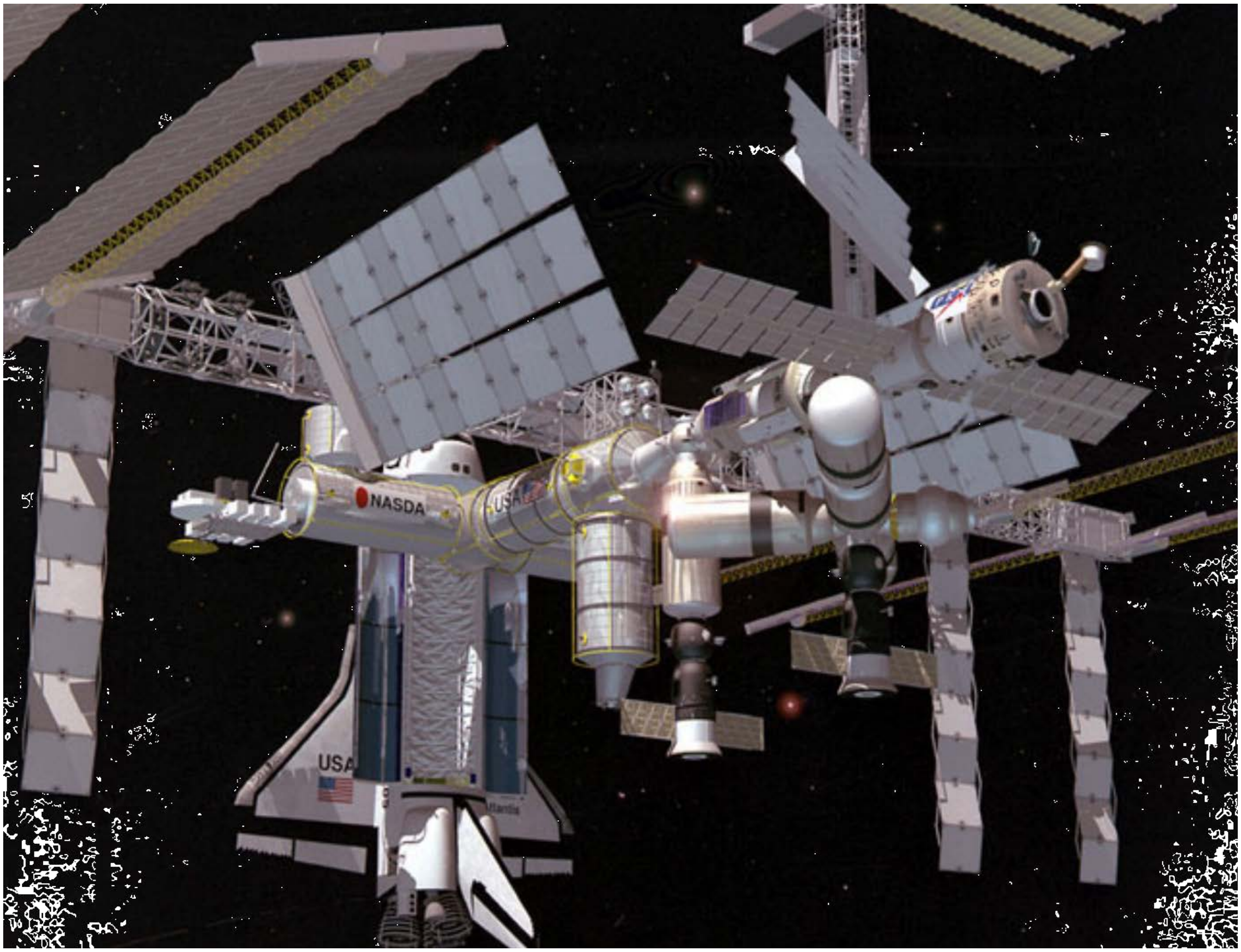
Flexible Spacecraft Modeling Program



Introduction

This program is used for creating state-space models of flexible space structures, such as a flexible satellite or a space station with rotating solar arrays and optical sensors. It is not a multi-body non-linear simulation or a finite elements modeling (FEM) program, but it uses modal data generated from a FEM, such as NASTRAN. It essentially provides the capability for the user to manage the FEM and to create state-space systems for control analysis by defining the inputs, outputs and selecting structural modes. Linear models are useful in analyzing spacecraft stability or performance to excitations at a fixed configuration, and not for simulating large angle maneuvering or multi-body payload slewing. They are a lot easier than non-linear multi-body models to analyze because the dynamic modeling is already implemented in the FEM. They can be used in analyzing attitude control stability, appendage gimbal control stability, jitter sensitivity, designing payload pointing servo systems and in general used in applications that do not require large angle maneuvering. They are also used for analyzing dynamic interactions between the spacecraft structure and gimbal control loops, perform small angle simulations, and to analyze the effects of spacecraft disturbances to optical or a micro-gravity sensors as a result of the interaction between the structure and the control loops. The inputs to the linear models are either, external forces and moments applied to the structure, such as, reaction control thrusters, control moment gyros, and disturbances, or they can be control torques at the hinges of pivoting appendages, such as solar arrays and payload gimbals. The system outputs are either translation or rotational sensors that measure position, velocity, or acceleration at certain locations on the spacecraft, or gimbal sensors measuring the rotations of pivoting appendages relative to the space structure.

The simplicity offered by the flexible spacecraft modeling program in comparison with the flight vehicle modeling program (that includes equations for both rigid-body motion and flexibility) is that the rigid-body dynamics, structural flexibility, and the dynamics of gimbaling appendages are all included in the modal data and used directly by this program. The rigid-body dynamics can be implemented in a FEM in terms of 3 to 6 rigid-body modes at zero frequency and damping. However, when the rigid-body dynamics is more complex to be implemented by rigid-body modes, such as, in multi-body or non-linear systems, a rigid-body model can be connected in parallel with the flexibility model that has the rigid-body modes removed and only structural modes are included. For example, in Figure 1, the rigid model may be a non-linear simulation or a state-space system generated by the flight vehicle modeling program, and it is connected in parallel with a flexible state-space system generated by the flexible spacecraft modeling program. They both receive the same forces and torques and their responses are combined, as shown.

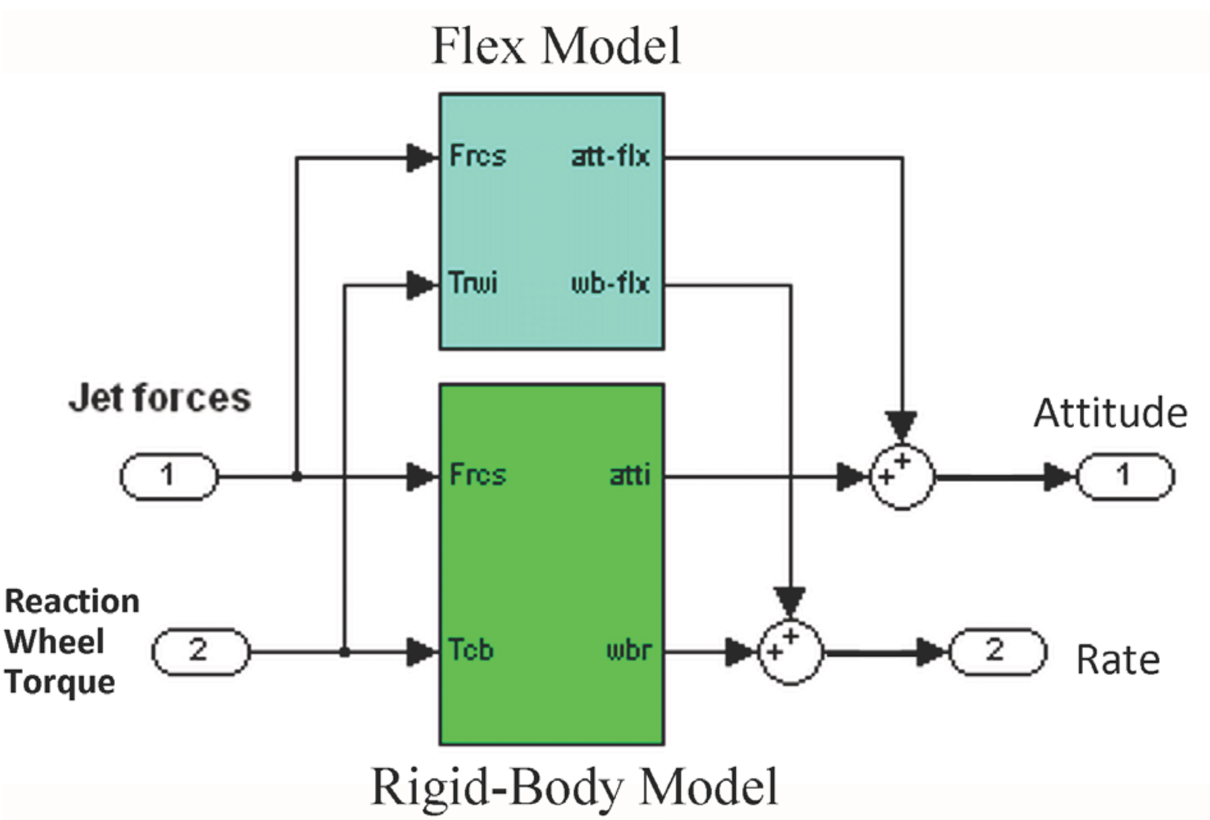


Figure 1 Rigid-Body and Flexible Subsystems can be connected in Parallel to Generate the Flexible Spacecraft Model

Data Files

The flexible spacecraft modeling program uses 4 types of input and output files:

- An input data file (.Inp) which includes the flexible spacecraft dataset that defines the spacecraft configuration, such as, inputs and outputs, flex modes, and it is processed by the program to generate the spacecraft system. This file is also generated interactively by a program utility.
- A modal data file with an extension (.Mod) that includes the structural modes. This file is generated by a finite elements modeling program and reformatted.
- A nodes map file with an extension (.Nod) that defines the spacecraft locations which are included in the modal data, for example, actuator and sensor nodes.
- An output systems file (.Qdr) where the linear state-space models are saved by the program.

