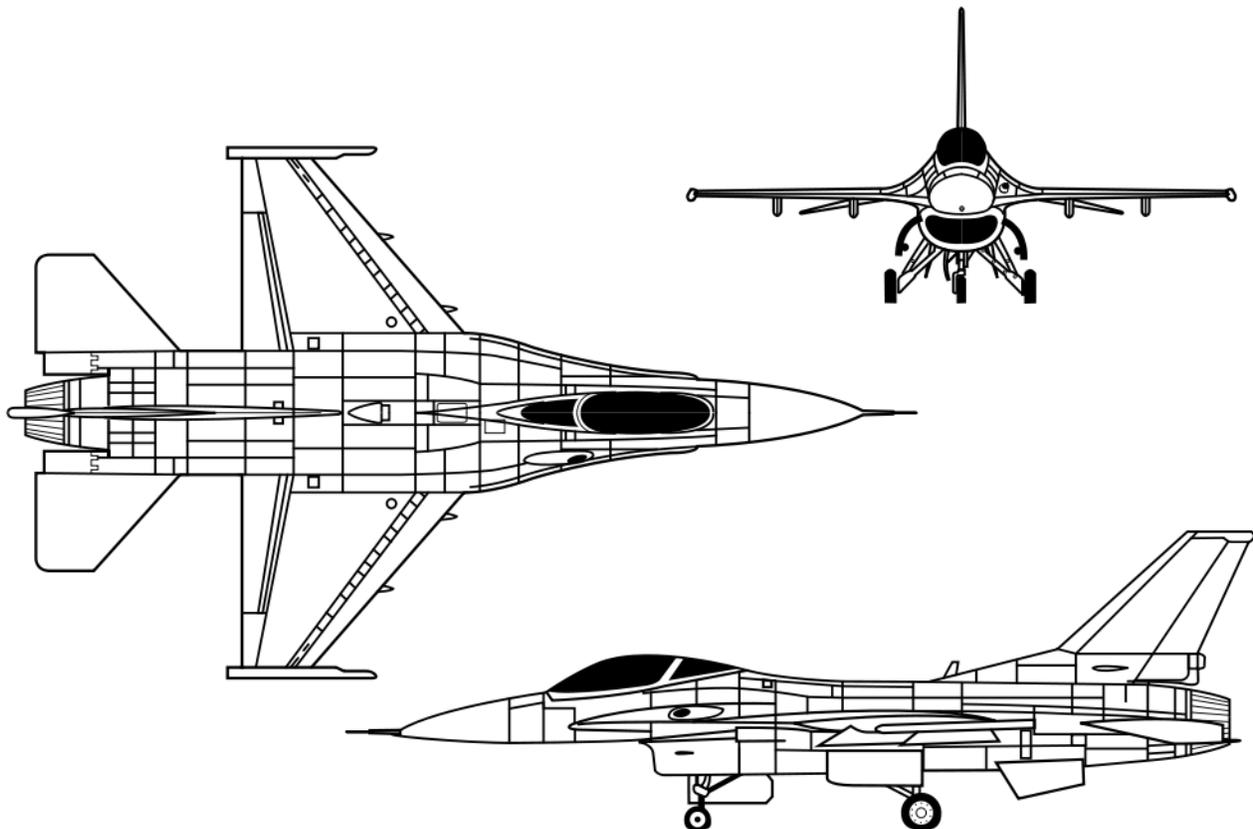


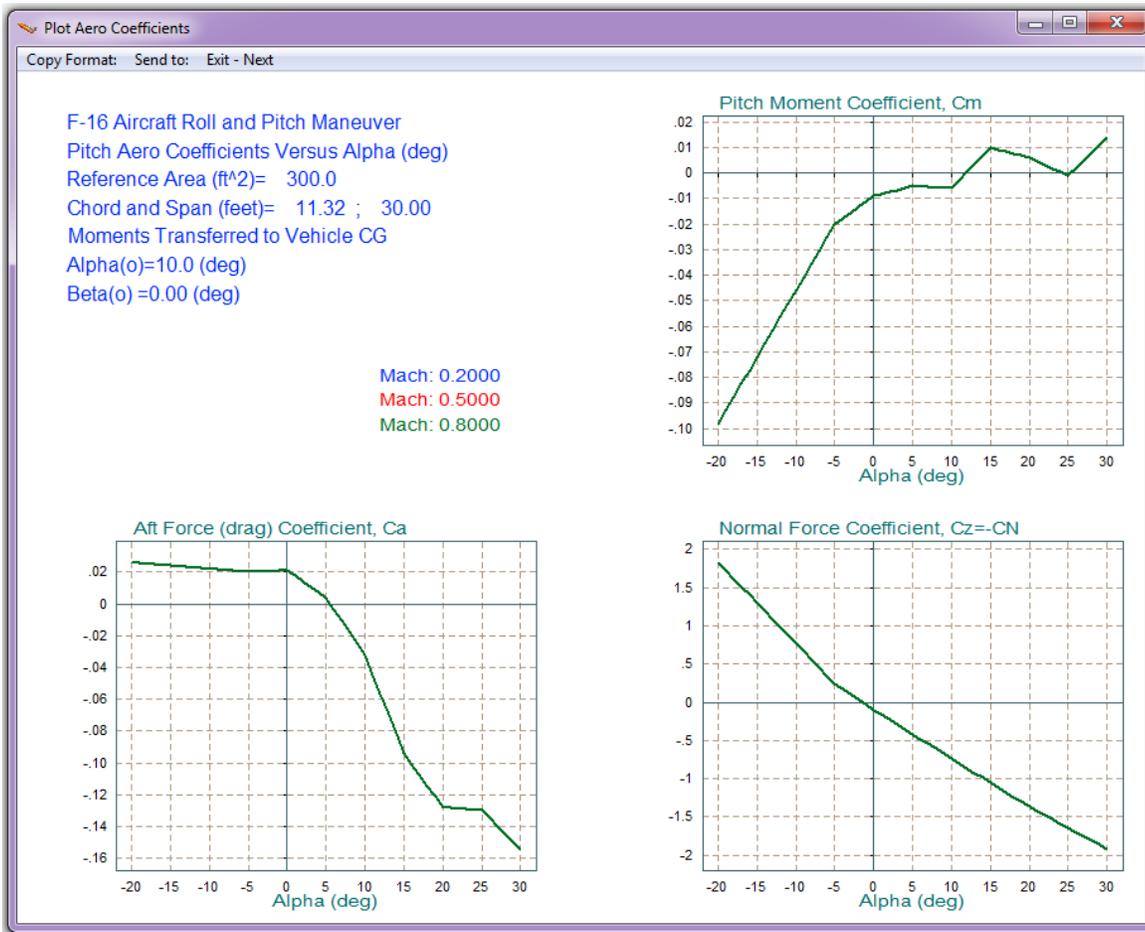
F-16 Fighter Aircraft



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.

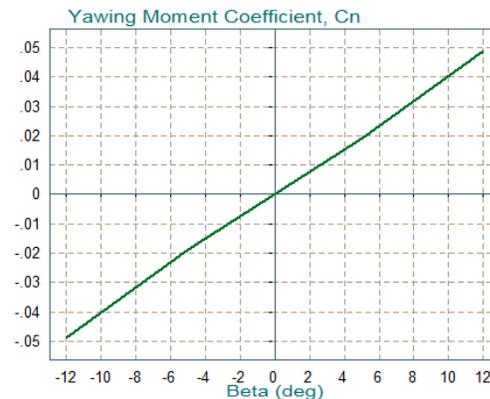
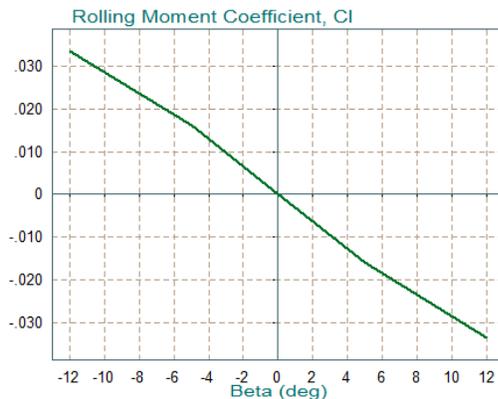
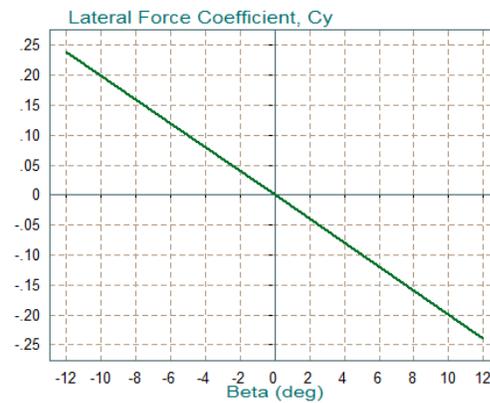
The files for the F-16 analysis example have already been created in the proper format and they are saved in directory "C:\Flixan\Trim\Examples\F-16 Fighter Aircraft". There are two trajectory files there. The first trajectory is in "Roll_Pitch_Man.Traj", where the aircraft takes-off, reaches level flight, 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.





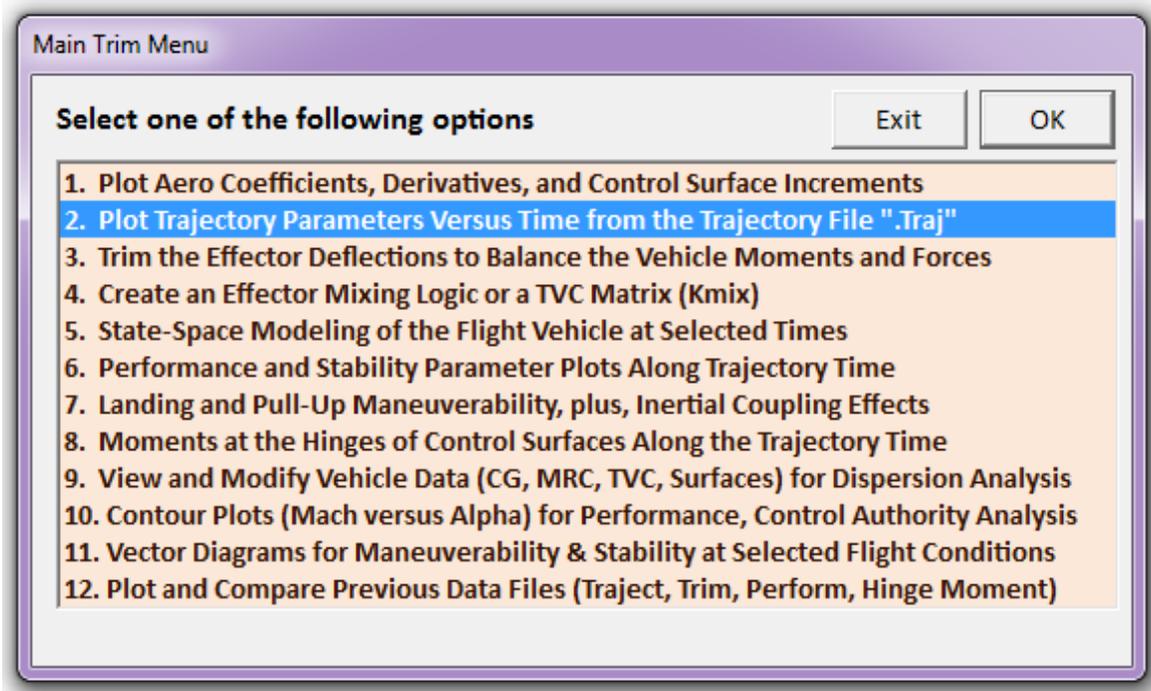
F-16 Aircraft Roll and Pitch Maneuver
 Lateral Aero Coefficients Versus Beta (deg)
 Reference Area (ft²)= 300.0
 Chord and Span (feet)= 11.32 ; 30.00
 Moments Transferred to Vehicle CG
 Alpha(o)=10.0 (deg)
 Beta(o)=0.00 (deg)

