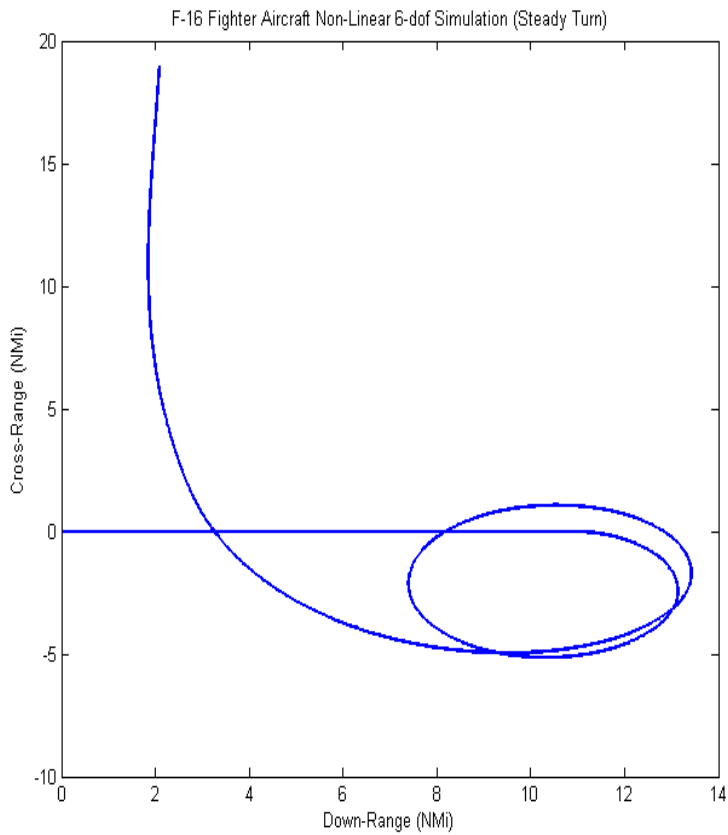


Figure 16.3 Down-Range versus Cross-Range showing the Steady Turn Maneuver.

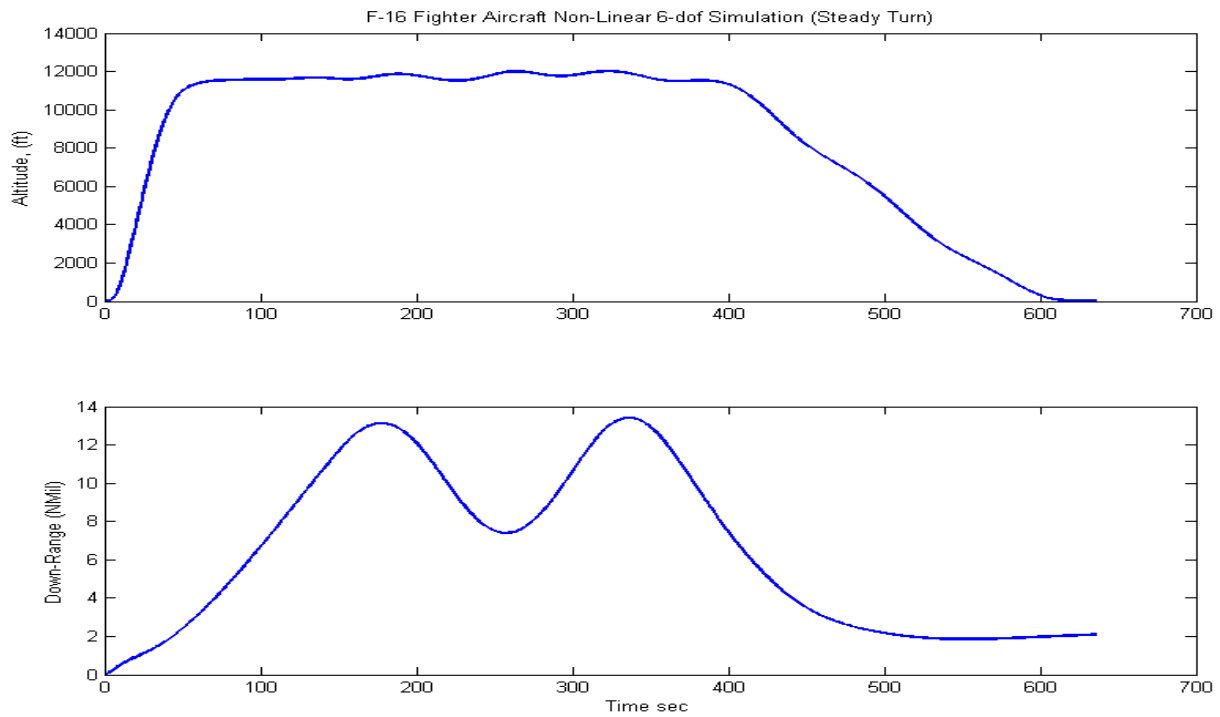


Figure 16.4 Altitude and the Downrange versus time, showing that it maintains an almost constant altitude during the turn. The altitude decreases at almost constant rate during descent. The Down-Range distance varies as the aircraft performs horizontal circles.