These files are described in more detail below

Modal Data File (.Mod)

The modal data file has a filename extension "*.Mod*", and it contains the modal data of the flexible space structure generated by a finite elements modeling program. In general it includes several hundred modes at increasing frequencies, starting from the first six rigid-body modes which are at zero frequency and they describe the rigid-body behavior of the spacecraft. The remaining are flexible modes associated with structural resonant frequencies. The structural model may also include the flexibility of the attached appendages (if any) with the gimbals "locked". The modal data file is not necessarily a direct output from a FEM program, but it is created by post-processing the FEM output to convert it to the standard format that is recognizable by the Flixan mode selection utility. This modal data reformatting prior to mode selection is also used for reducing the excessive amount of information that is typically generated by the FEM program.

During reformatting we usually include a smaller number of spacecraft locations. We read only the nodes which are possible candidates in the analysis models. Typically 15 to 45 nodes are sufficient to include in the modal data file. In general, the first six modes are the rigid body modes having zero natural frequency and damping coefficients. The remaining modes, starting from mode 7, are structural modes. Each mode in the modal data file consist of the following parameters: the mode frequency ω_f, in (rad/sec), the damping coefficient ζ, the generalized mass m_g, and the generalized modal displacements that consist of: 3 translations (φ) and 3 rotations or slopes (σ) in (rad/inch) at each node, relative to the spacecraft axes.

The example modal data file below contains modal data for a flexible space station structure consisting of 55 modes and 28 nodes. The shapes and slopes for the first mode are only shown, which is actually a rigid-body mode. The nodes are listed by the node id number, which are the big numbers in the first column. They are used in the original FEM to identify spacecraft locations. There might be several thousands in the original model but only 28 are retained in this file.

```
STRUCTURAL MODAL DATA
FLAXIBLE SPACE STRUCTURE WITH SOLAR ARRAYS
NUMBER OF MODES = 55   NODES= 28

Mode #  1, Omega= 0.0, Zeta=0.0, General.Mass=  1.0000
Node ID:  Along X      Along Y      Along Z      About X      About Y      About Z
  1060    0.10643D+00  0.74926D-04 -0.64510D-03 -0.13631D-07 -0.45285D-04 -0.11342D-04
  3000    0.97502D-01  0.74926D-04 -0.63436D-03 -0.13631D-07 -0.45285D-04 -0.11342D-04
  2060    0.88572D-01  0.74926D-04 -0.62363D-03 -0.13631D-07 -0.45285D-04 -0.11342D-04
  3100    0.00000D+00  0.00000D+00  0.00000D+00  0.00000D+00  0.00000D+00  0.00000D+00
  6070    0.41841D-01  0.10176D-03 -0.67460D-03 -0.13631D-07 -0.45285D-04 -0.11342D-04
   505    0.82939D-01  0.86029D-04 -0.66119D-03 -0.13631D-07 -0.45285D-04 -0.11342D-04
  6045    0.27333D-01  0.10176D-03 -0.65716D-03 -0.13631D-07 -0.45285D-04 -0.11342D-04
  6039    0.25100D-01  0.10176D-03 -0.65448D-03 -0.13631D-07 -0.45285D-04 -0.11342D-04
  6001    0.19520D-01  0.10176D-03 -0.64777D-03 -0.13631D-07 -0.45285D-04 -0.11342D-04
  1000    0.17290D-01  0.10176D-03 -0.64510D-03 -0.13631D-07 -0.45285D-04 -0.11342D-04
  7001    0.12824D-01  0.10176D-03 -0.63973D-03 -0.13631D-07 -0.45285D-04 -0.11342D-04
  7010    0.16632D-02  0.10176D-03 -0.62631D-03 -0.13631D-07 -0.45285D-04 -0.11342D-04
  2000   -0.57120D-03  0.10176D-03 -0.62363D-03 -0.13631D-07 -0.45285D-04 -0.11342D-04
  5001   -0.28039D-02  0.10176D-03 -0.62095D-03 -0.13631D-07 -0.45285D-04 -0.11342D-04
  5039   -0.83810D-02  0.10176D-03 -0.61424D-03 -0.13631D-07 -0.45285D-04 -0.11342D-04
  5045   -0.10614D-01  0.10176D-03 -0.61156D-03 -0.13631D-07 -0.45285D-04 -0.11342D-04
   410   -0.68540D-01  0.11749D-03 -0.60475D-03 -0.13631D-07 -0.45285D-04 -0.11342D-04
  5070   -0.25122D-01  0.10176D-03 -0.59412D-03 -0.13631D-07 -0.45285D-04 -0.11342D-04
  9017   -0.12152D-02  0.98025D-02 -0.39355D-01 -0.13631D-07 -0.45285D-04 -0.11342D-04
  9018   -0.45271D-02 -0.56588D-02  0.22381D-01 -0.13631D-07 -0.45285D-04 -0.11342D-04
  9007   -0.12152D-02  0.29089D-02 -0.11831D-01 -0.13631D-07 -0.45285D-04 -0.11342D-04
  1160   -0.71853D-01  0.12859D-03 -0.64510D-03 -0.13631D-07 -0.45285D-04 -0.11342D-04
  4000   -0.80783D-01  0.12859D-03 -0.63436D-03 -0.13631D-07 -0.45285D-04 -0.11342D-04
  2160   -0.89714D-01  0.12859D-03 -0.62363D-03 -0.13631D-07 -0.45285D-04 -0.11342D-04
  1050    0.97519D-01  0.77610D-04 -0.64510D-03 -0.13631D-07 -0.45285D-04 -0.11342D-04
  2050    0.79657D-01  0.77610D-04 -0.62363D-03 -0.13631D-07 -0.45285D-04 -0.11342D-04
  1150   -0.62938D-01  0.12591D-03 -0.64510D-03 -0.13631D-07 -0.45285D-04 -0.11342D-04
  2150   -0.80800D-01  0.12591D-03 -0.62363D-03 -0.13631D-07 -0.45285D-04 -0.11342D-04
-------------------------------------------------------------------------------------
```

Note that not all the flex modes have to be included in the linear analysis model. Some of the modes are weak and they can be excluded from the state-space model by means of a mode selection process to be discussed later.

Nodes Look-Up Table (.Nod)

The locations file or nodes map has a filename extension (.Nod). It describes the spacecraft nodes and provides information about the spacecraft locations which are included in the modal data file. The nodes file is used interactively as a look-up table by the mode selection program. It helps the user to identify actuator and sensor locations. A typical nodes file that corresponds to the previous modal data file is shown below and it consists of four columns of data.

1. The first column consists of short labels (40 characters long) that describe the spacecraft locations which are included in the modal data file. The nodes are listed in the same order as in the modal data file.
2. The second column includes the node numbers beginning from node 1 up to the max number of nodes (28 in this case) which are included in the modal data file (.Mod). The node numbers are used by the mode selection program to identify the actuator and sensor locations.
3. The third column contains the node IDs. These are the big numbers that identifying the nodes in the original FEM.
4. The last set of column data is optional and it not used by the program. It is only for reference and it includes the coordinates of the corresponding nodes along the spacecraft x, y, and z axes.

NODE IDENTIFICATION TABLE FOR THE LARGE SPACE STATION WITH SOLAR ARRAYS AND CMG

Node Description	Node No	FEM ID	Node Location X,Y,Z (feet)		
Payload boom, (top-right)	1	1060			
Payload boom, (center)	2	3000			
Payload boom, (top-left)	3	2060			
Unknown	4	3100			
Right Solar Array Boom	5	6070	0.0	232.35	18.0
Right Solar Array (Connect)	6	505			
Right SA Boom, Outboard the Hinge	7	6045			
Right SA Boom, Inboard the Hinge Servo	8	6039			
Right Boom (Sensor Assembly)	9	6001			
Right Keel/Boom Intrsect, CMG Location	10	1000			
CG Center of Structure	11	7001			
Left Keel/Boom Intersection	12	7010			
Unknown	13	2000			
Left Boom	14	5001			
Left Boom, Inboard the Hinge Servo	15	5039			
Left SA Boom, Outboard the Hinge Servo	16	5045			
Left Solar Array (Connect)	17	410			
Left SA Boom, Extreme end	18	5070	0.0	-224.63	16.0
Right Habitat Module	19	9017			
Module, (Front Dock)	20	9018			
Center Habitat Module	21	9007			
Bottom Payload Boom (Right)	22	1160			
Bottom Payload Boom (Center)	23	4000			
Bottom Payload Boom (Left) Antenna	24	2160			
Top Right RCS Thruster Assembly	25	1050	0.0	73.7	-185.0
Top Left RCS Thrusters Assembly	26	2050	0.0	-65.58	-185.0
Bottom Right RCS Thruster Assembly	27	1150	0.0	73.7	144.0
Bottom Left RCS Thrusters Assembly	28	2150	0.0	-65.58	144.0

Input Data File (.Inp)

This file includes several datasets to be used by the Flixan program. It also includes the input dataset used by the flexible spacecraft modeling program. It can be created interactively, saved and processed by the program to generate the spacecraft linear model. It consists of data that describe the spacecraft configuration, inputs, outputs, structural modes, and rotating appendages.