Mach: 0.2000
 Mach: 0.5000
 Mach: 0.8000



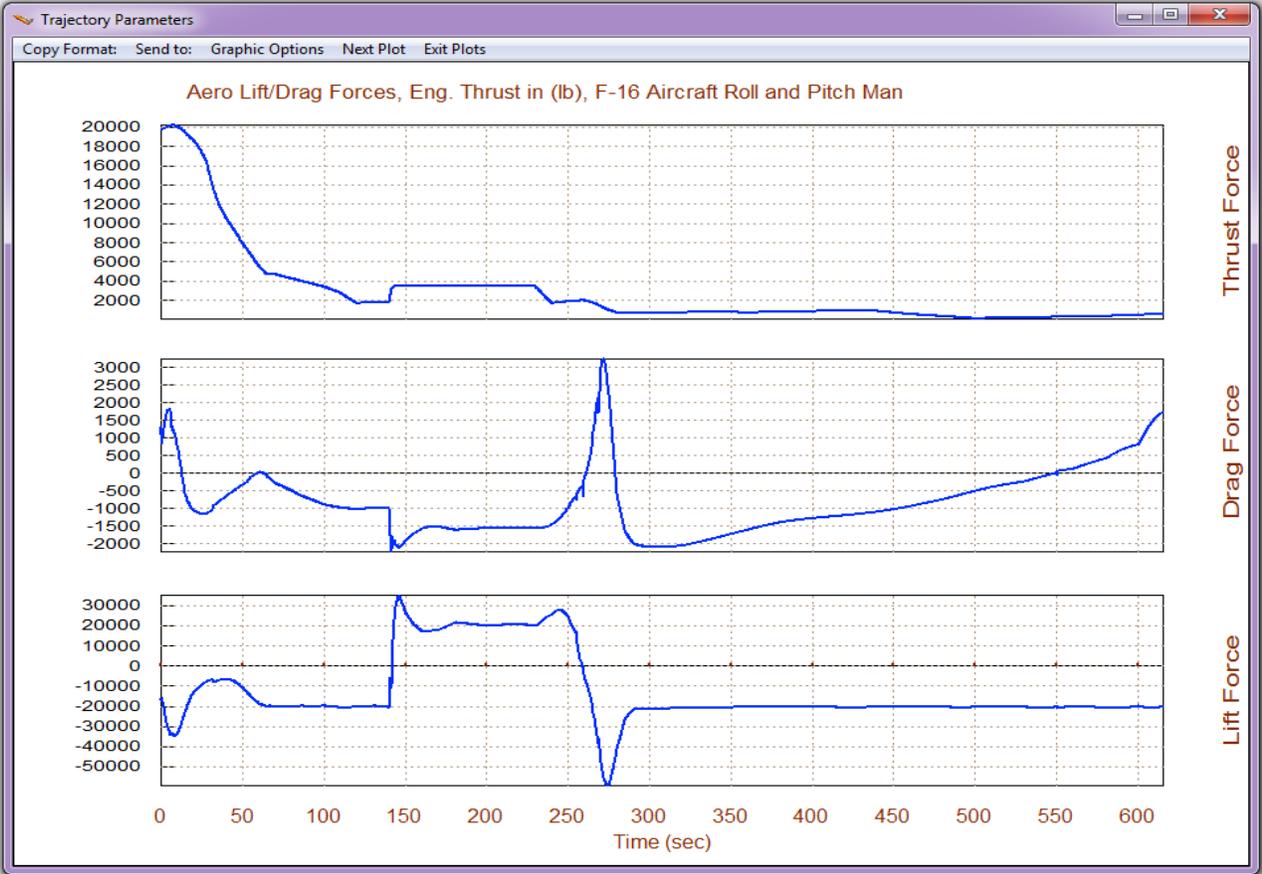
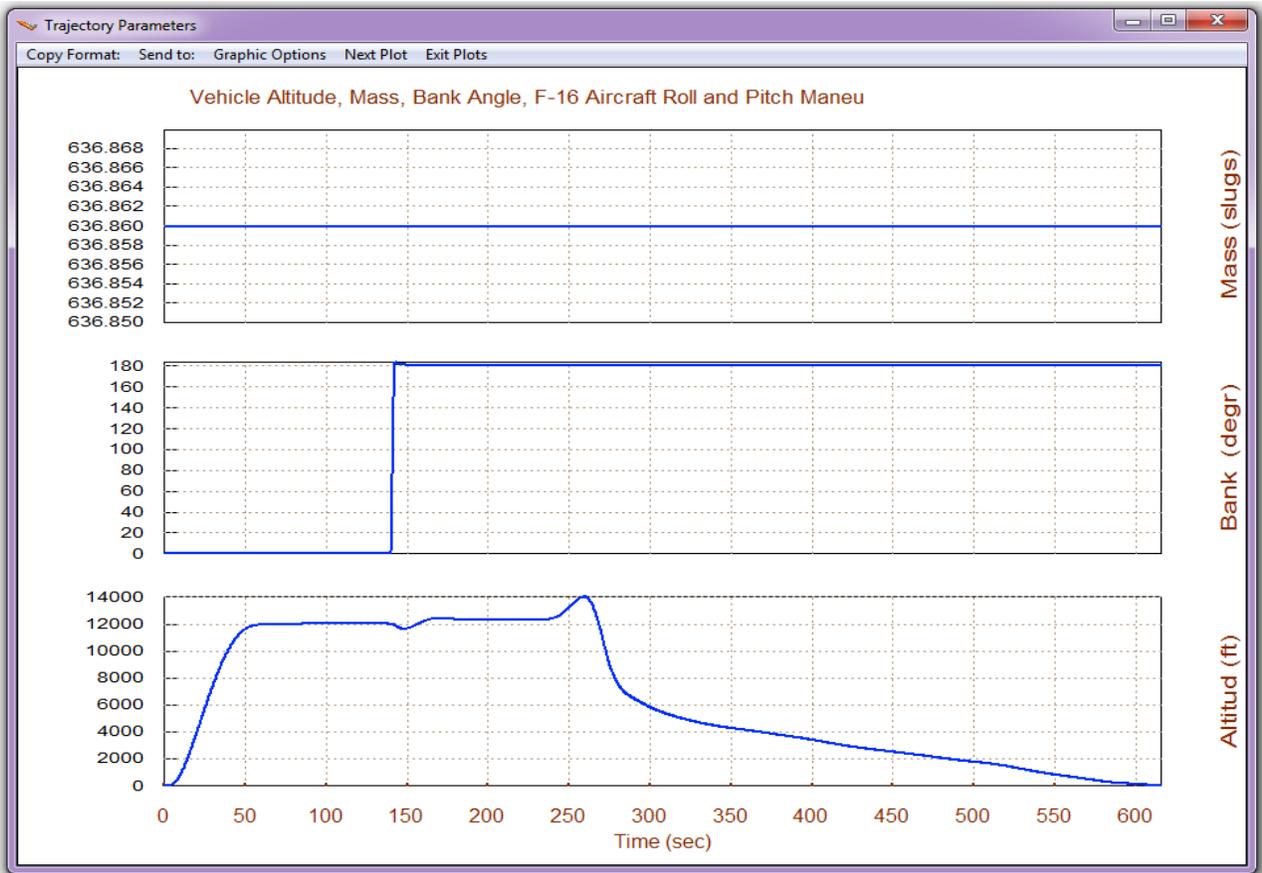
2. Checking the Trajectory Data

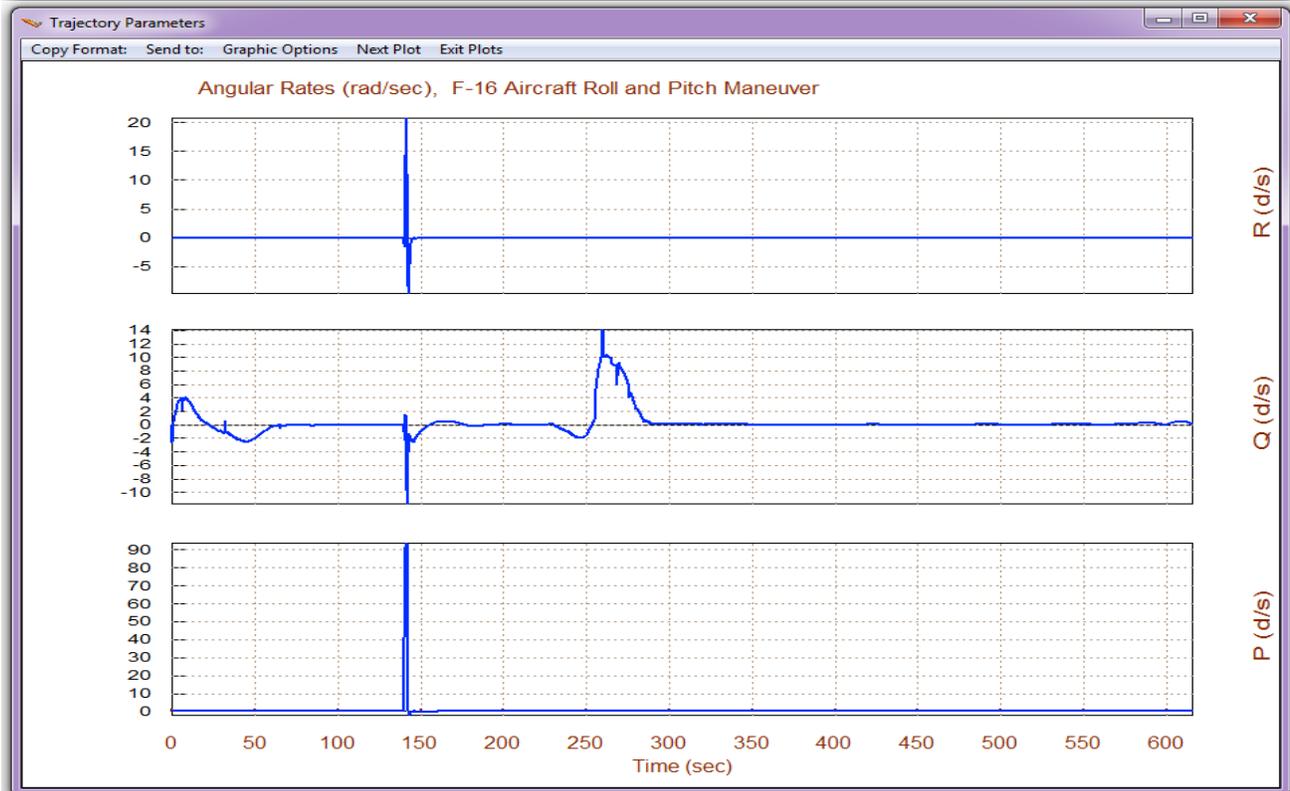
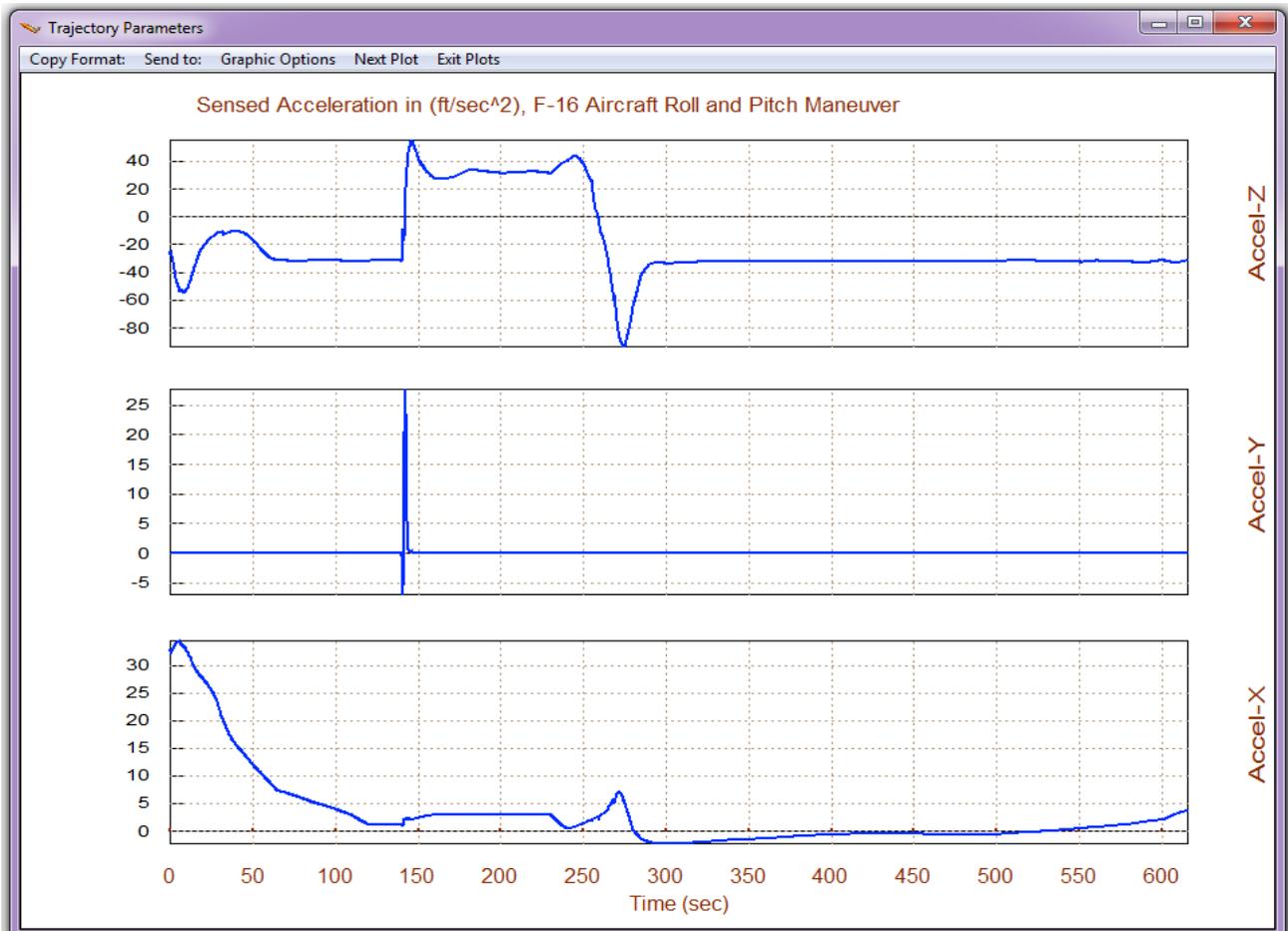
It is also important to take a look at the trajectory data before beginning the analysis. So after returning to the Trim main menu, select the second option which is for "*Plotting the Trajectory Parameters Versus Time*" and click the "OK" button.