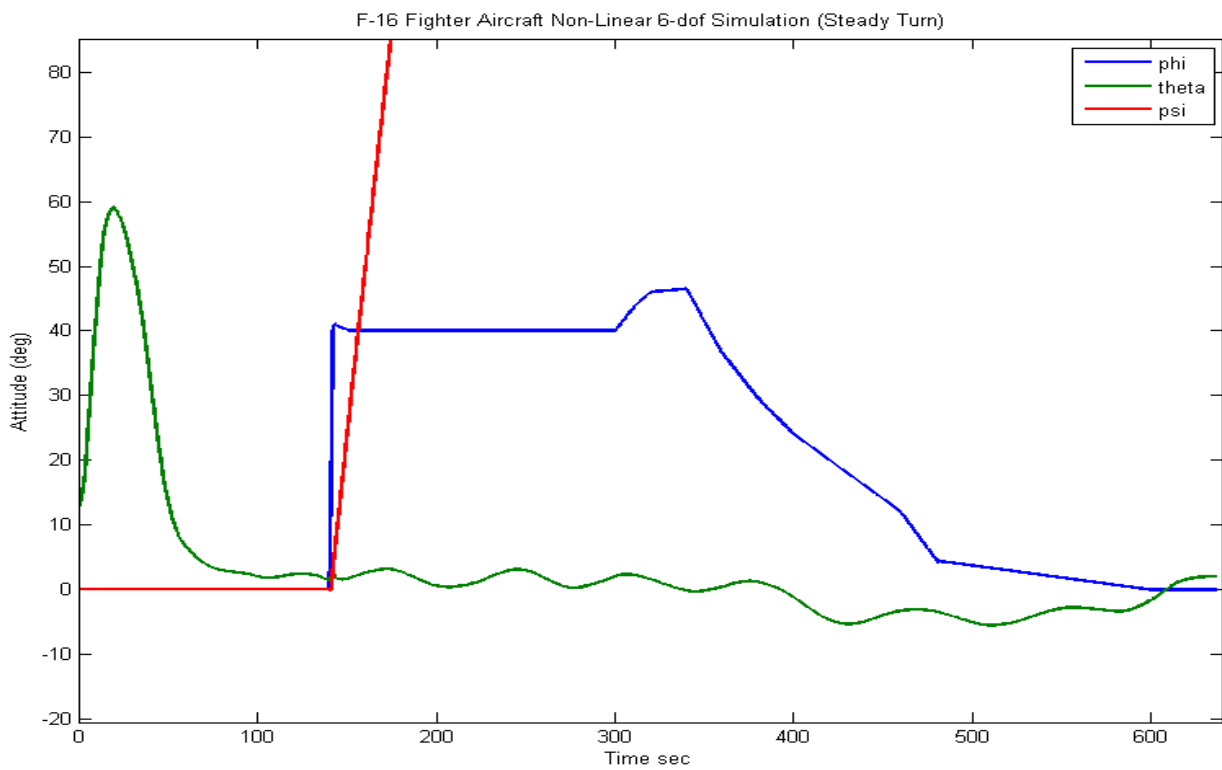


Figure 16.5 Shows the Euler Angles. The Bank angle is maintained at 40° for approximately 3 min during the steady turn.