- The data-set begins with an ID label “FLEXIBLE SPACECRAFT FE MODEL ...” that defines the purpose of the dataset and the Flixan flexible spacecraft program that will process the data.
- The next line is the spacecraft title. There are also comment lines below the title that briefly describe the spacecraft model. The title and comment lines are also transferred to the spacecraft system in the (.Qdr) file.
- The next set of data specifies the input forces and torques. It includes the corresponding node location and the directions of the forces or torques. The directions are defined by unit vectors.
- There is also data that define the output sensors. It includes translational or rotational sensors, the sensor location (node number), the sensor direction (1,2,3), for (x, y, and z) translation, or for (roll, pitch, and yaw) rotation. You must also specify the type of sensor, (1,2,3) for (position, rate, or acceleration), and either translation or rotation.
- The input data-set also includes a reduced set of modal data that was selected from the modal data file (.Mod) during the input data file preparation process, as we shall demonstrate. This reduced set of modes consists of: mode frequencies (rad/sec), damping coefficients (ζ), generalized mass, generalized modal shapes (ϕ) and modal slopes (σ) at specified locations.

- At the bottom of the dataset there is an optional reference to a filename that contains the information required to unlock the appendages gimbals and to apply gimbal torques. This is done by the inertial coupling coefficients (also known as H-parameters matrix) included in this file. This file is only required when the spacecraft includes gimbaling appendages.

The input file may also contain datasets to be processed by other Flixan programs in relationship with the current spacecraft analysis, such as the flight vehicle modeling program, system interconnections, transfer function datasets, etc. A sample input data file for a flexible spacecraft can be found in file "*Surveillance-Sat.Inp*" in folder "*Examples\ Surveillance Satellite React-Wheels*".

Inertial Coupling Coefficients File (.Hpr)

The inertial coupling coefficients file is optional and it is only required when the spacecraft has rotating bodies, such as solar arrays or gimbaling instruments. It contains the H-parameters matrix that introduces dynamic coupling between gimbaling appendages and spacecraft flexibility. The modal data are calculated assuming that the hinges are locked and they are later released in the simulation equations by the inertial coupling coefficients. The H-parameters matrix is also obtained from the FEM and it is extracted from the mass matrix, the upper and lower right quadrants of the mass matrix. It couples the spacecraft flexibility with the equations that rotate the appendages relative to the spacecraft as a result of the applied torques at the hinges. The inertial coupling coefficients "*.Hpr*" file must have the format shown below in order to be accessible by the Flixan program. The H-parameter matrix rows correspond to the modes. The first six rows correspond to the 6 rigid-body modes, if they are included. The matrix columns correspond to the hinges.

In the following example we have an H-parameters matrix of 100 rows and 4 columns, corresponding to a structure of 100 modes and 4 gimbaling appendages. Each element in this matrix determines the amount of excitation of a flex mode (determined by row) from the rotational acceleration at the appendage gimbal (determined by column). The (.Hpr) data file also includes the moments of inertia matrix of the appendages, that is, (4 x 4) in this case, which is located below the H-parameters matrix. The gimbals are placed in the same order as the columns of the H-parameters. The last set of data in this file includes the unit vector directions of the four hinges, also in the same order. Note that the rotational directions of the hinge vectors are not used by this program because the information is already captured in the rigid-body segment of the H-parameters matrix, which are the first six rows. The directions, however, are included in this file because it is also used by other programs.

When the spacecraft includes gimbaling bodies that require the H-parameters file, the (.Hpr) filename must be included in the last statement of the spacecraft dataset in file (.Inp), below the modal data as already described with file "*Surveillance-Sat.Hpr*" in the example.

```
Inertial Coupling Coefficients (H-Parameters) File Name for the 4 gimbaling bodies:
Surveillance-Sat.Hpr
```

If this line is missing at the end of the dataset, the program will assume that the flexible spacecraft has no gimbals, or that its gimbals are "locked" and the state-space model will not provide the capability to simulate the relative motion at the hinges. It will lack the additional gimbal torque inputs, gimbal rotation states and outputs associated with the gimbaling bodies.

```
INERTIAL COUPLING COEFFICIENTS (FROM NASTRAN) FOR
Surveillance Satellite with Rotating Solar Arrays and Optical Sensor
NUMBER OF MODES, GIMBALS:           100, 4
Units (ft-lb-sec^2)

-2.269347606E-01  1.747074520E-01 -1.915053482E-01 -2.195309075E-01         Mode # 1
-1.133417583E+00 -1.374561104E-02  3.669942078E-01 -2.549929767E-01         Mode # 2
 4.682515329E-02  7.409226449E-01 -2.031611937E-01 -2.588066122E-01
……
 7.590326391E-02  1.119420489E-01 -5.917569875E-04 -3.510433226E-03
-3.350520970E-02 -3.483536353E-03 -1.103515707E-02 -1.353584642E-02         Mode # 99
-2.108828453E-03  4.130124619E-02  9.495321928E-03 -2.236874122E-03         Mode # 100

 MOMENTS OF INERTIA MATRIX OF THE ROTATING BODIES (slug-ft^2)
 6.3954598075    -0.049079742633   0.000000000E+00  0.00000000    Payload Inertia (elev)
-0.049079742633   1.889057024167   0.000000000E+00  0.00000000    Payload Inertia (azmth)
 0.000000000E+00  0.000000000E+00  3.170436278333   0.00000000      Right Solar Array
 0.000000000E+00  0.000000000E+00  0.000000000E+00  3.1704239175    Left Solar Array

 Hinge Direction Unit Vectors for the 4 Gimbal Appendages, Payload Elevat, Azimuth, 2 Sol.Arr
 1.0              0.0              0.0              0.0
 0.0             -1.0              1.0              1.0
 0.0              0.0              0.0              0.0
```

State-Space Systems File (.Qdr): The spacecraft state-space model output created by the flexible spacecraft modeling program is saved in a standard Flixan systems file (.Qdr). The system title is the same as the title of the input data set. The definitions of the state-space system variables are listed below the quadruple matrices. This system is usually combined together with the attitude control system and other subsystems to form a closed-loop or open-loop system models that can be used for further analysis. For more details read the Surveillance Satellite example.

Flexible Spacecraft Equations

In the Flexible Spacecraft Modeling program the spacecraft dynamics is defined in terms of mode shapes and frequencies, including the rigid-body modes which are usually the first six modes. The mode shapes and frequencies are imported from the finite elements program assuming that all hinges are “locked” at fixed orientation angles. Rotating appendages are optional, and they are introduced in the model by the H-parameters matrix (H). The gimbals are then released to apply torques and the gimbal rotations can be calculated by the introduction of the H-parameters matrix.

The dynamic model consists of three sets of equations. The first set describes how the structural modes are excited by the external forces and torques. The second set of equations calculates the rotation of the appendage bodies (α) relative to the spacecraft as a result of the torques at the joints (T_α) that control the angles. The third set of equations represents the measurements at the sensors which are mounted on the spacecraft structure. The interaction between the structural modes and the rotating appendages is defined by the inertial coupling coefficients matrix (H). This linear multi-body model is only applicable for small angle simulations, less than 5°. For large angle maneuvering, a non-linear multi-body simulation is necessary because the dynamics vary significantly with the orientation angles. However, this linear model is extremely useful for stability analysis, jitter analysis to gimbal or external disturbances, control design, analyze the dynamic interaction between flexibility, attitude control system, and the control systems of the gimbaling appendages, frequency domain analysis, etc. Some of these functions cannot be performed by multi-body non-linear simulations, which require also a lot more effort to develop.

The following second order matrix equation describes the excitation of the bending modes generalized displacement vector ($\underline{\eta}$) by the external forces and torques (F and T) and also by the interaction with the gimbal accelerations $\ddot{\underline{\alpha}}$.

$$M_G\left(\ddot{\eta}+2\varsigma\Omega\dot{\eta}+\Omega^2\eta\right)+H\underline{\ddot{\alpha}}=\Phi^T\begin{bmatrix}F\\T\end{bmatrix}$$

The following equation describes the rotations of the gimbaling bodies $\underline{\alpha}$ relative to the spacecraft, as a result of the applied torques at the hinges ($\underline{T}_\alpha$) and also due to coupling with the structural modes $\underline{\eta}$ via the transpose of the inertial coupling coefficients matrix (H). The moments of inertia matrix ($I_{\underline{\alpha}}$) and the coupling coefficients matrix (H) are extracted from the mass matrix of the finite elements model.

$$I_\alpha\,\underline{\ddot{\alpha}}+H^T\,\underline{\ddot{\eta}}=\underline{T}_\alpha$$

Where:

$\underline{\eta}$ is the modal displacement vector for (n) modes

M_G is a (n x n) diagonal matrix whose elements are the modal masses

Ω is a (n x n) diagonal matrix containing the modal frequencies (ω_{fi}) in (rad/sec)

ς is the modal damping coefficient vector for n modes, typically (ς=0.005)

$\underline{\alpha}$ is a vector of dimension (m) representing the rotation angles of the appendages relative to the spacecraft, where (m) is the number of gimbaling bodies

H is the Inertial Coupling Coefficients matrix of dimension (n x m). It couples the accelerations at the gimbals with the modal displacements $\underline{\eta}$ as shown in both equations.

Φ^T is the mode shapes matrix of size (n x 6) containing the generalized modal displacements at the points where the external forces, moments, and disturbances are applied to the space structure.

$\underline{F}$ is a vector of the externally applied forces along x, y, and z

$\underline{T}$ is a vector of the externally applied torques about x, y, and z axes

I_α is an (m x m) moments of inertia matrix of the (m) gimbaling bodies about their axis of rotation in (ft-lf-sec^2)

$\underline{T}_\alpha$ is a vector of size (m) representing the control torques in (ft-lb) at the payload gimbals.