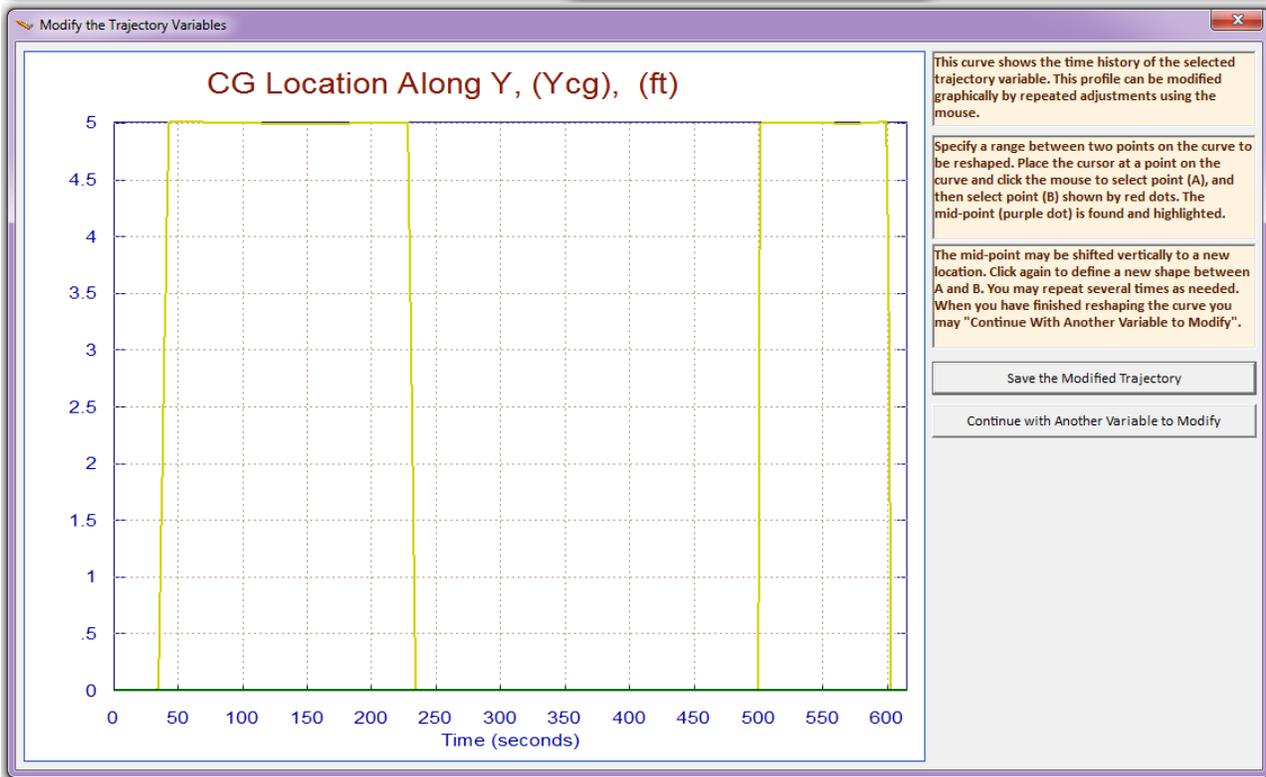
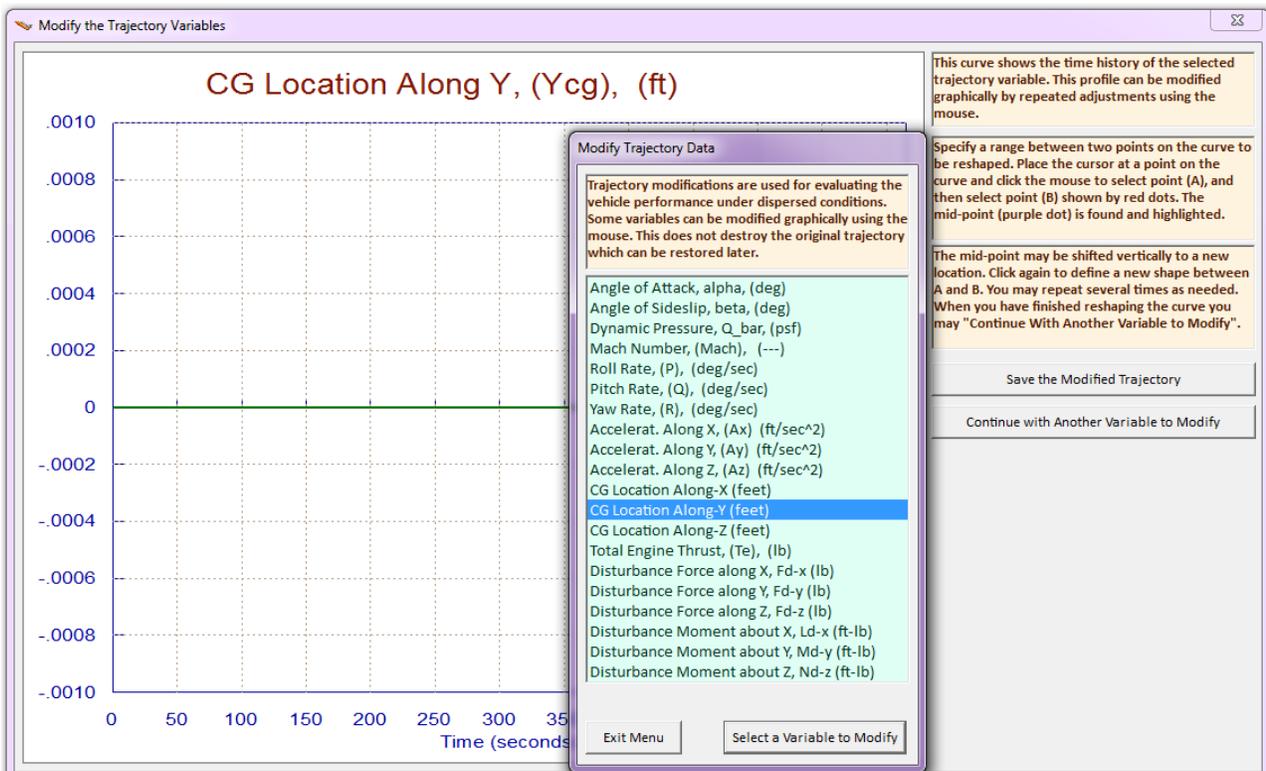
The following plots show the trajectory parameters, as a function of time, which are read from the selected trajectory file "*Roll_Pitch_Man.Traj*". The first plot shows the CG location during the flight, which does not vary in this case. The next plot shows α which is initially positive for the aircraft 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).

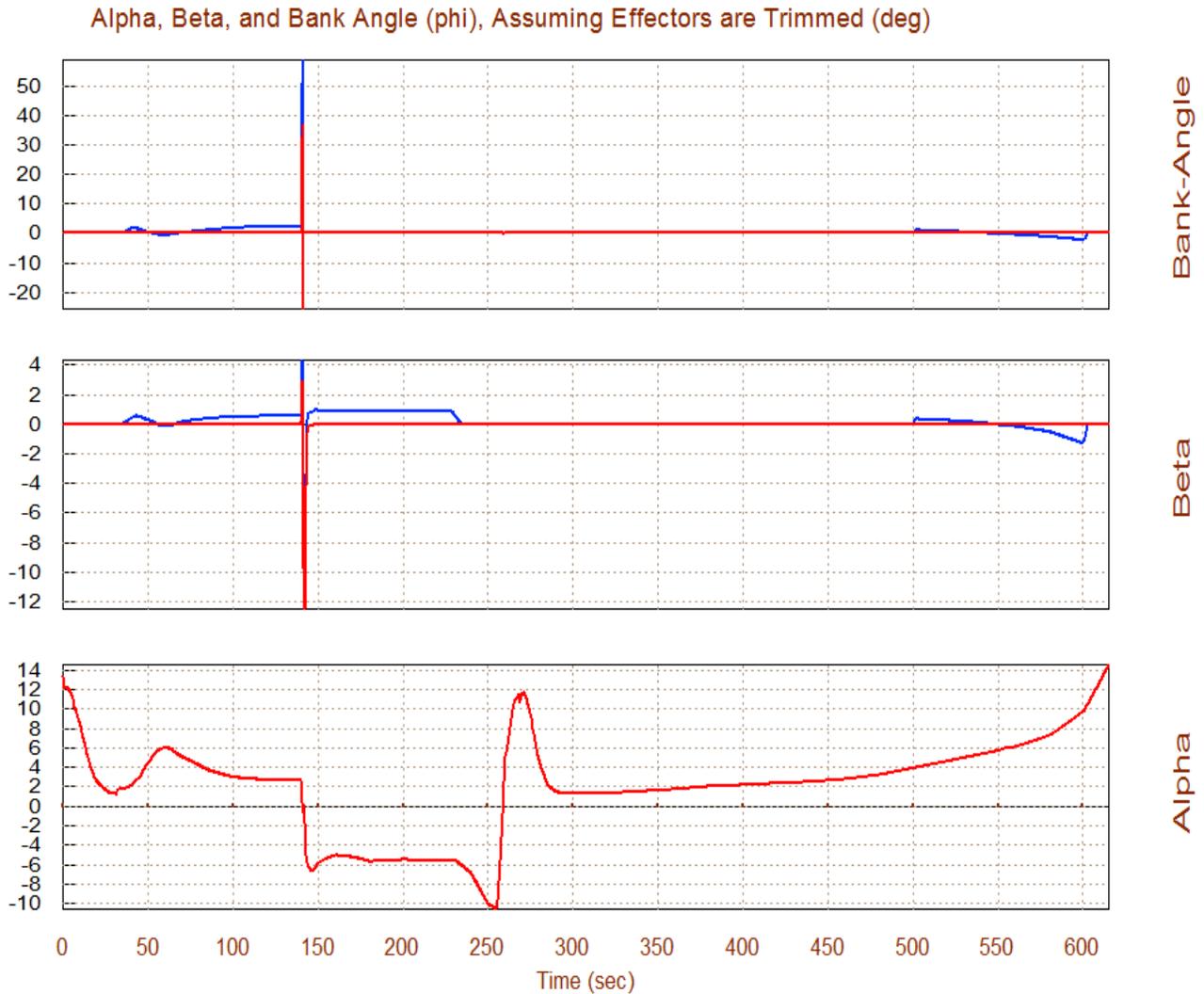
On the top of each plotting window there is a horizontal menu bar that includes several options. If you click on "Next Plot" it will move to the next trajectory data plot. If you click on "Exit Plots" it will go back to the Trim main menu shown above.





