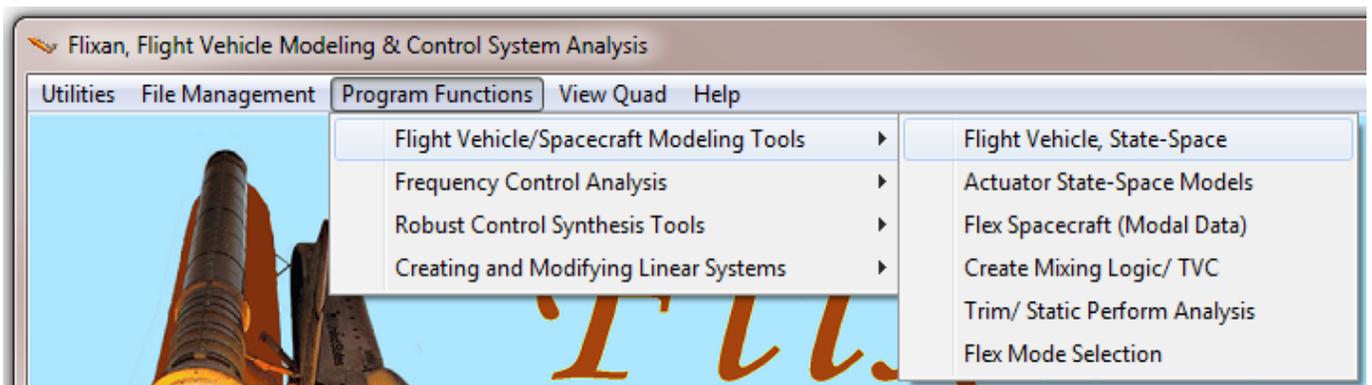
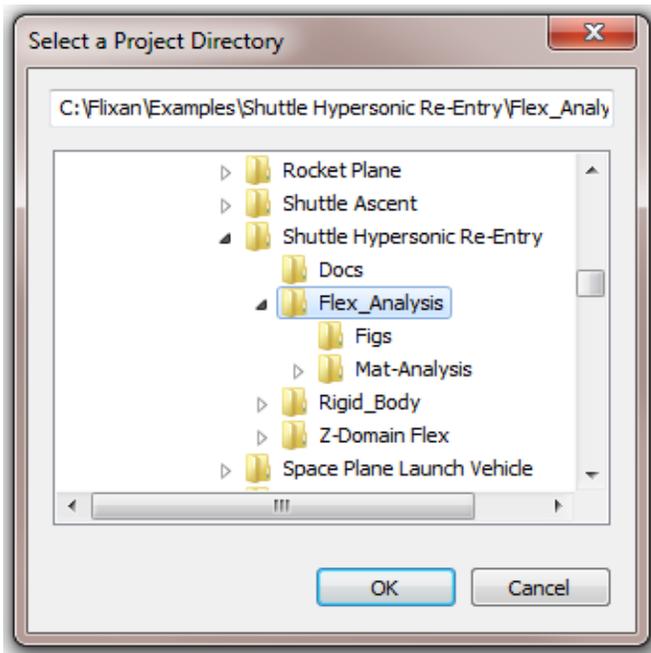


# 4 Flight Vehicle Modeling Program

The Flixan flight vehicle modeling program (FVMP) is used for generating dynamic models of flight vehicles at fixed flight conditions. The models can be rigid or flexible structures, and they may include propellant sloshing, tail-wags-dog dynamics, and other features defined by options. It runs either interactively or in batch mode. The user must first select the folder where the vehicle project files are located using the directory selection window. The Flixan main menu comes up, and the program can be selected by clicking on “*Program Functions*”, then “*Flight Vehicle/ Spacecraft Modeling Tools*”, and then “*Flight Vehicle State-Space Models*”, as shown below.



The block diagram in Figure 1 shows the files used by the flight vehicle modeling program and its interaction with the user. The main file is the input data file (.Inp) that contains one or more datasets with the information needed to create the vehicle models. Each dataset includes the vehicle mass properties, the aerodynamic data, trajectory data, engine and control surface data, propellant sloshing parameters, sensor data, and if the vehicle is flexible it also includes a set of structural modes. For robustness  $\mu$ -analysis and for developing  $\mu$ -synthesis models for control design the program also requires a dataset with parameter uncertainties.

In order to select flex modes and to implement structural flexibility the program requires additional data files generated from finite element models that have extensions (.Mod, and .Nod). For aero-elastic models that include dynamic coupling between flexibility and aerodynamics and also aerosurface accelerations, the program requires additional GAFD files that have an extension (.Gaf). The program communicates with the user by means of menus and dialogs, but it can also run in batch mode. It reads the data files, processes the data, and generates the vehicle state-space system from the data. The system is then saved in a systems file that has an extension (.Qdr). The system title is the same as the title included in the vehicle dataset, and the comment lines from the dataset are also copied in the system.

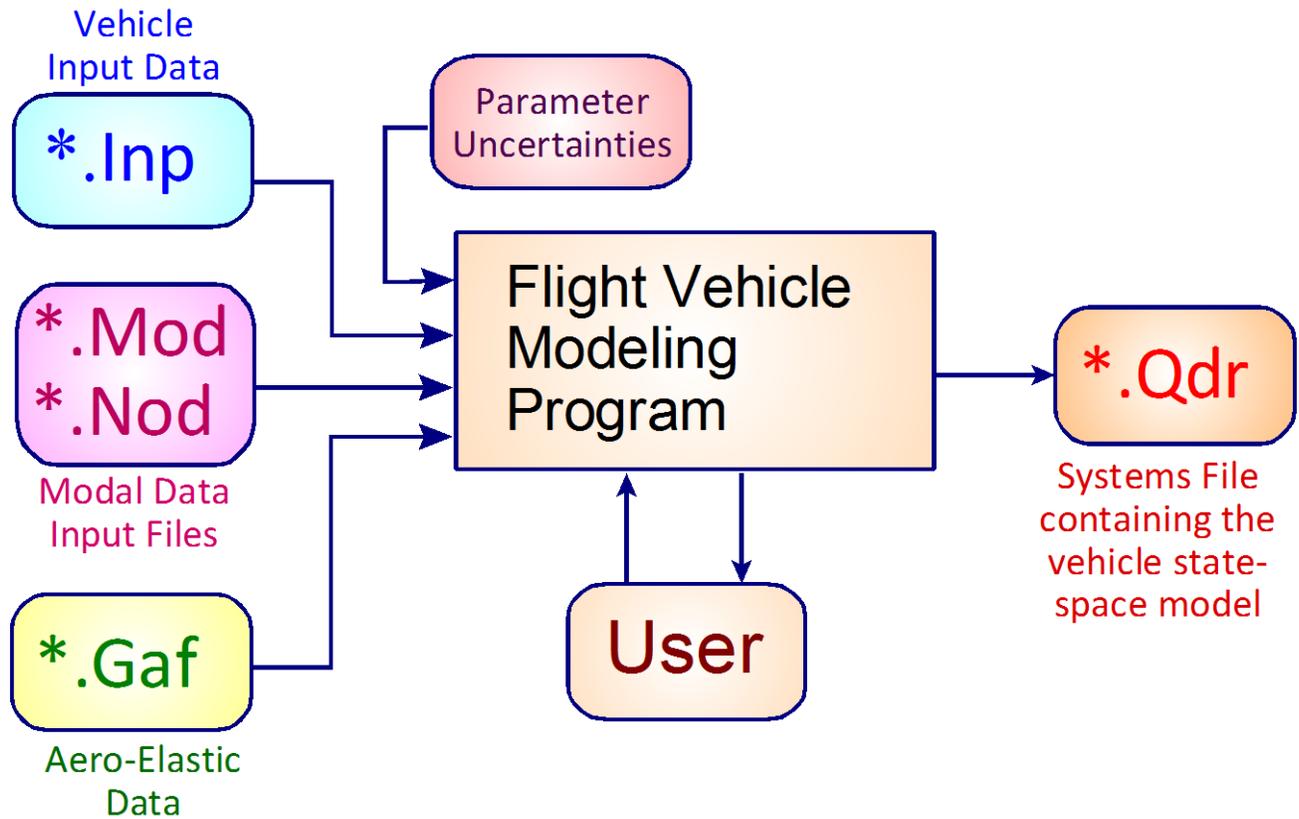


Figure 1 Block Diagram of Flight Vehicle Modeling Program with Input and Output Files

## 4.1 Vehicle Input Data Set

The complexity of the dynamic model and the configuration details are specified in the vehicle input data and in the flags which are set in the input data file (.Inp). An input data file may include more than one set of vehicle data with different specs and applications. For example, a rigid-body set, and a flexible vehicle set, that must also include a set of structural modes. A typical flight vehicle dataset is shown below. The first line begins with a label id: "FLIGHT VEHICLE INPUT DATA" which identifies the nature of the data and the flight vehicle modeling program that will process the data. The second line (below the id label) is a title that describes the vehicle type and flight condition. For example: "Space Shuttle Orbiter Flex Model during Reentry". Then, below the title we have comment lines beginning with an exclamation mark (!). They are optional and used to provide a short description of the vehicle configuration, the flight condition or the type and purpose of the model and analysis. The comments will also appear in the utility dialogs and they are transferred to the state-space model and placed below the title in the systems file (.Qdr). You may include up to 20 comment lines.

The line below the title and the comment lines is the flags line. These are short label flags set by the user, either directly by editing the dataset or they can be set interactively via the FVMP dialog when entering the vehicle data. There are four flag labels, all in one line, that turn on different modeling options.

1. The first flag defines the vehicle rates, and it is either "Body Axes" (default) or "Stability Axes".
2. The second flag defines the type of vehicle attitude in the system outputs. It is either "Attitude=Euler Angles" (default) or "Attitude=Rate Integral", integral of the body rates.
3. The third flag is used to turn-on the aero-elasticity and the inertial coupling data for the aero-surfaces. It is either "Without GAFD" (default) or "Include GAFD" when there is a GAFD data file available.
4. The fourth flag is for turning-on the turn-coordination logic. Sometimes we need to create a dynamic model of an aircraft for control design purposes that includes the bank-to-yaw turn-coordination cross-coupling in the design model. This is a feed-forward term that commands a yaw rate as a function of the bank angle. It simplifies and separates the two control functions because the gains derived from LQR or H-infinity "assume" that the system already includes turn-coordination. When the flag is set to "With Turn Coordination" the dynamic model includes this cross-coupling term. Otherwise, the default state is: "No Turn Coordination".

```
FLIGHT VEHICLE INPUT DATA .....
Space Shuttle Orbiter Flex Model during Early Re-Entry (for batch)
! The following vehicle model is a Space Shuttle vehicle during the early phase of atmospheric
! re-entry where it is flying at a high angle of attack and it is using both RCS jets and
! control surfaces for attitude control. This set uses an additional file (Shuttle Orb.Gaf) that
! contains the GAFD and inertial coupling coefficients used in modeling aeroelasticity. This
! vehicle set is the same as above, but includes two additional statements at the bottom used
! for selecting GAFD frequencies to match the modal frequencies.
! It also selects GAFD surfaces to match this vehicle surfaces. It requires a GAFD data file.
!
Body Axes Output, Attitude=Euler Angles, Include GAFD, No Turn Coordination

Vehicle Mass (lb-sec^2/ft), Gravity Accelerat. (g) (ft/sec^2), Earth Radius (Re) (ft) : 7460.4      32.17      0.20896E+08
Moments and products of Inertias Ixx, Iyy, Izz, Ixy, Ixz, Iyz, in (lb-sec^2-ft) : 804000.0, 7325110.0, 7564300.0, 0.0, 0.0, 0.0
CG location with respect to the Vehicle Reference Point, Xcg, Ycg, Zcg, in (feet) : -82.85,      0.0,      2.7
Vehicle Mach Number, Velocity Vo (ft/sec), Dynamic Pressure (psf), Altitude (feet) : 25.0      18640.0      4.0      245500.0
Inertial Acceleration Vo_dot, Sensed Body Axes Accelerations Ax,Ay,Az (ft/sec^2) : -7.39      -1.14      0.0000      -12.15
Angles of Attack and Sideslip (deg), alpha, beta rates (deg/sec) : 40.0      0.0      -0.5      0.0000
Vehicle Attitude Euler Angles, Phi_o,Thet_o,Psi_o (deg), Body Rates Po,Qo,Ro (deg/sec) : 0.0      39.15      0.0      0.0      0.0      0.0
Wind Gust Vel wrt Vehi (Azim & Elev) angles (deg), or Force(lb), Torque(ft-lb), locat:xyz : Gust      2680.0      45.0      90.0
Surface Reference Area (feet^2), Mean Aerodynamic Chord (ft), Wing Span in (feet) : 2680.0      35.0,      79.0
Aero Moment Reference Center (Xmrc,Ymrc,Zmrc) Location in (ft), (Partial_rho/ Partial_H) : -81.36,      0.0,      2.97,      -2.07e-10
Aero Force Coef/Deriv (1/deg), Along -X, {Cao,Ca_alf,PCa/PV,PCa/Ph,Ca_alfdot,Ca_q,Ca_bet} : 0.103,      -0.007,      -0.4e-6,      0.8e-7,0.0,
Aero Force Coef/Derivat (1/deg), Along Y, {Cy0,Cy_bet,Cy_r,Cy_alf,Cy_p,Cy_befdot,Cy_V} : 0.0,      -0.023,      0.39,      0.0,      -0.54,      0.0,
Aero Force Coef/Deriv (1/deg), Along Z, {Czo,Cz_alf,Cz_q,Cz_bet,PCz/Ph,Cz_alfdot,PCz/PV} : -2.6,      -0.086,      -1.7,      0.0,      0.0,      0.0,
Aero Moment Coef/Derivat (1/deg), Roll: {Clo,Cl_beta,Cl_betdot,Cl_p,Cl_r,Cl_alfa} : 0.0,      -0.007,      0.0,      -0.65,      0.25,
Aero Moment Coef/Deriv (1/deg), Pitch: {Cmo,Cm_alfa,Cm_alfdot,Cm_bet,Cm_q,PCm/PV,PCm/Ph} : 0.0012,      -0.008,      0.0,      0.0,      -17.4,
Aero Moment Coef/Derivat (1/deg), Yaw : {Cno,Cn_beta,Cn_betdot,Cn_p,Cn_r,Cn_alfa} : 0.0,      -0.0011,      0.0,      0.26,      -1.1,
```

The block of vehicle data below the flags consists of: mass properties, moments and products of inertia, CG location, trajectory parameters, alpha and beta, vehicle Euler angles, nominal rates and accelerations, vehicle altitude, direction of wind-gust disturbance, aerodynamic parameters, aero derivatives, the moments reference center, etc. The wind gust is the last input in the state-space model. It represents a change of the wind velocity in (feet/sec). It can be shaped in a simulation to resemble a realistic gust such as a cosine function. The wind direction relative to the vehicle axes is constant and defined in the input data in terms of two angles: azimuth and elevation (in degrees). When the dynamic pressure is small, such as on a spacecraft, the wind gust disturbances become ineffective and the disturbance definition can be changed from wind gust velocity, to a disturbance force or torque at a specific location point. The direction of the force or torque with respect to the aircraft is also defined in terms of the two angles relative to the vehicle axes. The force application point in (x, y, z) coordinates is also required.

The next group of data defines the parameters of the aerosurfaces which are control inputs to the vehicle model. The first line in the control surface data defines the number of surfaces included in the model and the TWD flag, which is either “With TWD” or “No TWD” (default). Then we have blocks of data for each individual pivoting aerosurface consisting of: a short title of the aerosurface, the trim angle position (deg), the max and min aerosurface deflections from trim (deg), the orientation angles of the hinge line relative to vehicle axes, the aerosurface mass properties, moment arm between the hinge to the surface CG, the surface chord, the hinge moment derivatives, the location of the hinge line center in vehicle coordinates, and the aerodynamic force and moment derivatives due to surface deflection and rate of deflection. Some of the aerosurface parameters are not required, depending on the type of model and the flags set, for example, the surface mass properties, geometry and locations are ignored when the TWD option is off, or when the GAFD data is included because this information is included in the GAFD file.

```

Number of Control Surfaces, With or No TWD (Tail-Wags-Dog and Hinge Moment Dynamics) ? : 5 With TWD

Control Surface No: 1 Left Outbd Elevon
Trim Angle, Max/Min Deflection Angles from Trim, Hinge Line Angles: phi_h, lamda_h (deg): -5.0 30.000 -35.000 +2.5000 0.000
Surface Mass, Inertia about Hinge, Moment Arm (Hinge to Surface CG), Surface Chord, Area : 55.0 227.4 1.8 6.322 75.823
Hinge Moment Derivatives (1/deg), { Chm_Alpha, Chm_Beta, Chm_Delta, Chm_Mach } : -0.0047 -0.00055 -0.0097 0.0000
Location of the Hinge Line Center with respect to Vehicle Reference (feet), {Xcs,Ycs,Zcs}: -118.6 -33.16 10.4
Forces (-x,y,z) due to Deflect. and Rates {Ca_del,Cy_del,Cz_del, Ca_deld,Cy_deld,Cz_deld}: 0.00022 -0.0018 -0.0062 0.0 0.0
Moments due to Deflections and Rates {Cl_del,Cm_del,Cn_del,Cl_deldot,Cm_deldot,Cn_deldot}: 0.0028 -0.0018 0.0006 0.0 0.0

Control Surface No: 2 Left Inbrd Elevon
Trim Angle, Max/Min Deflection Angles from Trim, Hinge Line Angles: phi_h, lamda_h (deg): -7.0 30.000 -35.000 +1.3 0.0
Surface Mass, Inertia about Hinge, Moment Arm (Hinge to Surface CG), Surface Chord, Area : 100.0 820.3 2.5 8.594 134.96
Hinge Moment Derivatives (1/deg), { Chm_Alpha, Chm_Beta, Chm_Delta, Chm_Mach } : -0.0047 -0.00055 -0.0097 0.0000
Location of the Hinge Line Center with respect to Vehicle Reference (feet), {Xcs,Ycs,Zcs}: -118.6 -18.4 11.1
Forces (-x,y,z) due to Deflect. and Rates {Ca_del,Cy_del,Cz_del, Ca_deld,Cy_deld,Cz_deld}: 0.00025 -0.0009 -0.00 0.0 0.0
Moments due to Deflections and Rates {Cl_del,Cm_del,Cn_del,Cl_deldot,Cm_deldot,Cn_deldot}: 0.0006 -0.0032 0.0001 0.0 0.0

Control Surface No: 3 Right Inbd Elevon
Trim Angle, Max/Min Deflection Angles from Trim, Hinge Line Angles: phi_h, lamda_h (deg): -7.0 30.000 -35.000 -1.3 0.000
Surface Mass, Inertia about Hinge, Moment Arm (Hinge to Surface CG), Surface Chord, Area : 100.0 785.0 2.5 8.594 134.96
Hinge Moment Derivatives (1/deg), { Chm_Alpha, Chm_Beta, Chm_Delta, Chm_Mach } : -0.0047 -0.00055 -0.0097 0.0
Location of the Hinge Line Center with respect to Vehicle Reference (feet), {Xcs,Ycs,Zcs}: -118.6 18.4 11.1
Forces (-x,y,z) due to Deflect. and Rates {Ca_del,Cy_del,Cz_del, Ca_deld,Cy_deld,Cz_deld}: 0.00025 0.0009 -0.008 0.0 0.0
Moments due to Deflections and Rates {Cl_del,Cm_del,Cn_del,Cl_deldot,Cm_deldot,Cn_deldot}: -0.0006 -0.0032 -0.0001 0.0 0.0

Control Surface No: 4 Right Outbd Elevon
Trim Angle, Max/Min Deflection Angles from Trim, Hinge Line Angles: phi_h, lamda_h (deg): -5.0 30.000 -35.000 -2.5 0.000
Surface Mass, Inertia about Hinge, Moment Arm (Hinge to Surface CG), Surface Chord, Area : 55.0 227.4 1.8 6.322 75.823
Hinge Moment Derivatives (1/deg), { Chm_Alpha, Chm_Beta, Chm_Delta, Chm_Mach } : -0.0047 0.00055 -0.0097 0.0000
Location of the Hinge Line Center with respect to Vehicle Reference (feet), {Xcs,Ycs,Zcs}: -118.6 33.16 10.4
Forces (-x,y,z) due to Deflect. and Rates {Ca_del,Cy_del,Cz_del, Ca_deld,Cy_deld,Cz_deld}: 0.00022 0.0018 -0.0062 0.0
Moments due to Deflections and Rates {Cl_del,Cm_del,Cn_del,Cl_deldot,Cm_deldot,Cn_deldot}: -0.0028 -0.0018 -0.0006 0.0 0.0

```

The next group of data defines the parameters for the TVC engines or the RCS jets which are also control inputs to the system. The first line in the engines data defines the number of engines or RCS, and it may also include the engines TWD flag, which is either “*Include TWD*” or “*No TWD*” (default). In this example the TWD flag is not included because the jets are not gimbaling. There is also short title that identifies each engine or RCS thruster. Below that we have data for each individual engine or jet consisting of: a short label that defines the thruster, its nominal thrust, the maximum thrust if the engine is throttling. For a non-throttling engine the maximum thrust must be equal to the nominal thrust. A short label on the right side of the engine title defines if the engine is “*Gimbaling*” or “*Throttling*”. Some engines may only be gimbaling and some may only be throttling, or they may be doing both. The engine mounting angles or trim positions are also defined, as described in Figure (2.1-26), and also the maximum pitch and yaw deflections from trim in (deg), if gimbaling. In this example they are zero because the thrusters are not gimbaling. The data also includes the gimbaling nozzle mass, its moment of inertia about the pivot, and the moment arm distance between the nozzle CG and the gimbal. They are needed for the TWD calculations and they are not used when the engines are fixed or the TWD flag is off, such as in this case. We also have the (x,y,z) gimbal locations in vehicle coordinates.

Number of Thruster Engines, Include or Not the Tail-Wags-Dog and Load-Torque Dynamics ? : 11

RCS Jet No: 1	Back, Left, Up, +Z	(three 800 lb jets)	: BLU Jet	Throttling	Node 16
Engine Nominal Thrust, and Maximum Thrust in (lb)	(for throttling)		: 0.0	2400.0	
Mounting Angles wrt Vehicle (Dyn,Dzn), Maximum Deflections from Mount (Dymax,Dzmax) (deg):	-88.5			39.3	0.0 0.0
Eng Mass (slug), Inertia about Gimbal (lb-sec <sup>2</sup> -ft), Moment Arm, engine CG to gimbal (ft):	1.0			1.0	1.0
Thruster location with respect to the Vehicle Reference Axes, Xgimb, Ygimb, Zgimb, (ft):	-128.1,			-11.5,	-5.8
RCS Jet No: 2	Back, Right, Up, +Z	(three 800 lb jets)	: BRU Jet	Throttling	Node 11
Engine Nominal Thrust, and Maximum Thrust in (lb)	(for throttling)		: 0.0	2400.0	
Mounting Angles wrt Vehicle (Dyn,Dzn), Maximum Deflections from Mount (Dymax,Dzmax) (deg):	-88.5			-131.3	0.0 0.0
Eng Mass (slug), Inertia about Gimbal (lb-sec <sup>2</sup> -ft), Moment Arm, engine CG to gimbal (ft):	1.0			1.0	1.0
Thruster location with respect to the Vehicle Reference Axes, Xgimb, Ygimb, Zgimb, (ft):	-128.1,			11.5,	-5.8

In the dynamic model, the "on-off" behavior of a reaction control jet or the thrust variation of a throttling engine from its nominal thrust is implemented by means of throttle inputs, where a throttle control input is defined to be a change in thrust divided by the nominal thrust. The actual thrust and the maximum thrust are defined in the input data. In the state-space system created, a throttle input to an RCS jet is allowed to vary between (0 and 1), where 0 represents zero thrust and 1 represents max thrust. This also allows us to model a pair of opposite firing thrusters by means of a single control input that receives inputs: (-1, 0, and +1). For a thrust varying engine (described as throttling engine), the throttle control input ( $\delta_{Th}$ ) represents throttle variations relative to nominal thrust ( $T_e$ ), and it can vary between (0 and  $\pm 1$ ). It represents thrust variations above and below the normal engine thrust. The actual thrust is calculated internally in the dynamic model, as:  $T = T_e (1 \pm \delta_{Th})$ . The throttle inputs are not necessarily “on-off” type, but they are continuous functions. Zero throttle input corresponds to the nominal engine thrust which is defined in the data, +1 represents maximum thrust, and -1 represents minimum thrust.

The vehicle data may also include other types of effectors such as: external torques, reaction wheels (RW), and control moment gyros (CMG) which are described in the spacecraft equations and in the examples.

The outputs of the dynamic system are defined by different types of sensors that can be placed in different locations on the vehicle. A gyro measures rotations in either: roll, pitch, or yaw. Even though they are referred to as gyros they can be defined to measure either: angular position in (rad), rotational rate (rad/sec), or angular acceleration in (rad/sec<sup>2</sup>). The number of rotational sensors in the example below is 3 measuring rate in roll, pitch, and yaw. Similarly, an accelerometer can measure translation at a specific location along the vehicle x, y, or z axes, and although they are called accelerometers they can be set to measure either: translation in (feet), velocity (feet/sec), or acceleration in (feet/sec<sup>2</sup>). In this case we have 3 translational sensors that measure acceleration in x, y, and z. The gyro and accelerometer measurements consist of rigid-body plus local flex motion. They can also be configured to measure only flex motion. For example: “Pos.Flex” or “Acc.Flex”, etc. Read the Shuttle Coulomb Damper example for details. The locations of the accelerometers must be included in vehicle coordinates. There are also vane sensors that measure angles of attack and sideslip at specific vehicle locations, normally in the front part of vehicle. The vane measurements are affected by the vehicle motion and also by local flexibility. The vane locations are also required in vehicle coordinates. The flight vehicle program does not create sensor dynamic models. The dynamic system outputs are externally combined with transfer functions that characterize the sensor dynamics and bandwidth. They are used for flight control feedback or for monitoring vehicle performance.