The sensor measurements vector $\underline{X}_s$ measure both: rigid and flex spacecraft motion in different locations on the structure, that is, either translations or rotations. Each measurement consists of a linear combination of (n) generalized modal displacements η_i, multiplied with the mode shapes (Φ_S).

$$\underline{X}_S=\Phi_S\,\underline{\eta}=\sum_{i=1}^{n}\phi_{si}\,\eta_i$$

Where:

$\underline{X}_s$ is a sensor measurement vector of dimension (6) representing three translations and three rotations at each point (s)

Φ_s is a (6 x n) modal matrix containing the mode shapes and slopes for (n) modes at the sensor location (s)

Flex Spacecraft Model Preparation and Mode Selection

During model preparation we must create a set of data in an input file "*.Inp*" that characterizes the input/ output structure of the spacecraft and includes other parameters, such as input forces, torques, sensor types, directions, etc. The flexible spacecraft input dataset also includes a selected set of dominant flex modes. The dataset may then be processed by the flex spacecraft modeling program to generate the flex spacecraft state-space system. A typical finite element model consists of a large number of element masses and degrees of freedom used for modeling a complex vehicle structure. This results in a very large number of flexible modes. Several hundreds of the FEM modes (usually below a certain cut-off frequency) are extracted and saved in the modal data file (.Mod). It is not practical to include all the modes from the modal data file in the control analysis model, because, (a) it will slow down the analysis, (b) it will complicate the control design, (c) a much smaller number of modes, (20-40 modes), is usually sufficient to approximate the dynamic behavior of the spacecraft within the control bandwidth and a couple of decades higher. During this data preparation process, the user must select certain inputs and outputs that represent the controls, disturbances, gimbals, measurements, and other sensitive locations on the spacecraft. The program searches the modal data file and selects a smaller set of strong modes that should efficiently represent the spacecraft dynamics between the inputs and outputs defined.

The modes are selected by a process that will be described later, based on their modal strength which is calculated by the amount of mode controllability at the points of excitation, and the mode observability at the sensors. The mode strength may vary depending on the locations and directions of the actuators and sensors. The selection of modes in the analysis model strongly depends on what kind of analysis the user intends to perform. If the model is to be used for attitude control stability analysis and it uses attitude sensors for stabilization and thrusters for control, the modes must be selected according to strength between the reaction control jets and the ACS sensors. If, on the other hand, sensitivity analysis is required to determine, for example, the effect of disturbances to on board optical instruments, the modes in the analysis model must be selected based on the modal strengths between the disturbance points and the locations of the optical instruments.

The original FEM output contains also a very large number of nodes that represent locations in the structural model. Each node in the FEM is identified with a long 5 to 7 digits number. For control analysis, however, a much smaller number of modes and nodes are needed in the analysis model. A typical flex model used for control analysis requires between 15 to 40 nodes at locations such as, actuators, sensors, disturbance forces, fuel tanks, etc. The flex spacecraft modeling program activates a mode selection process during model preparation, where the user selects a set of dominant modes from the modal data file (.Mod). Prior to model preparation the analyst must create a nodes map file *".Nod"* that will be used by the mode selection program in look-up table displays. The modes are presented on a bar plot display and they are selected interactively by the user according to their relative strength calculated between inputs and outputs. The extracted set of modal data is also scaled in this process, if needed, because they may have been created in different units and directions, and they are included in the input data file.

When the spacecraft has gimbaling appendages with coupling coefficients defined in the H-parameters file (.Hpr), the following line must be included as a last statement in the spacecraft input data-set which defines the coefficients filename, as described earlier. If the (.Hpr) filename line is not included, but the spacecraft data-set ends with the selected modal data, the program will assume that the flexible spacecraft has no gimbals.

```
Inertial Coupling Coefficients (H-Parameters) File Name for the 4 gimbaling bodies:
Surveillance-Sat.Hpr
```

Flexible Spacecraft Modeling Process

The block diagram in Figure 3 highlights the flexible spacecraft modeling program functions of transforming a FEM to flexible spacecraft systems that can be used for control analysis. The characteristics, features, and purpose of those state-space systems are directed by the user choices and the process is described in detail in the following sections.