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.



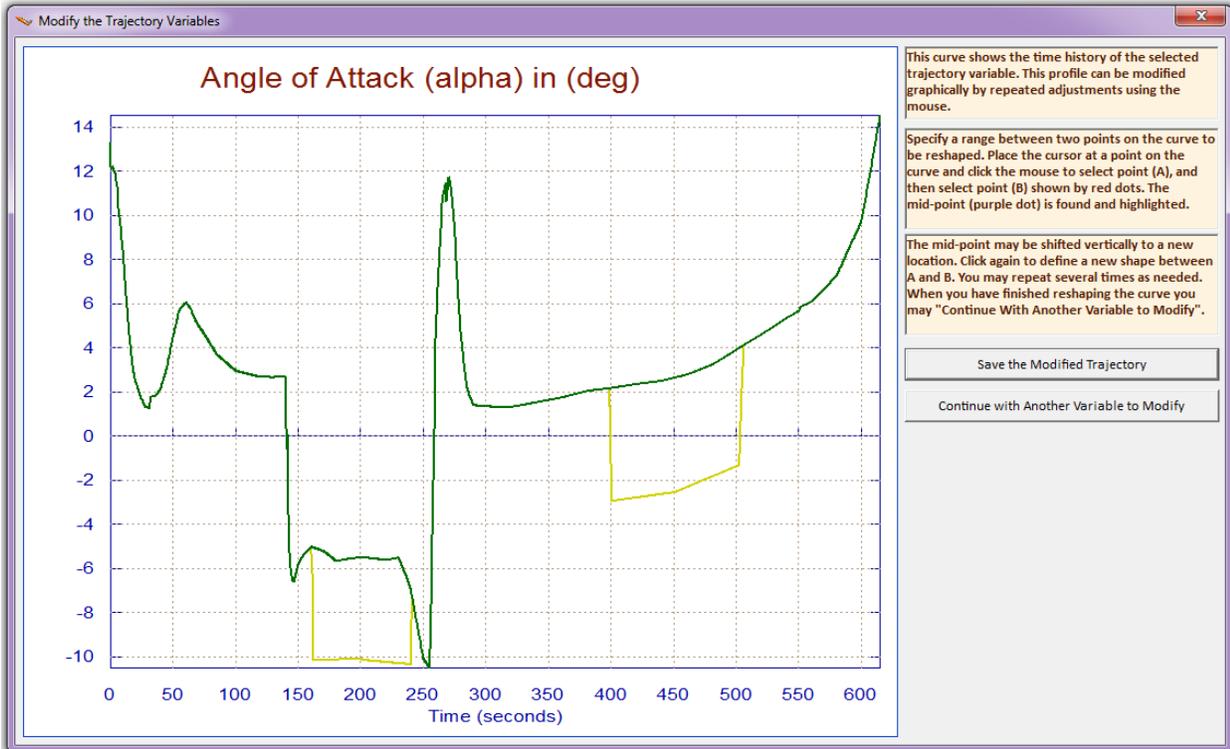
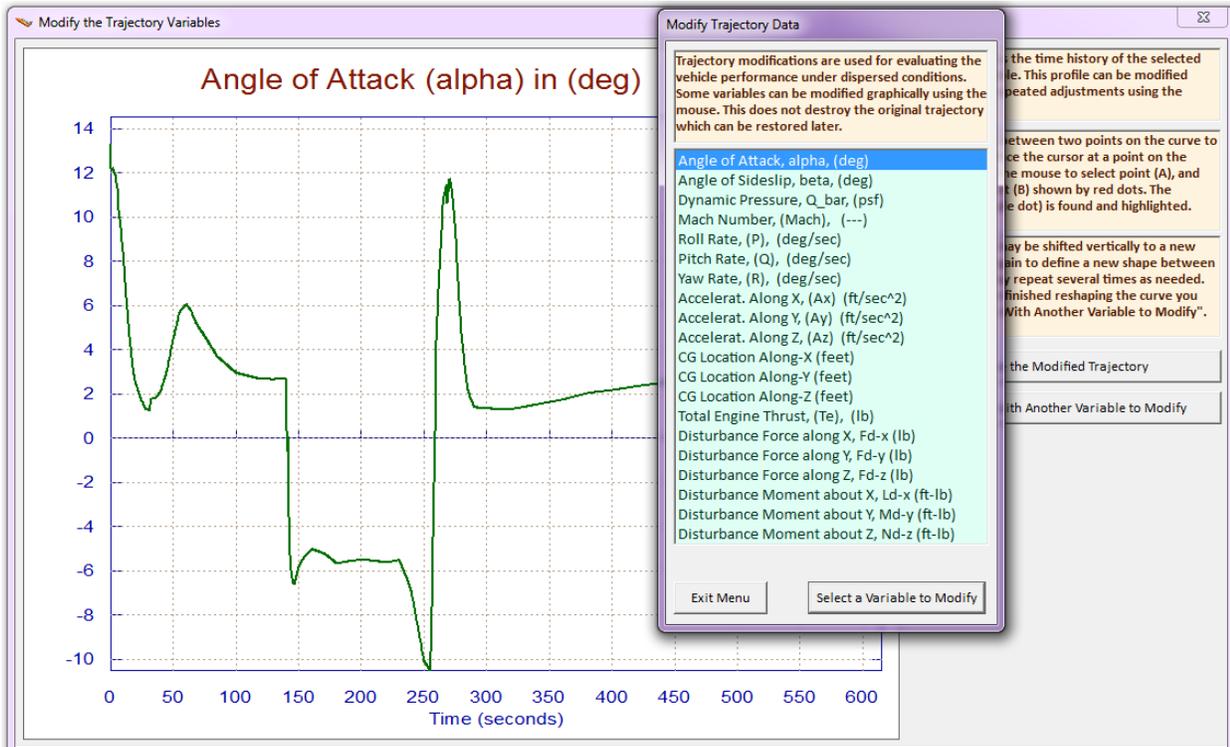


The Y-CG shift also causes approximately 1 (deg) of sideslip beta and a small bank angle (phi).

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.



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".



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 4

K Matrix Name

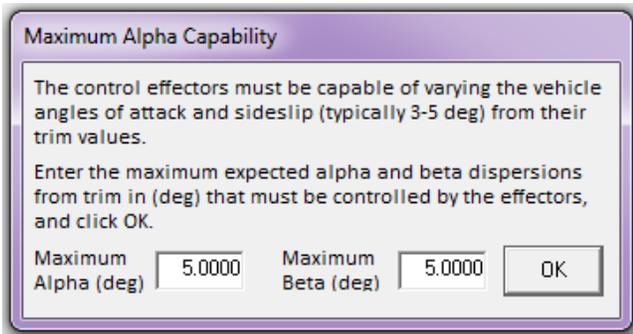
Mixing Logic for F-16 Aircraft (No Coupling)

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

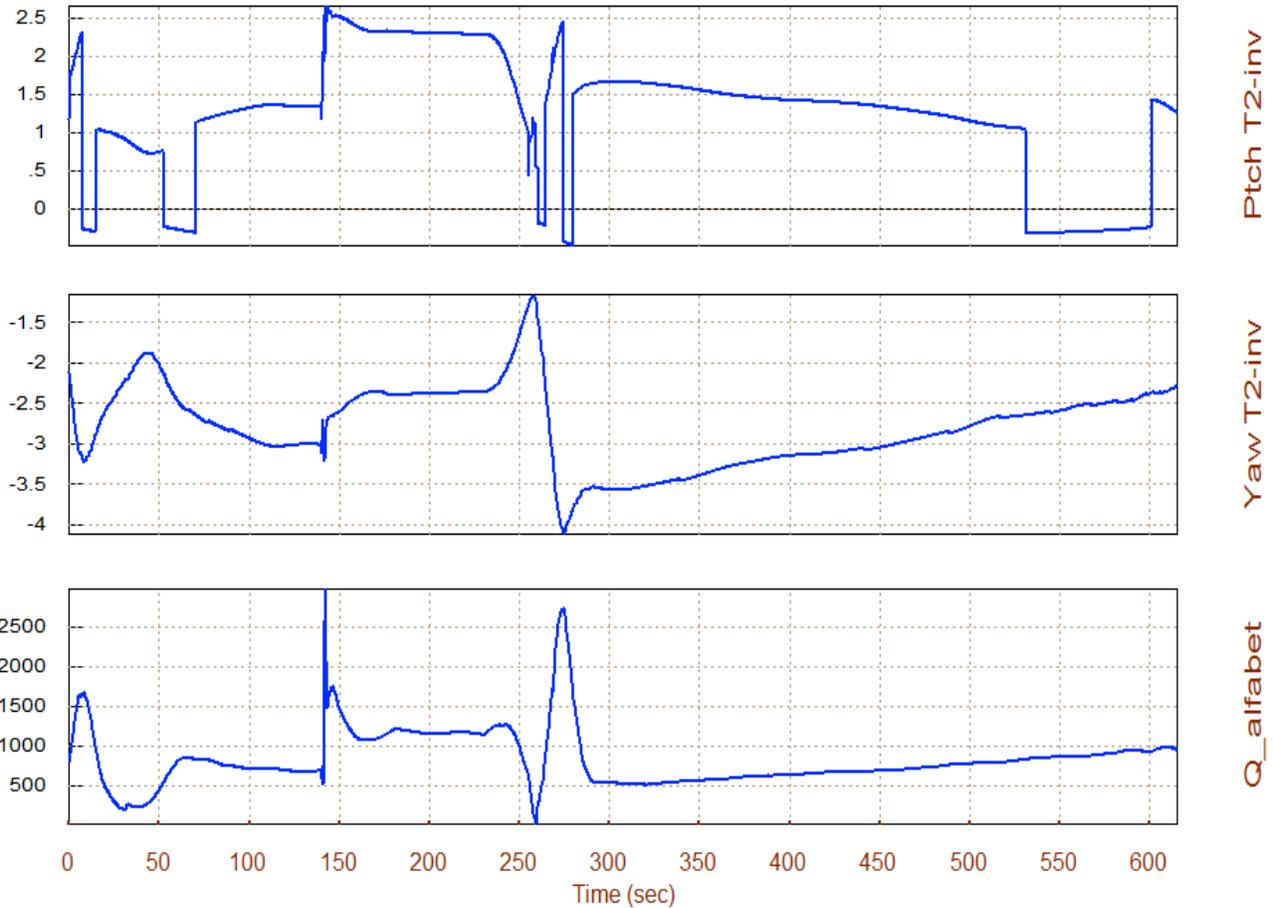
This Mixing Logic Matrix Ignores the Dynamic Coupling between the 4 directions. It uses the Aileron for Roll, the Elevon for Pitch, the Rudder for Yaw, and the throttle control for axial acceleration.

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.