Additional sloshing parameters are required in the input data-set for the implementation of propellant sloshing inside a tank. The slosh mass (in slugs), the slosh frequency under 1g loading in (rad/sec), the damping coefficient ( $\zeta$ ), and the (x, y, z) position of the slosh mass in (feet), in vehicle coordinates. The frequencies and damping coefficients are defined twice, separately in the pitch and yaw directions, because they may be different due to asymmetric propellant tanks. The damping coefficient for slosh is low, typically around ( $\zeta=0.001$ ). To temporarily remove the effect of sloshing in the model we may set the slosh mass to zero.

The bottom lines in the vehicle data-set define the structural flexibility of the vehicle. For a rigid-body model we set the “*Number of Bending Modes: 0*”. Otherwise, we must enter the number of flex modes to be combined with the vehicle data (50 in this case), and we must also include the title of the selected modal data set in the next line, below the number of modes line. The selected modes are a set of modal data that is saved in the same input file (.Inp) below the vehicle rigid-body data. They were previously selected by running the mode selection utility program. Each mode is evaluated according to its modal strength between actuators and sensors. They were also scaled to match and to combine with the vehicle data. We will describe this process later, but for now we assume that the selected modal data-set is already in the input data file. Its title in this example it is “*Shuttle Early Hypersonic Atmospheric Re-Entry, First 50 Modes*”. It was created during the mode selection process, and it is ready to be processed by the vehicle modeling program. This title must also be included at the bottom of the vehicle data-set, as already described. Otherwise, a modal data set must be selected later from a menu in the flex data tab in the FVMP interactive dialog.

```

Number of Gyros, (Attitude and Rate), Node 38 : 3
Gyro No 1 Axis:(Pitch,Yaw,Roll), (Attitude or Rate), Location in Vehicle Axes (feet) : Roll Rate -48.4, 0.0, 7.5
Gyro No 2 Axis:(Pitch,Yaw,Roll), (Attitude or Rate), Location in Vehicle Axes (feet) : Pitch Rate -48.4, 0.0, 7.5
Gyro No 3 Axis:(Pitch,Yaw,Roll), (Attitude or Rate), Location in Vehicle Axes (feet) : Yaw Rate -48.4, 0.0, 7.5

Number of Accelerometers, (x,y,z) : 3
Acceleromet No 1 Axis:(X,Y,Z), (Acceleration,Flex_Posit,Flex_Veloc,Flex_Accel), Locat(ft): X-axis Acceleration -32.2, 0.0, -1.
Acceleromet No 2 Axis:(X,Y,Z), (Acceleration,Flex_Posit,Flex_Veloc,Flex_Accel), Locat(ft): Y-axis Acceleration -32.2, 0.0, -1.
Acceleromet No 3 Axis:(X,Y,Z), (Acceleration,Flex_Posit,Flex_Veloc,Flex_Accel), Locat(ft): Z-axis Acceleration -32.2, 0.0, -1.

Number of Vane Sensors, (Alpha or Beta) : 0

Number of Slosh Modes : 0

Number of Bending Modes : 50
Shuttle Early Hypersonic Atmospheric Re-Entry, First 50 Modes
Selected GAFD Mode Numbers from GAFD File : 1 2 3 4 5 6 7 8 9 10 11 12 13
Selected GAFD Surface Numbers from GAFD File : 1 2 3 4 5
-----

```

Aero-elasticity describes additional coupling between aerodynamics and structural flexibility and it is often not included in the dynamic model because it is not easy to calculate the aeroelastic data. However, when a GAFD file is available we must include it because it provides a more refined flex model. The aeroelastic data and the inertial coupling parameters are included in a file with extension (.Gaf). The inertial coupling parameters couple the surface accelerations with flexibility and they are generated by the finite-elements program. The (\*.Gaf) file contains frequencies and aero-surfaces that may be more in number and in different sequence than the mode frequencies and aero-surfaces included in the vehicle data-set. So we need a process to map the two sets of frequencies and surfaces data. This is done in the last two lines of the vehicle data-set, see above. The line below the modal data title includes the frequency numbers from the GAFD file that correspond to the frequencies in the selected modal data set. It matches the mode frequencies with frequencies in the (.Gaf) file. The last line matches the surface numbers from the GAFD with the surfaces in the vehicle data file, because there may be more surfaces and in different order. They should typically be the same surfaces and in the same order as in the vehicle data-set. If you forget to include the last two lines the program will request this mapping information using interactive menus.

The data below is a set of selected modes which is saved in the input file (.Inp) together with the vehicle data. They are likely to be the dominant modes between the vehicle actuators and sensors. It is typically created by the Flixan mode selection utility after processing the modal data files (\*.Mod, and \*.Nod) generated from a finite elements program, such as Nastran. The modal data-set below includes 50 modes (only the first one is shown). They are already scaled to match the vehicle units and directions and they are ready to be processed by the vehicle modeling program and to create the flexible vehicle state-space system. An input data file may contain more than one set of selected modal data with different titles, generated for different applications and directions.

SELECTED MODAL DATA AND LOCATIONS FOR ALL AXES

Shuttle Early Hypersonic Atmospheric Re-Entry, First 50 Modes

! The first 50 flex modes were selected that correspond to the GAFD frequencies

MODE # 1/ 1, Frequency (rad/sec), Damping (zeta), Generalized Mass=	9.1779	0.50000E-02	7714.4				
DEFINITION OF LOCATIONS (NODES)	phi along X	phi along Y	phi along Z	sigm about X	sigm about Y	sigm about Z	
Modal Data at the 5 Control Surfaces (Hinges)							
Left Outboard Elevon Hinge Li	1726	-0.38329D-01	0.32463D-02	0.45568D-01	-0.59548D-04	-0.89157D-03	0.65199D-04
Left Inboard Elevon Hinge Lin	1721	-0.39217D-01	0.32014D-02	0.44843D-01	0.00000D+00	0.00000D+00	0.00000D+00
Right Inboard Elevon Hinge Li	1571	-0.40218D-01	-0.55768D-02	0.45595D-01	0.00000D+00	0.00000D+00	0.00000D+00
Right Outboard Elevon Hinge L	1576	-0.40174D-01	-0.56246D-02	0.47212D-01	0.12074D-03	-0.90312D-03	-0.74039D-05
RUDDER NO.1 HINGE TAIL	2376	-0.51453D-02	-0.68149D-03	0.32814D-01	0.00000D+00	0.00000D+00	0.00000D+00
Modal Data at the 11 Engines, (x,y,z)...							
RCS THRUST POINT (BLU)	1963	-0.18018D-01	-0.10362D-02	0.30835D-01	0.00000D+00	0.00000D+00	0.00000D+00
RCS THRUST POINT (BRU)	1893	-0.18538D-01	-0.81625D-03	0.31420D-01	0.00000D+00	0.00000D+00	0.00000D+00
RCS THRUST POINT (BLD)	1967	-0.21845D-01	-0.12074D-02	0.29622D-01	0.00000D+00	0.00000D+00	0.00000D+00
RCS THRUST POINT (BRD)	1897	-0.22273D-01	-0.86932D-03	0.30108D-01	0.00000D+00	0.00000D+00	0.00000D+00
RCS THRUST POINT (BL+Y)	1969	-0.20146D-01	-0.11740D-02	0.27158D-01	0.00000D+00	0.00000D+00	0.00000D+00
RCS THRUST POINT (BR-Y)	1899	-0.20741D-01	-0.92556D-03	0.27822D-01	0.00000D+00	0.00000D+00	0.00000D+00
RCS THRUSTER (FU)	2988	-0.17500D-02	0.18328D-02	0.30856D+00	0.00000D+00	0.00000D+00	0.00000D+00
RCS THRUSTER (FLD & FRD)	2945	-0.18498D-02	0.18263D-02	0.30874D+00	0.00000D+00	0.00000D+00	0.00000D+00
RCS THRUSTER (FLD & FRD)	2945	-0.18498D-02	0.18263D-02	0.30874D+00	0.00000D+00	0.00000D+00	0.00000D+00
RCS THRUSTER (FL-Y)	2987	-0.21360D-01	0.14524D-02	0.30226D+00	0.00000D+00	0.00000D+00	0.00000D+00
RCS THRUSTER (FR+Y)	2944	-0.21701D-01	0.18937D-02	0.30271D+00	0.00000D+00	0.00000D+00	0.00000D+00
Modal Data at the 3 Gyros ...							
RATE GYRO (for control)	1490	-0.44093D-01	0.12177D-02	0.20418D+00	0.35437D-03	-0.38225D-02	0.15265D-05
RATE GYRO (for control)	1490	-0.44093D-01	0.12177D-02	0.20418D+00	0.35437D-03	-0.38225D-02	0.15265D-05
RATE GYRO (for control)	1490	-0.44093D-01	0.12177D-02	0.20418D+00	0.35437D-03	-0.38225D-02	0.15265D-05
Modal Data at the 3 Accelerometers, along (x,y,z)...							
CABIN ACCEL FWD BKHD (for con	307	0.00000D+00	0.17707D-02	0.30067D+00			
CABIN ACCEL FWD BKHD (for con	307	0.00000D+00	0.17707D-02	0.30067D+00			
CABIN ACCEL FWD BKHD (for con	307	0.00000D+00	0.17707D-02	0.30067D+00			
Modal Data at the Disturbance Point							
ENG.1 GIMBAL	2077	-0.21664D-01	-0.82916D-03	0.40440D-01	0.68930D-05	-0.11568D-02	0.98251D-05

MODE # 2/ 2, Frequency (rad/sec), Damping (zeta), Generalized Mass=	9.4123	0.50000E-02	7714.4			
DEFINITION OF LOCATIONS (NODES)	phi along X	phi along Y	phi along Z	sigm about X	sigm about Y	sigm about Z

A modal data set begins with an id line "SELECTED MODAL DATA AND LOCATIONS" (shown in red), which identifies that the following data as set of selected modes to be processed by Flixan. The second line (shown in blue), in this case "Shuttle Early Hypersonic Reentry" is the title of the modes set and it matches the title that was included at the bottom of the vehicle data-set. Below the title we have the comments lines (green), and then the modal data for the 50 modes. Each mode includes a frequency in (rad/sec), damping coefficient (zeta), and the modal mass (slugs). Below this line we have the 3 generalized mode shapes and the 3 mode slopes at important locations on the vehicle, such as: the aero-surfaces, the RCS jets, the 3 rate gyros, the 3 accelerometers, disturbance points, CMG, etc.

The following vehicle data-set is for a twin booster rocket with 2 aerosurfaces, TWD, 2 sloshing propellant tanks, rate gyros, accelerometers, and 8 structural modes. It does not include aero-elasticity data.

FLIGHT VEHICLE INPUT DATA .

Zulu, Stage-1, Max-Q, 8 Flex Modes with Slosh

! This is a Launch Vehicle during First Stage at Maximum Dynamic Pressure. It is launched from  
! a high altitude to maximize orbit performance. At Max-Q and while flying at 2.5 Mach it  
! experiences a strong wind shear that causes 4 deg of angle of attack. The vehicle has two side  
! liquid oxygen rockets that can provide 320,000 (lb) of thrust each. The two fuel tanks, one  
! on each side cause a significant amount of slosh disturbance.

Body Axes Output, Attitude=Euler Angles, Without GAFD, No Turn Coordination

Vehicle Mass (lb-sec <sup>2</sup> /ft), Gravity Accelerat. (g) (ft/sec <sup>2</sup> ), Earth Radius (Re) (ft)	:	8878.0	32.174	0.20896E+08	
Moments and products of Inertias Ixx, Iyy, Izz, Ixy, Ixz, Iyz, in (lb-sec <sup>2</sup> -ft)	:	519500.0	1671000.0	2110000.0	0.0000
CG location with respect to the Vehicle Reference Point, Xcg, Ycg, Zcg, in (feet)	:	-126.05	0.0000	0.007	
Vehicle Mach Number, Velocity Vo (ft/sec), Dynamic Pressure (psf), Altitude (feet)	:	2.5	2000.0	220.00	83000.
Inertial Acceleration Vo_dot, Sensed Body Axes Accelerations Ax,Ay,Az (ft/sec <sup>2</sup> )	:	62.000	54.000	0.0000	21.000
Angles of Attack and Sideslip (deg), alpha, beta rates (deg/sec)	:	4.0000	0.0000	0.0000	0.0000
Vehicle Attitude Euler Angles, Phi_o, Thet_o, Psi_o (deg), Body Rates Po,Qo,Ro (deg/sec)	:	0.0000	44.000	0.0000	0.0000
Wind Gust Vel wrt Vehi (Azim & Elev) angles (deg), or Force(lb), Torque(ft-lb), locat:xyz:	:	Gust	45.0	45.0	
Surface Reference Area (feet <sup>2</sup> ), Mean Aerodynamic Chord (ft), Wing Span in (feet)	:	47.3	7.7000	7.7000	
Aero Moment Reference Center (Xmrc,Ymrc,Zmrc) Location in (ft), {Partial_rho/ Partial_H}	:	-127.2	0.0000	0.0000	0.0000
Aero Force Coef/Deriv (1/deg), Along -X, {Cao,Ca_alf,PCa/PV,PCa/Ph,Ca_alfdot,Ca_q,Ca_bet}	:	0.63	0.001	0.0000	0.0000
Aero Force Coeff/Derivat (1/deg), Along Y, {Cyo,Cy_bet,Cy_r,Cy_alf,Cy_p,Cy_betdot,Cy_v}	:	0.0	-0.06	0.0000	0.0000
Aero Force Coeff/Deriv (1/deg), Along Z, {Czo,Cz_alf,Cz_q,Cz_bet,PCz/Ph,Cz_alfdot,PCz/PV}	:	-1.1	-0.31	0.0000	0.0000
Aero Moment Coeff/Derivat (1/deg), Roll: {Clo, Cl_beta, Cl_betdot, Cl_p, Cl_r, Cl_alfa}	:	0.0	-0.0005	0.0000	0.0000
Aero Moment Coeff/Deriv (1/deg), Pitch: {Cmo,Cm_alfa,Cm_alfdot,Cm_bet,Cm_q,PCm/PV,PCm/Ph}	:	2.3	0.6	0.0000	0.0000
Aero Moment Coeff/Derivat (1/deg), Yaw : {Cno, Cn_beta, Cn_betdot, Cn_p, Cn_r, Cn_alfa}	:	0.0	-0.26	0.0000	0.0000

Number of Control Surfaces, With or No TWD (Tail-Wags-Dog and Hinge Moment Dynamics) ? : 5 With TWD

Control Surface No: 1		Left Outbrd Elevon
Trim Angle, Max/Min Deflection Angles from Trim, Hinge Line Angles: phi_h, lamda_h (deg):	-5.0	30.0 -35.0 +2.500 0.000
Surface Mass, Inertia about Hinge, Moment Arm (Hinge to Surface CG), Surface Chord, Area :	55.0	227.4 1.8 6.322 75.823
Hinge Moment Derivatives (1/deg), { Chm_Alpha, Chm_Beta, Chm_Delta, Chm_Mach }	-0.0047	-0.00055 -0.0097 0.00
Location of the Hinge Line Center with respect to Vehicle Reference (feet), {Xcs,Ycs,Zcs}:	-118.6	-33.16 10.4
Forces (-x,y,z) due to Deflect. and Rates {Ca_del,Cy_del,Cz_del, Ca_deld,Cy_deld,Cz_deld}:	0.00022	-0.0018 -0.0062 0.0 0.0
Moments due to Deflections and Rates {Cl_del,Cm_del,Cn_del,Cl_deldot,Cm_deldot,Cn_deldot}:	0.0028	-0.0018 0.0006 0.0 0.0
Control Surface No: 2		Left Inbrd Elevon
Trim Angle, Max/Min Deflection Angles from Trim, Hinge Line Angles: phi_h, lamda_h (deg):	-7.0	30.0 -35.0 +1.3 0.0
Surface Mass, Inertia about Hinge, Moment Arm (Hinge to Surface CG), Surface Chord, Area :	100.0	820.3 2.5 8.594 134.96
Hinge Moment Derivatives (1/deg), { Chm_Alpha, Chm_Beta, Chm_Delta, Chm_Mach }	-0.0047	-0.00055 -0.0097 0.0
Location of the Hinge Line Center with respect to Vehicle Reference (feet), {Xcs,Ycs,Zcs}:	-118.6	-18.4 11.1
Forces (-x,y,z) due to Deflect. and Rates {Ca_del,Cy_del,Cz_del, Ca_deld,Cy_deld,Cz_deld}:	0.00025	-0.0009 -0.008 0.0 0.0
Moments due to Deflections and Rates {Cl_del,Cm_del,Cn_del,Cl_deldot,Cm_deldot,Cn_deldot}:	0.0006	-0.0032 0.0001 0.0 0.0

Number of Thruster Engines, Include or Not the Tail-Wags-Dog and Load-Torque Dynamics ? : 2 WITH TWD

TVC Engine No: 1	(Gimbaling Throttling Single_Gimbal)	Left TVC	Gimbaling
Engine Nominal Thrust, and Maximum Thrust in (lb) (for throttling)	:	320000.0	320000.0
Mounting Angles wrt Vehicle (Dyn,Dzn), Maximum Deflections from Mount (Dymax,Dzmax) (deg):	0.5	0.0	5.0 5.0
Eng Mass (slug), Inertia about Gimbal (lb-sec <sup>2</sup> -ft), Moment Arm, engine CG to gimbal (ft):	47.0	260.00	0.2
Gimbal location with respect to the Vehicle Reference Axes, Xgimb, Ygimb, Zgimb, in (ft) :	-144.6	-8.7	0.0
TVC Engine No: 2	(Gimbaling Throttling Single_Gimbal)	Right TVC	Gimbaling
Engine Nominal Thrust, and Maximum Thrust in (lb) (for throttling)	:	320000.0	320000.0
Mounting Angles wrt Vehicle (Dyn,Dzn), Maximum Deflections from Mount (Dymax,Dzmax) (deg):	0.5	0.0	5.0 5.0
Eng Mass (slug), Inertia about Gimbal (lb-sec <sup>2</sup> -ft), Moment Arm, engine CG to gimbal (ft):	47.0	260.00	0.2
Gimbal location with respect to the Vehicle Reference Axes, Xgimb, Ygimb, Zgimb, in (ft) :	-144.6	8.7	0.0

Number of Gyros, (Attitude and Rate)	:	3
Gyro No 1 Axis:(Pitch,Yaw,Roll), (Attitude, Rate, Accelerat), Sensor Location in (feet)	:	Roll Rate -102.00 0.00 0.00
Gyro No 2 Axis:(Pitch,Yaw,Roll), (Attitude, Rate, Accelerat), Sensor Location in (feet)	:	Pitch Rate -102.00 0.00 0.00
Gyro No 3 Axis:(Pitch,Yaw,Roll), (Attitude, Rate, Accelerat), Sensor Location in (feet)	:	Yaw Rate -102.00 0.00 0.00

Number of Accelerometers, Along Axis: (x,y,z)	:	2
Acceleromet No 1 Axis:(X,Y,Z), (Position, Velocity, Acceleration), Sensor Location (ft)	:	Y-axis Accelerat. -102.00 0.00 0.00
Acceleromet No 2 Axis:(X,Y,Z), (Position, Velocity, Acceleration), Sensor Location (ft)	:	Z-axis Accelerat. -102.00 0.00 0.00

Number of Vane Sensors, (Measuring Alpha or Beta) : 0

Number of Slosh Modes	:	2
Left Tank (slug), Frequ Wy,Wz at lg (rad/s), Damping (zeta-y-z), Locat {Xsl,Ysl,Zsl} (ft):	350.0	2.31 2.31 0.001 0.001 -135.00 -8.7
Rght Tank (slug), Frequ Wy,Wz at lg (rad/s), Damping (zeta-y-z), Locat {Xsl,Ysl,Zsl} (ft):	350.0	2.31 2.31 0.001 0.001 -135.00 8.7

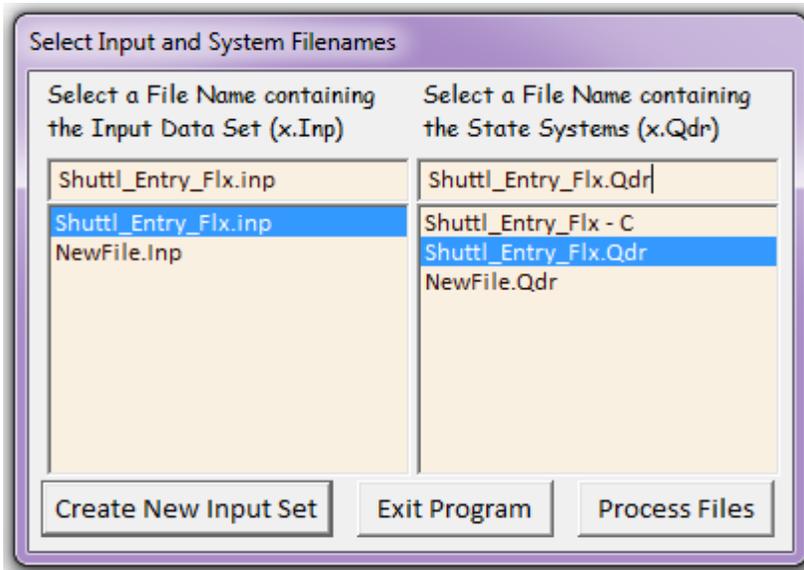
Number of Bending Modes : 8

Zulu, Stage-1, Max-Q, 8 Flex Modes, Pitch Modes

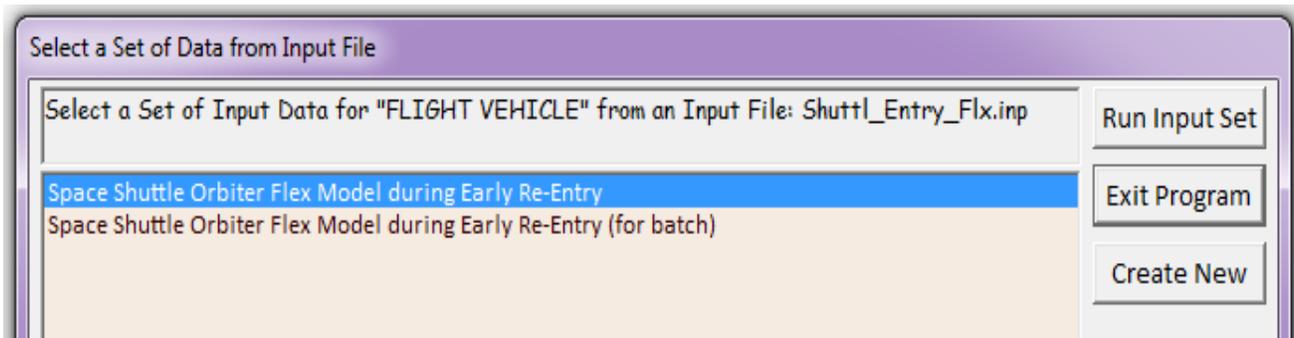
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## 4.2 Running the Vehicle Modeling Program

To run the flight vehicle modeling program, you must first select the option from the Flixan main menu, and then from the filename selection menu select the input data file that contains the vehicle data, and a systems file (.Qdr) where the vehicle system will be saved, and click on “*Process Files*”.