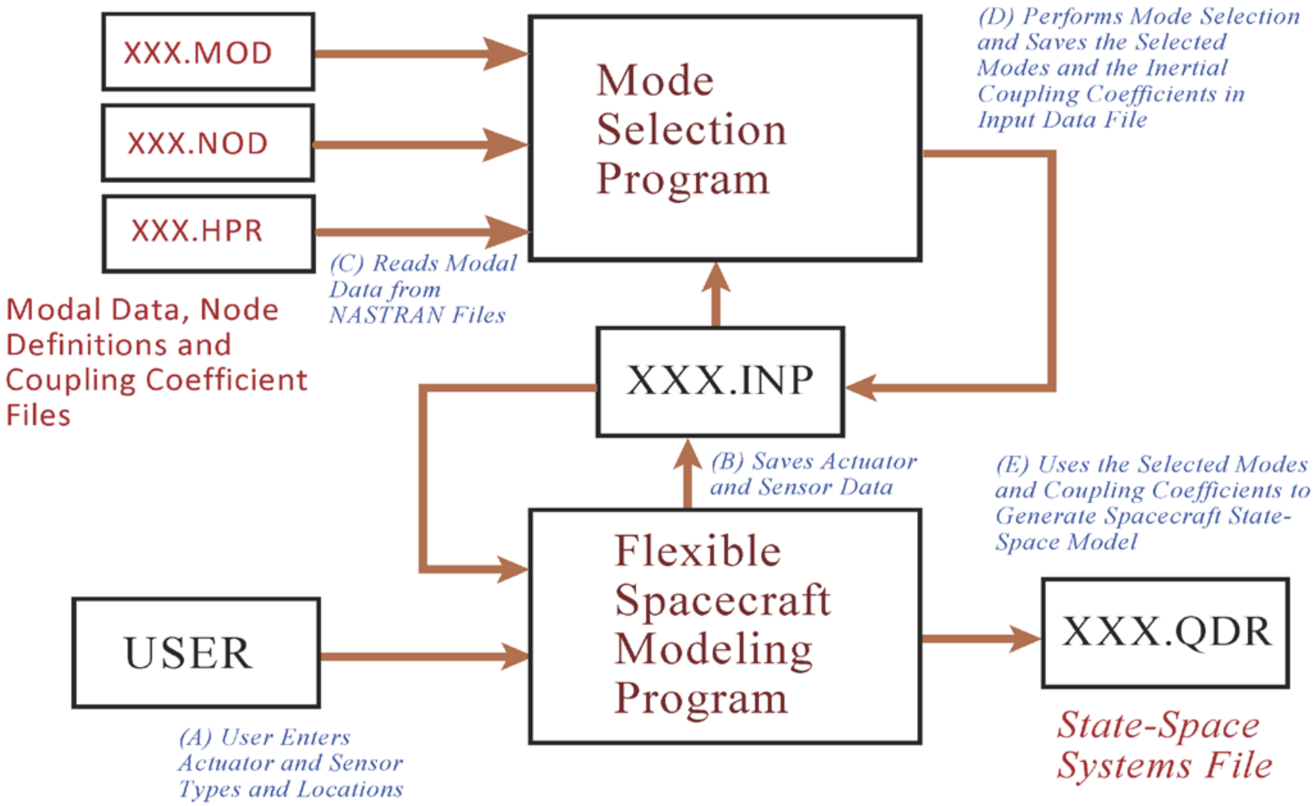


Figure 2 Flexible Spacecraft Modeling Process with Input/ Output Data Files

```
FLEXIBLE SPACECRAFT FE MODEL ...
Flex Spacecraft with Gimbaling Telescope and Reaction Wheels (67-modes)        |
! The following is a conceptual multi-body Space Surveillance satellite consisting of
! a core spacecraft body, two rotating Solar Arrays, and an optical payload which can
! gimbal in two directions, azimuth and elevation. It has 3 reaction wheels for
! attitude control, 8 RCS jets for desaturating the reaction wheels, and 4 servos to
! control the 4 gimbals, two for controlling the optical sensor (azimuth and
! elevation) position, and two for rotating the solar arrays. 67 modes were selected
! for this model, 6 rigid and 61 flexible.

Number of Input Forces applied on flex structure nodes (N_force)                  :  8
Input Force Number, Node Number (see map), Force Direction unit vector along (x,y,z)     :  1   21    1.000    0.000    0.000
Input Force Number, Node Number (see map), Force Direction unit vector along (x,y,z)     :  2   22    1.000    0.000    0.000
Input Force Number, Node Number (see map), Force Direction unit vector along (x,y,z)     :  3   23    0.000    1.000    0.000
Input Force Number, Node Number (see map), Force Direction unit vector along (x,y,z)     :  4   24    0.000   -1.000    0.000
Input Force Number, Node Number (see map), Force Direction unit vector along (x,y,z)     :  5   25    0.000   -1.000    0.000
Input Force Number, Node Number (see map), Force Direction unit vector along (x,y,z)     :  6   26    0.000    1.000    0.000
Input Force Number, Node Number (see map), Force Direction unit vector along (x,y,z)     :  7   27    1.000    0.000    0.000
Input Force Number, Node Number (see map), Force Direction unit vector along (x,y,z)     :  8   28    1.000    0.000    0.000

Number of Input Torques applied on flex structure nodes (N_torque)               :  6
Input Torque Number, Node Number (map), Torque Direction unit vector about (x,y,z)  RWA  :  1   17    1.000    0.000    0.0
Input Torque Number, Node Number (map), Torque Direction unit vector about (x,y,z)  RWA  :  2   18    0.000    1.000    0.0
Input Torque Number, Node Number (map), Torque Direction unit vector about (x,y,z)  RWA  :  3   19    0.000    0.000    1.0
Input Torque Number, Node Number (map), Torque Direction unit vector about (x,y,z)  Dist :  4    8    1.000    0.000    0.000
Input Torque Number, Node Number (map), Torque Direction unit vector about (x,y,z)  Dist :  5    8    0.000    1.000    0.000
Input Torque Number, Node Number (map), Torque Direction unit vector about (x,y,z)  Dist :  6    8    0.000    0.000    1.000

Number of Linear Sensors Measuring Translations on the flex structure nodes (N_transl)   :  2
Translation Sensor Numb, Node Numb, Along (1=X,2=Y,3=Z), Type (1=Posit,2=Veloc,3=Acceler):  1    7    1    3
Translation Sensor Numb, Node Numb, Along (1=X,2=Y,3=Z), Type (1=Posit,2=Veloc,3=Acceler):  2    7    2    3

Number of Gyro Sensors Measuring Rotations on the flex structure nodes (N_rotat)       : 13
Rotation Sensor Numbr, Node Number, About (1=X,2=Y,3=Z), Type (1=Posit,2=Veloc,3=Acceler):  1    6    1    2
Rotation Sensor Numbr, Node Number, About (1=X,2=Y,3=Z), Type (1=Posit,2=Veloc,3=Acceler):  2    6    2    2
Rotation Sensor Numbr, Node Number, About (1=X,2=Y,3=Z), Type (1=Posit,2=Veloc,3=Acceler):  3    6    3    2
Rotation Sensor Numbr, Node Number, About (1=X,2=Y,3=Z), Type (1=Posit,2=Veloc,3=Acceler):  4    6    1    1
Rotation Sensor Numbr, Node Number, About (1=X,2=Y,3=Z), Type (1=Posit,2=Veloc,3=Acceler):  5    6    2    1
Rotation Sensor Numbr, Node Number, About (1=X,2=Y,3=Z), Type (1=Posit,2=Veloc,3=Acceler):  6    6    3    1
Rotation Sensor Numbr, Node Number, About (1=X,2=Y,3=Z), Type (1=Posit,2=Veloc,3=Acceler):  7    9    2    1
Rotation Sensor Numbr, Node Number, About (1=X,2=Y,3=Z), Type (1=Posit,2=Veloc,3=Acceler):  8    9    3    1
Rotation Sensor Numbr, Node Number, About (1=X,2=Y,3=Z), Type (1=Posit,2=Veloc,3=Acceler):  9   10    2    1
Rotation Sensor Numbr, Node Number, About (1=X,2=Y,3=Z), Type (1=Posit,2=Veloc,3=Acceler): 10   10    3    1
Rotation Sensor Numbr, Node Number, About (1=X,2=Y,3=Z), Type (1=Posit,2=Veloc,3=Acceler): 11   11    1    1
Rotation Sensor Numbr, Node Number, About (1=X,2=Y,3=Z), Type (1=Posit,2=Veloc,3=Acceler): 12   12    2    1
Rotation Sensor Numbr, Node Number, About (1=X,2=Y,3=Z), Type (1=Posit,2=Veloc,3=Acceler): 13   13    3    1

Number of Flexible Modes (max=600), Mode Shapes and Mode Frequencies are included below  : 67

MODE#  1/  1, Frequency (rad/sec), Damping (zeta), Generalized Mass=    0.0000      0.50000E-02    12.000
MODE# 67/ 95, Frequency (rad/sec), Damping (zeta), Generalized Mass=    740.88      0.50000E-02    12.000