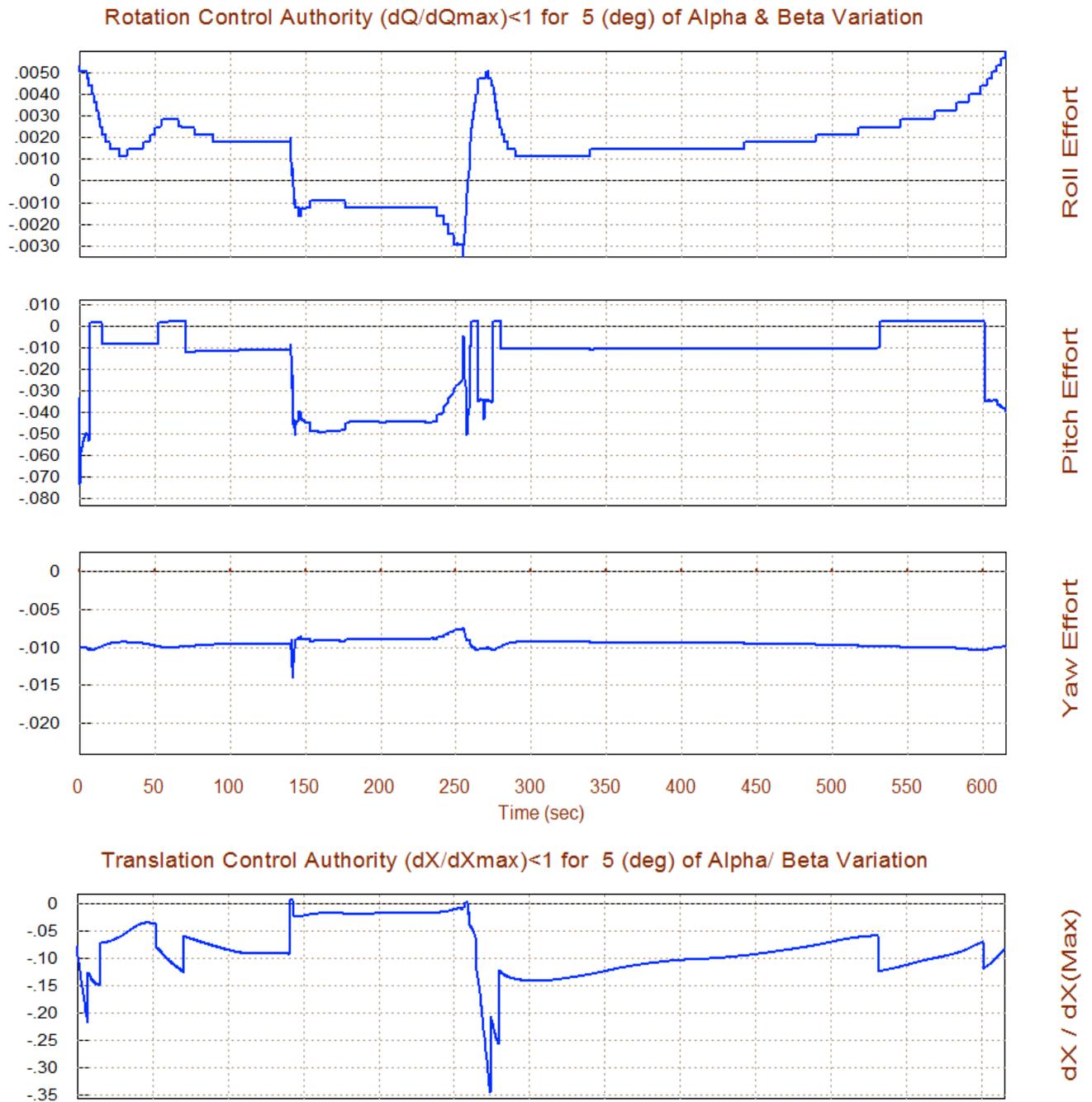
Repeat to change other Inputs, Outputs, or Matrix Elements. Then click on "Save Changes" to save the new values and titles or Exit the dialog.



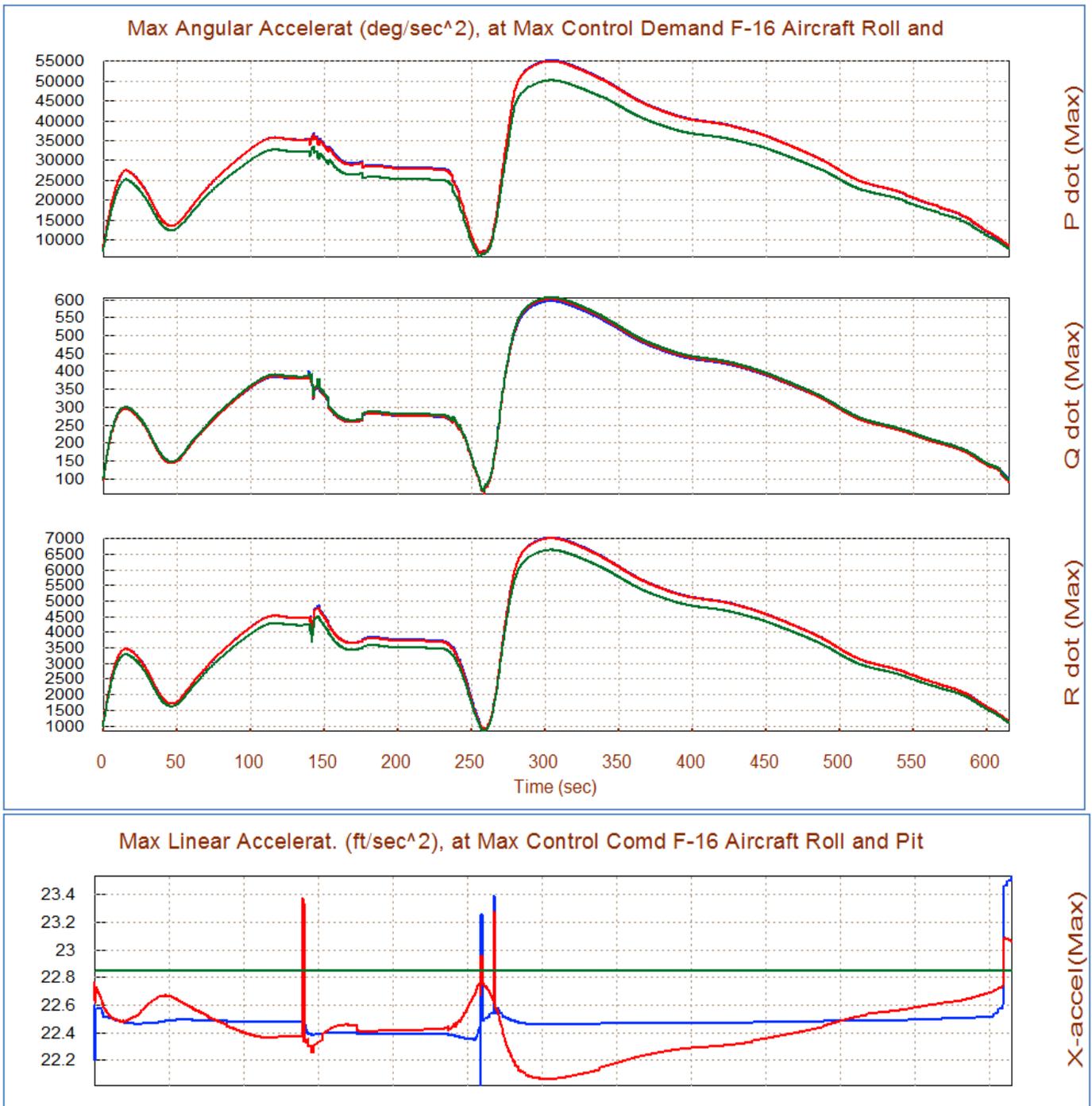
Short-Period (w) / Time-to-Double-Ampl-Inverse (/sec), $Q_{\alpha\beta}$ (deg-lb/ft²)



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.



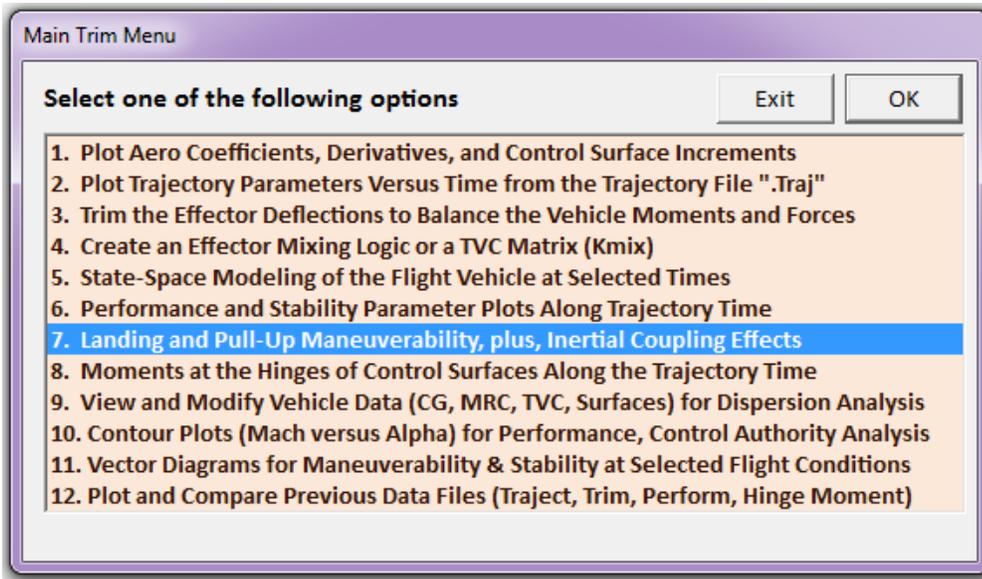
The above plots show the aircraft control authority to react against the max alpha and max beta disturbances as they are defined by equations (3.24) and (3.26). The control authority should be less than 0.5 in all directions. This aircraft has obviously plenty of control authority against the $(\alpha_{max}, \beta_{max})$ disturbances in all 4 directions. The LCDP and the $C_n\beta$ -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.



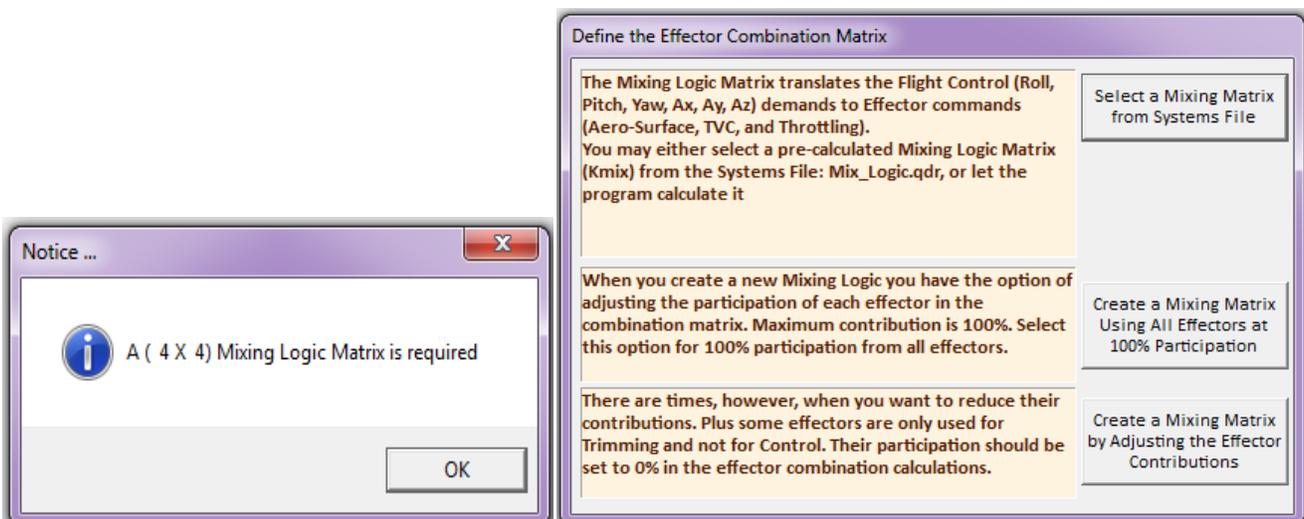
The decoupling matrices generated by the Flixan program (both fixed and variable) provide some additional max acceleration in the roll and yaw directions. Overall, Kmix0 has a little more advantage in performance, although it does not provide axial decoupling.