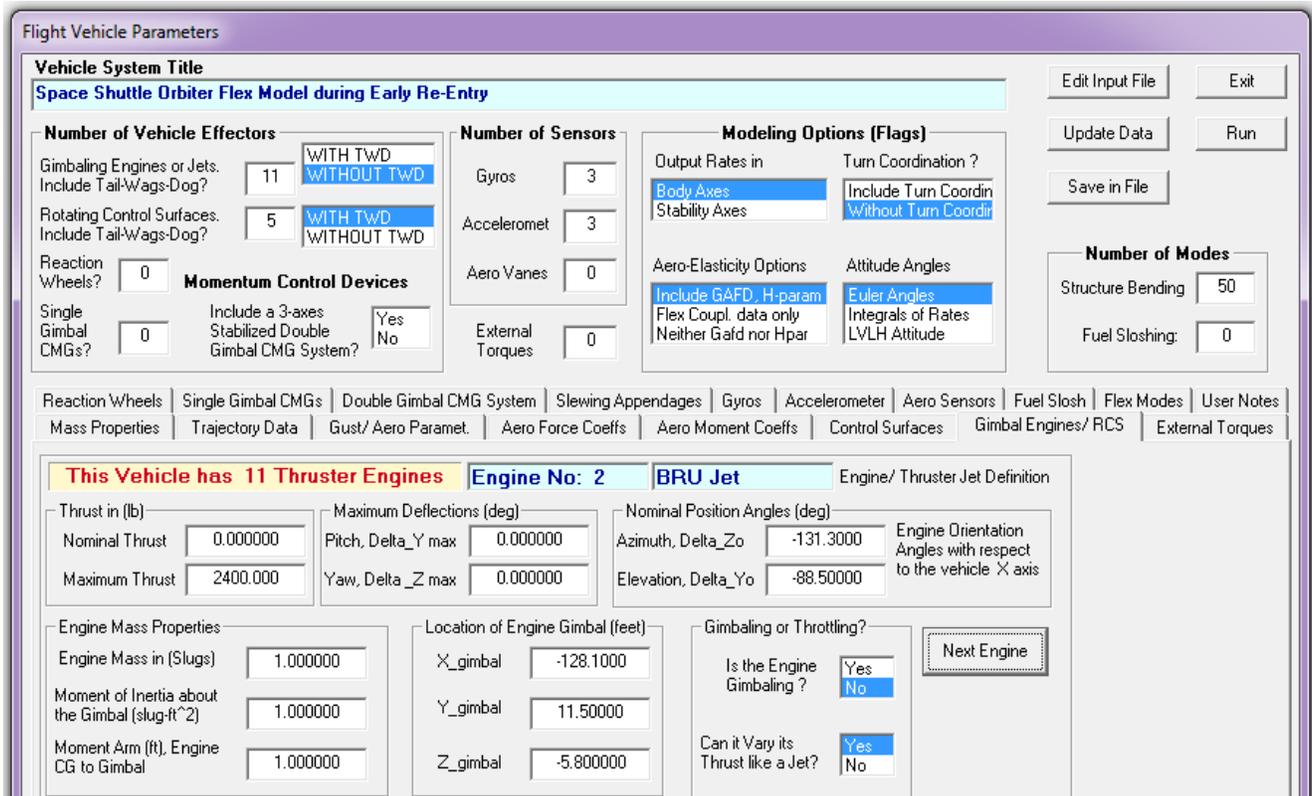


The menu below shows the titles of the flight vehicle data-sets, which are already saved in the input file. In this case we have two sets. We select the title of one of the sets “*Shuttle Orbiter Flex Model for Early Re-Entry*” and click on “*Run Input Set*” to process the data. Notice that there are other options available in these menus for creating a new vehicle data-set from scratch using either one of the dialogs. When the vehicle data does not exist in file, you may click on “*Create a New Input Set*” and the program will open-up dialogs for entering the vehicle data interactively. Creating a new set of vehicle data is described in Section 4.5. However, in this case we assume that the data is already present, and click on “*Run*” to process it and to create the vehicle system in file (.Qdr).

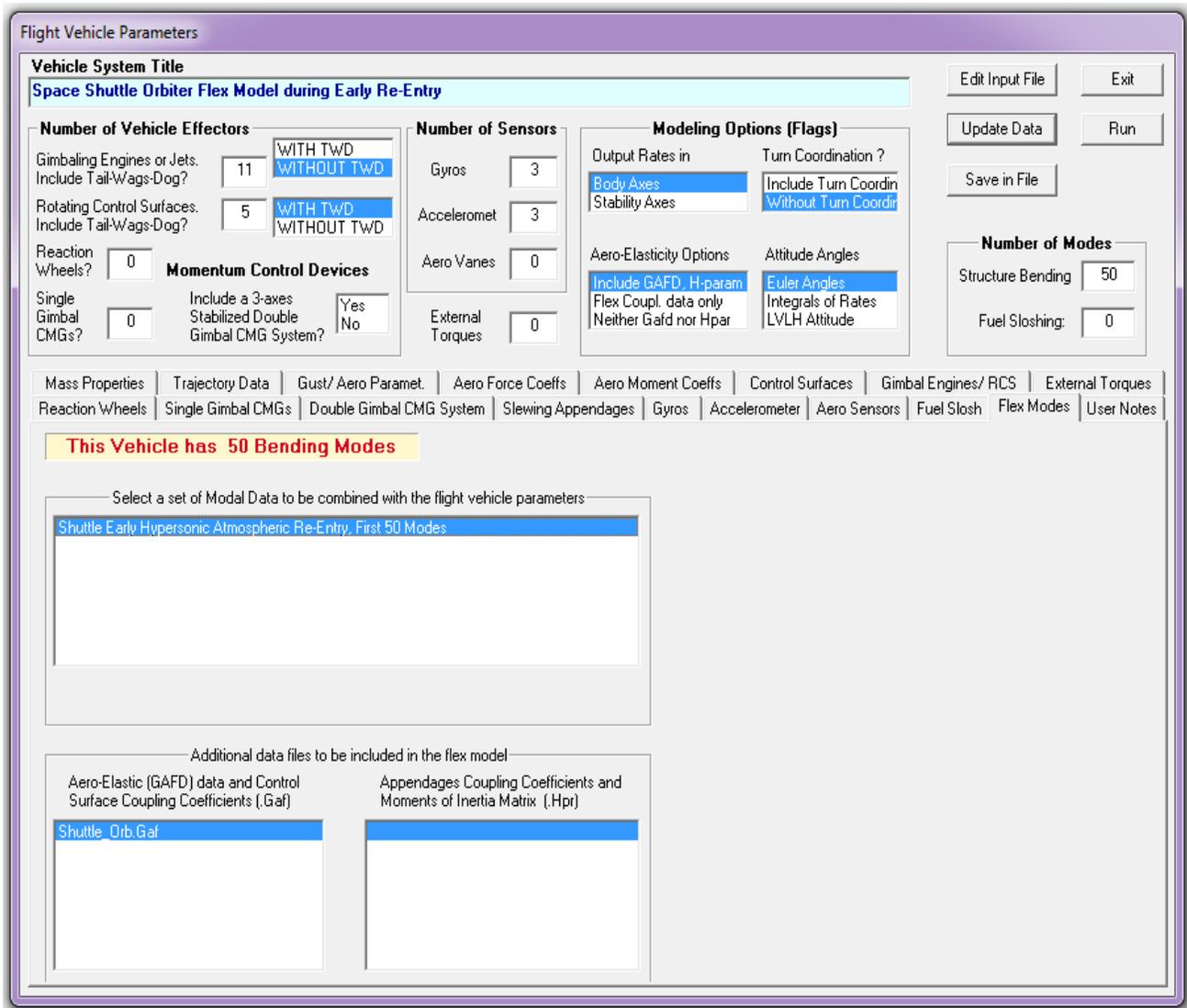


For a vehicle that includes aero-elasticity and inertial coupling parameters a GAFD data file (.Gaf) must already be prepared for all frequencies and aero-surfaces that correspond to the selected mode frequencies and the aero-surfaces defined in the (.Inp) file. You must remember to place the GAFD file in the same directory as the vehicle input data file (.Inp) and set the aero-elasticity flag in the vehicle data to “*Include GAFD*”. There may be more GAFD frequencies than selected mode frequencies but there should be a GAFD frequency that corresponds to each of the selected mode frequencies.

The following dialog with multiple tabs belongs to the vehicle modeling program. It is used for browsing and editing the flight vehicle data-set that was selected from the input file. It can also be used for entering a new set of vehicle data interactively. However, in this case we are just browsing the selected data-set that already exists in file, prior to processing it. It shows the vehicle title at the top of the dialog, the number of engines or RCS jets, the number of aero-surfaces, the tail-wag-dog flags for the engines and surfaces, the modeling option flags, the number of flex modes (50), slosh modes, etc. The “Includes GAFD” option is on, the “Turn-coordination” is off, and the output rates are in body axes. The dialog tabs correspond to groups of vehicle data, such as: aero-surface data, engines or RCS jets, mass properties, aerodynamic moment coefficients, flexibility, etc. It is currently showing the RCS data consisting of 11 RCS jets, which are throttling. They have zero nominal thrust and a max thrust of 2400 (lb). The thrusters are defined as “Throttling” and “Not Gimbaling”. The orientation of each thruster is defined in terms of the ( $\Delta z$  and  $\Delta y$ ) angles, and its location is defined in vehicle reference axes along x, y, z. The nozzle mass properties are irrelevant in this case because the thrusters do not gimbal. It is currently showing Jet No: 2. If you click on “Next Engine” it will advance to Jet No: 3.



You may also select the “Flex Modes” tab to make sure that the modal data title and the GAFD file are selected in the appropriate menus. The top menu shows the title of the selected modal data set which is already saved in the input file “Shuttle-Entry-Flx.Inp”. There is only one set of modes in this file and its title is: “Shuttle Early Hypersonic Atmospheric Re-Entry, First 50 Modes”. The lower left menu is for selecting a GAFD file. There is only one (.Gaf) file: “Shuttle\_Orb.Gaf” in the project directory and it gets selected by default.



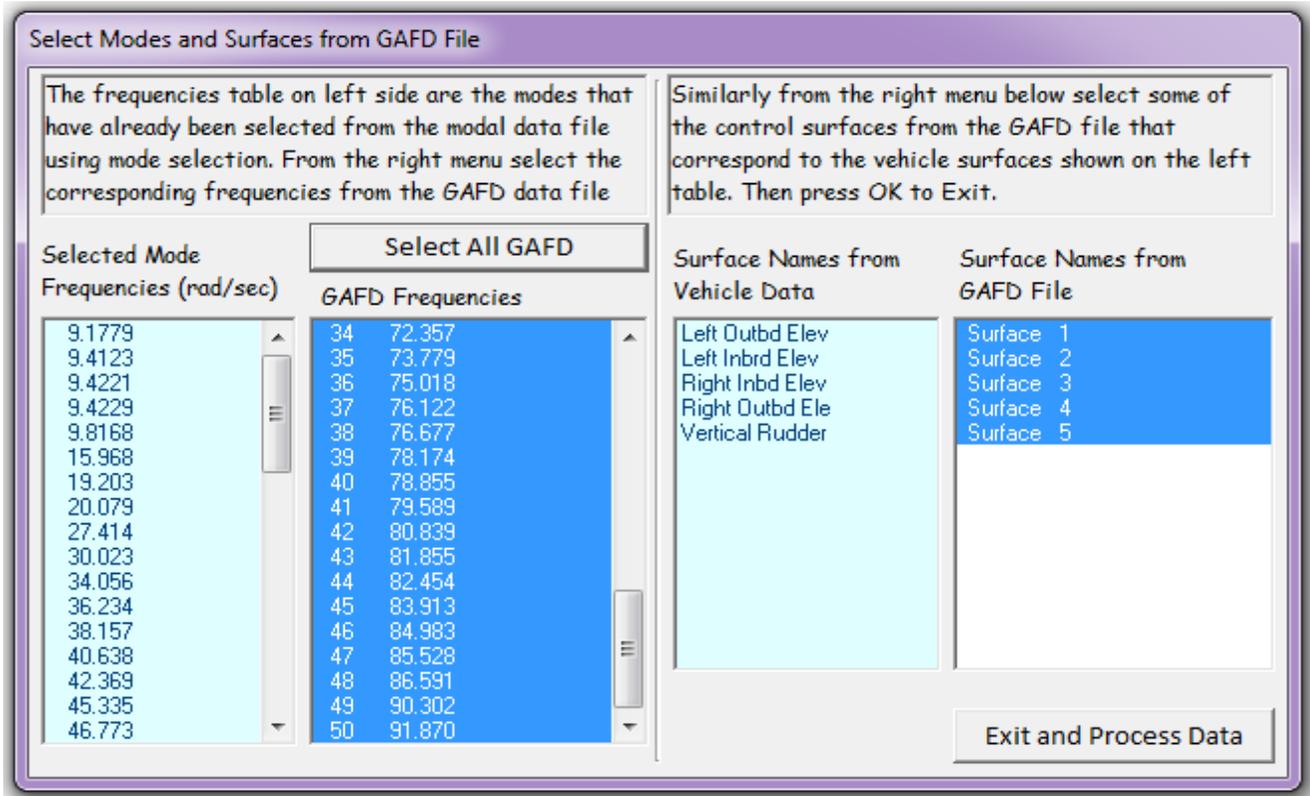
The buttons on the upper right hand side of the dialog perform different functions:

- **Edit** the input data file.
- **Modify** the existing data, Update and Save the data in the same input file as a new data-set, using a different title.
- **Exit** the program without processing the data.
- **Run** to process the data-set.

Click on “Run” and the program will process the data-set, combine it with the modal, and the GAFD data file containing the aeroelastic and inertial coupling coefficients corresponding to the flex mode frequencies, and it will save the vehicle system in the (\*.Qdr) file using the same title.

The following dialog is used for matching the GAFD frequencies with the modal data frequencies, and the control surfaces from the (.Gaf) file with the surfaces in the (.Inp) file, as already described. This is because we typically want to allow the (.Gaf) file to include more elements and to be more complete than the specific model being analyzed. The following two pairs of menus are used for matching the aero-elastic data from the GAFD file with the selected flex modes. The cyan and white pair of display on the left side are for selecting the GAFD frequencies in the white menu. The left cyan field is not a menu but it is showing the selected mode frequencies. The frequencies from the GAFD file that correspond to the flex modes are selected from the white menu. In this case, however, we select all

GAFD frequencies because they are identical and equal to the mode frequencies. The white menu should include more or at least the same number of frequencies as the cyan display. The selected frequencies should be close but not necessarily identical to the modal frequencies.



The same argument applies for the second pair of menus on the right side used to match aero-surfaces from the GAFD file with those in the input file. The GAFD file may contain more surfaces than those used in the vehicle data and we may have to ignore some. The cyan display shows the titles of the vehicle surfaces in the order they appear in the vehicle data-set. They are the surfaces that will be included in the model. The white menu on the right shows the vehicle surfaces as defined in the GAFD file and they should be in the same order and correspond to those in the cyan display. In this case we select all surfaces because they are the same and in the same order as those in the vehicle data.

You may use the menus to select one frequency and one surface at a time, but in this case it is much faster to click on "Select All GAFD" and it will select all frequencies and all surfaces. Finally, click on "Exit and Process Data" and the program combines the vehicle data, the modal data, and the GAFD data to create the flexible vehicle state-space model in file "Shuttl-Entry-Flx.Qdr" using the same title as the vehicle data "Shuttle Orbiter Flex Model for Early Re-Entry". The flight vehicle data and files in this example can also be processed in batch mode which is a lot faster. In this case the selected GAFD frequencies and surfaces are not selected from the menus but they must be included in the vehicle data-set. For more details on how to process vehicle data with GAFD in batch mode we recommend the users to study the "Shuttle Hypersonic Reentry" example in folder "... \Examples\ Shuttle Hypersonic Re-Entry\ Flex\_Analysis", and also the Rocket-Plane example in folder "... \Examples\Rocket Plane\Flex With Gafd".

## 4.3 Modeling the Structural Flexibility

The structural flexibility of the flight vehicle is defined by a finite elements model (FEM) which is generated by a FEM program, such as, Nastran or Patran. In order to generate an efficient vehicle model that accurately produces its response to disturbances we must combine the FEM with the rigid vehicle equations as it is described in section 2.7. The FEM consists of modal data that define the vehicle structural behavior in detail at multiple structural locations, called the nodes. It is in general a very big file, with an extension (.Mod) that includes a large number of modes and nodes, and not very practical to be used directly for modeling. In addition, the FEM data are usually defined in units and in directions which are different from the vehicle model units and directions. So there is an interactive process involved, called “*Mode Selection*”, for processing the FEM data file and extracting a smaller number of modes, those which are substantially strong between the actuators and sensors. The selected modes are also scaled and placed in the input data file (.Inp) in order to be processed by Flixan, as we already described.

In the next two sections we describe how to model the vehicle flexibility. If the vehicle is defined as rigid body in the input data or if the modal data have already been selected and saved together with vehicle parameters in the input file (.Inp), you may skip Sections 4.3 and 4.4 and process the data as already described in Section 4.2. Section 4.4 deals with a more complex subject of modeling aero-elasticity which defines the dynamic coupling between aerodynamic forces and the vehicle flexibility. It also includes a description of the inertial coupling coefficients that define structure excitation due to aerosurface rotational accelerations.

### Modal Data Files

The flexibility of the structure in the vehicle model is characterized by a number of bending modes. Each bending mode is defined by a mode frequency in (rad/sec), the damping coefficient ( $\zeta$ ), the generalized mass, and the generalized mode shapes ( $\phi$ ) and slopes ( $\sigma$ ), at important vehicle locations (nodes), such as: the actuator application points and the sensors. A typical modal data file is big and contains hundreds of flex modes frequencies and shapes of the structure at a fixed configuration. It also includes multiple vehicle locations. However, 20 to 40 nodes on the structure are sufficient for control analysis purposes. We begin with a modal data file that contains the full set of modes. The mode selection program recognizes a modal data file by its extension (.Mod). You may take a look at some of the modal data files in the example folders, such as file “*Shuttle\_Orb.Mod*” in directory “*Flixan\Flight\Examples\Shuttle Hypersonic Re-Entry\Flex\_Analysis*”. It has a couple of titles at the top of the file that identify the kind of file, and the vehicle type and configuration. Below the titles there is a line that defines the number of modes and how many structural nodes are included in this file. The modal data file includes many frames of data, a frame for each mode and all frames have the same structure. The first line in each frame includes the modal frequency in (rad/sec), the damping coefficient ( $\zeta$ ), and the modal mass in (lb-sec<sup>2</sup>/inch). The lines that follow in each frame consist of 7 columns. Each row corresponds to a vehicle location (node).

The node identification number is a large number that was defined in the FEM and it is included in the first column. The next 3 columns are the modal displacements that define translations along x, y, z, and the next 3 columns are the modal slopes that define rotations about x, y, z at the specific vehicle location. A modal data file often includes a lot of modes and more structural locations than those needed for the vehicle analysis. It is a good practice when requesting modal data from structures to ask for more nodes than you think you will need, in case that you may need them later because of an unexpected design modification. It is always easier for a structures person to include a few more points

in the beginning than to go back and modify the finite elements model. The modal data file is created by reformatting the Nastran output by a user supplied program. It is converted to the standard (.Mod) format that is recognizable by the Flixan Mode Selection program. The modal data format is shown below and it is pretty easy to duplicate in a post-processing program. There may be several thousand nodes in a Nastran model but we only need to copy a few in the modal data file. It is recommended that you extract 20 to 40 nodes even if you are not sure that you will need all of them in the dynamic model. The nodes which are typically important to include are the locations of: the engine gimbals, the RCS jets, the hinges of the control surfaces, disturbance points, sensors such as: IMU, accelerometers, gyros, and angle of attack sensors, and the locations of the slosh masses.

### Modal Data File "Shuttle\_Orb.Mod"

Structural Modal Data for ... (units are in pounds and inches)

Space Shuttle Orbiter Vehicle During Entry

NUMBER OF MODES, NUMBER OF NODES

: 80, 40

Mode Number	Frequency (rad/sec)	Damping (zeta)	Generalized Mass (slug)	1	9.1779	0.005	642.87
Node ID:	Along X	Along Y	Along Z	About X	About Y	About Z	
294	0.000000D+00	0.468367D-02	-0.795743D+00	0.000000D+00	0.000000D+00	0.000000D+00	
3504	0.000000D+00	0.333529D-03	-0.793648D+00	0.000000D+00	0.000000D+00	0.000000D+00	
352	0.265984D-01	0.100059D+00	0.384304D+00	0.000000D+00	0.000000D+00	0.000000D+00	
369	0.262976D-01	-0.998114D-01	0.385536D+00	0.000000D+00	0.000000D+00	0.000000D+00	
411	0.237531D-01	0.165316D+00	-0.282369D-01	0.000000D+00	0.000000D+00	0.000000D+00	
418	0.234281D-01	-0.164964D+00	-0.277417D-01	0.000000D+00	0.000000D+00	0.000000D+00	
2169	0.386642D-01	0.000000D+00	0.000000D+00	0.336726D-05	-0.651870D-04	-0.152503D-04	
2173	0.387766D-01	0.000000D+00	0.000000D+00	-0.748488D-05	-0.663426D-04	0.997418D-05	
1886	0.192967D-01	-0.892515D-03	-0.287889D-01	0.000000D+00	0.000000D+00	0.000000D+00	
1890	0.207408D-01	-0.861926D-03	-0.301258D-01	0.000000D+00	0.000000D+00	0.000000D+00	
1893	0.185376D-01	-0.816255D-03	-0.314201D-01	0.000000D+00	0.000000D+00	0.000000D+00	
1897	0.222735D-01	-0.869319D-03	-0.301079D-01	0.000000D+00	0.000000D+00	0.000000D+00	
1899	0.207408D-01	-0.925557D-03	-0.278218D-01	0.000000D+00	0.000000D+00	0.000000D+00	
1956	0.187557D-01	-0.110340D-02	-0.281826D-01	0.000000D+00	0.000000D+00	0.000000D+00	
1959	0.201455D-01	-0.112284D-02	-0.307635D-01	0.000000D+00	0.000000D+00	0.000000D+00	
1963	0.180177D-01	-0.103621D-02	-0.308355D-01	0.000000D+00	0.000000D+00	0.000000D+00	
1967	0.218445D-01	-0.120740D-02	-0.296220D-01	0.000000D+00	0.000000D+00	0.000000D+00	
1969	0.201455D-01	-0.117401D-02	-0.271582D-01	0.000000D+00	0.000000D+00	0.000000D+00	
2420	0.381235D-01	-0.158861D-02	-0.248556D-01	0.000000D+00	0.000000D+00	0.000000D+00	
2077	0.216639D-01	-0.829165D-03	-0.404404D-01	-0.574416D-06	-0.964041D-04	-0.818756D-06	
2080	0.333059D-01	-0.122723D-02	-0.379932D-01	-0.453544D-05	-0.787697D-04	-0.354365D-05	
2243	0.329084D-01	-0.119877D-02	-0.374159D-01	-0.237023D-05	-0.973202D-04	-0.371943D-05	
1571	0.402185D-01	-0.557683D-02	-0.455948D-01	0.000000D+00	0.000000D+00	0.000000D+00	
1806	0.395075D-01	-0.172486D-02	-0.428881D-01	0.000000D+00	0.000000D+00	0.000000D+00	
1576	0.401741D-01	-0.562461D-02	-0.472122D-01	-0.100620D-04	-0.752599D-04	0.616989D-06	
1818	0.399342D-01	-0.134595D-02	-0.464264D-01	0.000000D+00	0.000000D+00	0.000000D+00	
1721	0.392166D-01	0.320142D-02	-0.448427D-01	0.000000D+00	0.000000D+00	0.000000D+00	
1826	0.385146D-01	-0.737673D-03	-0.419497D-01	0.000000D+00	0.000000D+00	0.000000D+00	
1726	0.383289D-01	0.324626D-02	-0.455683D-01	0.496230D-05	-0.742973D-04	-0.543323D-05	
1839	0.378889D-01	-0.943030D-03	-0.425513D-01	0.000000D+00	0.000000D+00	0.000000D+00	
2944	0.217011D-01	0.189369D-02	-0.302712D+00	0.000000D+00	0.000000D+00	0.000000D+00	
2945	0.184976D-02	0.182632D-02	-0.308738D+00	0.000000D+00	0.000000D+00	0.000000D+00	

We must also create a small nodes file that associates the vehicle locations with the node ids. The nodes file will be used as a look-up table in Section (4.4) during the mode selection process to help the analyst to identify the vehicle locations that will be included in the selected modes. It has the same filename as the modal data file and a filename extension (.Nod). It is also called the “nodes map”. The map begins with a title at the top, followed by a list of nodes in columns. Each line defines a node in the (.Mod) file. The left column includes a short description of each node in the sequence that they appear in the modal data file (.Mod). The second column is the node number (1 to  $N_{max}$ ) in ascending sequence (it is not the node id). The third column is the node id which is a large number (typically 4-5 digits long) created by the finite elements program and is included here for node identification. The last 3 columns are optional and they are only used for reference. They include the x, y, z location of each node in vehicle coordinates.

The nodes map is used as a look-up table during mode selection. The list of nodes appears in interactive menus when running the mode selection program and it helps the analyst to identify important vehicle locations. The menus are used to select vehicle locations and the program reads the corresponding mode shapes from the modal data file and calculates the modal strength between actuator and sensor points for each mode for the purpose of selecting the dominant flex modes. For more details take a look at some of the (.Nod) files in the examples. They all have the same format. The following table shows a typical node identification file for a Space Shuttle vehicle.