DEFINITION OF LOCATIONS (NODES)              phi along X   phi along Y   phi along Z   sigm about X  sigm about Y  sigm about Z

                                Node Numb    Modal Data at the  8 Force Application Points
RCS Jet #1     (+X)                21       0.35959D-01   0.28256D+00  -0.10725D-01   0.41546D-01   0.57240D-02   0.15120D-01
RCS Jet #2     (+X)                22       0.89610D-03  -0.29061D-01   0.27685D-01   0.80617D-01   0.77184D-01  -0.28494D-01
RCS Jet #3     (+Y)                23       0.46756D-01  -0.10690D+00  -0.23578D-01   0.40200D-01   0.75886D-01  -0.11727D+00
RCS Jet #4     (-Y)                24       0.46677D-01  -0.85016D-01   0.27199D-01   0.10546D-01  -0.28846D-01  -0.51748D-01
RCS Jet #5     (-Y)                25      -0.57787D-02  -0.61323D-01   0.57778D-01   0.10965D+00   0.12716D+00   0.59734D-01
RCS Jet #6     (+Y)                26      -0.30158D-01  -0.45443D-01  -0.76508D-01   0.75504D-01   0.52528D-01  -0.53203D-01
RCS Jet #7     (+X)                27      -0.32138D-01  -0.12351D+00  -0.12644D+00   0.96364D+00  -0.13267D+00   0.10840D+01
RCS Jet #8     (+X)                28      -0.76304D-01  -0.42040D+00  -0.12345D+00   0.96360D+00  -0.13264D+00   0.10842D+01

                                Node Numb    Modal Data at the  6 Torque Application Points
Reaction Wheel #1 Spin Axis        17      -0.38234D-01   0.54279D-02  -0.12327D-01   0.15698D+00  -0.54276D-01   0.16211D+00
Reaction Wheel #2 Spin Axis        18       0.23872D-02  -0.32136D-01   0.14296D-01  -0.73282D-01   0.71947D-01   0.14665D+00
Reaction Wheel #3 Spin Axis        19      -0.41638D-01  -0.34842D-01  -0.32082D-01  -0.92395D-01  -0.95136D-01   0.15960D+00
Cryo Cooler Pump                    8       0.27854D-01   0.27903D+00   0.18476D+00   0.18584D+00  -0.40835D-01   0.44672D-01
Cryo Cooler Pump                    8       0.27854D-01   0.27903D+00   0.18476D+00   0.18584D+00  -0.40835D-01   0.44672D-01
Cryo Cooler Pump                    8       0.27854D-01   0.27903D+00   0.18476D+00   0.18584D+00  -0.40835D-01   0.44672D-01

                                Node Numb    Modal Data at the  2 Linear Translation Measurement Points
Accelerometers                      7       0.54855D-02  -0.25231D-01  -0.31773D-01  -0.57026D-01  -0.61675D-01   0.15947D-01
Accelerometers                      7       0.54855D-02  -0.25231D-01  -0.31773D-01  -0.57026D-01  -0.61675D-01   0.15947D-01

                                Node Numb    Modal Data at the 13 Rotation Measurement Points
Inertial Attitude Sensors           6       0.20068D-01  -0.41742D-01  -0.56465D-01  -0.56683D-01  -0.42977D-01   0.17095D-01
Inertial Attitude Sensors           6       0.20068D-01  -0.41742D-01  -0.56465D-01  -0.56683D-01  -0.42977D-01   0.17095D-01
Inertial Attitude Sensors           6       0.20068D-01  -0.41742D-01  -0.56465D-01  -0.56683D-01  -0.42977D-01   0.17095D-01
Inertial Attitude Sensors           6       0.20068D-01  -0.41742D-01  -0.56465D-01  -0.56683D-01  -0.42977D-01   0.17095D-01
Inertial Attitude Sensors           6       0.20068D-01  -0.41742D-01  -0.56465D-01  -0.56683D-01  -0.42977D-01   0.17095D-01
Inertial Attitude Sensors           6       0.20068D-01  -0.41742D-01  -0.56465D-01  -0.56683D-01  -0.42977D-01   0.17095D-01
Second Mirror                       9      -0.22816D-01   0.13193D+00   0.19216D+00   0.17636D+00  -0.40523D-01   0.51331D-01
Second Mirror                       9      -0.22816D-01   0.13193D+00   0.19216D+00   0.17636D+00  -0.40523D-01   0.51331D-01
Sensitive Instrument 2             10      -0.69981D-01   0.84027D-02  -0.16241D+00  -0.79921D-01  -0.75637D-01   0.20849D-01
Sensitive Instrument 2             10      -0.69981D-01   0.84027D-02  -0.16241D+00  -0.79921D-01  -0.75637D-01   0.20849D-01
Sensitive Instrument 3             11      -0.43498D-01   0.20726D-01  -0.45681D-01  -0.61583D-01  -0.55313D-01   0.30511D-01
Sensitive Instrument 4             12      -0.51402D-01   0.24421D-01  -0.54644D-01  -0.63424D-01  -0.58200D-01   0.29567D-01
Sensitive Instrument 5             13      -0.43168D-01   0.13531D-01  -0.58378D-01  -0.63422D-01  -0.58252D-01   0.29587D-01

Inertial Coupling Coefficients (H-Parameters) File Name for the   4 gimbaling bodies     :  Surveillance-Sat.Hpr
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Figure 3 Flexible Spacecraft Input Dataset Used to Generate the Flexible Spacecraft Model

1. We begin with a finite elements model of the spacecraft generated using NASTRAN or any other FEM program. If the spacecraft has gimbaling appendages, such as, rotating instruments, antennas, solar arrays, telescopes, etc. the modal data must be calculated with the gimbals locked at fixed positions. To release and rotate the gimbals we also need an (.Hpr) file with the H-parameters. This file is also created by the FEM program. Otherwise, if there are no gimbaling bodies you will not need an (.Hpr) file. You may need to generate several FEMs with the joints locked at different orientation angles in order to analyze the system performance at different hinge positions.