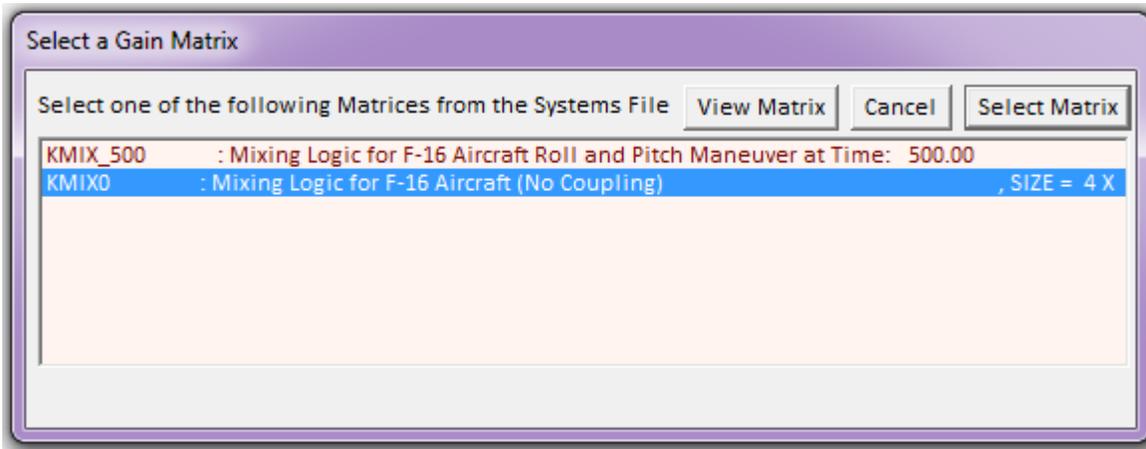
6. Additional Maneuverability Parameters

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.

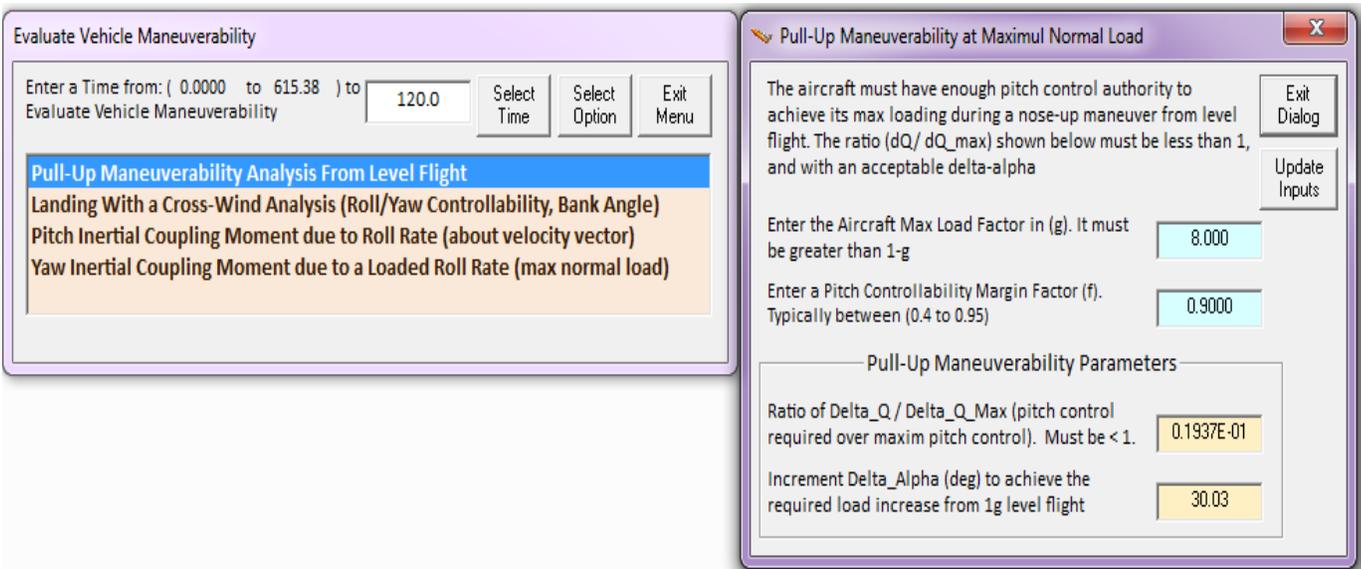


Like before, the effector mixing logic is needed in the performance calculations. We must read the mixing matrix Kmix0 that was used earlier. In the effector mixing logic selection dialog click on the top button "Select a Mixing Matrix from File" to select the matrix Kmix0 from file "Mix_Logic.Qdr",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

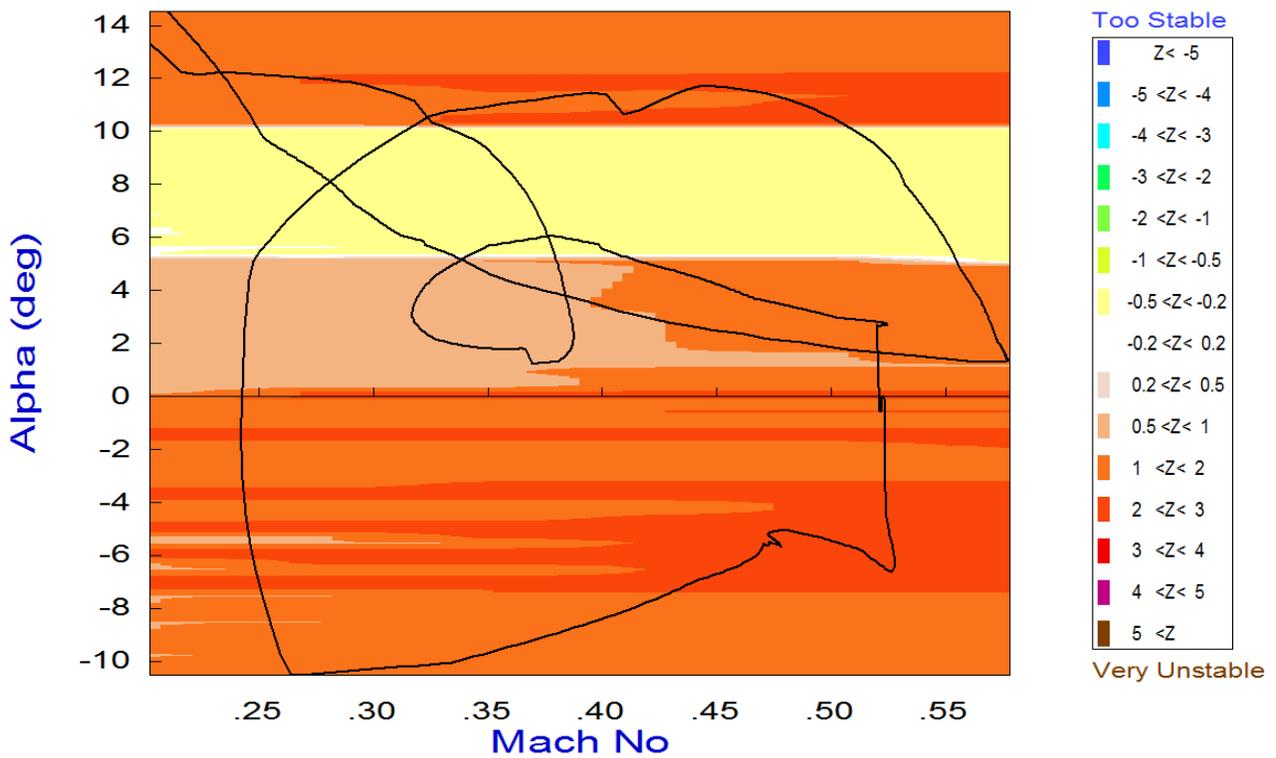




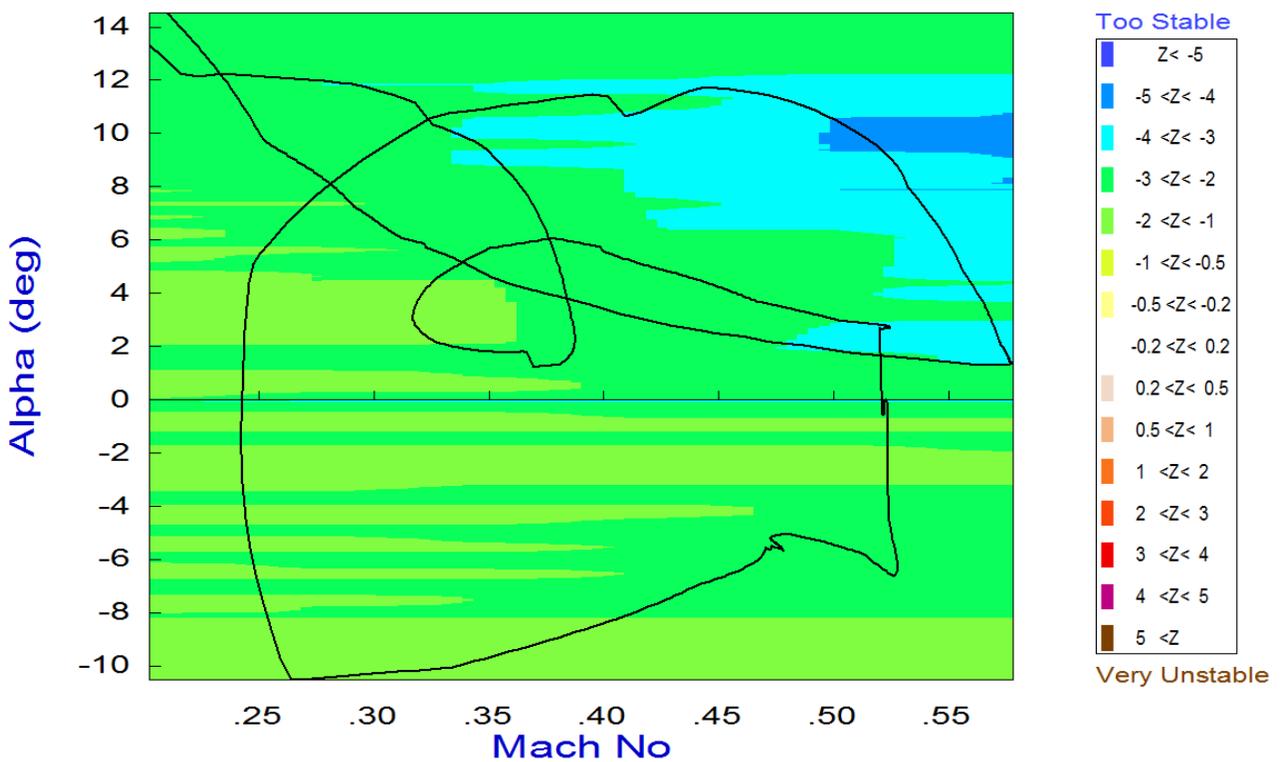
The following menu/dialog shows the four maneuverability analysis options, but you must first enter a time along the trajectory. In this case we enter 120 sec, which corresponds to level flight before the 180° flip, and click on the "Select Time" button. From the menu we select the top option which calculates 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).