### Nodes Map File "Shuttle\_Orb.Nod"

#### Shuttle Orbiter Nodes List

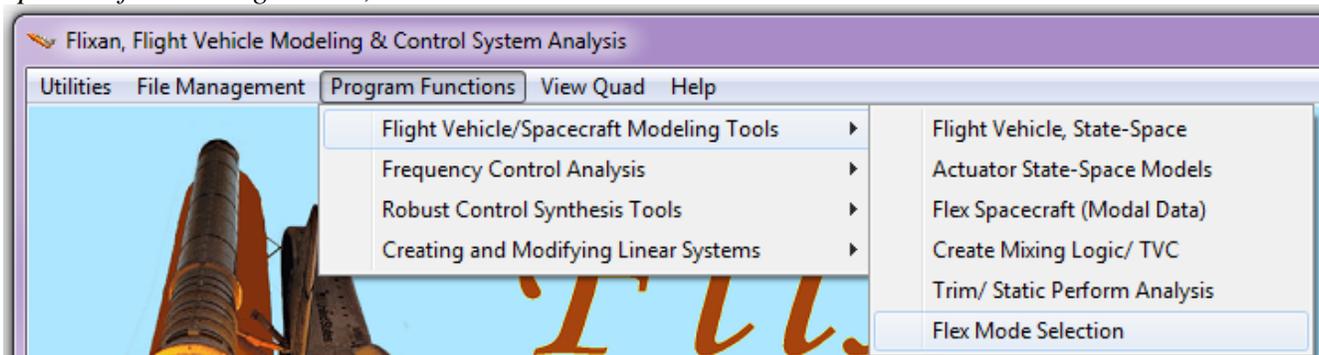
Node Description	Node No	Nastran ID	Node Location X,Y,Z (feet)		
COULOMB DMP.PT.ON PYLD	1	294	-103.8	6.989	-34.50
COULOMB DMP.PT.ON PYLD	2	3504	-103.8	-6.989	-34.50
V-Square DAMPER Point	3	352	-93.02	6.710	-32.18
V-Square DAMPER Point	4	369	-93.02	-6.710	-32.18
V-Square DAMPER Point	5	411	-93.02	7.292	-33.34
V-Square DAMPER Point	6	418	-93.02	-7.292	-33.34
RATE GYRO 1	7	2169	-108.6	-1.750	-24.60
RATE GYRO 4	8	2173	-108.6	1.750	-24.60
RCS THRUST POINT	9	1886	-129.6	11.42	-39.42
RCS THRUST POINT	10	1890	-128.5	12.49	-38.25
RCS THRUST POINT (BRU)	11	1893	-127.4	11.00	-40.04
RCS THRUST POINT (BRD)	12	1897	-128.5	9.172	-36.88
RCS THRUST POINT (BR-Y)	13	1899	-130.4	12.49	-38.25
RCS THRUST POINT	14	1956	-129.6	-11.42	-39.42
RCS THRUST POINT	15	1959	-127.4	-12.49	-38.25
RCS THRUST POINT (BLU)	16	1963	-127.4	-11.00	-40.04
RCS THRUST POINT (BLD)	17	1967	-128.5	-9.172	-36.88
RCS THRUST POINT (BL+Y)	18	1969	-130.4	-12.49	-38.25
BODY FLAP	19	2420	-132.1	-0.8333	-24.12
ENG.1 GIMBAL	20	2077	-120.4	0.000	-36.92
ENG.3 GIMBAL	21	2080	-122.3	4.417	-28.55
ENG.2 GIMBAL	22	2243	-122.3	-4.417	-28.55
Right Inboard Elevon Hinge Line	23	1571	-115.6	17.59	-23.38
INBOARD ELEVON R	24	1806	-118.5	17.53	-24.05
Right Outboard Elevon Hinge Line	25	1576	-115.6	32.16	-24.72
OTBOARD ELEVON R	26	1818	-117.4	36.08	-25.30
Left Inboard Elevon Hinge Line	27	1721	-115.6	-17.59	-23.38
INBOARD ELEVON L	28	1826	-118.5	-17.53	-24.05
Left Outboard Elevon Hinge Line	29	1726	-115.6	-32.16	-24.72
OTBOARD ELEVON L	30	1839	-119.7	-36.08	-25.27
RCS THRUSTER (FR+Y)	31	2944	-30.39	5.971	-29.93
RCS THRUSTER (FLD & FRD)	32	2945	-29.24	1.199	-34.45

## 4.4 Mode Selection

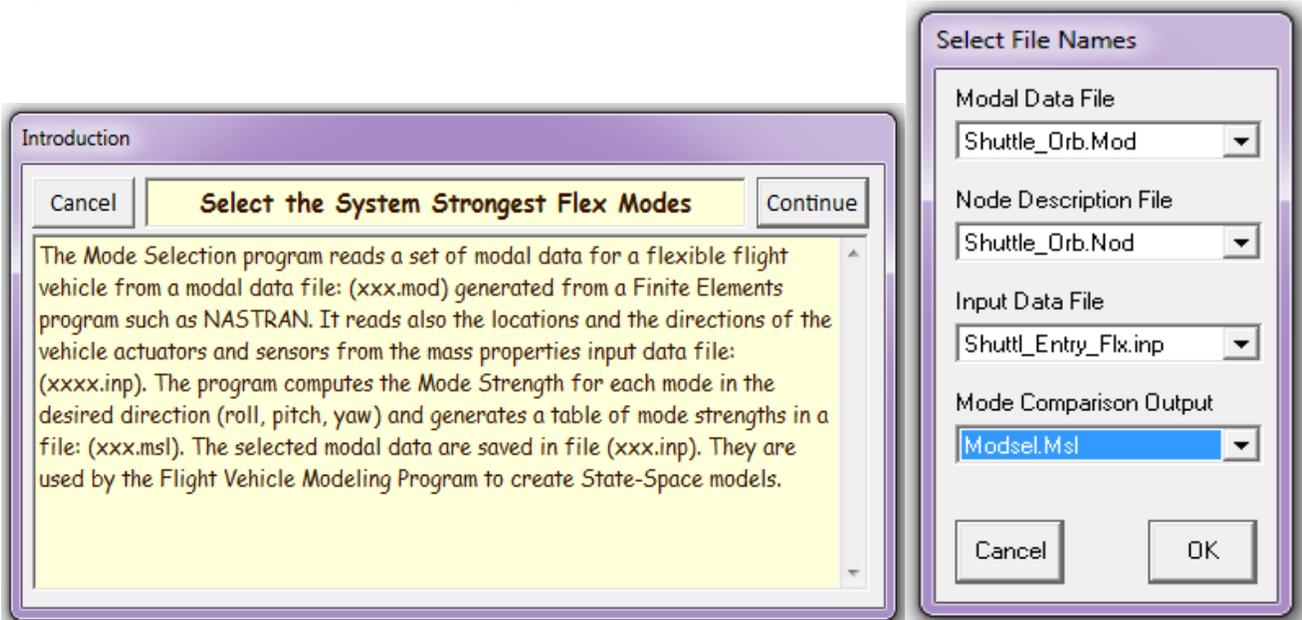
In Section 4.1 we described how flexibility is introduced in the vehicle model by a selected set of strong modes that can be excited by the effectors and disturbance points and they are observable at the sensors. We will now describe the process of selecting a set of dominant flexure modes that will eventually be combined with the vehicle data to produce the flex vehicle model. The selected modes are fewer than those included in the big modal data file (.Mod), even though this modal data file may also be extracted from an even bigger FEM output. The (.Mod) file may contain thousands of mode frequencies and structure nodes. However, only a small number of modes (typically less than 50) are often sufficient to define the vehicle structural characteristics with a satisfactory accuracy. The number of modes that we typically select to combine with the vehicle data may vary from a few (less than 10) to several hundred (200 to 500) depending on the type of analysis. The selected dominant modes are not saved in a separate file but they are included in the same input file (.Inp) with the vehicle data, as a separate dataset, as already demonstrated. Mode selection is the process of scanning through the big modal data file (.Mod) and extracting a smaller set of mode frequencies, at fewer vehicle locations, i.e. only at the effector and sensor locations which are specified in the vehicle input data.

The mode selection process is implemented in a Flixan utility that extracts a smaller set of modes to be processed by the vehicle modeling program. The modal data file includes mode shapes in multiple locations (nodes), and only the nodes that correspond to vehicle locations defined in the input data will be included in the selected modes set, for example, the engines, aerosurfaces, and sensors. The mode selection process compares and chooses flex modes according to their modal strength. The modal strength of each mode is a function of controllability and observability between selected vehicle effectors and sensors. The selection process compares the modal strengths and selects a smaller number of modes which are strong in certain directions between different parts of the structure. The frequencies and damping coefficients of the selected modes and the mode shapes that correspond to the vehicle actuator and sensor locations (defined in the input data) are extracted from the (.Mod) file. They are saved in the input data file (.Inp) as a selected set of modes. They will be processed later by the vehicle modeling program and will be combined with the rigid vehicle data to generate the flex vehicle model, as we have already demonstrated in section 4.2.

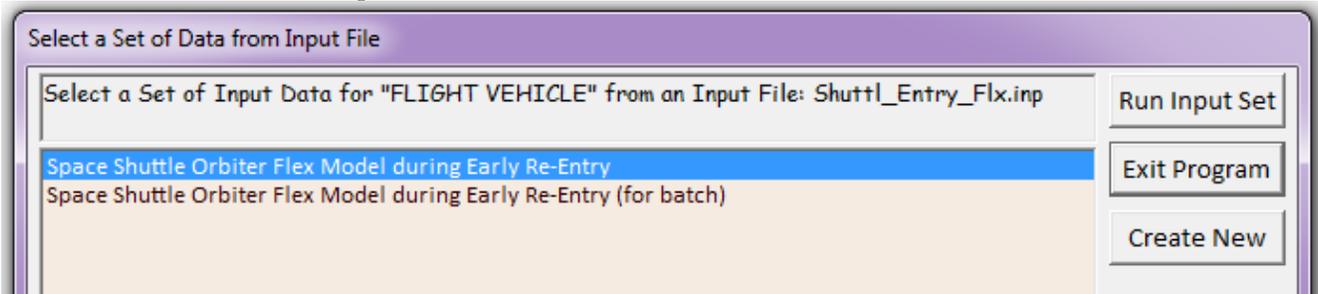
The modal data are usually calculated in units and axes directions which are different from the flight vehicle units and directions. The mode selection utility provides the capability to scale the selected modal data to the proper units and directions in order to match the vehicle data before saving them. To begin the mode selection process, start Flixan, select the project directory where the vehicle data and the modal data files are located, and from the main menu go to “*Program Functions*”, “*Flight Vehicle/Spacecraft Modeling Tools*”, and then “*Flex Mode Selection*”.



Click “Continue” in the following introduction, and use the filename selection menus on the right to select the modal data file (.Mod), the nodes map file (.Nod), the input data file (.Inp) that contains the flight vehicle data, and also enter an output file to save the modal strength results.

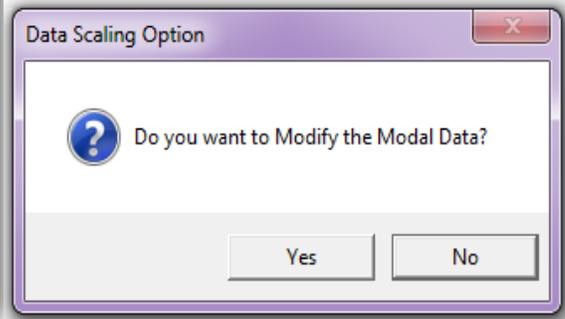
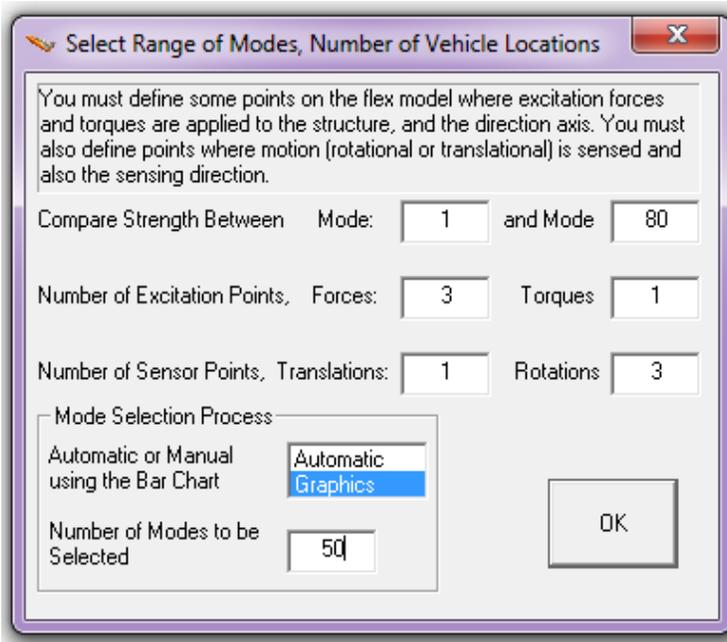


The next step is to locate the flight vehicle data-set in the input file (.Inp). This data-set will be used for generating the vehicle state-space model. It is also used by the mode selection program to identify structural locations for the engines, surfaces, gyros, accelerometers, slosh masses, etc. which are defined in the vehicle data. The following menu shows the titles of vehicle data-sets which are already saved in the input file. Select one of the vehicle data-sets that will be used to generate the flex vehicle model, and click on “Run Input Set”.



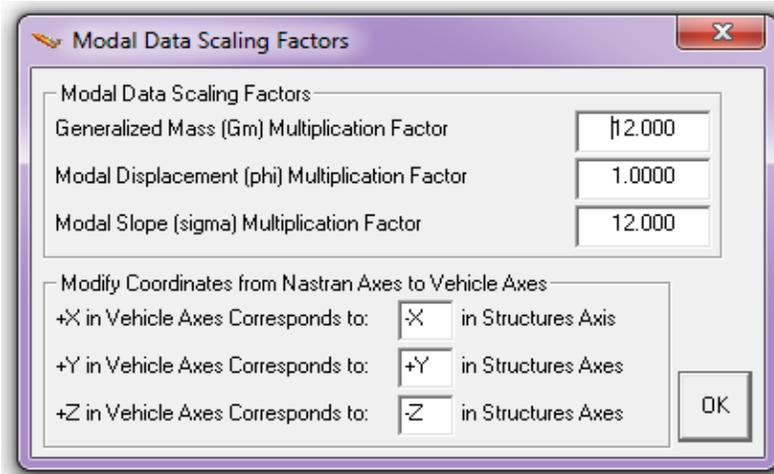
We must use the dialog below to define the following options:

1. The range of modes to be compared, (in this case we compare modes from 1 to 80). In some cases the first six modes are rigid-body modes and we must start from mode # 7.
2. The number of excitation force and torque points used in mode selection. These nodes are only used for mode strength comparison purposes and they are not necessarily vehicle actuator locations.
3. The number of translational and rotational sensor points used in mode selection. These nodes are only used for mode strength comparison purposes and they are not necessarily vehicle sensor locations.
4. The Mode Selection process has two options: (a) the modes are either automatically selected based on the modal strength or (b) they are selected manually using a graphics bar plot that plots the relative mode strength versus the mode number.



The mode selection process is sometimes repeated several times by trying different combinations of actuator and sensor locations, types, and directions, in order to observe how different choices affect the mode strength results. A manual selection of modes is finally used that may be influenced from several selection attempts. Click “OK” to continue. The next dialog is asking you if you want to modify/scale the modal data. Click “Yes” in this case.

The dialog below is used for scaling and modifying the modal data. As we already mentioned the default units from a Nastran model are often different from the units of the vehicle model and we must, therefore, convert the modal data to units which are compatible with our vehicle data. The directions of the coordinate axes may also be different between the two models. The x and z directions are often reversed in the Nastran models because +x is usually defined towards the back of the vehicle and +z is up. The y direction is usually the same in both models. The modal data, therefore, are almost always scaled during mode selection. The generalized mass is often originally defined in “snails” (lb-sec<sup>2</sup>/inch), and it must be multiplied by 12 to be converted to “slugs” (lb-sec<sup>2</sup>/foot). Similarly, the generalized modal rotations (slopes) are often defined in (rad/inch) in the Nastran model and they must be multiplied by 12 in order to be converted to (rad/foot). The modal displacements are not modified



because they change from (inches/inch) to (feet/foot). The mode selection process provides the following dialog which enables us to convert the modal data in order to match the vehicle data. It includes initially the default conversion values described. The scaling values, signs, and axes directions can be over-written by the user to perform the necessary conversions between Nastran and vehicle data, in both, units and in directions.

The next step is to identify the excitation and sensor points on the structure that will be used to calculate and to compare the mode strengths in the mode selection process. In our previous dialog example we decided to use 3 forces and 1 torque as excitation points. In the same dialog we also defined 1 translational and 3 rotational measurement points. We must define the nodes of those excitation and sensor points. They are to be used only for mode selection purposes and they are not necessarily the same locations as the vehicle gimbals and the flight control sensors, which will be defined later.

The mode selection program provides interactive menus that can be used by the analyst to define the locations of the excitation and sensor points. It displays the nodes map in a menu/ dialog form which allows the user to select the excitation and sensor locations in the structure model, and also the directions of the excitation and measurement. Each selection defines a node number and the program reads the corresponding mode shapes at all frequencies. From the mode shapes and from the directions of the excitations and sensors the program calculates the modal strength at each frequency.

For example, in the case below, the program wants to define a node for the force excitation #1. We select the 3<sup>rd</sup> node which corresponds to the Shuttle main Engine #1, and the force direction is defined along +Z. Click “OK” to continue.

**Table of Vehicle Structure FEM Nodes**

In mode selection, in order to calculate the relative mode strength of a number of modes in a specified direction you must define some node points in the Nastran model where the excitation forces or torques will be applied and also the forcing directions.

Similarly, you must also define the sensor points (translations or rotations) and the sensing directions.

**Select a Location (Node) for Force Excitation : 1**

LOX Slosh Mass	1	238	142.0	0.0
LH2 Slosh Mass	2	239	86.0	0.0
Shuttle Main Engine # 1	3	2088	19.0	0.0
Shuttle Main Engine # 2 (left)	4	2254	17.0	-4.5
Shuttle Main Engine # 3 (right)	5	2091	17.0	4.5
Solid Rocket Booster # 4 (left)	6	1367	0.0	-21.0
Solid Rocket Booster # 5 (right)	7	367	0.0	21.0
IMU/ Accelerometer (right)	8	2322	108.3	1.0
IMU/ Accelerometer (left)	9	2323	108.3	-1.0
Aft Payload Gyro (a)	10	2179	-166.72	0.0
Aft Payload Gyro (b)	11	2183	-166.72	0.0
Booster Gyro (right)	12	372	-166.72	0.0
Booster Gyro (left)	13	1372	-166.72	0.0
Forward Payload Gyro	14	1502	0.0	0.0

Axis

- Along-X
- Along-Y
- Along-Z

Direction

- + (positive)
- (negative)

OK

Cancel

In the next dialog the user is asked to define a node for the translational sensor #1. We select the 8<sup>th</sup> node which corresponds to the accelerometers base. The measurement direction is along +Z direction. Click “OK” to continue. The user must also define the location and measuring direction of the rotational sensor #1. Node #12 is selected for this sensor, the right booster gyro, and the sensing direction is in the +pitch axis.

**Table of Vehicle Structure FEM Nodes**

In mode selection, in order to calculate the relative mode strength of a number of modes in a specified direction you must define some node points in the Nastran model where the excitation forces or torques will be applied and also the forcing directions.

Similarly, you must also define the sensor points (translations or rotations) and the sensing directions.

**Select a Location (Node) for Translation Sensor 1**

LOX Slosh Mass	1	238	142.0	0.0
LH2 Slosh Mass	2	239	86.0	0.0
Shuttle Main Engine # 1	3	2088	19.0	0.0
Shuttle Main Engine # 2 (left)	4	2254	17.0	-4.5
Shuttle Main Engine # 3 (right)	5	2091	17.0	4.5
Solid Rocket Booster # 4 (left)	6	1367	0.0	-21.0
Solid Rocket Booster # 5 (right)	7	367	0.0	21.0
IMU/ Accelerometer (right)	8	2322	108.3	1.0
IMU/ Accelerometer (left)	9	2323	108.3	-1.0
Aft Payload Gyro (a)	10	2179	-166.72	0.0
Aft Payload Gyro (b)	11	2183	-166.72	0.0
Booster Gyro (right)	12	372	-166.72	0.0
Booster Gyro (left)	13	1372	-166.72	0.0
Forward Payload Gyro	14	1502	0.0	0.0

OK  
Cancel

Axis  
Along-X  
Along-Y  
Along-Z

Direction  
+ (positive)  
- (negative)

**Table of Vehicle Structure FEM Nodes**

In mode selection, in order to calculate the relative mode strength of a number of modes in a specified direction you must define some node points in the Nastran model where the excitation forces or torques will be applied and also the forcing directions.

Similarly, you must also define the sensor points (translations or rotations) and the sensing directions.

**Select a Location (Node) for Rotational Sensor: 1**

LOX Slosh Mass	1	238	142.0	0.0
LH2 Slosh Mass	2	239	86.0	0.0
Shuttle Main Engine # 1	3	2088	19.0	0.0
Shuttle Main Engine # 2 (left)	4	2254	17.0	-4.5
Shuttle Main Engine # 3 (right)	5	2091	17.0	4.5
Solid Rocket Booster # 4 (left)	6	1367	0.0	-21.0
Solid Rocket Booster # 5 (right)	7	367	0.0	21.0
IMU/ Accelerometer (right)	8	2322	108.3	1.0
IMU/ Accelerometer (left)	9	2323	108.3	-1.0
Aft Payload Gyro (a)	10	2179	-166.72	0.0
Aft Payload Gyro (b)	11	2183	-166.72	0.0
Booster Gyro (right)	12	372	-166.72	0.0
Booster Gyro (left)	13	1372	-166.72	0.0
Forward Payload Gyro	14	1502	0.0	0.0

OK  
Cancel

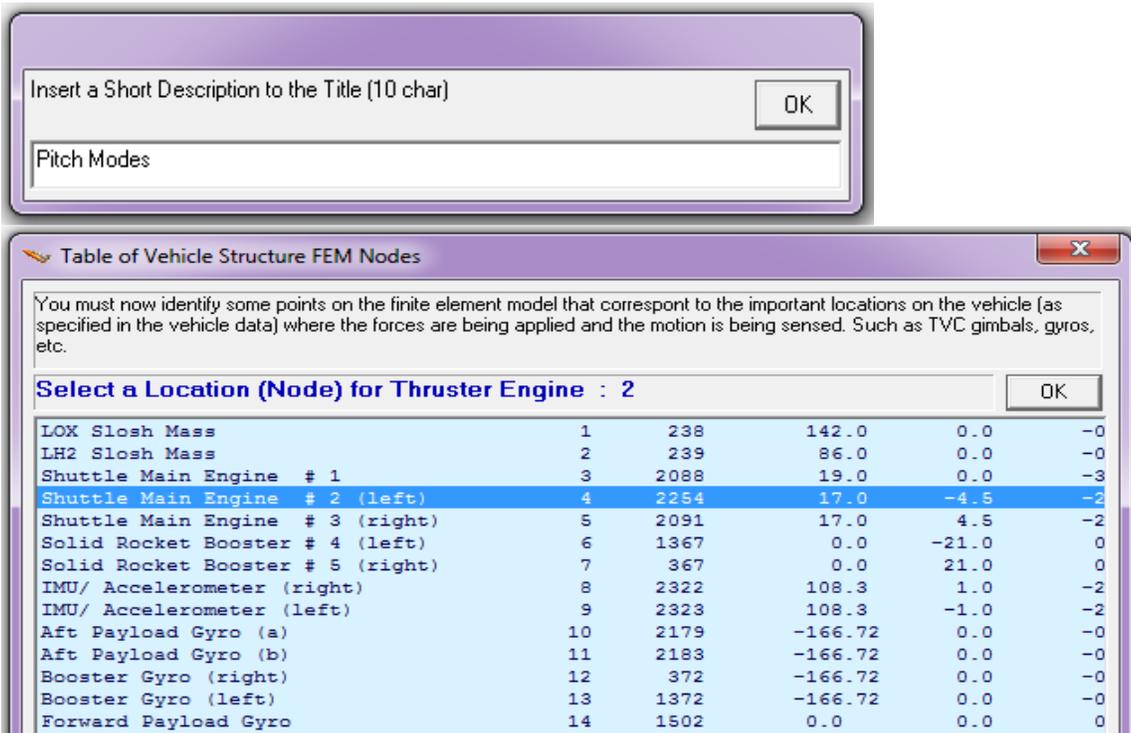
Axis  
Roll  
Pitch  
Yaw

Direction  
+ (positive)  
- (negative)

We must define excitation and measurement nodes for the remaining locations which are defined in the previous dialog (3-forces, 1-torque, 1-translation, and 3-rotations). At this point we assume that all the excitation and sensor points for the mode strength comparison and selection process are specified, together with their corresponding directions. The strength of each mode is calculated by the values of the mode shapes at the nodes where the forces and torques are applied and also their directions. It is also a function of the mode shapes and slopes at the sensors and also the measuring directions. High values of the mode shape at the excitation and sensor points imply a strong contribution from that mode. The mode selection program calculates the modal strength for each mode and saves it in file “*Modsel.Msl*”.

However, the mode selection process is not finished yet because the program needs additional information from the user before it can create the reduced set of modes in the input data file. The selected set of modes will consist of the selected dominant mode frequencies and the mode shapes only at the locations that correspond to those which are defined in the vehicle input data, such as, the engine gimbals, sensors, etc. This is why we need the vehicle data-set during mode selection, in order to match the vehicle locations with structural nodes from the FEM. This requires a similar node identification process where the user must select structure nodes that correspond to the vehicle engines, control surfaces, sloshing propellant tanks, sensors, and disturbance points, which are specified in the vehicle input data. These locations are not necessarily the same as those used in the mode strength comparison. The program will open up menus similar to the previous menus and it will ask the user to identify locations for the engines, control surfaces, sensors, etc. It presents the nodes map again for the user to match important vehicle locations of the vehicle data with the corresponding structural nodes. The nodes selection menus are slightly different this time, using a different color because they are for a different purpose.

In the example shown the user is expected to define structure nodes for the locations that correspond in the vehicle data-set, which are: the 5 engine gimbals, the 3 gyros (roll, pitch, and yaw), the 2 accelerometers ( $N_y$  and  $N_z$ ), the 2 slosh masses (for the LOX and LH2 tanks), and one disturbance point. The user must also enter a short label that will be included in the title of the selected modes set, to identify the type and direction of the modes, for example, "Pitch Modes" In the example below we select Node #4 to correspond with the gimbal of Shuttle Main Engine #2. Notice, that each sensor in the flight vehicle input data measures only one direction. If you want a measurement in 3 axes you must define 3 separate sensors. For the three (roll, pitch, yaw) gyros we must select node #12 three times for the 3 axes because they are all in the same location. Similarly, for the two accelerometers ( $N_y$  and  $N_z$ ) we must select node #8 twice because they are in the same location. We must also choose nodes #1 and #2 for the LOX and the LH2 slosh masses, and a node for a disturbance point (not used in this case).