2. The FEM data must be reduced by retaining a smaller number of spacecraft locations (15-45 nodes), that correspond to points that may possibly be used for actuators, sensors, disturbance excitations, sloshing tanks, etc. The generalized mode shapes, slopes, generalized masses, modal frequencies, and nodes are extracted from the FEM output, reformatted in order to be accessible by Flixan, and saved as a file having an extension (.Mod). After reformatting we typically retain several hundred modes below a cut-off frequency that may be 100 times higher than the control system bandwidth.

3. We must also prepare a nodes file having an extension (.Nod) that contains a table of the nodes which are included in the modal data file, and in the same sequence. It consists of a short description of the location, the node number, the node ID number in the FEM, and the x, y, z location of the node (optional). The nodes file will be used in the interactive menus for the purpose of selecting spacecraft locations during model preparation and flex mode selection.

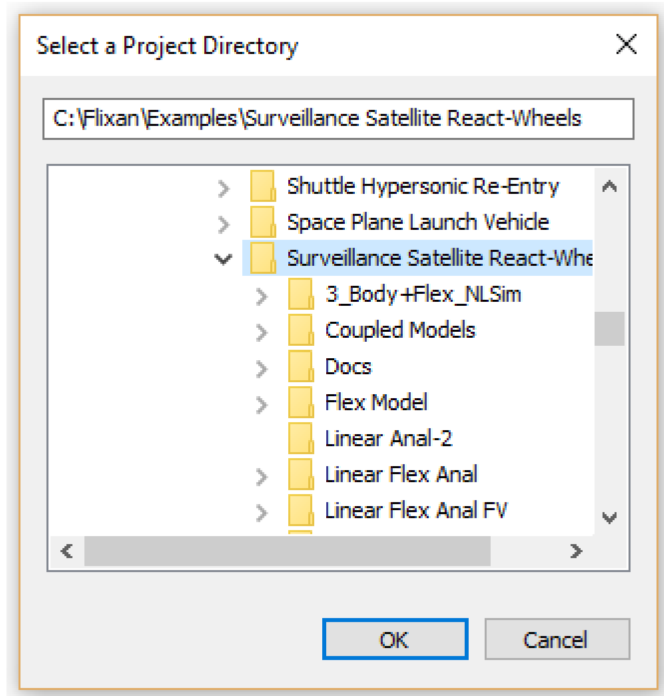
4. If the spacecraft has pivoting appendages such as rotating sensors, or solar arrays, the program also requires a coupling coefficients data file (.Hpr). This file is a matrix with columns equal to the number of gimbaling bodies, and rows equal to the number of modes. The moments of inertia matrix of the gimbaling appendages and the hinge direction vectors are also included at the bottom of the (Hpr) file.

5. If the dataset of the flexible spacecraft is already created in the input file, the user simply selects the spacecraft title from a menu and runs it using the flexible spacecraft modelling program. The program reads the effector and sensor data, the selected modal data, the coupling coefficients file, it will processes the dataset, generates the state-space system, and save it in the systems file *(.Qdr)*. It will also save the definitions of the state-space variables below the system matrices.

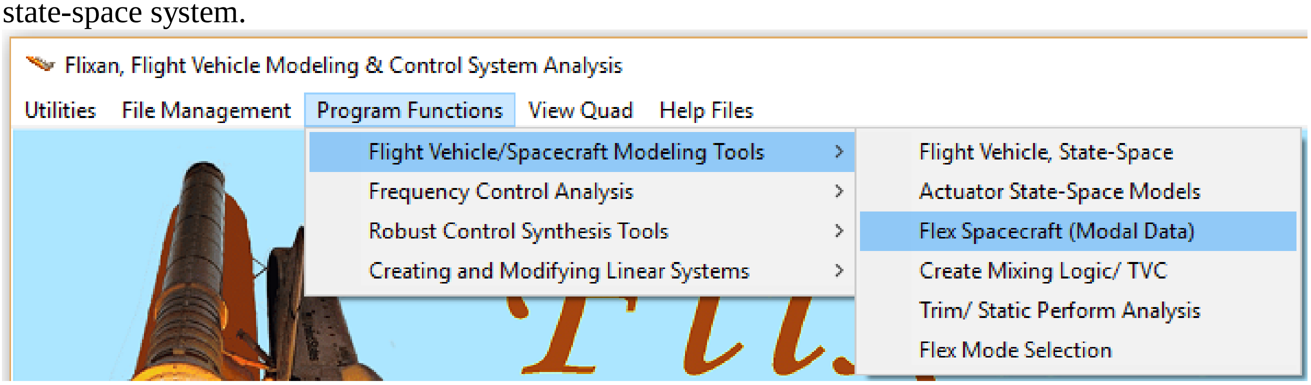
6. Otherwise, if the spacecraft dataset is not present, the next step is to prepare the dataset, save it in an input file (.Inp) and process it. This is an interactive process of defining the spacecraft effector and sensor data, title, selecting modes, and the coupling coefficients file, and it will be described in the next section. The flexible spacecraft data-set is finally saved in the input file *(.Inp)* under the label "*Flexible Spacecraft FE Model ...*" and processed by the program.

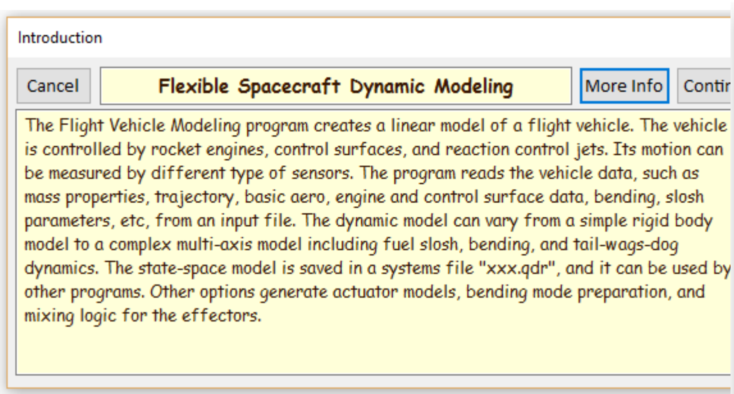
Generating the Spacecraft Model from Scratch

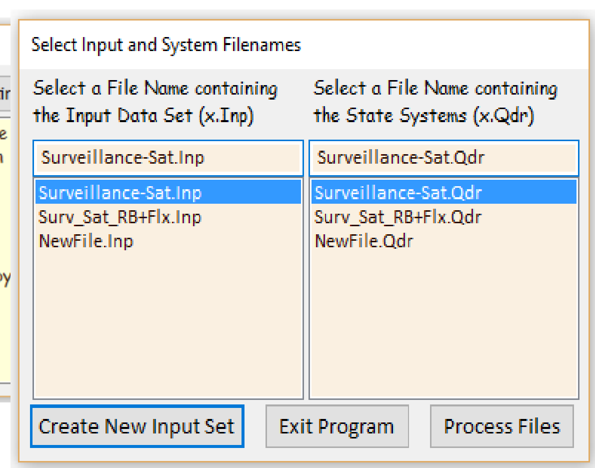
Let us now create a flexible spacecraft dataset interactively using the model preparation utility and process it to generate the flexible structure system. We must first define locations and directions of the input forces and torques, that is, RCS jets inputs, reaction wheel torques, and disturbances. We must also define sensors locations and directions, for example, attitude control measurements, accelerometers, and structure locations to be used for various types of sensitive instruments. This example is located in directory "*Flixan\ Examples\ Surveillance Satellite React-Wheels*".



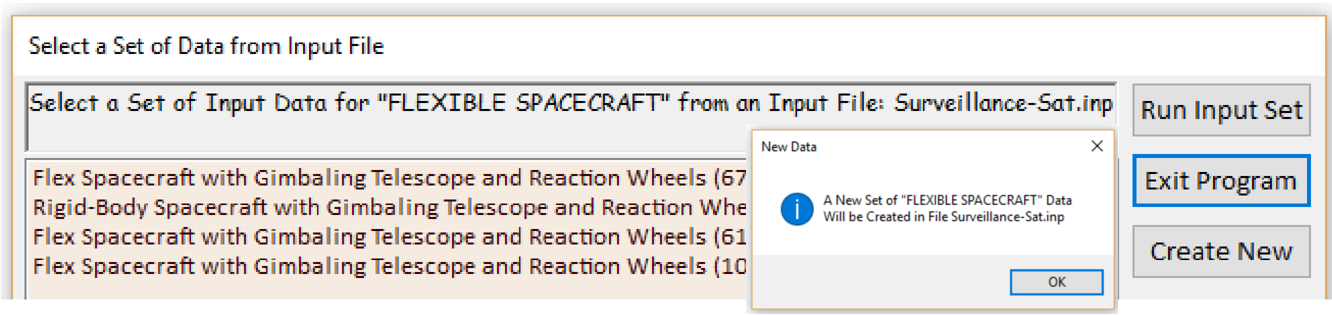
Start the Flixan program and select the project directory, as shown. Then go to Flixan main menu and select, "*Program Functions*", "*Flight Vehicle/ Spacecraft Modeling Tools*", and then "*Flexible Spacecraft from Modal Data*" program, as shown below. You must also select an input filename to save the spacecraft dataset that will be created, and a systems filename for saving the spacecraft state-space system.



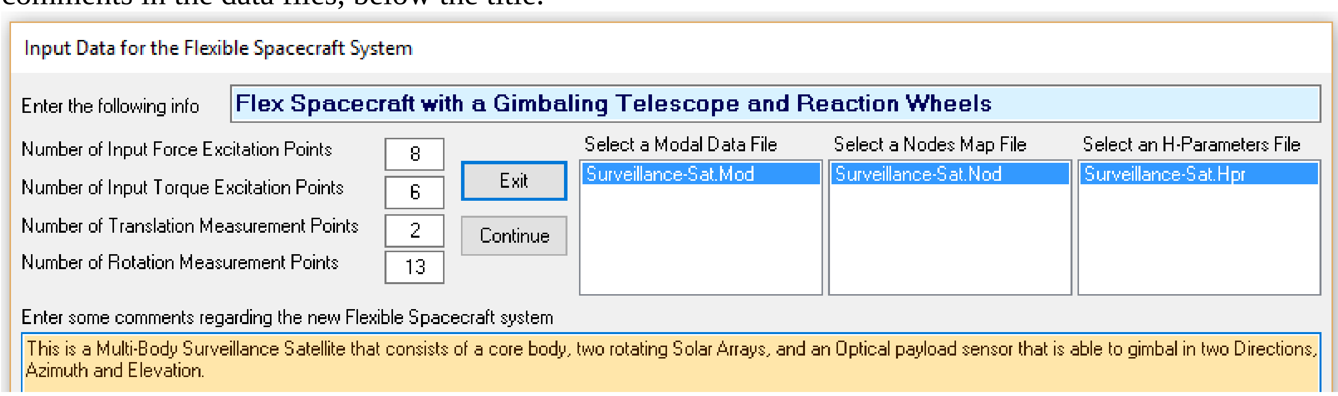




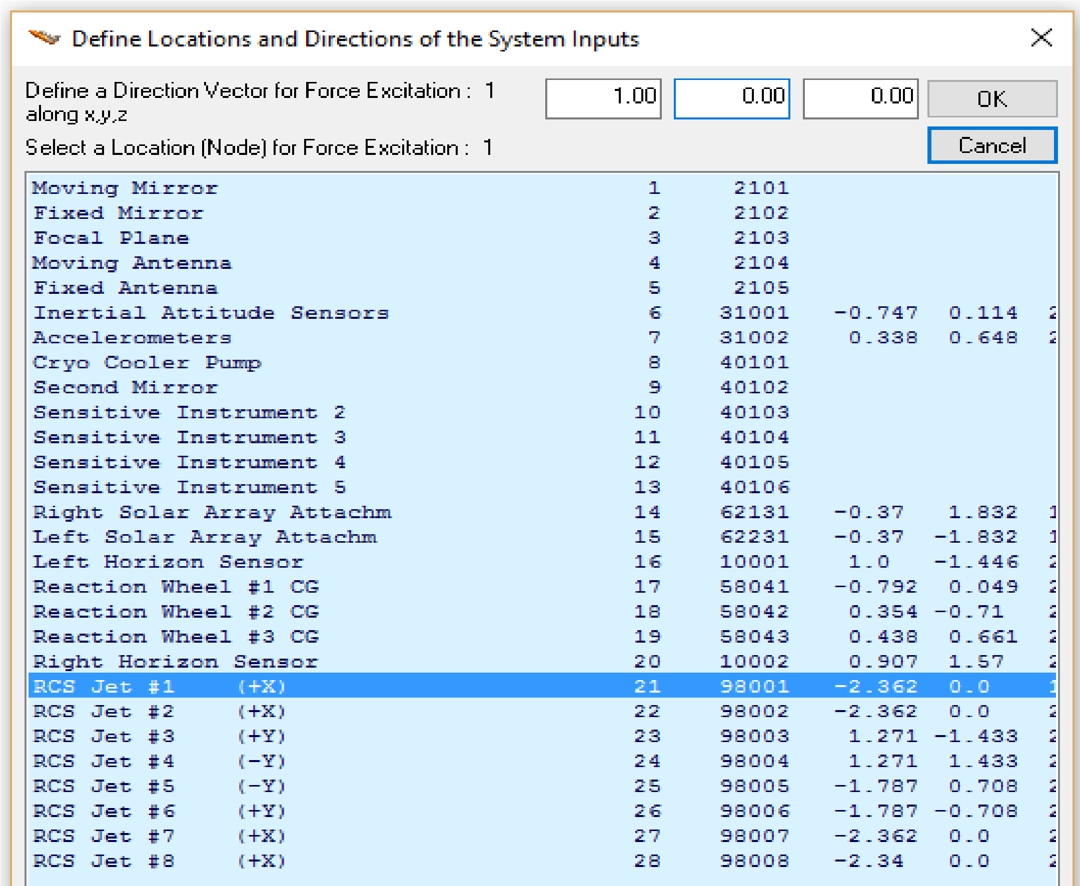
The following menu shows the titles of the “Flexible Spacecraft” datasets which are already saved in the input file (.Inp). There are four spacecraft datasets already there, but in this example we do not select and process any, but we click on “*Create New*” to create a new flexible spacecraft dataset interactively.