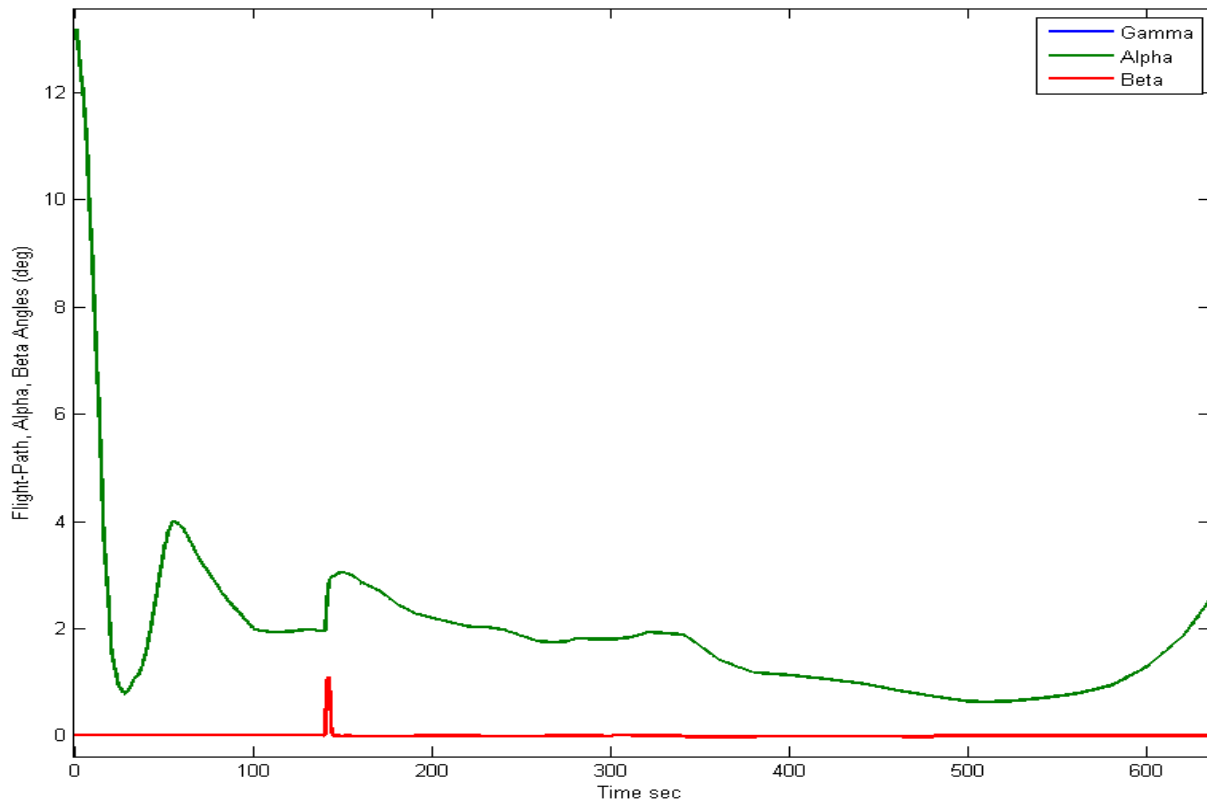


Figure 16.6 Shown the Angles of Attack and Sideslip. The small beta transient occurs during the 40 (deg) roll maneuver. During the steady turn, however, beta is maintained at zero by the turn-coordination system.