In this example we selected Node #4 which corresponds to the gimbal of Shuttle Main Engine #2, Node #7 corresponds to the gimbal of Right SRB Engine #5, and Node #12 to correspond to the rate gyro which is located in the right SRB booster. Node #8 corresponds to the navigation base where the IMU and accelerometers are. Node #1 corresponds to the location of the LOX slosh mass.

**Table of Vehicle Structure FEM Nodes**

You must now identify some points on the finite element model that correspond to the important locations on the vehicle (as specified in the vehicle data) where the forces are being applied and the motion is being sensed. Such as TVC gimbals, gyros, etc.

Select a Location (Node) for Thruster Engine : 5

LOX Slosh Mass	1	238	142.0	0.0	-0
LH2 Slosh Mass	2	239	86.0	0.0	-0
Shuttle Main Engine # 1	3	2088	19.0	0.0	-3
Shuttle Main Engine # 2 (left)	4	2254	17.0	-4.5	-2
Shuttle Main Engine # 3 (right)	5	2091	17.0	4.5	-2
Solid Rocket Booster # 4 (left)	6	1367	0.0	-21.0	0
<b>Solid Rocket Booster # 5 (right)</b>	<b>7</b>	<b>367</b>	<b>0.0</b>	<b>21.0</b>	<b>0</b>
IMU/ Accelerometer (right)	8	2322	108.3	1.0	-2
IMU/ Accelerometer (left)	9	2323	108.3	-1.0	-2
Aft Payload Gyro (a)	10	2179	-166.72	0.0	-0
Aft Payload Gyro (b)	11	2183	-166.72	0.0	-0
Booster Gyro (right)	12	372	-166.72	0.0	-0
Booster Gyro (left)	13	1372	-166.72	0.0	-0
Forward Payload Gyro	14	1502	0.0	0.0	0

**Table of Vehicle Structure FEM Nodes**

You must now identify some points on the finite element model that correspond to the important locations on the vehicle (as specified in the vehicle data) where the forces are being applied and the motion is being sensed. Such as TVC gimbals, gyros, etc.

Select a Location (Node) for Gyro/Rate Sensor : 1

LOX Slosh Mass	1	238	142.0	0.0	-0
LH2 Slosh Mass	2	239	86.0	0.0	-0
Shuttle Main Engine # 1	3	2088	19.0	0.0	-3
Shuttle Main Engine # 2 (left)	4	2254	17.0	-4.5	-2
Shuttle Main Engine # 3 (right)	5	2091	17.0	4.5	-2
Solid Rocket Booster # 4 (left)	6	1367	0.0	-21.0	0
Solid Rocket Booster # 5 (right)	7	367	0.0	21.0	0
IMU/ Accelerometer (right)	8	2322	108.3	1.0	-2
IMU/ Accelerometer (left)	9	2323	108.3	-1.0	-2
Aft Payload Gyro (a)	10	2179	-166.72	0.0	-0
Aft Payload Gyro (b)	11	2183	-166.72	0.0	-0
<b>Booster Gyro (right)</b>	<b>12</b>	<b>372</b>	<b>-166.72</b>	<b>0.0</b>	<b>-0</b>
Booster Gyro (left)	13	1372	-166.72	0.0	-0
Forward Payload Gyro	14	1502	0.0	0.0	0

Table of Vehicle Structure FEM Nodes

You must now identify some points on the finite element model that correspond to the important locations on the vehicle (as specified in the vehicle data) where the forces are being applied and the motion is being sensed. Such as TVC gimbals, gyros, etc.

Select a Location (Node) for Accelerometer : 1

LOX Slosh Mass	1	238	142.0	0.0	-0
LH2 Slosh Mass	2	239	86.0	0.0	-0
Shuttle Main Engine # 1	3	2088	19.0	0.0	-3
Shuttle Main Engine # 2 (left)	4	2254	17.0	-4.5	-2
Shuttle Main Engine # 3 (right)	5	2091	17.0	4.5	-2
Solid Rocket Booster # 4 (left)	6	1367	0.0	-21.0	0
Solid Rocket Booster # 5 (right)	7	367	0.0	21.0	0
IMU/ Accelerometer (right)	8	2322	108.3	1.0	-2
IMU/ Accelerometer (left)	9	2323	108.3	-1.0	-2
Aft Payload Gyro (a)	10	2179	-166.72	0.0	-0
Aft Payload Gyro (b)	11	2183	-166.72	0.0	-0
Booster Gyro (right)	12	372	-166.72	0.0	-0
Booster Gyro (left)	13	1372	-166.72	0.0	-0
Forward Payload Gyro	14	1502	0.0	0.0	0

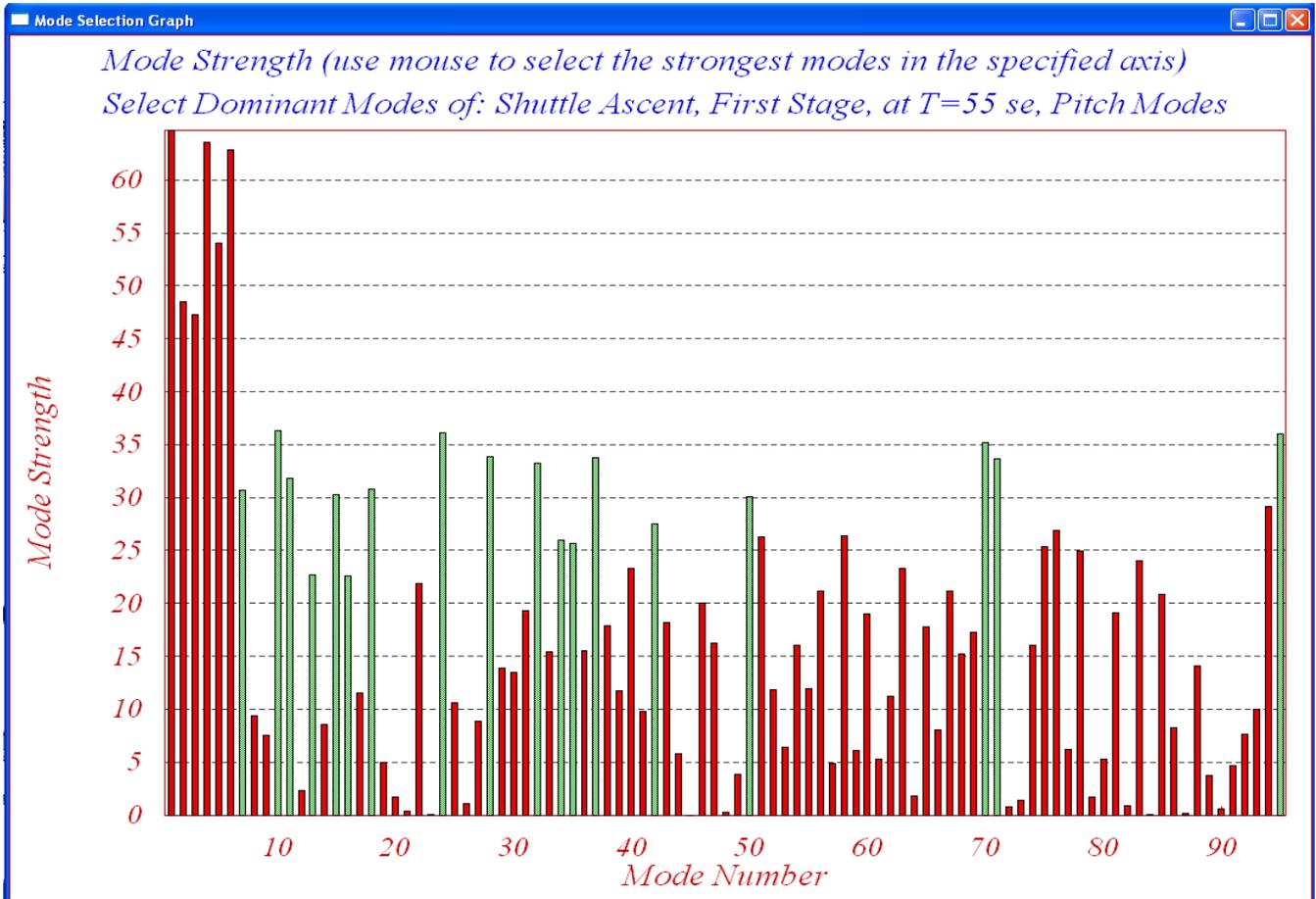
Table of Vehicle Structure FEM Nodes

You must now identify some points on the finite element model that correspond to the important locations on the vehicle (as specified in the vehicle data) where the forces are being applied and the motion is being sensed. Such as TVC gimbals, gyros, etc.

Select a Location (Node) for Slosh Mass Locat.: 1

LOX Slosh Mass	1	238	142.0	0.0	-0
LH2 Slosh Mass	2	239	86.0	0.0	-0
Shuttle Main Engine # 1	3	2088	19.0	0.0	-3
Shuttle Main Engine # 2 (left)	4	2254	17.0	-4.5	-2
Shuttle Main Engine # 3 (right)	5	2091	17.0	4.5	-2
Solid Rocket Booster # 4 (left)	6	1367	0.0	-21.0	0
Solid Rocket Booster # 5 (right)	7	367	0.0	21.0	0
IMU/ Accelerometer (right)	8	2322	108.3	1.0	-2
IMU/ Accelerometer (left)	9	2323	108.3	-1.0	-2
Aft Payload Gyro (a)	10	2179	-166.72	0.0	-0
Aft Payload Gyro (b)	11	2183	-166.72	0.0	-0
Booster Gyro (right)	12	372	-166.72	0.0	-0
Booster Gyro (left)	13	1372	-166.72	0.0	-0
Forward Payload Gyro	14	1502	0.0	0.0	0

At this point the mode strength comparison is complete. The program saves the relative mode strength for each mode in file "Modsel.Dat" and expects the user to manually select the dominant modes. It opens a mode comparison bar-chart for manually selecting the modes. Each mode appears as a vertical red bar of mode strength plotted against the mode numbers, and the height of each bar is logarithmically proportional to its modal strength. The strong modes appear tall and the weak modes are short. The user can select some of the strongest modes to be retained manually, by pointing the mouse cursor on a bar and clicking the mouse. The modes change color from red to green when they are selected. Notice that, the first six modes in this case, although strong, they were not selected because they are rigid-body modes, and the rigid-body dynamics are already included in the vehicle model. 18 flex modes were selected in this example. When you finish selecting the modes press the "Enter" button on the keyboard and it will save the selected modal data set in the input data file (.Inp).



The analyst may also enter some notes or comments in the field below that will provide some information about the mode selection process. Describe, for example, what types of modes were selected, the reasoning behind the choices made, such as: conditions, effector and sensor locations, directions, etc. The user notes may be useful at a later time and they are included as comment lines in the selected modes set, below the title.

The image shows a dialog box titled "Enter Notes". It contains a text area with the following text: "The first 50 modes were selected from all three: roll, pitch, and yaw axes". There is an "OK" button to the right of the text area.

The selected and scaled set of mode frequencies and shapes are finally saved in the input file under the specified title and ready to be processed by the vehicle modeling program. The title can be changed as needed to better define the selected modes. The title of the selected modes must also be included in the last line of the vehicle input data (below the line that specifies the number of flex modes) in order for the flight vehicle modeling program to associate the modes with the vehicle data.

A selected set of modes from our Space Shuttle example is shown below. The top red line is the id line that identifies the set as modal data “*Selected Modal Data and Locations for the Pitch Axis*”. The second line (blue) is the title of the modal data set “*Shuttle Ascent, Max-Q, T=55 sec*”. The third line (green) is the comments. The modal data set consists of blocks of data for each mode including: the frequency, damping coefficient, and generalized modal mass. Each block includes the mode shapes and slopes (three translations along x, y, z, and three rotations about x, y, z) at every selected mode. They correspond to the vehicle locations defined in the vehicle data. The data is already scaled by the mode selection program and ready to be processed by the vehicle modeling program together with the vehicle data.

```

SELECTED MODAL DATA AND LOCATIONS FOR THE PITCH MODES
Shuttle Ascent, Max_Q, T=55 sec, Rigid Body with Slosh/TWD, Pitch Modes
! Pitch Modes selected between the five engine gimbals and the pitch gyro and accelerometer sensors

MODE # 1/ 7, Frequency (rad/sec), Damping (zeta), Generalized Mass= 12.151 0.50000E-02 0.12000E+06
DEFINITION OF LOCATIONS (NODES) phi along X phi along Y phi along Z sigm about X sigm about Y sigm

Node ID# Modal Data at the 5 Engines, (x,y,z)...
Shuttle Main Engine # 1 2088 0.61387D+00 -0.61734D-01 -0.15612D+01 0.42653D-02 -0.13384D-01
Shuttle Main Engine # 2 (left) 2254 0.50962D+00 -0.91117D-01 -0.15971D+01 0.29002D-02 -0.13111D-01
Shuttle Main Engine # 3 (right) 2091 0.50867D+00 -0.92870D-01 -0.15757D+01 0.44489D-02 -0.23288D-01
Solid Rocket Booster # 4 (left) 1367 -0.44066D-01 0.13004D+00 -0.78224D+00 -0.17006D+00 -0.25292D-01
Solid Rocket Booster # 5 (right) 367 -0.31986D-01 -0.13981D+00 -0.78234D+00 0.17183D+00 -0.25481D-01

Node ID# Modal Data at the 3 Gyros ...
Booster Gyro (right) 372 -0.18730D-01 0.10486D+01 0.88193D+00 0.19468D+00 -0.99742D-03
Booster Gyro (right) 372 -0.18730D-01 0.10486D+01 0.88193D+00 0.19468D+00 -0.99742D-03
Booster Gyro (right) 372 -0.18730D-01 0.10486D+01 0.88193D+00 0.19468D+00 -0.99742D-03

Node ID# Modal Data at the 2 Accelerometers, along (x,y,z)...
IMU/ Accelerometer (right) 2322 0.00000D+00 0.39853D-01 -0.23900D+00
IMU/ Accelerometer (right) 2322 0.00000D+00 0.39853D-01 -0.23900D+00

Node ID# Modal Data at the 2 Slosh Masses...
LOX Slosh Mass 238 0.00000D+00 -0.83451D-02 -0.68063D+00 0.00000D+00 0.00000D+00
LH2 Slosh Mass 239 0.00000D+00 0.93311D-02 -0.37481D+00 0.00000D+00 0.00000D+00

Node ID# Modal Data at the Disturbance Point
LOX Slosh Mass 238 0.00000D+00 -0.83451D-02 -0.68063D+00 0.00000D+00 0.00000D+00

MODE # 2/ 10, Frequency (rad/sec), Damping (zeta), Generalized Mass= 15.140 0.50000E-02 0.12000E+06
DEFINITION OF LOCATIONS (NODES) phi along X phi along Y phi along Z sigm about X sigm about Y sigm

Node ID# Modal Data at the 5 Engines, (x,y,z)...
Shuttle Main Engine # 1 2088 0.21481D+01 -0.12488D-01 -0.12885D+01 -0.76709D-03 -0.10757D+00
Shuttle Main Engine # 2 (left) 2254 0.12522D+01 0.63631D-02 -0.14857D+01 -0.15500D-02 -0.10868D+00
Shuttle Main Engine # 3 (right) 2091 0.12599D+01 0.42062D-03 -0.15161D+01 -0.24712D-03 -0.12589D+00
Solid Rocket Booster # 4 (left) 1367 -0.71271D-01 -0.19005D+00 -0.60001D+00 0.31932D-01 -0.12724D-01
Solid Rocket Booster # 5 (right) 367 -0.70664D-01 0.18430D+00 -0.61031D+00 -0.30578D-01 -0.12991D-01

Node ID# Modal Data at the 3 Gyros ...
Booster Gyro (right) 372 -0.59885D-01 -0.13794D+00 0.29224D+00 -0.26555D-01 0.36988D-05
Booster Gyro (right) 372 -0.59885D-01 -0.13794D+00 0.29224D+00 -0.26555D-01 0.36988D-05
Booster Gyro (right) 372 -0.59885D-01 -0.13794D+00 0.29224D+00 -0.26555D-01 0.36988D-05

Node ID# Modal Data at the 2 Accelerometers, along (x,y,z)...
IMU/ Accelerometer (right) 2322 0.00000D+00 -0.40880D-01 0.13408D+01
IMU/ Accelerometer (right) 2322 0.00000D+00 -0.40880D-01 0.13408D+01

Node ID# Modal Data at the 2 Slosh Masses...
LOX Slosh Mass 238 0.00000D+00 -0.39555D-03 -0.70534D+00 0.00000D+00 0.00000D+00
LH2 Slosh Mass 239 0.00000D+00 -0.70712D-03 0.84404D+00 0.00000D+00 0.00000D+00

Node ID# Modal Data at the Disturbance Point
LOX Slosh Mass 238 0.00000D+00 -0.39555D-03 -0.70534D+00 0.00000D+00 0.00000D+00
-----

```

## 4.5 Aero-Elasticity

The structural modes equations that were described in the previous section assume that flexibility is excited by forces and torques at specific points on the vehicle structure. The structure, however, is also excited by variations in the aerodynamic forces and in the vehicle rates. Flexibility also affects the aerodynamic coefficients and the aerosurface hinge moments as a function of variation in vehicle shape. These dynamic coupling effects between aerodynamics and structural flexibility are captured in the aeroelastic model. The aeroelasticity program in Flixan requires a separate Generalized Aero Force Derivative (GAFD) file that contains the aeroelastic coefficients and also the inertial coupling coefficients. The GAFD file has an extension (.Gaf) and it includes the coefficients required for the implementation of aeroelastic coupling between the structure and aerodynamics. It defines how the structure is excited by the aerodynamic forces generated by variations in the angles of attack and sideslip, the aero-surfaces, and also by the body rates. It also defines how the aerodynamic forces and moments on the vehicle are affected by the structure flexibility. Other GAFD coefficients calculate the moments at the surface hinges as a function of the angles of attack and sideslip variations, the aero-surface deflections, the structural bending, and also the body rates. The GAFD file also includes the inertial coupling coefficients (or h-parameters) that define how the flex structure is excited by the angular accelerations of the aerosurfaces about their hinges.

To activate the aeroelasticity feature in Flixan, in addition to the GAFD file, the user must also set the GAFD flag to “*Include GAFD*” in the vehicle input which is near the top of the dataset. Otherwise, the option “*Without GAFD*” will be used by default, in which case the program will ignore the aeroelastic data and generate a simplified flex model using only the modal data. In which case it assumes that flexibility is excited by forces and torques at the hinges which are generated by aero forces from flat panel rotations and by reaction forces caused by the accelerations of rigid surfaces.

### Generalized Aerodynamic Force Derivatives (GAFD)

An example GAFD data file is “*Shuttle\_Orb.Gaf*” which is located in the “Shuttle Hypersonic Reentry” example. The Generalized Aerodynamic Force Derivatives (GAFD) file consists of four sets of coefficients.

- The first set defines how the vehicle aerodynamic forces and moments ( $C_Y$ ,  $C_Z$ ,  $C_l$ ,  $C_m$ ,  $C_n$ ) coefficients are affected by the modal displacements ( $\eta$ ), and modal rates ( $\dot{\eta}$ ).
- The second set defines how the generalized modal displacement ( $\eta_j$ ) of a mode ( $j$ ) is excited by the aerodynamic forces caused by the vehicle motion ( $\alpha$ ,  $\beta$ ), body rates ( $p$ ,  $q$ ,  $r$ ), surface deflection ( $\delta_{si}$ ), flexure interactions from other modes, and the rates of the above.
- The third set defines how the moment at the hinge of a control surface is affected by changes in the following: the angles of attack and sideslip ( $\alpha$ ,  $\beta$ ), the body rates, the surface deflections ( $\delta_{si}$ ), and the modal displacements ( $\eta_j$ ), and also by the rates of the above variables. The hinge moments affect the actuator performance and used for sizing the actuators.
- The fourth set is the inertial coupling coefficients or h-parameters that define how the structure modal displacement ( $\eta_j$ ) of a mode ( $j$ ) is excited by the angular accelerations of the aero-surfaces  $\ddot{\delta}_{si}$ , about their hinges.

The GAFD files used in the examples were created from structures groups and they are already processed and scaled to be readable by the Flixan program and to match the units and axes directions defined in the vehicle data. Usually, the original aeroelastic data file is created from structures CFD models. It may also include rigid-body aerodynamic force and moment derivatives due to changes in the angle of attack, sideslip, body rates, accelerations, control surface deflections, and surface rates. Those rigid-body coefficients, however, are not used in our GAFD files (.Gaf) because they are based on approximate vehicle shapes and aerodynamics. In our Flixan models we prefer to use aerodynamic data and surface increment derivatives generated from aerodynamics groups using wind-tunnel data, rather than CFD. They are usually more accurate and they are included in the vehicle input data-set, as already described. The aeroelastic data preparation process is beyond the scope of this document. However, in the next few paragraphs we will present a brief description on how the GAFD originates in order to help the control analyst have a better understanding of what kind of information is required for the implementation of aero-elasticity. The GAFD coefficients are obtained from the structures and loads people where they combine the finite element models with approximate aerodynamic CFD models and analyze for possible flutter problems.

The GAFD data are obtained by post processing the generalized aerodynamic forces  $[Q_{ij}]$  which is a mass matrix obtained from a “Doublet Lattice” program which is included in the finite elements modeling package. The  $Q_{ij}$  terms can be used for flutter analysis, loads, and “controller in the loop” stability analysis. The generalized aerodynamic forces are complex and are a function of Mach number and a reduced frequency. For each Mach number and reduced frequency a complex generalized force matrix is generated. In flutter analysis, a Mach number and a reduced frequency is assumed and the flutter solution is calculated. If the solution indicates that the flutter frequency is at a different frequency than the assumed reduced frequency, then that solution is invalid. The flutter analysis is then repeated until the flutter frequency equals the assumed reduced frequency. This iterative process is not used in the “controller in the loop” stability analysis. A complex generalized aerodynamic force matrix is constructed which is independent of reduced frequency. The real part of this complex matrix consists of displacement coefficients and the imaginary part consists of the velocity coefficients. The inputs to the Doublet Lattice program are the modal data (mode shapes and mode frequencies) obtained from the finite elements model. The aerodynamic shape of the vehicle is modeled by means of flat plates in the Doublet Lattice program, and it computes the aerodynamic coefficients at different Mach numbers. The program finally combines the NASTRAN model with the aerodynamic model and produces the Generalized Aerodynamic Forces, the  $Q_{ij}$  matrix.