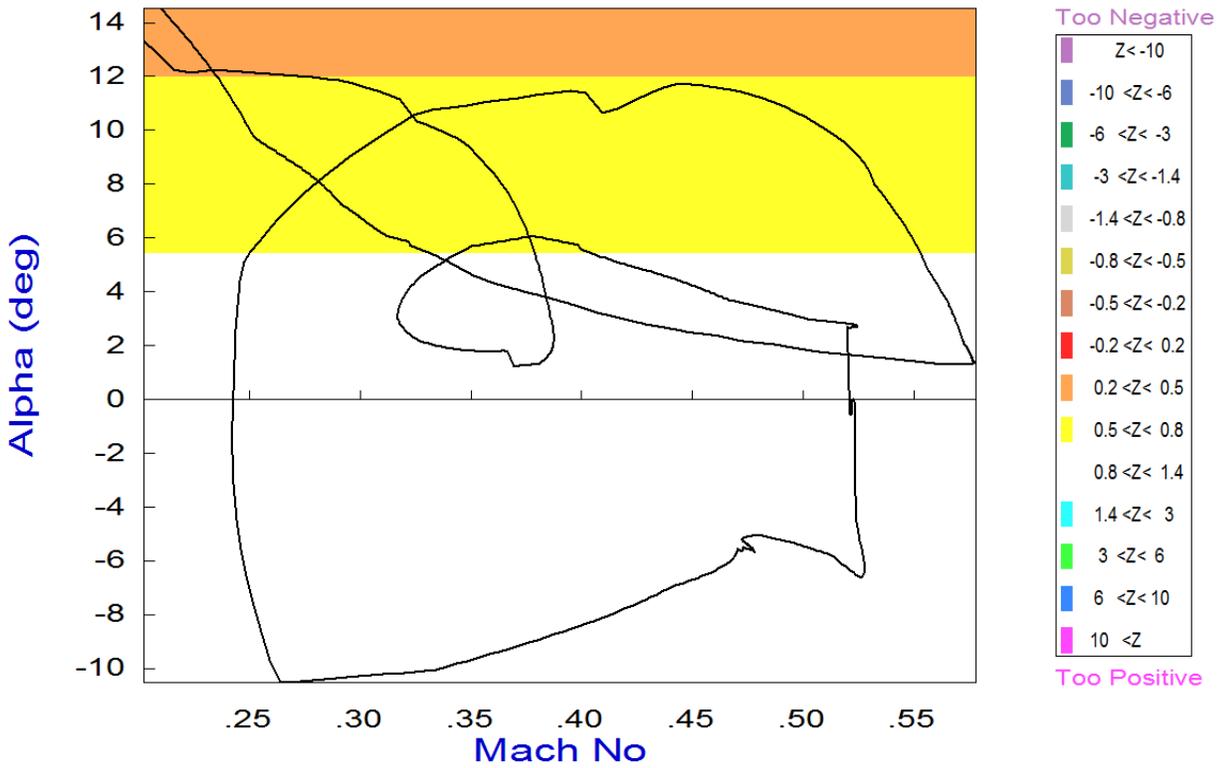
Pitch Stability Contour Plot (Mach vs Alpha)



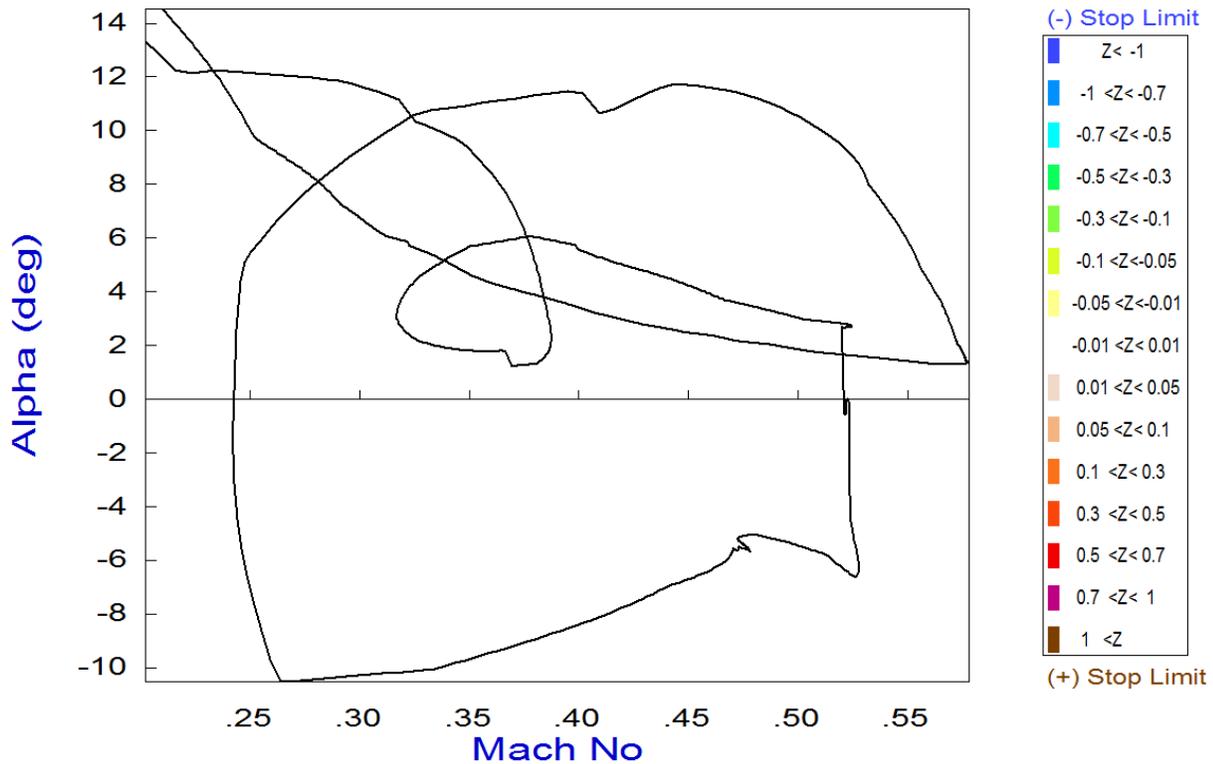
Lateral Stability Contour Plot (Mach vs Alpha)



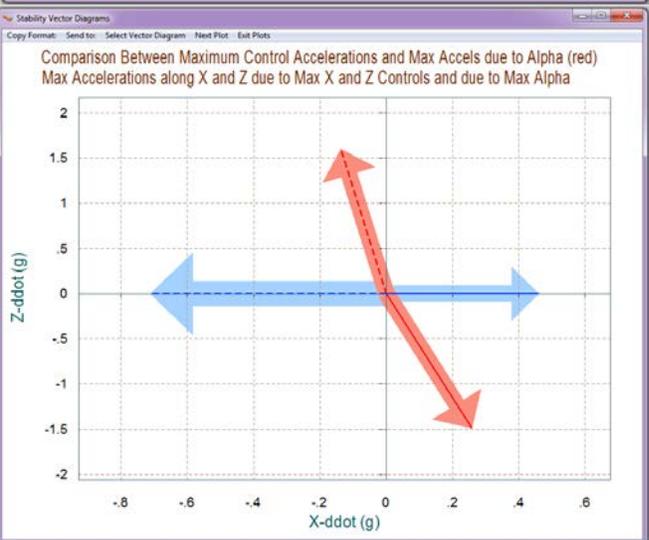
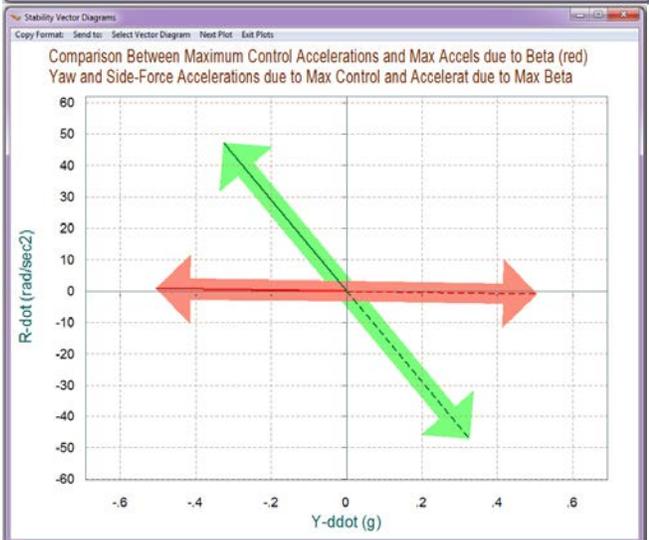
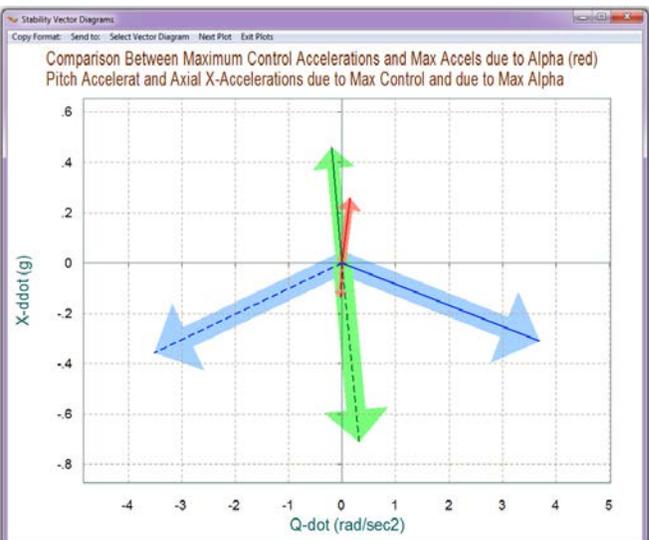
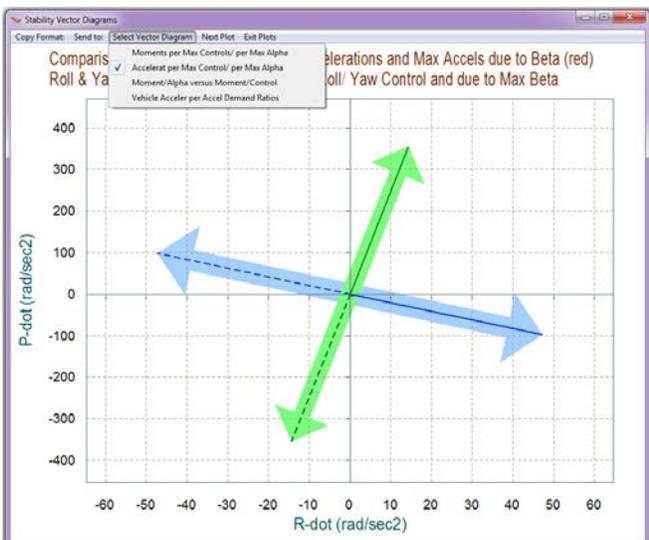
Roll Departure (LCDP) Contour Plot (Mach vs Alpha)



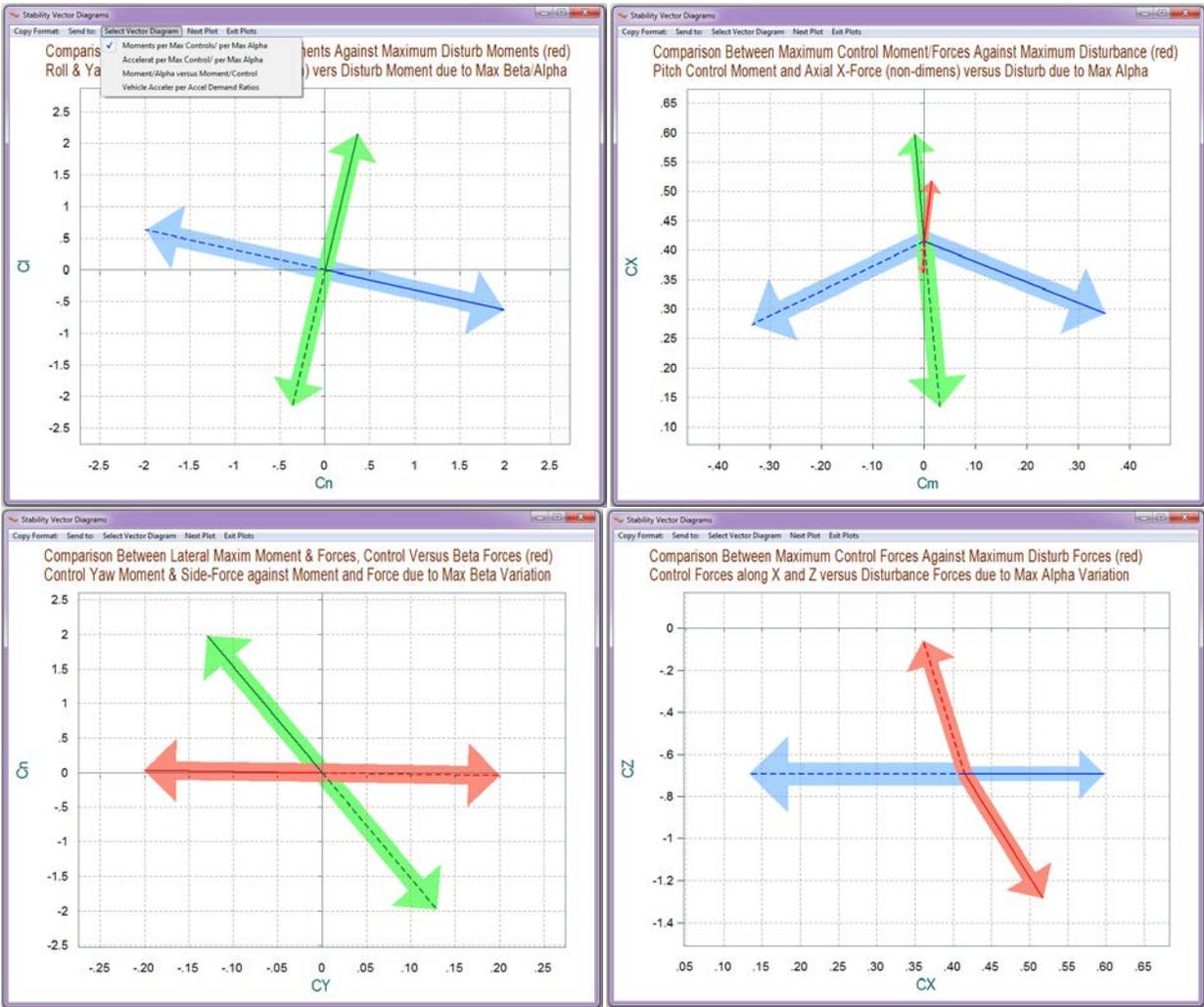
Roll Control Effort Contour Plot (Mach vs Alpha)