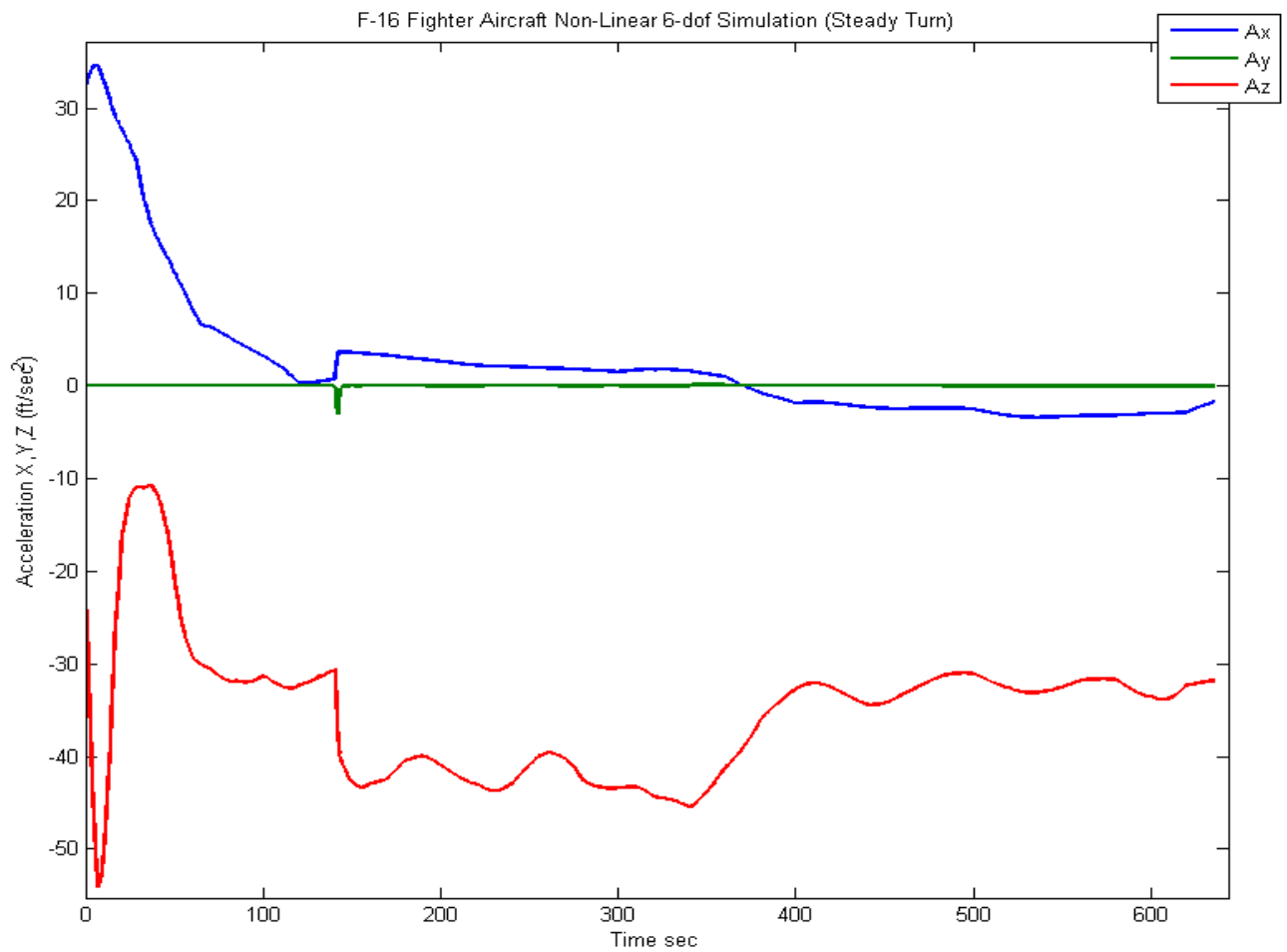


Figure 16.7 The axial acceleration trend follows the engine thrust. The side acceleration (A_y) is maintained at zero during the turn by the turn-coordination system. The normal acceleration (A_z) is close to -32.2 during level flight. It increases, however, to 43 (ft/sec²) during the turn.

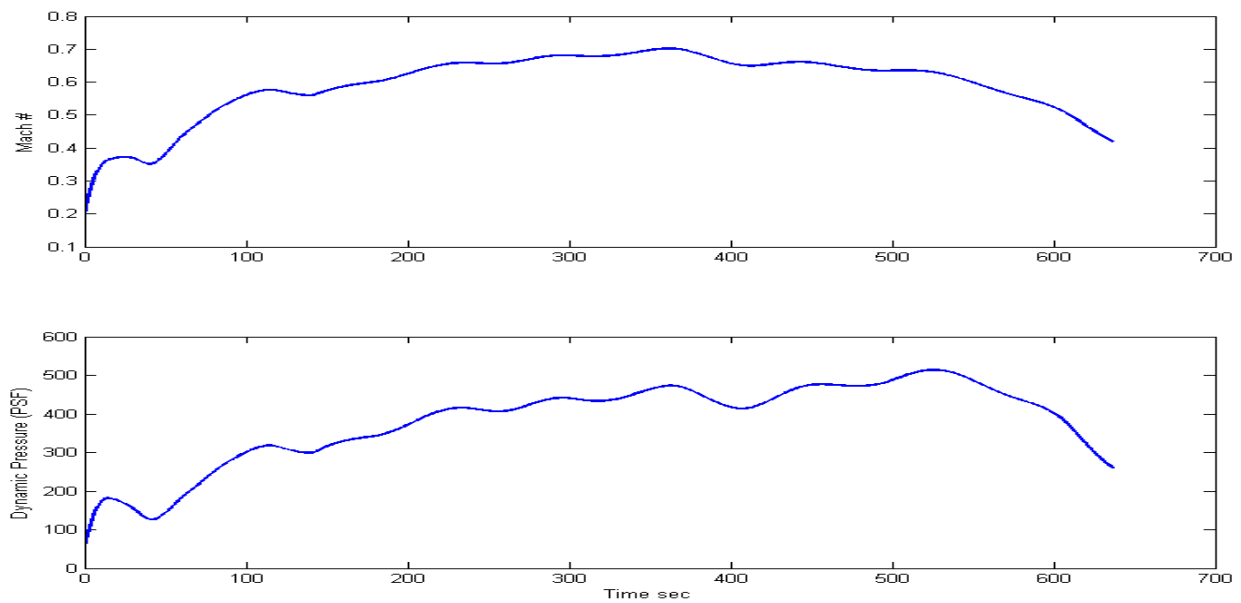


Figure 16.8 Mach Number and Dynamic Pressure.