The GAFD data at a given Mach number consists of matrix pairs; a displacements matrix and a velocities matrix. The displacements matrix consists of force coefficients along y and z (x is ignored), roll, pitch, and yaw moment coefficients, modal excitation coefficients, and hinge moment coefficients. The coefficients define variations due to changes in  $\{\beta, \alpha, p, q, r, \eta_i, \delta_j\}$ . The rates matrix describes how the coefficients are affected by the derivatives of:  $\{\beta, \alpha, p, q, r, \eta_i, \delta_j\}$ . The matrix pairs are computed at different frequencies, at the 6 rigid body frequencies and at each bending frequency. The displacements matrix for (i) number of modes and for (j) control surfaces is:

$$\begin{pmatrix} C_Y \\ C_Z \\ C_l \\ C_m \\ C_n \\ C_{\eta 1} \\ C_{\eta 2} \\ C_{\eta i} \\ C_{h1} \\ C_{hj} \end{pmatrix} = \begin{bmatrix} C_{Y\beta} & C_{Y\alpha} & C_{Yp} & C_{Yq} & C_{Yr} & C_{Y\eta_1} & C_{Y\eta_2} & C_{Y\eta_i} & C_{Y\delta_1} & C_{Y\delta_j} \\ C_{Z\beta} & C_{Z\alpha} & C_{Zp} & C_{Zq} & C_{Zr} & C_{Z\eta_1} & C_{Z\eta_2} & C_{Z\eta_i} & C_{Z\delta_1} & C_{Z\delta_j} \\ C_{l\beta} & C_{l\alpha} & C_{lp} & C_{lq} & C_{lr} & C_{l\eta_1} & C_{l\eta_2} & C_{l\eta_i} & C_{l\delta_1} & C_{l\delta_j} \\ C_{m\beta} & C_{m\alpha} & C_{mp} & C_{mq} & C_{mr} & C_{m\eta_1} & C_{m\eta_2} & C_{m\eta_i} & C_{m\delta_1} & C_{m\delta_j} \\ C_{n\beta} & C_{n\alpha} & C_{np} & C_{nq} & C_{nr} & C_{n\eta_1} & C_{n\eta_2} & C_{n\eta_i} & C_{n\delta_1} & C_{n\delta_j} \\ C_{\eta 1\beta} & C_{\eta 1\alpha} & C_{\eta 1p} & C_{\eta 1q} & C_{\eta 1r} & C_{\eta 1\eta_1} & C_{\eta 1\eta_2} & C_{\eta 1\eta_i} & C_{\eta 1\delta_1} & C_{\eta 1\delta_j} \\ C_{\eta 2\beta} & C_{\eta 2\alpha} & C_{\eta 2p} & C_{\eta 2q} & C_{\eta 2r} & C_{\eta 2\eta_1} & C_{\eta 2\eta_2} & C_{\eta 2\eta_i} & C_{\eta 2\delta_1} & C_{\eta 2\delta_j} \\ C_{\eta i\beta} & C_{\eta i\alpha} & C_{\eta i p} & C_{\eta i q} & C_{\eta i r} & C_{\eta i \eta_1} & C_{\eta i \eta_2} & C_{\eta i \eta_i} & C_{\eta i \delta_1} & C_{\eta i \delta_j} \\ C_{h1\beta} & C_{h1\alpha} & C_{h1p} & C_{h1q} & C_{h1r} & C_{h1\eta_1} & C_{h1\eta_2} & C_{h1\eta_i} & C_{h1\delta_1} & C_{h1\delta_j} \\ C_{hj\beta} & C_{hj\alpha} & C_{hj p} & C_{hj q} & C_{hj r} & C_{hj \eta_1} & C_{hj \eta_2} & C_{hj \eta_i} & C_{hj \delta_1} & C_{hj \delta_j} \end{bmatrix} \begin{Bmatrix} \beta \\ \alpha \\ p \\ q \\ r \\ \eta_1 \\ \eta_2 \\ \eta_i \\ \delta_1 \\ \delta_j \end{Bmatrix}$$

The Velocities matrix for (i) number of modes and for (j) control surfaces is:

$$\begin{pmatrix} C_Y \\ C_Z \\ C_l \\ C_m \\ C_n \\ C_{\eta 1} \\ C_{\eta 2} \\ C_{\eta i} \\ C_{h1} \\ C_{hj} \end{pmatrix} = \begin{bmatrix} C_{Y\dot{\beta}} & C_{Y\dot{\alpha}} & C_{Y\dot{p}} & C_{Y\dot{q}} & C_{Y\dot{r}} & C_{Y\dot{\eta}_1} & C_{Y\dot{\eta}_2} & C_{Y\dot{\eta}_i} & C_{Y\dot{\delta}_1} & C_{Y\dot{\delta}_j} \\ C_{Z\dot{\beta}} & C_{Z\dot{\alpha}} & C_{Z\dot{p}} & C_{Z\dot{q}} & C_{Z\dot{r}} & C_{Z\dot{\eta}_1} & C_{Z\dot{\eta}_2} & C_{Z\dot{\eta}_i} & C_{Z\dot{\delta}_1} & C_{Z\dot{\delta}_j} \\ C_{l\dot{\beta}} & C_{l\dot{\alpha}} & C_{l\dot{p}} & C_{l\dot{q}} & C_{l\dot{r}} & C_{l\dot{\eta}_1} & C_{l\dot{\eta}_2} & C_{l\dot{\eta}_i} & C_{l\dot{\delta}_1} & C_{l\dot{\delta}_j} \\ C_{m\dot{\beta}} & C_{m\dot{\alpha}} & C_{m\dot{p}} & C_{m\dot{q}} & C_{m\dot{r}} & C_{m\dot{\eta}_1} & C_{m\dot{\eta}_2} & C_{m\dot{\eta}_i} & C_{m\dot{\delta}_1} & C_{m\dot{\delta}_j} \\ C_{n\dot{\beta}} & C_{n\dot{\alpha}} & C_{n\dot{p}} & C_{n\dot{q}} & C_{n\dot{r}} & C_{n\dot{\eta}_1} & C_{n\dot{\eta}_2} & C_{n\dot{\eta}_i} & C_{n\dot{\delta}_1} & C_{n\dot{\delta}_j} \\ C_{\eta 1\dot{\beta}} & C_{\eta 1\dot{\alpha}} & C_{\eta 1\dot{p}} & C_{\eta 1\dot{q}} & C_{\eta 1\dot{r}} & C_{\eta 1\dot{\eta}_1} & C_{\eta 1\dot{\eta}_2} & C_{\eta 1\dot{\eta}_i} & C_{\eta 1\dot{\delta}_1} & C_{\eta 1\dot{\delta}_j} \\ C_{\eta 2\dot{\beta}} & C_{\eta 2\dot{\alpha}} & C_{\eta 2\dot{p}} & C_{\eta 2\dot{q}} & C_{\eta 2\dot{r}} & C_{\eta 2\dot{\eta}_1} & C_{\eta 2\dot{\eta}_2} & C_{\eta 2\dot{\eta}_i} & C_{\eta 2\dot{\delta}_1} & C_{\eta 2\dot{\delta}_j} \\ C_{\eta i\dot{\beta}} & C_{\eta i\dot{\alpha}} & C_{\eta i\dot{p}} & C_{\eta i\dot{q}} & C_{\eta i\dot{r}} & C_{\eta i\dot{\eta}_1} & C_{\eta i\dot{\eta}_2} & C_{\eta i\dot{\eta}_i} & C_{\eta i\dot{\delta}_1} & C_{\eta i\dot{\delta}_j} \\ C_{h1\dot{\beta}} & C_{h1\dot{\alpha}} & C_{h1\dot{p}} & C_{h1\dot{q}} & C_{h1\dot{r}} & C_{h1\dot{\eta}_1} & C_{h1\dot{\eta}_2} & C_{h1\dot{\eta}_i} & C_{h1\dot{\delta}_1} & C_{h1\dot{\delta}_j} \\ C_{hj\dot{\beta}} & C_{hj\dot{\alpha}} & C_{hj\dot{p}} & C_{hj\dot{q}} & C_{hj\dot{r}} & C_{hj\dot{\eta}_1} & C_{hj\dot{\eta}_2} & C_{hj\dot{\eta}_i} & C_{hj\dot{\delta}_1} & C_{hj\dot{\delta}_j} \end{bmatrix} \begin{Bmatrix} \dot{\beta} \\ \dot{\alpha} \\ \dot{p} \\ \dot{q} \\ \dot{r} \\ \dot{\eta}_1 \\ \dot{\eta}_2 \\ \dot{\eta}_i \\ \dot{\delta}_1 \\ \dot{\delta}_j \end{Bmatrix}$$

The rates matrix describes variations due to changes in the derivatives of:  $\{\beta, \alpha, p, q, r, \eta_i, \delta_j\}$ . The GAFD file is prepared by post-processing the double-lattice output, which is a much bigger data file, after re-scaling and re-formatting it in a more readable and user friendly form, which is also the format recognizable by the vehicle modeling program. It contains the aero-elastic coefficients at frequencies that correspond to the modes that will be included in the model. The sequence of the aero-surfaces in the GAFD file must be the same as the sequence of the surfaces in the vehicle data. In addition to the aero-elasticity derivatives the file contains also the off-diagonal blocks of the Nastran mass matrix. They are called “*Inertial Coupling Terms*” or “*H-Parameters*”, and they are described in the flex equations (2.3-1) and the hinge moment equations (2.5-4). The inertial coupling terms couple the aero-surface angular accelerations with flexibility. The coupling is in both directions, surface accelerations exciting flexibility and flexibility creating moments at the hinges. This effect is due to the reaction forces alone, not aero. The number of GAFD frequencies must be equal to or greater than the reduced set of selected mode frequencies, and the GAFD data must also be selected so that their frequencies correspond to the selected mode frequencies.

Now let us take a look inside a typical GAFD file “*Shuttle\_Orb.Gaf*”, for example. The second line (below the title) indicates that there are five rigid body directions (alpha, beta, p, q, and r). These are the rigid vehicle variables that will induce aerodynamic forces and will excite flexibility. The file includes multiple frequencies that correspond to the structural modes. It includes also five control surfaces that also excite flexibility. In the next line we must define four parameters that are used in the normalization of the GAFD data, the Mach number, the vehicle velocity (feet/sec), the vehicle reference area (ft<sup>2</sup>), and the reference length in (feet). In the next few lines we include parameters related with the control surfaces, the reference areas in (ft<sup>2</sup>), their reference lengths in (ft), and their moments of inertia about the hinge in (slug-ft<sup>2</sup>). The aero-surfaces must be defined in the same order as in the vehicle data. In the next line we include the GAFD frequencies that should correspond to the flex mode frequencies.

The next group of data is a matrix consisting of the inertial coupling coefficients that couple the control surface accelerations with the flex modes. They should be in the same order as the surfaces in the vehicle data.

The aero-elastic coefficients are extracted from the doublet lattice matrices. They are separated in two main categories: displacements and rates matrices. The aeroelastic derivatives from the displacements lattice matrix consist of the following groups of coefficients:

- The first set defines how the aerodynamic forces and moments vary as a function of generalized modal displacements  $\eta_{(j)}$ ,  $j=1: N_{\text{modes}}$ .
- The next group of data defines the opposite, how each generalized modal displacement  $\eta_{(j)}$  is excited by variations in  $(\alpha, \beta, p, q, r)$ .
- The next group is a  $(N_{\text{modes}} \times N_{\text{modes}})$  matrix that defines coupling between modes. Modal excitation of a mode (j) due to modal displacements of other modes.
- The next group is modal excitations due to control surface deflections  $(\delta_{si})$ .
- Hinge moment coefficients increments due to vehicle  $(\alpha, \beta, p, q, r)$  displacements from trimmed positions.
- Hinge moment coefficients due modal displacements,  $(\eta_{(j)}, j=1: N_{\text{modes}})$
- Hinge moment coefficients due to surface deflections  $(\delta_{si})$  from trimmed deflections.

The aeroelastic derivatives from the rates lattice matrix consist of the following groups of coefficients which are functions of rates

- The first set define how the aerodynamic forces and moments vary as a function of generalized modal rates  $\dot{\eta}_{(j)}$ ,  $j=1: N_{\text{modes}}$ .
- The next group of data describes the opposite, how each generalized modal displacement  $\eta_{(j)}$  is excited by the derivatives of:  $(\alpha, \beta, p, q, r)$ .
- The next group of data is a  $(N_{\text{modes}} \times N_{\text{modes}})$  matrix that defines modal excitation of a mode (j) due to modal rates of other modes.
- The next group is modal excitations due to angular rates of the control surfaces  $(\dot{\delta}_{si})$ .
- Hinge moment coefficient increments due to vehicle rates:  $(\alpha\text{-dot}, \beta\text{-dot}, p\text{-dot}, q\text{-dot}, r\text{-dot})$
- Hinge moment coefficients due modal rates  $(\dot{\eta}_{(j)}, j=1: N_{\text{modes}})$ , and
- Hinge moment coefficients due to surface angular rates  $(\dot{\delta}_{si})$ .

The equation below describes how a flex mode (j) is excited by aero-surface accelerations via the inertial coupling coefficients. It is also excited by ( $\alpha$ ,  $\beta$ , body rates p, q, r, and surface deflections  $\delta_{si}$ ), and also the rates of the above variables, via the aero-elastic coefficients.

$$m_g(j) \left( s^2 + 2\zeta_j \omega_j s + \omega_j^2 \right) \eta_j(s) = - \sum_{l=1}^{N_{surf}} h_s(l, j) \ddot{\delta}_s(l)$$

$$+ \bar{Q} S_{ref}^* \left[ \begin{aligned} &+ C_{\eta_j \alpha} \alpha_w + C_{\eta_j \beta} \beta_w + \left( \frac{l_{ch}^*}{2V_0} \right) \left( C_{\eta_j \dot{\alpha}} \dot{\alpha}_w + C_{\eta_j q} q \right) + \left( \frac{l_{ch}^*}{2V_0} \right)^2 C_{\eta_j \dot{q}} \dot{q} \\ &+ \left( \frac{l_{sp}^*}{2V_0} \right) \left( C_{\eta_j \dot{\beta}} \dot{\beta}_w + C_{\eta_j p} p + C_{\eta_j r} r \right) + \left( \frac{l_{sp}^*}{2V_0} \right)^2 \left( C_{\eta_j \dot{p}} \dot{p} + C_{\eta_j \dot{r}} \dot{r} \right) \\ &+ \sum_{k=1}^{N_{surf}} \left[ C_{\eta_j \delta_s} \delta_s(k) + C_{\eta_j \dot{\delta}_s} \left( \frac{\bar{c}_{sk}}{2V_0} \right) \dot{\delta}_s(k) \right] + \sum_{i=1}^{N_{mode}} \left[ C_{\eta_j \eta_i} \eta_i + \left( \frac{C_{\dot{\eta}_i}}{V_0} \right) \dot{\eta}_i \right] \end{aligned} \right]$$

The equation below describes how the aero-surface hinge moments are generated by ( $\alpha$ ,  $\beta$ , body rates, and surface deflections), and also the rates of the above, via the hinge moment coefficients. It also shows the effects of flexibility on the hinge moments via the inertial coupling coefficients  $h_s(k, j)$ .

$$M_{hs}(k) = \text{Terms due to rigid vehicle motion} - \sum_{j=1}^{N_{mod}} \left[ h_s(k, j) \ddot{\eta}(j) \right]$$

$$+ \bar{Q} S_{sk} \bar{c}_{sk} \left[ C_{hak} \alpha_w + C_{h\beta k} \beta_w + \left( \frac{l_{ch}^*}{2V_0} C_{h\dot{\alpha}k} \dot{\alpha}_w + \frac{l_{sp}^*}{2V_0} C_{h\dot{\beta}k} \dot{\beta}_w \right) \right]$$

$$+ \bar{Q} S_{sk} \bar{c}_{sk} \left[ \left( \frac{l_{ch}^*}{2V_0} C_{hkq} q + \frac{l_{sp}^*}{2V_0} (C_{hkp} p + C_{hkr} r) \right) + \left( \left( \frac{l_{ch}^*}{2V_0} \right)^2 C_{hk\dot{q}} \dot{q} + \left( \frac{l_{sp}^*}{2V_0} \right)^2 (C_{hk\dot{p}} \dot{p} + C_{hk\dot{r}} \dot{r}) \right) \right]$$

$$+ \bar{Q} S_{sk} \bar{c}_{sk} \sum_{l=1}^{N_{Surf}} \left[ C_{h\delta(k,l)} \delta_s(l) + \left( \frac{\bar{c}_{s(l)}}{2V_0} \right) C_{h\dot{\delta}(k,l)} \dot{\delta}_s(l) \right]$$

$$+ \bar{Q} S_{sk} \bar{c}_{sk} \sum_{j=1}^{N_{Mode}} \left[ C_{h\eta(k,j)} \eta(j) + \left( \frac{C_{h\dot{\eta}(k,j)}}{V_0} \right) \dot{\eta}(j) \right]$$

Where:

- $S_{ref}^*$  is the aerodynamic surface area in (ft<sup>2</sup>) used to scale the GAFD data. It may not be the same as the vehicle surface reference area  $S_{ref}$ .
- $l_{ch}^*, l_{sp}^*$  are the reference chord and span in (ft) used to normalize the GAFD data. It may not be the same as the chord or span ( $l_{ch}, l_{sp}$ ) used in the rigid body equations.
- $c_{sk}$  is the control surface (k) reference length in (feet) to normalize the GAFD data.
- $\delta_{s(k)}$  is the clockwise rotation in (radians) of a control surface (k) about its hinge vector. The rotation is only due to actuator displacement and it does not include structural flexibility.
- $h_{s(k,j)}$  are the inertial coupling coefficients (h-parameters) in (lb-sec<sup>2</sup>) that couple mode (j) excitation to surface (k) acceleration.
- $\eta_i$  is the generalized modal displacement in (feet) of a flex mode (j).

The following variables describe the aero-elastic and hinge-moment coefficients:

$Cm\eta_j$	pitch moment increment due to $j^{\text{th}}$ mode generalized displacement
$Cy\eta_j$	side-force increment due to $j^{\text{th}}$ mode generalized displacement
$C\eta_j\alpha$	$j^{\text{th}}$ mode excitation due to an increment in the angle of attack
$C\eta_j p$	$j^{\text{th}}$ mode excitation due an increment in roll rate
$C\eta_j\eta_k$	$j^{\text{th}}$ mode excitation due to an increment of a mode (k) displacement
$C\eta_j\delta_k$	$j^{\text{th}}$ mode excitation due to $k^{\text{th}}$ aero-surface deflection
$Cm\dot{\eta}_j$	pitch moment increment due to $j^{\text{th}}$ mode displacement rate
$Cy\dot{\eta}_j$	side-force increment due to $j^{\text{th}}$ mode displacement rate
$C\eta_j\dot{\alpha}$	$j^{\text{th}}$ mode excitation due an increment in the rate of angle of attack
$C\eta_j\dot{p}$	$j^{\text{th}}$ mode excitation due an increment in roll acceleration
$C\eta_j\dot{\eta}_k$	$j^{\text{th}}$ mode excitation due to an increment of a mode (k) displacement rate
$C\eta_j\dot{\delta}_k$	$j^{\text{th}}$ mode excitation due to $k^{\text{th}}$ aero-surface deflection rate
$Ch_k\alpha$	hinge moment at surface (k) due an increment in the angle of attack
$Ch_k r$	hinge moment at surface (k) due an increment in the yaw rate
$Ch_k\eta_j$	hinge moment at surface (k) due an increment of a mode (j) displacement
$Ch_k\delta_l$	hinge moment at surface (k) due a surface (l) deflection increment
$Ch_k\dot{\alpha}$	hinge moment at surface (k) due an increment in the rate of angle of attack
$Ch_k\dot{r}$	hinge moment at surface (k) due an increment in the yaw acceleration
$Ch_k\dot{\eta}_j$	hinge moment at surface (k) due an increment of a mode (j) displacement rate
$Ch_k\dot{\delta}_l$	hinge moment at surface (k) due a surface (l) deflection rate

The following data is a GAFD file for a Shuttle vehicle during reentry. It includes the inertial coupling coefficients, the aero-elastic coefficients, and the hinge-moment coefficients for 5 surfaces and the first 50 flex modes.

## GAFD File "Shuttle\_Orb.GAF", includes the H-Parameters

**GENERALIZED AERO FORCE DERIVATIVES (GAFD) and INERTIAL COUPLING PARAMETERS (H-param) Data for the Shuttle Entry**

Number of: Rigid Body Vehicle Degrees of Freedom, Flexible Modes, Control Surfaces=	5	50	5
Mach No, Velocity (ft/sec), Vehicle Reference Area (ft <sup>2</sup> ), Aerodynamic Chord (ft) =	25.0	18000.0	26900.0 39.56
Control Surface Reference Areas in (ft <sup>2</sup> ) {2 Outboard/Inboard Elevons, Rudder} =	75.82	134.96	134.96 75.82
Control Surface Reference Chords in (feet) {2 Outboard/Inboard Elevons, Rudder} =	6.322	8.59	8.594 6.322 6.1
Moments of Inertia of the Control Surfaces about the Hinge, (ft-lb-sec <sup>2</sup> ) =	227.4	820.3	785.0 227.4 254.38
Modal Frequencies in (radian/sec) =	0.91779E+01	0.94122E+01	

**INERTIAL COUPLING PARAMETERS in (lb-sec<sup>2</sup>-ft)**

Inertial Coupling (H-param) for Surface ( 1), for Modes (j=1,2,Nmode), .....	0.28734E+01	-0.24189E+01
Inertial Coupling (H-param) for Surface ( 2), for Modes (j=1,2,Nmode), .....	0.65518E+01	-0.31975E+01
Inertial Coupling (H-param) for Surface ( 3), for Modes (j=1,2,Nmode), .....	0.64592E+01	0.27719E+01
Inertial Coupling (H-param) for Surface ( 4), for Modes (j=1,2,Nmode), .....	0.29671E+01	0.22707E+01
Inertial Coupling (H-param) for Surface ( 5), for Modes (j=1,2,Nmode), .....	0.10041E+00	-0.67174E+01

**FORCE/ MOMENT COEFFICIENTS DUE TO MODAL DISPLACEMENTS (ETA) - NON DIMENSIONAL**

Cy due to Generalized Displacement eta(j), {Cy_eta(j)}, where (j=1,2,3,,Nmode)	-0.91586E-05	-0.38911E-03
Cz due to Generalized Displacement eta(j), {Cz_eta(j)}, where (j=1,2,3,,Nmode)	-0.71568E-07	-0.10300E-05
Cl (roll) due to Generalized Displacement eta(j), {Cl_eta(j)}, where (j=1,2,3,Nmode)	0.35548E-06	0.65812E-04
Cm (ptch) due to Generalized Displacement eta(j), {Cm_eta(j)}, where (j=1,2,3,Nmode)	0.74382E-08	0.50080E-07
Cn (yaw) due to Generalized Displacement eta(j), {Cn_eta(j)}, where (j=1,2,3,Nmode)	0.24838E-04	0.35673E-03

**MODAL EXCITATION COEFFIC. DUE TO VEHICLE ROTATION: (alpha, beta, p,q,r)**

Ceta(j) due to change in alpha, (Ceta(j)_alpha), (1/rad), where (j=1,2,.. n modes)...	-0.13497E-05	0.85751E-05
Ceta(j) due to change in beta, (Ceta(j)_beta), (1/rad), where (j=1,2,.. n modes)...	-0.21035E-03	-0.22198E-01
Ceta(j) due to roll rate (p), (Ceta(j)_p), (1/rad/sec), where (j=1,2,.. n modes)...	0.32665E-05	0.27380E-02
Ceta(j) due to pitch rate (q), (Ceta(j)_q), (1/rad/sec), where (j=1,2,.. n modes)...	-0.77263E-05	0.19004E-03
Ceta(j) due to yaw rate (r), (Ceta(j)_r), (1/rad/sec), where (j=1,2,.. n modes)...	-0.14193E-02	0.21156E-01

**MODAL EXCITATION COEFFICIENTS DUE TO OTHER MODAL DISPLACEMENTS (Etas) - NON DIMENSIONAL**

Ceta( 1) due to Mode eta(j), {Ceta(i)_eta(j)}, for (j=1,2,.. n modes).....	0.27416E-08	0.44621E-07
Ceta( 2) due to Mode eta(j), {Ceta(i)_eta(j)}, for (j=1,2,.. n modes).....	-0.11715E-07	0.17773E-06
Ceta( 3) due to Mode eta(j), {Ceta(i)_eta(j)}, for (j=1,2,.. n modes).....	0.16304E-08	0.20609E-06
Ceta( 4) due to Mode eta(j), {Ceta(i)_eta(j)}, for (j=1,2,.. n modes).....	-0.28338E-08	-0.55094E-07
Ceta( 5) due to Mode eta(j), {Ceta(i)_eta(j)}, for (j=1,2,.. n modes).....	-0.35759E-08	-0.73494E-07
Ceta( 50) due to Mode eta(j), {Ceta(i)_eta(j)}, for (j=1,2,.. n modes).....	-0.70602E-06	0.29796E-03

**MODAL EXCITATION COEFFICIENTS DUE TO CONTROL SURFACE DISPLACEMENTS Delta(k) in (rad) - NON DIMENSIONAL**

Ceta( 1) due to Surface delta(j), {Ceta(i)_delt(j)}, (1/rad), for (j=1,2,Nsurface)	0.83492E-05	0.48124E-04
Ceta( 2) due to Surface delta(j), {Ceta(i)_delt(j)}, (1/rad), for (j=1,2,Nsurface)	-0.39698E-03	-0.21795E-02
Ceta( 3) due to Surface delta(j), {Ceta(i)_delt(j)}, (1/rad), for (j=1,2,Nsurface)	0.14720E-03	0.72046E-03
Ceta( 4) due to Surface delta(j), {Ceta(i)_delt(j)}, (1/rad), for (j=1,2,Nsurface)	-0.29321E-04	-0.15488E-03
Ceta( 5) due to Surface delta(j), {Ceta(i)_delt(j)}, (1/rad), for (j=1,2,Nsurface)	-0.10688E-04	-0.57579E-04
Ceta( 6) due to Surface delta(j), {Ceta(i)_delt(j)}, (1/rad), for (j=1,2,Nsurface)	-0.40453E-02	-0.23649E-01
Ceta( 50) due to Surface delta(j), {Ceta(i)_delt(j)}, (1/rad), for (j=1,2,Nsurface)	0.26426E-02	-0.13389E-02

**HINGE MOMENT COEFFICIENTS DUE TO VEHICLE MOTION (Change in alpha,beta, p,q,r) - NON DIMENSIONAL**

Hinge Moment at Surf( 1) due to (alfa,beta,p,q,r), {Ch_alfa,Ch_beta,Ch_p,Ch_q,Ch_r}	-0.14979E+00	-0.27663E-01
Hinge Moment at Surf( 2) due to (alfa,beta,p,q,r), {Ch_alfa,Ch_beta,Ch_p,Ch_q,Ch_r}	-0.79503E-01	0.34136E-01
Hinge Moment at Surf( 3) due to (alfa,beta,p,q,r), {Ch_alfa,Ch_beta,Ch_p,Ch_q,Ch_r}	-0.78676E-01	-0.34546E-01
Hinge Moment at Surf( 4) due to (alfa,beta,p,q,r), {Ch_alfa,Ch_beta,Ch_p,Ch_q,Ch_r}	-0.14927E+00	0.27672E-01
Hinge Moment at Surf( 5) due to (alfa,beta,p,q,r), {Ch_alfa,Ch_beta,Ch_p,Ch_q,Ch_r}	-0.76125E-04	0.24899E+01