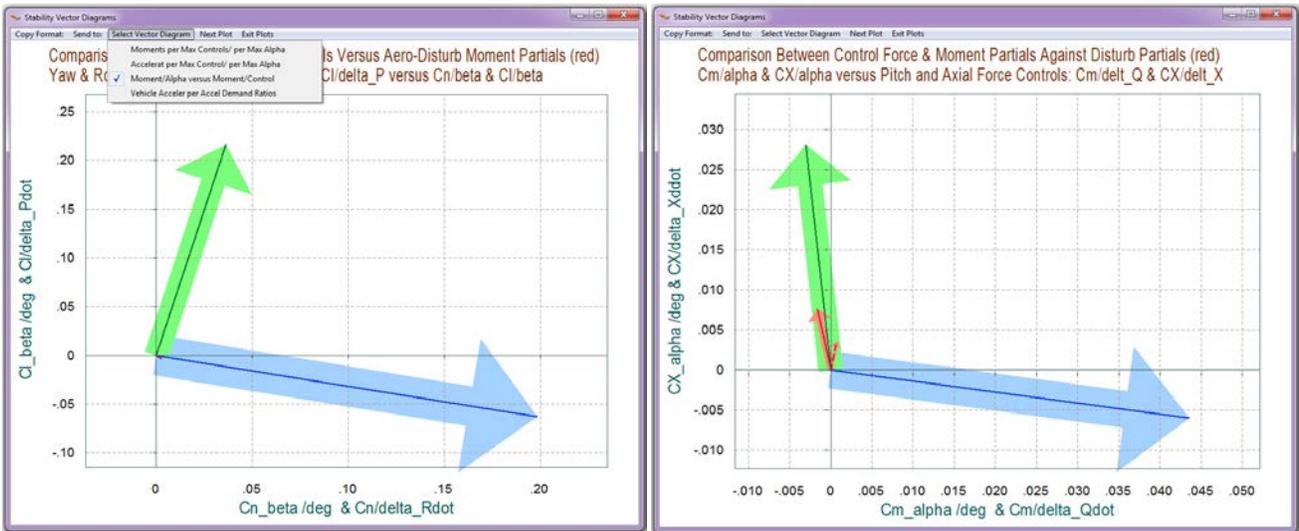
From the vector diagrams top menu bar we may select the type of vector diagrams. Click on "Select Vector Diagrams" and from the vertical pop-up menu select "Accelerations per Max Controls, and Accelerations per Max Alpha/Beta". The first diagram below shows the full roll/ yaw acceleration range achieved 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.



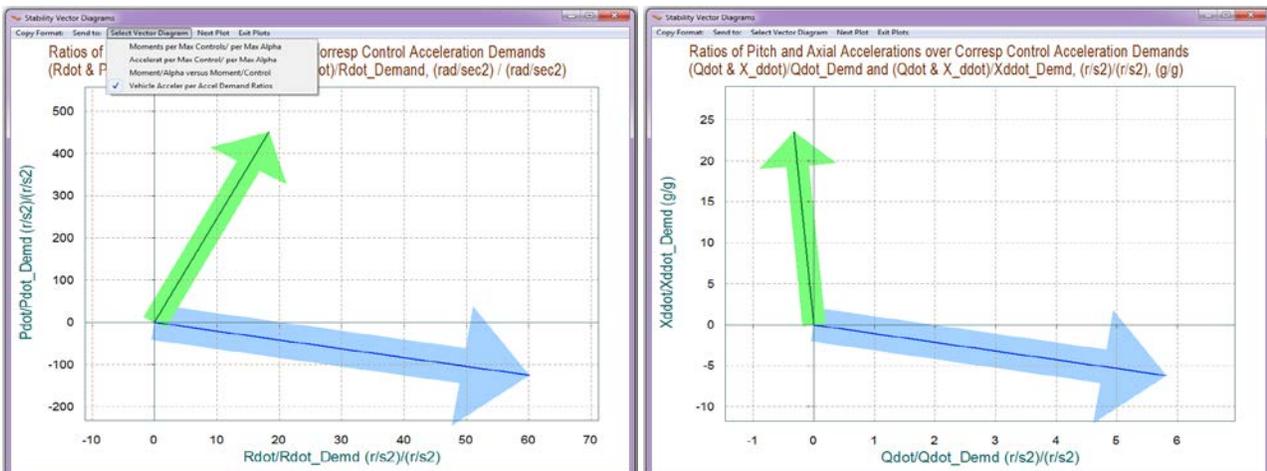
Similarly, the four vector diagrams below show the normalized (non-dimensional) moments and forces. From the vector diagrams top menu bar click on "Select Vector Diagrams" and from the vertical pop-up menu select "Moments/Forces per Max Controls, and Moments/Forces per Max Alpha/Beta". The top diagram 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.



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.

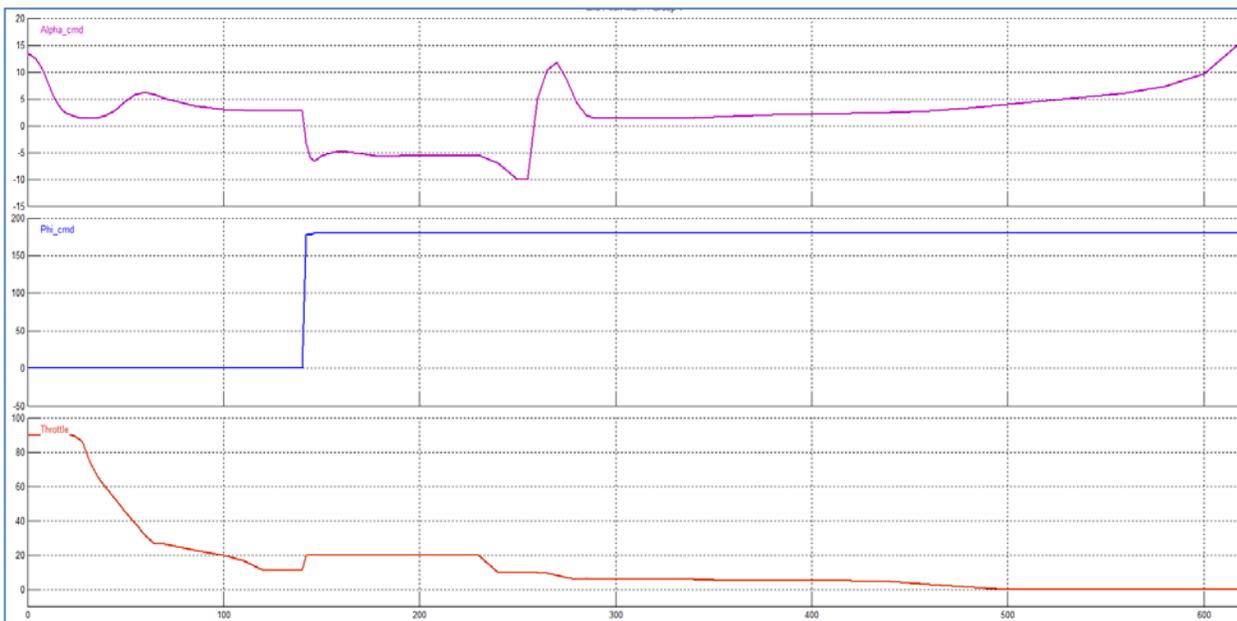


Figure 4 Pilot Commands for the 180° Roll and Pitch Maneuver

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

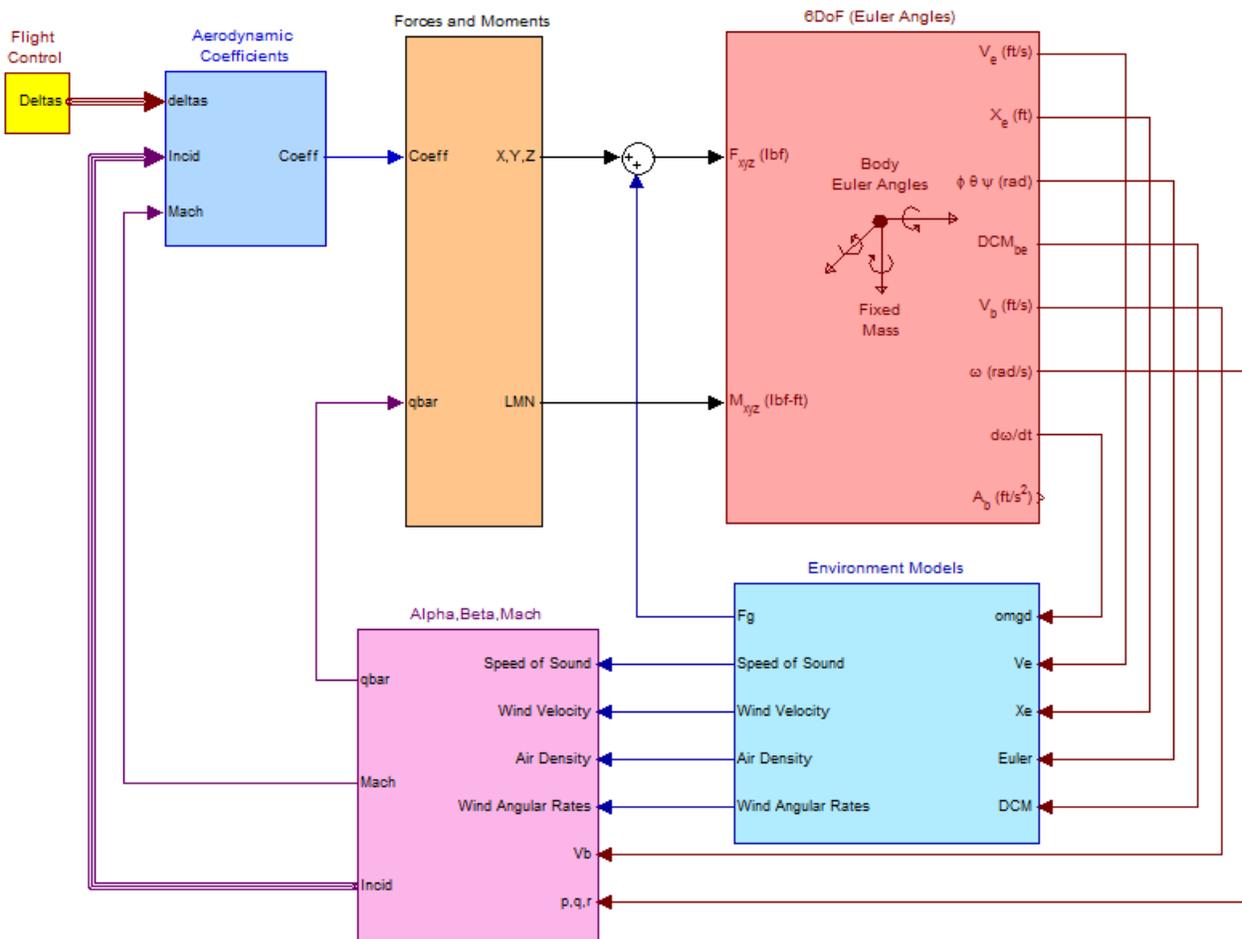


Figure 5 F-16 Simulation Model in File: "F16_6dof_Sim.Mdl"

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*".