**HINGE MOMENTS COEFFICIENTS DUE TO MODAL DISPLACEMENTS (Eta) - NON DIMENSIONAL**

Hinge Moment at Surface (i= 1), due to Modes (j=1,2,3,,Nmode), {Ch(i)_eta(j)}	-0.14097E-06	-0.32901E-05
Hinge Moment at Surface (i= 2), due to Modes (j=1,2,3,,Nmode), {Ch(i)_eta(j)}	-0.64099E-06	-0.51432E-05
Hinge Moment at Surface (i= 3), due to Modes (j=1,2,3,,Nmode), {Ch(i)_eta(j)}	0.64689E-06	0.51864E-05
Hinge Moment at Surface (i= 4), due to Modes (j=1,2,3,,Nmode), {Ch(i)_eta(j)}	0.14169E-06	0.52839E-05
Hinge Moment at Surface (i= 5), due to Modes (j=1,2,3,,Nmode), {Ch(i)_eta(j)}	0.36458E-06	0.18191E-04

**HINGE MOMENTS COEFFICIENTS DUE TO SURFACE DEFLECTIONS Delta(j) in (rad) - NON DIMENSIONAL**

Hinge Moment at Surface (i= 1) due Surf. Deflect(j=1,2,3,,Nsurf), {Ch(i)_delt(j)}	-0.49590E+00	-0.11643E+00
Hinge Moment at Surface (i= 2) due Surf. Deflect(j=1,2,3,,Nsurf), {Ch(i)_delt(j)}	-0.20967E+00	-0.72956E+00
Hinge Moment at Surface (i= 3) due Surf. Deflect(j=1,2,3,,Nsurf), {Ch(i)_delt(j)}	-0.86948E-02	-0.18272E-01
Hinge Moment at Surface (i= 4) due Surf. Deflect(j=1,2,3,,Nsurf), {Ch(i)_delt(j)}	-0.27410E-02	-0.44335E-02
Hinge Moment at Surface (i= 5) due Surf. Deflect(j=1,2,3,,Nsurf), {Ch(i)_delt(j)}	0.56964E-02	0.12198E-01

FORCE/ MOMENT COEFFICIENTS DUE TO MODAL RATES (Eta\_Dot) - NON DIMENSIONAL

Cy due to Modal Displacement Rate eta_dot, {Cy_eta(j)_dot}, where (j=1,2,3,, Nmode)	0.13938E-01	-0.23549E+00
Cz due to Modal Displacement Rate eta_dot, {Cz_eta(j)_dot}, where (j=1,2,3,, Nmode)	-0.21827E-03	0.32916E-05
Cl (roll) due to Modal Displ Rate eta_dot, {Cl_eta(j)_dot}, where (j=1,2,3,, Nmode)	-0.10518E-02	0.38271E-01
Cm (ptch) due to Modal Displ Rate eta_dot, {Cm_eta(j)_dot}, where (j=1,2,3,, Nmode)	-0.14474E-04	0.40727E-03
Cn (yaw) due to Modal Displ Rate eta_dot, {Cn_eta(j)_dot}, where (j=1,2,3,, Nmode)	0.15653E-02	0.10921E-01

MODAL EXCITATION COEFFIC. DUE TO VEHICLE RATES: (alpha\_dot, beta\_dot, p\_dot, q\_dot, r\_dot)

Ceta(j) due to alpha_dot, (Ceta(j)_alpha_dot), (1/rad/sec), for (j=1,2,.. n modes)...	0.19118E-04	-0.84713E-03
Ceta(j) due to beta_dot, (Ceta(j)_beta_dot), (1/rad/sec), for (j=1,2,.. n modes)...	-0.14672E-04	-0.44200E-01
Ceta(j) due to roll accelerat (p_dot), (Ceta(j)_pdot), (1/rad/sec2), (j=1,2,n modes).	0.31664E-06	0.60499E-03
Ceta(j) due to pitch accelerat (q_dot), (Ceta(j)_qdot), (1/rad/sec2), (j=1,2,n modes).	0.97832E-05	-0.41204E-03
Ceta(j) due to yaw accelerat (r_dot), (Ceta(j)_rdot), (1/rad/sec2), (j=1,2,n modes).	-0.12173E-02	-0.38031E-01

MODAL EXCITATION COEFFICIENTS DUE TO MODAL RATES (Eta\_dot) -NON DIMENSIONAL

Ceta( 1) due to Mode Rate eta(j)_dot, {Ceta(i)_eta(j)_dot}, for (j=1,2,.. Nmodes)...	-0.29782E-06	-0.19582E-05
Ceta( 2) due to Mode Rate eta(j)_dot, {Ceta(i)_eta(j)_dot}, for (j=1,2,.. Nmodes)...	0.32548E-04	-0.72432E-03
Ceta( 3) due to Mode Rate eta(j)_dot, {Ceta(i)_eta(j)_dot}, for (j=1,2,.. Nmodes)...	-0.20360E-04	0.16462E-03
Ceta( 4) due to Mode Rate eta(j)_dot, {Ceta(i)_eta(j)_dot}, for (j=1,2,.. Nmodes)...	0.28421E-05	-0.28605E-04
Ceta( 5) due to Mode Rate eta(j)_dot, {Ceta(i)_eta(j)_dot}, for (j=1,2,.. Nmodes)...	0.77741E-06	0.87210E-05
Ceta( 50) due to Mode Rate eta(j)_dot, {Ceta(i)_eta(j)_dot}, for (j=1,2,.. Nmodes)...	0.80768E-03	-0.31422E-02

MODAL EXCITATION COEFFICIENTS DUE TO CONTROL SURFACE RATES (Delta\_dot) in (rad/sec) - NON DIMENSIONAL

Ceta( 1) due to Surface Rate delta(j)_dot, {Ceta(i)_delt(j)_dot}, (1/rad/sec).....	-0.19894E-04	0.12222E-04
Ceta( 2) due to Surface Rate delta(j)_dot, {Ceta(i)_delt(j)_dot}, (1/rad/sec).....	0.13740E-02	0.40367E-03
Ceta( 3) due to Surface Rate delta(j)_dot, {Ceta(i)_delt(j)_dot}, (1/rad/sec).....	-0.67040E-03	-0.95475E-03
Ceta( 4) due to Surface Rate delta(j)_dot, {Ceta(i)_delt(j)_dot}, (1/rad/sec).....	0.10841E-03	0.85585E-04
Ceta( 5) due to Surface Rate delta(j)_dot, {Ceta(i)_delt(j)_dot}, (1/rad/sec).....	0.32719E-04	0.22192E-04
Ceta( 50) due to Surface Rate delta(j)_dot, {Ceta(i)_delt(j)_dot}, (1/rad/sec).....	0.89602E-02	0.20782E-01

HINGE MOMENT COEFFICIENTS DUE TO VEHICLE RATES (Rates of alpha,beta, p,q,r) - NON DIMENSIONAL

Hinge Moment at Surface ( 1), due to Rate of alpha,beta,p,q,r, Ch_alpha_dot, etc.	-0.53297E+00	-0.30159E-01
Hinge Moment at Surface ( 2), due to Rate of alpha,beta,p,q,r, Ch_alpha_dot, etc.	-0.54079E+00	-0.12020E+00
Hinge Moment at Surface ( 3), due to Rate of alpha,beta,p,q,r, Ch_alpha_dot, etc.	-0.56556E+00	0.12791E+00
Hinge Moment at Surface ( 4), due to Rate of alpha,beta,p,q,r, Ch_alpha_dot, etc.	-0.53202E+00	0.32859E-01
Hinge Moment at Surface ( 5), due to Rate of alpha,beta,p,q,r, Ch_alpha_dot, etc.	0.18525E-02	0.17513E+01

HINGE MOMENTS COEFFICIENTS DUE TO MODAL RATES (Eta\_dot) - NON DIMENSIONAL

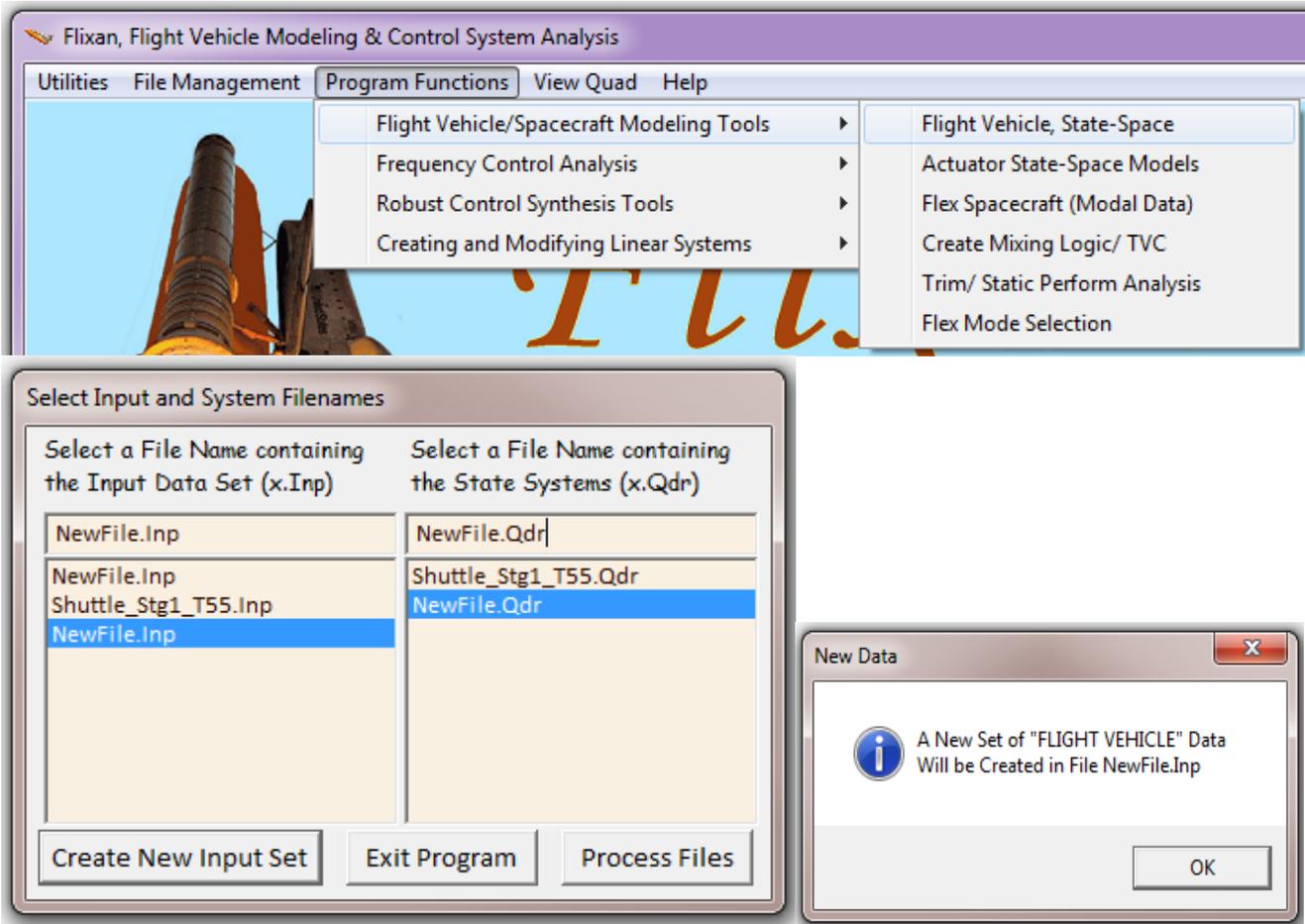
Hinge Moment at Surface (i= 1), due to Modal Rates (j=1,2,3..), {Ch(i)_eta(j)_dot}	0.76625E-05	-0.13242E-02
Hinge Moment at Surface (i= 2), due to Modal Rates (j=1,2,3..), {Ch(i)_eta(j)_dot}	-0.11396E-03	-0.24421E-02
Hinge Moment at Surface (i= 3), due to Modal Rates (j=1,2,3..), {Ch(i)_eta(j)_dot}	0.11593E-03	0.26397E-02
Hinge Moment at Surface (i= 4), due to Modal Rates (j=1,2,3..), {Ch(i)_eta(j)_dot}	-0.87002E-05	0.13396E-02
Hinge Moment at Surface (i= 5), due to Modal Rates (j=1,2,3..), {Ch(i)_eta(j)_dot}	-0.97202E-04	0.10498E-01

HINGE MOMENTS COEFFICIENTS DUE TO SURFACE RATES Delta\_dot(k) in (rad/sec) - NON DIMENSIONAL

Hinge Moment at Surface (i= 1) due to Surf. Rates (j=1,2,3..), {Ch(i)_delt(j)_dot}	-0.31012E+01	-0.24992E+00
Hinge Moment at Surface (i= 2) due to Surf. Rates (j=1,2,3..), {Ch(i)_delt(j)_dot}	-0.56626E+00	-0.36149E+01
Hinge Moment at Surface (i= 3) due to Surf. Rates (j=1,2,3..), {Ch(i)_delt(j)_dot}	0.35358E-02	-0.38872E-02
Hinge Moment at Surface (i= 4) due to Surf. Rates (j=1,2,3..), {Ch(i)_delt(j)_dot}	0.81291E-02	0.45393E-02
Hinge Moment at Surface (i= 5) due to Surf. Rates (j=1,2,3..), {Ch(i)_delt(j)_dot}	0.47320E-02	0.16826E-01

## 4.6 Creating a New Set of Vehicle Data

This section describes how to create a new set of vehicle data in an input file, either from scratch or by modifying a previous set and saving it under a new title in the same file. We begin the Flixan program and select the project folder as shown earlier. From the top main menu bar, select “*Project Functions*”, “*Flight Vehicle/ Spacecraft Modeling Tools*”, and “*Flight Vehicle State-Space*”. From the filename selection menu you must select a vehicle input data file and the systems file, like before. In this example we will enter the data interactively using the program dialogs. We may choose a new and empty input file and perhaps rename it later when the data entering and possible file editing is complete. Enter a new filename “*NewFile.Inp*”, an output systems file “*NewFile.Qdr*”, and click on “*Create a New Input Set*”, as shown below.



The program will ask you to confirm that you want to create a new vehicle set in this input file and then it will open the FVMP data entry dialog that has multiple tabs. It is the same dialog that was used for browsing the data in previous sections. This time, however, the dialog is completely empty, as shown in figure, and it is used for entering the vehicle data. Even the title is initially generic and expected to be modified. We begin by filling-in the top section of the dialog before editing the tabs.

Remember to click on the “*Update Data*” button to update the internal memory every time you change tabs. Do not click on “*Save in File*” until you have completed entering all the data, and ready to save the set and to process it. It is also a good idea to edit the actual input file for any final touch-ups on the vehicle data before processing it.

Flight Vehicle Parameters

**Vehicle System Title**  
 Enter New System Title

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

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

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

**Number of Modes**  
 Structure Bending 0  
 Fuel Sloshing: 0

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

**Vehicle Mass Properties**

Moments/ Products of Inertia (slg-ft<sup>2</sup>)  
 Ixx 0.000000 Ixy 0.000000  
 Iyy 0.000000 Ixz 0.000000  
 Izz 0.000000 Iyz 0.000000

Location of Center of Gravity (ft)  
 Xcg 0.000000  
 Ycg 0.000000  
 Zcg 0.000000

Vehicle Mass in (slugs) 0.000000  
 Accelerat. due to Gravity (ft/sec<sup>2</sup>) 0.000000  
 Earth Radius (Re) in (feet) 0.000000

We begin by entering the new vehicle title, the number of engines or jets, the number of aero-surfaces, external torques, reaction wheels, control moment gyros, number of slosh and structural resonances. You must also enter the number of gyro, accelerometer, vane sensors, and also set the modeling option flags and the tail-wag-dog settings. Then we click on the “*Mass Properties*” tab, enter the mass data, as shown below, and click on the “*Update Data*” button.

Flight Vehicle Parameters

**Vehicle System Title**  
 Space Shuttle at Mach: 1.4

**Number of Vehicle Effectors**  
 Gimballing Engines or Jets. Include Tail-Wags-Dog? 5 WITH TWD / WITHOUT TWD  
 Rotating Control Surfaces. Include Tail-Wags-Dog? 0 WITH TWD / WITHOUT TWD  
 Reaction Wheels? 0  
 Single Gimbal CMGs? 0  
**Momentum Control Devices**  
 Include a 3-axis Stabilized Double Gimbal CMG System? Yes/No

**Number of Sensors**  
 Gyros 3  
 Acceleromet 2  
 Aero Vanes 0  
 External Torques 0

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

**Number of Modes**  
 Structure Bending 0  
 Fuel Sloshing: 2

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

**Vehicle Mass Properties**

Moments/ Products of Inertia (slg-ft<sup>2</sup>)  
 Ixx 0.2700000E+08 Ixy 0.000000  
 Iyy 0.2200000E+09 Ixz 9000000.  
 Izz 0.2400000E+09 Iyz 0.000000

Location of Center of Gravity (ft)  
 Xcg 84.00000  
 Ycg 0.000000  
 Zcg -2.200000

Vehicle Mass in (slugs) 100000.0  
 Accelerat. due to Gravity (ft/sec<sup>2</sup>) 32.20000  
 Earth Radius (Re) in (feet) 0.2000000E+08

Click on the “*Trajectory Data*” tab to enter the trajectory parameters, which are: the vehicle velocity, acceleration, the sensed acceleration along the x, y, and z axes, the Mach #, dynamic pressure, the  $\alpha$ ,  $\beta$  trim angles,  $\dot{\alpha}$ ,  $\dot{\beta}$  rates, the Euler angles, the steady-state body rates, and the vehicle altitude. They are obtained from point mass or 6-dof simulations.

**Flight Vehicle Parameters**

**Vehicle System Title**  
Space Shuttle at Mach: 1.4

**Number of Vehicle Effectors**  
 Gimbaling Engines or Jets. Include Tail-Wags-Dog? 5 **WITH TWD**  
 Rotating Control Surfaces. Include Tail-Wags-Dog? 0 **WITH TWD**  
 Reaction Wheels? 0 **Momentum Control Devices**  
 Single Gimbal CMGs? 0 Include a 3-axis Stabilized Double Gimbal CMG System? **No**

**Number of Sensors**  
 Gyros 3  
 Accelerometer 2  
 Aero Vanes 0  
 External Torques 0

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

**Number of Modes**  
 Structure Bending 0  
 Fuel Sloshing: 2

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

**Trajectory Data**

**Inertial Velocity/ Accelerat**  
 Velocity (ft/sec) 1400.000  
 Accelerat (ft/sec^2) 52.00000

**Body Sensed Accelerat.**  
 Axial 50.00000  
 Ay 0.000000  
 Az 4.000000 (ft/sec^2)

Dynamic Pressure, Q bar, (psf) 600.0000  
 Vehicle Altitude (H) in (feet) 37000.00  
 Mach Number 1.400000

**Angles of Attack, Sideslip in (deg), Rates**  
 Alpha -4.500000 Alpha Dot 0.000000  
 Beta 0.000000 Beta Dot 0.000000

**Euler Angles in (deg), Angular Rates (deg/sec)**  
 Phi 0.000000 Po 0.000000  
 Theta 66.00000 Qo 0.000000  
 Psi 0.000000 Ro 0.000000

Then click on “*Gust/Aero Parameters*” tab to define an external disturbance. This is usually defined as “Wind-Gust” coming towards the vehicle from a fixed direction relative to the vehicle. It is a scalar input to the vehicle system that represents the velocity of the wind-gust in (feet/sec) with respect to the vehicle. The direction of the gust vector is fixed and it is defined by two orientation angles ( $\epsilon_{WG}$  &  $\psi_{WG}$ ) relative to the body axes, as it is described in Section (2.1-9).

An external disturbance may also be defined as an “*External Force*” or as “*External Torque*” in the input data, coming from a fixed direction that is defined by the same two angles relative to the vehicle. This is useful in spacecraft applications where the dynamic pressure is zero and a wind-gust has no meaning. The x, y, z location of the force application point must also be entered and it will be included in the data, in the same line next to the ( $\epsilon_{WG}$  &  $\psi_{WG}$ ) orientation angles. If the external disturbance is a torque the orientation angles define the vector about which the torque is applied.

In this tab we must also define the vehicle reference area, the reference lengths: chord and span, the location of the moment reference center which is the reference for the aero moments, and the partial of the air density per altitude in (feet), as shown below, and click on “*Update Data*”.

In the next two tabs we enter the basic aerodynamic force and moment coefficients and derivatives. The aero-forces tab includes the aero force coefficients at trimmed condition ( $C_{A0}$ ,  $C_{Z0}$ ) and also the aerodynamic force derivatives per degree along (-x, +y, +z).  $C_Z$  is defined to be along the z axis, which is in the opposite direction from the normal force coefficient  $C_N$ . There are partials of the force coefficients with respect to altitude change (1/feet), and also partials of the force coefficients with respect to gust to velocity change (1/ft/sec). The moment coefficients tab is similar, as shown below.

Flight Vehicle Parameters

Vehicle System Title

Space Shuttle at Mach: 1.4

Number of Vehicle Effectors

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

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

Reaction Wheels?  **Momentum Control Devices**

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

Number of Sensors

Gyros

Acceleromet

Aero Vanes

External Torques

Modeling Options (Flags)

Output Rates in  Turn Coordination ?  / Without Turn Coordin

Aero-Elasticity Options  Flex Coupl. data only / Neither Gafd nor Hpar

Attitude Angles  Integrals of Rates / LVLH Attitude

Edit Input File Exit

Update Data Run

Save in File

Number of Modes

Structure Bending

Fuel Sloshing:

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

Air Forces (-X)

Cao= Ca (at nominal alpha)	<input type="text" value="0.00000"/>	Ca_alpha dot (1/deg/sec)	<input type="text" value="0.00000"/>
Ca_alpha (1/deg)	<input type="text" value="-0.500000E-03"/>	Ca_beta (1/deg)	<input type="text" value="-0.500000E-03"/>
Ca_q (1/deg/sec)	<input type="text" value="0.00000"/>	Partial Ca/ Patial H (1/feet)	<input type="text" value="0.00000"/>
Partial Ca/ Patial V (1/ft/sec)	<input type="text" value="0.00000"/>		

**Aerodynamic Force Coefficients.**  
Along vehicle axes: -X +Y +Z

Lateral Forces (Y)

Cyo= Cy (at nominal beta)	<input type="text" value="0.00000"/>	Cy_alpha (1/deg)	<input type="text" value="0.00000"/>
Cy_beta (1/deg)	<input type="text" value="-0.270000E-01"/>	Cy_r (1/deg/sec)	<input type="text" value="0.00000"/>
Cy_p (1/deg/sec)	<input type="text" value="0.00000"/>	Cy_beta dot (1/deg/sec)	<input type="text" value="0.00000"/>
Partial Cy/ Patial V (1/ft/sec)	<input type="text" value="0.00000"/>		

Normal Forces (Z)

Czo= Cz (at nominal alpha)	<input type="text" value="0.00000"/>	Cz_beta (1/deg)	<input type="text" value="0.00000"/>
Cz_alpha (1/deg)	<input type="text" value="-0.350000E-01"/>	Cz_alpha dot (1/deg/sec)	<input type="text" value="0.00000"/>
Cz_q (1/deg/sec)	<input type="text" value="0.00000"/>	Partial Cz/ Patial H (1/feet)	<input type="text" value="0.00000"/>
Partial Cz/ Patial V (1/ft/sec)	<input type="text" value="0.00000"/>		

Flight Vehicle Parameters

Vehicle System Title

Space Shuttle at Mach: 1.4

Number of Vehicle Effectors

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

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

Reaction Wheels?  **Momentum Control Devices**

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

Number of Sensors

Gyros

Acceleromet

Aero Vanes

External Torques

Modeling Options (Flags)

Output Rates in  Turn Coordination ?  / Without Turn Coordin

Aero-Elasticity Options  Flex Coupl. data only / Neither Gafd nor Hpar

Attitude Angles  Integrals of Rates / LVLH Attitude

Edit Input File Exit

Update Data Run

Save in File

Number of Modes

Structure Bending

Fuel Sloshing:

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

Rolling Moments

Cl= Cl (at nominal beta)	<input type="text" value="0.00000"/>	Cl_beta-dot (1/deg/sec)	<input type="text" value="0.00000"/>
Cl_beta (1/deg)	<input type="text" value="-0.280000E-01"/>	Cl_alpha (1/deg)	<input type="text" value="0.00000"/>
Cl_p (1/deg/sec)	<input type="text" value="0.00000"/>	Cl_r (1/deg/sec)	<input type="text" value="0.00000"/>

**Aerodynamic Moment Coefficients.**  
About vehicle axes: X, Y, and Z

Pitching Moments

Cmo= Cm (at nominal alpha)	<input type="text" value="0.00000"/>	Cm_alpha-dot (1/deg/sec)	<input type="text" value="0.00000"/>
Cm_alpha (1/deg)	<input type="text" value="-0.100000E-01"/>	Cm_beta (1/deg)	<input type="text" value="-0.400000E-03"/>
Cm_q (1/deg/sec)	<input type="text" value="0.00000"/>	Partial Cm/ Patial H (1/feet)	<input type="text" value="0.00000"/>
Partial Cm/ Patial V (1/ft/sec)	<input type="text" value="0.00000"/>		

Yawing Moments

Cno= Cn (at nominal beta)	<input type="text" value="0.00000"/>	Cn_beta-dot (1/deg/sec)	<input type="text" value="0.00000"/>
Cn_beta (1/deg)	<input type="text" value="0.250000E-01"/>	Cn_alpha (1/deg)	<input type="text" value="0.00000"/>
Cn_p (1/deg/sec)	<input type="text" value="0.00000"/>	Cn_r (1/deg/sec)	<input type="text" value="0.00000"/>

Select the “*Gimbaling Engines or RCS*” tab to enter, for example, the data for the three Space Shuttle main engines and the two SRB’s. The engines are defined to be either gimbaling, or throttling, or both. We begin with SSME Engine #1. The number of engines was already defined in the top part of the dialog, and it determines the system inputs. We must enter the engine nominal thrust and maximum thrust. They are both the same in this case because the engine is not a variable thrust engine. When the max thrust is bigger than nominal thrust it defines the amount of the engine throttling capability. This engine is mounted or trimmed at a pitch angle  $-16^\circ$  (relative to the  $-x$  direction), and its gimbaling capability is  $\pm 10^\circ$  from the trim position. The two menus on the lower right are for defining that the engine is gimbaling but not throttling. The engine mass  $M_e$ , its moment of inertia about the pivot  $I_e$ , and the distance between the engine CG and the gimbal  $l_e$  must also be defined for the TWD calculations, ( $l_e$  is positive when the engine CG is further back from gimbal). The gimbal location ( $X_e$ ,  $Y_e$ ,  $Z_e$ ) must also be defined in vehicle coordinates. Click on “*Next Engine*” to define the parameters for the remaining four gimbaling engines. When you finish entering the engine data remember to click on the “*Update Data*” button before moving on to the other tabs.

For an RCS thruster we would define its nominal thrust to be zero (the off state) and also its maximum jet thrust. The throttle input to the dynamic model will vary between zero and 1. Zero corresponds to zero thrust and one corresponds to full thrust. For a throttling engine we should enter the nominal thrust and the maximum thrust (which is above the nominal). The difference also defines the minimum thrust which is below the nominal. The throttle input to the dynamic model will vary between zero and  $\pm 1$ . Zero corresponds to nominal thrust,  $+1$  to max thrust, and  $-1$  to min thrust.

**Flight Vehicle Parameters**

**Vehicle System Title**  
Space Shuttle at Mach: 1.4

**Number of Vehicle Effectors**  
Gimbaling Engines or Jets. Include Tail-Wags-Dog? 5 WITH TWD WITHOUT TWD  
Rotating Control Surfaces. Include Tail-Wags-Dog? 0 WITH TWD WITHOUT TWD  
Reaction Wheels? 0  
Momentum Control Devices  
Single Gimbal CMGs? 0 Include a 3-axis Stabilized Double Gimbal CMG System? Yes No

**Number of Sensors**  
Gyros 3  
Acceleromet 2  
Aero Vanes 0  
External Torques 0

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

**Number of Modes**  
Structure Bending 0  
Fuel Sloshing: 2

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

**This Vehicle has 5 Thruster Engines Engine No: 1 Sh Main Eng 1 Engine/ Thruster Jet Definition**

Thrust in (lb) Maximum Deflections (deg) Nominal Position Angles (deg)  
Nominal Thrust 275000.0 Pitch, Delta\_Y max 10.00000 Azimuth, Delta\_Zo 0.000000 Engine Orientation Angles with respect to the vehicle X axis  
Maximum Thrust 275000.0 Yaw, Delta\_Z max 10.00000 Elevation, Delta\_Yo -16.00000

Engine Mass Properties Location of Engine Gimbal (feet) Gimbaling or Throttling?  
Engine Mass in (Slugs) 200.0000 X\_gimbal 19.00000 Is the Engine Gimbaling? Yes No  
Moment of Inertia about the Gimbal (slug-ft^2) 4000.000 Y\_gimbal 0.000000 Can it Vary its Thrust like a Jet? Yes No  
Moment Arm (ft), Engine CG to Gimbal 3.000000 Z\_gimbal -32.00000 Next Engine

A similar dialog tab is used for entering the parameters for the control surfaces. The control surfaces dialog requires the orientation angles ( $\phi_{hs}$  &  $\lambda_{hs}$ ) of the hinge vector with respect to the vehicle axes and also the surface aero derivatives and the hinge moment coefficients.

The next two figures show tabs for entering sensor information. The first one is a tab for rotational sensors (gyros). They measure vehicle rotation angles in (rad), rates in (rad/sec), or angular accelerations (rad/sec<sup>2</sup>). The measurements include rigid body plus flex contributions. The tab includes two menus for defining the direction and type of sensor. The direction is either: roll, pitch, or yaw, and the type is either: attitude, rate, or angular acceleration. The (x, y, z) location for each gyro is also required in vehicle coordinates. If the number of gyros is set to zero the default system outputs are: roll, pitch and yaw rigid body attitudes and rates. In the example below the vehicle has three rate gyros and the tab is currently showing rate gyro #3 which is a yaw rate gyro. It also shows its location in x, y, z coordinates. Click on the “*Next Gyro*” button and the dialog will allow you to enter the data for the remaining gyros.

The translation sensors tab is similar, and used mostly to define accelerometers. Accelerometers measure accelerations in (feet/sec<sup>2</sup>) at specific locations on the vehicle. Although they referred to as accelerometers they can also be set to measure displacement in (feet) or velocity in (feet/sec). The measurements are along the vehicle x, y, or z axes. The tab includes a menu that defines the direction of measurement along (x, y or z), and a menu for defining the type of measurement, which is either: displacement, velocity, or linear acceleration. The accelerometer location in vehicle coordinates is also required because the accelerometer is also measuring vehicle rotational acceleration due its distance from the CG. The accelerometer sensors can also be configured to turn off the rigid-body component from the measurement (see menu below) and measure only flexibility because there are situations where this option can be useful. If the number of the accelerometers is set to zero, the default output is the rigid body acceleration at the CG along x, y, and z. In the accelerometer example below the measurement is acceleration in the x-direction, measuring both: rigid and flex components. Click on the “*Next Accelerometer*” button and the dialog will allow you to enter the data for the other accelerometer.

Flight Vehicle Parameters

**Vehicle System Title**  
Space Shuttle at Mach: 1.4

**Number of Vehicle Effectors**  
 Gimbal Engines or Jets. Include Tail-Wags-Dog? 5  WITH TWD  WITHOUT TWD  
 Rotating Control Surfaces. Include Tail-Wags-Dog? 0  WITH TWD  WITHOUT TWD  
 Reaction Wheels? 0  **Momentum Control Devices**  
 Single Gimbal CMGs? 0  Include a 3-axis Stabilized Double Gimbal CMG System?  Yes  No

**Number of Sensors**  
 Gyros 3   
 Acceleromet 2   
 Aero Vanes 0   
 External Torques 0

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

**Number of Modes**  
 Structure Bending 0   
 Fuel Sloshing: 2

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

**This Vehicle has 3 Rotation Sensors**  
**Characteristics of Gyro No: 3**

Gyro Location  
 X gyro 108.00  
 Y gyro 0.0000  
 Z gyro -28.0000

Gyro Type, Axis  
 Roll  Pitch  Attitude  Rate  Accelerat  
 Yaw

Next Gyro

Flight Vehicle Parameters

**Vehicle System Title**  
Space Shuttle at Mach: 1.4

**Number of Vehicle Effectors**  
 Gimbal Engines or Jets. Include Tail-Wags-Dog? 5  WITH TWD  WITHOUT TWD  
 Rotating Control Surfaces. Include Tail-Wags-Dog? 0  WITH TWD  WITHOUT TWD  
 Reaction Wheels? 0  **Momentum Control Devices**  
 Single Gimbal CMGs? 0  Include a 3-axis Stabilized Double Gimbal CMG System?  Yes  No

**Number of Sensors**  
 Gyros 3   
 Acceleromet 2   
 Aero Vanes 0   
 External Torques 0

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

**Number of Modes**  
 Structure Bending 0   
 Fuel Sloshing: 2

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

**This Vehicle has 2 Accelerometers**  
**Characteristics of Acceleromet: 1**

Accelerometer Location  
 X accel 108.0000  
 Y accel 0.000000  
 Z accel -28.00000

Accelerometer Direction, Type  
 Along X  Along Y  Position  Velocity  Accelerat  
 Along Z

Rigid Body & Flex  Flexibility Only

Next Accelerom

There is also a tab for defining angle of attack and sideslip sensors ( $\alpha$  and  $\beta$  vane measurements). The vanes must be located in the front section of the vehicle, at a distance ( $l_v$ ) from the CG, ( $l_v$  is positive). The location of the vane sensor in vehicle coordinates is required.

The “*Fuel Sloshing*” tab is used for entering the parameters required for modeling propellant sloshing dynamics. Propellant sloshing is represented by the oscillatory motion of a slosh mass along two orthogonal directions (y and z) which are perpendicular to the vehicle acceleration vector  $A_T$ , see figure (2.4-2). The dialog requires the slosh mass in (slugs) which represents the moving part of the liquid, its frequency in (rad/sec) under 1g loading, the damping coefficient ( $\zeta$ ), and the approximate (x, y, z) location of the slosh mass. The slosh frequency is internally adjusted by the program from 1g according to the vehicle acceleration, since the slosh frequency is proportional to the square root of the acceleration. It is defined twice because pitch sloshing may be different from yaw sloshing due to an asymmetric tank. The damping coefficients are also defined separately in pitch and yaw for the same reason. In the example shown below we use the dialog to define slosh parameters for the two Shuttle tanks at  $t=123$  (sec), and it is currently showing the liquid hydrogen tank. After entering the data for the first tank, click on “*Next Slosh*” to enter the slosh parameters for the second tank. Remember to click on the “*Update Data*” button before selecting another tab.

**Flight Vehicle Parameters**

**Vehicle System Title**  
Space Shuttle at Mach: 1.4

**Number of Vehicle Effectors**  
Gimbaling Engines or Jets. Include Tail-Wags-Dog? 5  WITH TWD  WITHOUT TWD  
Rotating Control Surfaces. Include Tail-Wags-Dog? 0  WITH TWD  WITHOUT TWD  
Reaction Wheels? 0   
Momentum Control Devices  
Single Gimbal CMGs? 0  Include a 3-axis Stabilized Double Gimbal CMG System?  Yes  No

**Number of Sensors**  
Gyros 3  
Acceleromet 2  
Aero Vanes 0  
External Torques 0

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

**Number of Modes**  
Structure Bending 0  
Fuel Sloshing: 2

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

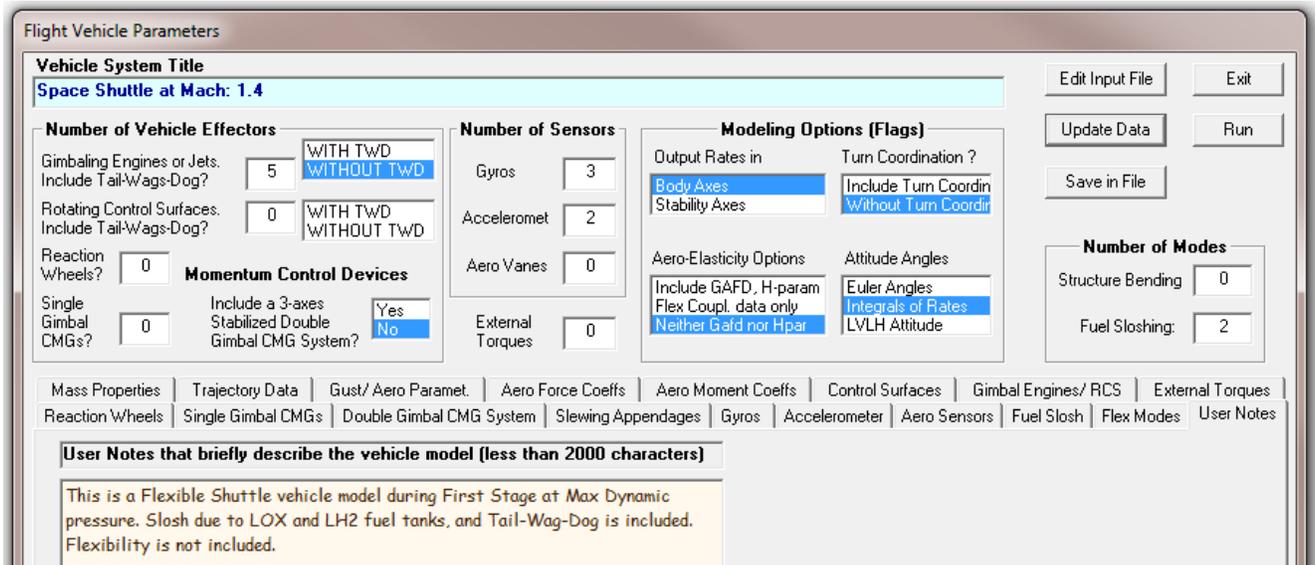
**This Vehicle has 2 Slosh Modes**

**Slosh Parameters for Slosh Mode: 2**

Pitch and Yaw Slosh Frequency at 1 g in (rad/sec) 2.0000 2.0000  
Pitch and Yaw Slosh Damping Coefficient (zeta) 0.10000E-02 0.10000E-02  
Z-Slosh Y-slosh

Slosh Mass Location  
X slosh 85.000  
Y slosh 0.0000  
Z slosh 0.0000  
Slosh Mass in (slugs) 500.00  
Next Slosh

It is also a good practice to enter some comments or user notes about the system that we have just created. Click on the “*User Notes*” tab and enter some comments describing the vehicle system in the field provided. Then click on “*Update Data*”. These notes will be included in the vehicle data-set as comment lines below the title. The comment lines in the vehicle input data file begin with a character “!”. Each line must be less than 100 characters long and up to 20 lines.



Having completed the entering of the vehicle data we may go back and inspect all the tabs to make sure that they are correctly entered, or updated if we are modifying an already existing data-set. We are now ready to save the new data in the input file. Click on “*Save Data*” button in the upper right section and it will save it in file. You may also click on “*Edit Input File*” to take a look inside this newly created vehicle data-set and correct any omissions, imperfections or possible errors that might have occurred during typing-in the data. When you are ready to process the data-set, click on “*Run*” and the vehicle modeling program will create the system and save it in the systems file, as already explained. The system will inherit the same title as the title defined in the input data. The comment lines will also be transferred from the vehicle data to the system below the title.

The program will also create definitions of the system’s inputs, states, and outputs, and they will be included in the (.Qdr) file, below the (A, B, C, D) matrices. The vehicle control inputs are: surface deflections, TVC engine deflections, or engine throttle variations, normalized between 0 and  $\pm 1$ , (1 corresponding to max thrust and -1 min thrust). When the TWD option is “on” two additional inputs per aero-surface (or TVC engine direction) are included in the system that represent the surface/ engine rate and angular acceleration. The deflection, rate, and acceleration inputs typically come from the actuator models, such as those described in Section 4. The TWD flag also creates additional hinge moment outputs that may be used as load-torque feed-back to the actuators as described in the vehicle equations and in the examples.

FLIGHT VEHICLE INPUT DATA .....

Space Shuttle at Mach: 1.4

! This is a Flexible Shuttle vehicle model during First Stage at Max Dynamic pressure. Slosh due  
! to LOX and LH2 fuel tanks, and Tail-Wag-Dog is included. Flexibility is not included.

Body Axes Output,Attitude=Rate Integr, No GAFD-Hpar, No Turn Coordination

Vehicle Mass (lb-sec<sup>2</sup>/ft), Gravity Accelerat. (g) (ft/sec<sup>2</sup>), Earth Radius (Re) (ft) : 100000. 32.2 0.2E+08  
Moments and Products of Inertia: Ixx, Iyy, Izz, Ixy, Ixz, Iyz, in (lb-sec<sup>2</sup>-ft) : 0.27E+08 0.22E+090.24E+09  
CG locatin with respect to the Vehicle Reference Point, Xcg, Ycg, Zcg, in (feet) : 84.0000 0.0 -2.2  
Vehicle Mach Number, Velocity Vo (ft/sec), Dynamic Presssure (psf), Altitude (feet) : 1.4 1400.0 600.0 37000.0  
Inertial Acceleration Vo\_dot, Sensed Body Axes Accelerations Ax,Ay,Az (ft/sec<sup>2</sup>) : 52.0 50.0 0.0 4.0  
Angles of Attack and Sideslip (deg), alpha, beta rates (deg/sec) : -4.50 0.0 0.0 0.0  
Vehicle Attitude Euler Angles, Phi\_o,Thet\_o,Psi\_o (deg), Body Rates Po,Qo,Ro (deg/sec) : 0.0 66.0 0.0 0.0 0.0 0.0  
W-Gust Azim & Elev angles (deg), or Torque/Force direction (x,y,z), Force Locat (x,y,z) : Gust 30.0 90.0  
Surface Reference Area (feet<sup>2</sup>), Mean Aerodynamic Chord (ft), Wing Span in (feet) : 2690.0 15.0 15.0  
Aero Moment Reference Center (Xmrc,Ymrc,Zmrc) Location in (ft), {Partial\_rho/ Partial\_H} : 84.0 0.0 -2.1 -0.94E-09  
Aero Force Coef/Deriv (1/deg), Along -X, {Cao,Ca\_alf,PCa/PV,PCa/Ph,Ca\_alfdot,Ca\_q,Ca\_bet} : 0.0 -0.50E-03 0.0 0.0  
Aero Force Coeff/Derivat (1/deg), Along Y, {Cyo,Cy\_bet,Cy\_r,Cy\_alf,Cy\_p,Cy\_betdot,Cy\_V} : 0.0 -0.27E-01 0.0 0.0 0.0  
Aero Force Coeff/Deriv (1/deg), Along Z, {Czo,Cz\_alf,Cz\_q,Cz\_bet,PCz/Ph,Cz\_alfdot,PCz/PV} : 0.0 -0.35E-01 0.0 0.0 0.0  
Aero Moment Coeff/Derivat (1/deg), Roll: {Clo, Cl\_beta, Cl\_betdot, Cl\_p, Cl\_r, Cl\_alfa} : 0.0 -0.28E-01 0.0 0.0 0.0  
Aero Moment Coeff/Deriv (1/deg), Pitch: {Cmo,Cm\_alfa,Cm\_alfdot,Cm\_bet,Cm\_q,PCm/PV,PCm/Ph} : 0.0 -0.01 0.0 -0.4E-03 0.0  
Aero Moment Coeff/Derivat (1/deg), Yaw : {Cno, Cn\_beta, Cn\_betdot, Cn\_p, Cn\_r, Cn\_alfa} : 0.0 0.25E-01 0.0 0.0  
  
Number of Thruster Engines, Include or Not the Tail-Wags-Dog and Load-Torque Dynamics ? : 5 NO TWD  
  
TVC Engine No: 1 (Gimbaling Throttling Single\_Gimbal) : ShMain Eng Mid Gimbaling  
Engine Nominal Thrust, and Maximum Thrust in (lb) (for throttling) : 275000. 275000.  
Trim Angles (Dyn,Dzn) wrt Vehicle x-axis, Maxim Deflections (Dymax,Dzmax) from Trim (deg) : -16.00 0.0 10.0 10.0  
Eng Mass (slug), Inertia about Gimbal (lb-sec<sup>2</sup>-ft), Moment Arm, engine CG to gimbal (ft) : 200.0 4000.0 3.00  
Gimbal location with respect to the Vehicle Reference Axes, Xgimb, Ygimb, Zgimb, in (ft) : 19.00 0.0 -32.0  
TVC Engine No: 2 (Gimbaling Throttling Single\_Gimbal) : ShMain Eng Lft Gimbaling  
Engine Nominal Thrust, and Maximum Thrust in (lb) (for throttling) : 275000. 275000.  
Trim Angles (Dyn,Dzn) wrt Vehicle x-axis, Maxim Deflections (Dymax,Dzmax) from Trim (deg) : -10.0 0.0 10.0 10.0  
Eng Mass (slug), Inertia about Gimbal (lb-sec<sup>2</sup>-ft), Moment Arm, engine CG to gimbal (ft) : 200.0 4000.0 3.0  
Gimbal location with respect to the Vehicle Reference Axes, Xgimb, Ygimb, Zgimb, in (ft) : 17.0 -4.5 -23.0  
TVC Engine No: 3 (Gimbaling Throttling Single\_Gimbal) : ShMain Eng Rgh Gimbaling  
Engine Nominal Thrust, and Maximum Thrust in (lb) (for throttling) : 275000. 275000.  
Trim Angles (Dyn,Dzn) wrt Vehicle x-axis, Maxim Deflections (Dymax,Dzmax) from Trim (deg) : -10.0 0.0 10.0 10.0  
Eng Mass (slug), Inertia about Gimbal (lb-sec<sup>2</sup>-ft), Moment Arm, engine CG to gimbal (ft) : 200.0 4000.00 3.0  
Gimbal location with respect to the Vehicle Reference Axes, Xgimb, Ygimb, Zgimb, in (ft) : 17.0 4.5 -23.0  
TVC Engine No: 4 (Gimbaling Throttling Single\_Gimbal) : SRB Eng Left Gimbaling  
Engine Nominal Thrust, and Maximum Thrust in (lb) (for throttling) : 0.23e+07 0.23e+07  
Trim Angles (Dyn,Dzn) wrt Vehicle x-axis, Maxim Deflections (Dymax,Dzmax) from Trim (deg) : 0.0 0.0 0.0 0.0  
Eng Mass (slug), Inertia about Gimbal (lb-sec<sup>2</sup>-ft), Moment Arm, engine CG to gimbal (ft) : 500.0 0.12e+5 -0.7  
Gimbal location with respect to the Vehicle Reference Axes, Xgimb, Ygimb, Zgimb, in (ft) : 0.00000 -21.0000 0.0  
TVC Engine No: 5 (Gimbaling Throttling Single\_Gimbal) : SRB Eng Right Gimbaling  
Engine Nominal Thrust, and Maximum Thrust in (lb) (for throttling) : 0.23e+07 0.23e+07  
Trim Angles (Dyn,Dzn) wrt Vehicle x-axis, Maxim Deflections (Dymax,Dzmax) from Trim (deg) : 0.0 0.0 0.0 0.0  
Eng Mass (slug), Inertia about Gimbal (lb-sec<sup>2</sup>-ft), Moment Arm, engine CG to gimbal (ft) : 500.0 0.12e+5 -0.7  
Gimbal location with respect to the Vehicle Reference Axes, Xgimb, Ygimb, Zgimb, in (ft) : 0.00000 21.0000 0.0  
  
Number of Gyros, (Attitude and Rate) : 3  
Gyro No 1 Axis:(Pitch,Yaw,Roll), (Attitude, Rate, Accelerat), Sensor Location in (feet) : Roll Rate 108.0 0.0 -28  
Gyro No 2 Axis:(Pitch,Yaw,Roll), (Attitude, Rate, Accelerat), Sensor Location in (feet) : Pitch Rate 108.0 0.0 -28  
Gyro No 3 Axis:(Pitch,Yaw,Roll), (Attitude, Rate, Accelerat), Sensor Location in (feet) : Yaw Rate 108.0 0.0 -28  
  
Number of Accelerometers, Along Axis: (x,y,z) : 2  
Acceleromet No 1 Axis:(X,Y,Z), (Position, Velocity, Acceleration), Sensor Location (ft) : Y-axis Accelerat. 108.0  
Acceleromet No 2 Axis:(X,Y,Z), (Position, Velocity, Acceleration), Sensor Location (ft) : Z-axis Accelerat. 108.0  
  
Number of Slosh Modes : 2  
Slosh Mass (slug), Frequenc lg (Wy,Wz) (rad/s), Damp (zeta-y-z), Locat.{Xsl,Ysl,Zsl} (ft) : 3000. 2.4 2.4 0.0015 0.001  
Slosh Mass (slug), Frequenc lg (Wy,Wz) (rad/s), Damp (zeta-y-z), Locat.{Xsl,Ysl,Zsl} (ft) : 500.0 2.0 2.0 0.0010 0.001  
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## Flex Modes

The input data file in addition to the rigid vehicle data it must also include flexibility data. When the vehicle is defined to include flex modes, an additional set of selected modes must be included in the input file. The number of modes must be included in the vehicle data, either via the dialog or by editing the input file. For example, go to the last line of the set and enter “*Number of Flex Modes: 50*”. You must also select and prepare a set of flex modes that will be combined with the vehicle data, as it was described in Section 3.3. The selected modal data set must also be saved in the input data file (.Inp) and must have a unique title. The title of the modal data set must also be included in the last line of the vehicle data below the line “*Number of Flex Modes: 50*”.

If you click on the "Flex Modes" tab it will show a menu with the title of the selected modal data set that is already saved in the input file. If there are more than one set of modes you may use this menu to select one of the sets that will be combined with the vehicle data. The lower-left menu is for selecting a GAFD file. In this case there is only one GAFD file: "*Shuttle\_Orb.Gaf*", which is selected by default.

**Flight Vehicle Parameters**

**Vehicle System Title**  
Space Shuttle Orbiter Flex Model during Early Re-Entry

**Number of Vehicle Effectors**  
 Gimballing Engines or Jets. Include Tail-Wags-Dog? 11  WITH TWD  WITHOUT TWD  
 Rotating Control Surfaces. Include Tail-Wags-Dog? 5  WITH TWD  WITHOUT TWD  
 Reaction Wheels? 0  
 Single Gimbal CMGs? 0  
**Momentum Control Devices**  
 Include a 3-axes Stabilized Double Gimbal CMG System?  Yes  No

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

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

**Number of Modes**  
 Structure Bending 50  
 Fuel Sloshing: 0

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

**This Vehicle has 50 Bending Modes**

Select a set of Modal Data to be combined with the flight vehicle parameters

Shuttle Early Hypersonic Atmospheric Re-Entry, First 50 Modes

Additional data files to be included in the flex model

Aero-Elastic (GAFD) data and Control Surface Coupling Coefficients (.Gaf)  
 Shuttle\_Orb.Gaf

Appendages Coupling Coefficients and Moments of Inertia Matrix (.Hpr)