The next dialog is used for entering the number and type of spacecraft inputs and outputs that will define the configuration of the spacecraft structure. Enter the new spacecraft title and the number of inputs and outputs. In this example we have 8 RCS input forces, and 6 torque inputs which are: 3 reaction wheel control torques and 3 disturbance torques. We also specify 2 translational measurements for accelerometers and 13 rotational measurements for control, plus other types of sensitivity measurements. We must also use the three menus on the right to select filenames: for the modal data file “*Surveillance-Sat.Mod*”, the nodes file “*Surveillance-Sat.Nod*”, and the H-parameters file for the 4 gimbaling appendages, “*Surveillance-Sat.Hpr*”. We may also enter a short paragraph in the yellow field at the bottom of the dialog describing the flexible spacecraft features. This paragraph will appear as comments in the data files, below the title.



After defining the number of spacecraft inputs and outputs our next step is to define structural locations for the input and output points specified in the previous dialog. That is, to associate the 8 RCS jet forces, the 6 torques, the two accelerometer measurements, and the 13 rotational sensors defined in the dialog above, with structural locations in the modal data file. The next two dialogs show how to select nodes for the RCS jet forces and also force directions. The menu is created from the Nodes file as already described. The excitation locations are defined by the node number and the directions are unit vectors. Node numbers #21 through #28 were selected and they correspond to RCS force excitations 1 through 8. Node #21 corresponds to force #1, representing RCS #1, where the force direction is along x: (1, 0, 0). Similarly, force #2 from RCS jet #2 corresponds to node #22 and it is also along x: (1, 0, 0). Force excitation #6 is from RCS jet #6 corresponding to node #26 and it is along y: (0, 1, 0). Force excitation #7 is from RCS jet #7 corresponding to node #27 and it is along x: (1, 0, 0), etc.

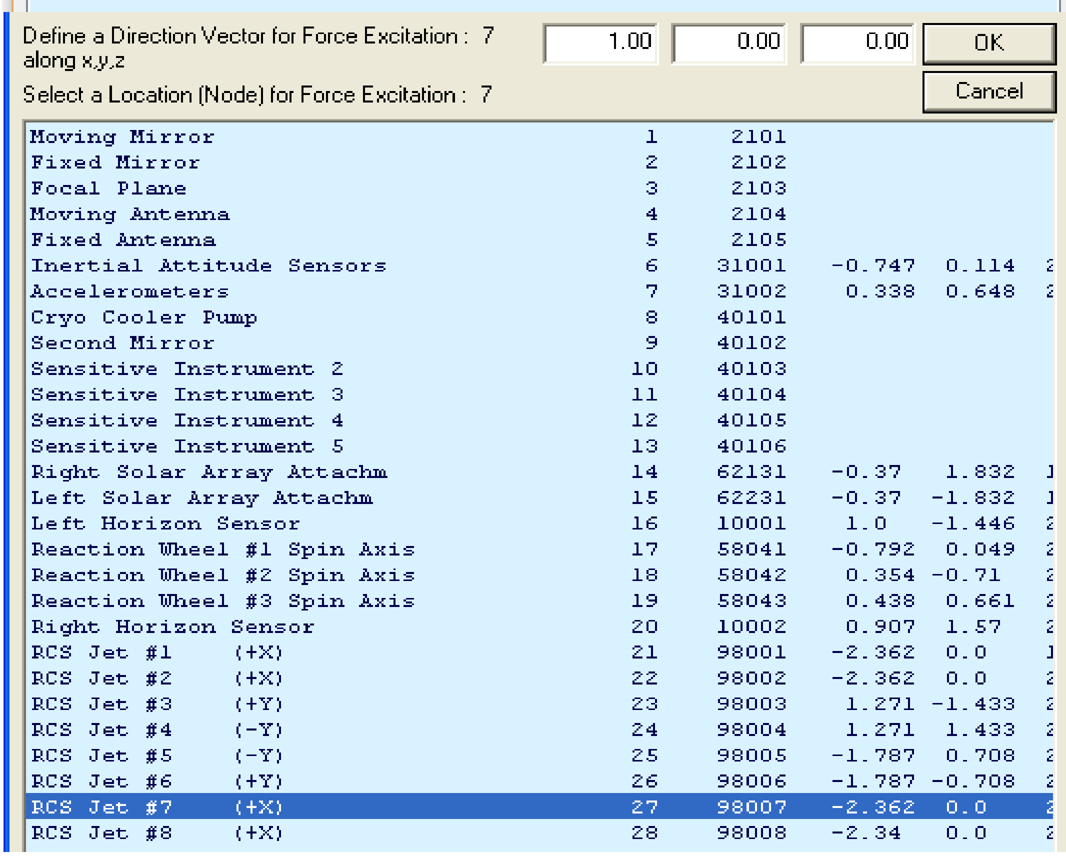


Define Locations and Directions of the System Inputs

Define a Direction Vector for Force Excitation : 1 along x,y,z — 1.00 — 0.00 — 0.00 — OK

Select a Location (Node) for Force Excitation : 1 — Cancel

Moving Mirror	1	2101		
Fixed Mirror	2	2102		
Focal Plane	3	2103		
Moving Antenna	4	2104		
Fixed Antenna	5	2105		
Inertial Attitude Sensors	6	31001	-0.747	0.114
Accelerometers	7	31002	0.338	0.648
Cryo Cooler Pump	8	40101		
Second Mirror	9	40102		
Sensitive Instrument 2	10	40103		
Sensitive Instrument 3	11	40104		
Sensitive Instrument 4	12	40105		
Sensitive Instrument 5	13	40106		
Right Solar Array Attachm	14	62131	-0.37	1.832
Left Solar Array Attachm	15	62231	-0.37	-1.832
Left Horizon Sensor	16	10001	1.0	-1.446
Reaction Wheel #1 CG	17	58041	-0.792	0.049
Reaction Wheel #2 CG	18	58042	0.354	-0.71
Reaction Wheel #3 CG	19	58043	0.438	0.661
Right Horizon Sensor	20	10002	0.907	1.57
RCS Jet #1 (+X)	21	98001	-2.362	0.0
RCS Jet #2 (+X)	22	98002	-2.362	0.0
RCS Jet #3 (+Y)	23	98003	1.271	-1.433
RCS Jet #4 (-Y)	24	98004	1.271	1.433
RCS Jet #5 (-Y)	25	98005	-1.787	0.708
RCS Jet #6 (+Y)	26	98006	-1.787	-0.708
RCS Jet #7 (+X)	27	98007	-2.362	0.0
RCS Jet #8 (+X)	28	98008	-2.34	0.0

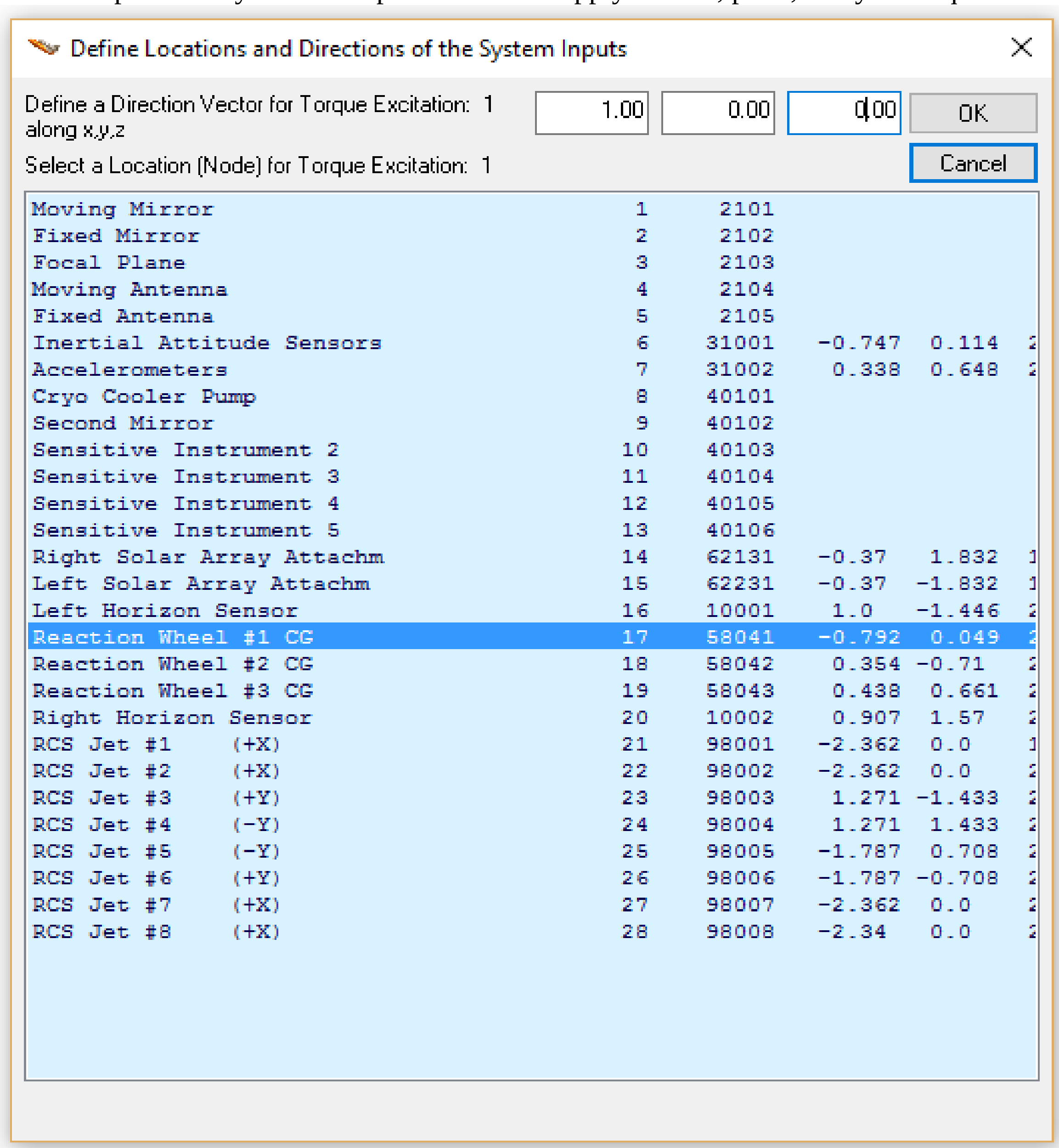


Define a Direction Vector for Force Excitation : 7 along x,y,z — 1.00 — 0.00 — 0.00 — OK

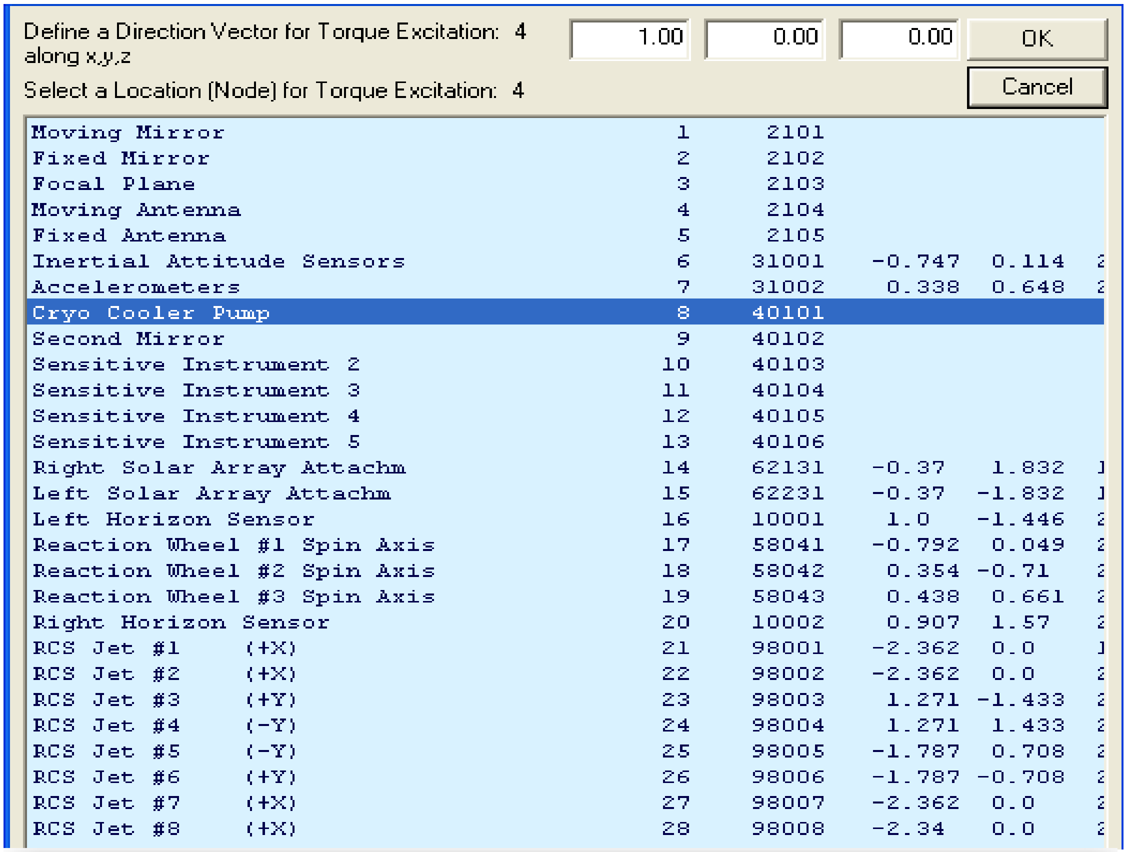
Select a Location (Node) for Force Excitation : 7 — Cancel

Moving Mirror	1	2101		
Fixed Mirror	2	2102		
Focal Plane	3	2103		
Moving Antenna	4	2104		
Fixed Antenna	5	2105		
Inertial Attitude Sensors	6	31001	-0.747	0.114
Accelerometers	7	31002	0.338	0.648
Cryo Cooler Pump	8	40101		
Second Mirror	9	40102		
Sensitive Instrument 2	10	40103		
Sensitive Instrument 3	11	40104		
Sensitive Instrument 4	12	40105		
Sensitive Instrument 5	13	40106		
Right Solar Array Attachm	14	62131	-0.37	1.832
Left Solar Array Attachm	15	62231	-0.37	-1.832
Left Horizon Sensor	16	10001	1.0	-1.446
Reaction Wheel #1 Spin Axis	17	58041	-0.792	0.049
Reaction Wheel #2 Spin Axis	18	58042	0.354	-0.71
Reaction Wheel #3 Spin Axis	19	58043	0.438	0.661
Right Horizon Sensor	20	10002	0.907	1.57
RCS Jet #1 (+X)	21	98001	-2.362	0.0
RCS Jet #2 (+X)	22	98002	-2.362	0.0
RCS Jet #3 (+Y)	23	98003	1.271	-1.433
RCS Jet #4 (-Y)	24	98004	1.271	1.433
RCS Jet #5 (-Y)	25	98005	-1.787	0.708
RCS Jet #6 (+Y)	26	98006	-1.787	-0.708
RCS Jet #7 (+X)	27	98007	-2.362	0.0
RCS Jet #8 (+X)	28	98008	-2.34	0.0

In the next three dialogs we must select locations and directions for the first 3 torques which are reaction wheel torques. Nodes #17, #18, #19, correspond to RW #1, #2, and #3. The torque directions in body axes are about x, y, and z respectively. The dialog below is used to select the first wheel. The next two are selected from similar dialogs. Note that the wheels are usually very near to each other and are mounted inside a solid structure. A single node is therefore sufficient for the reaction wheel array, but in this example we may select 3 separate nodes to apply the roll, pitch, and yaw torques.



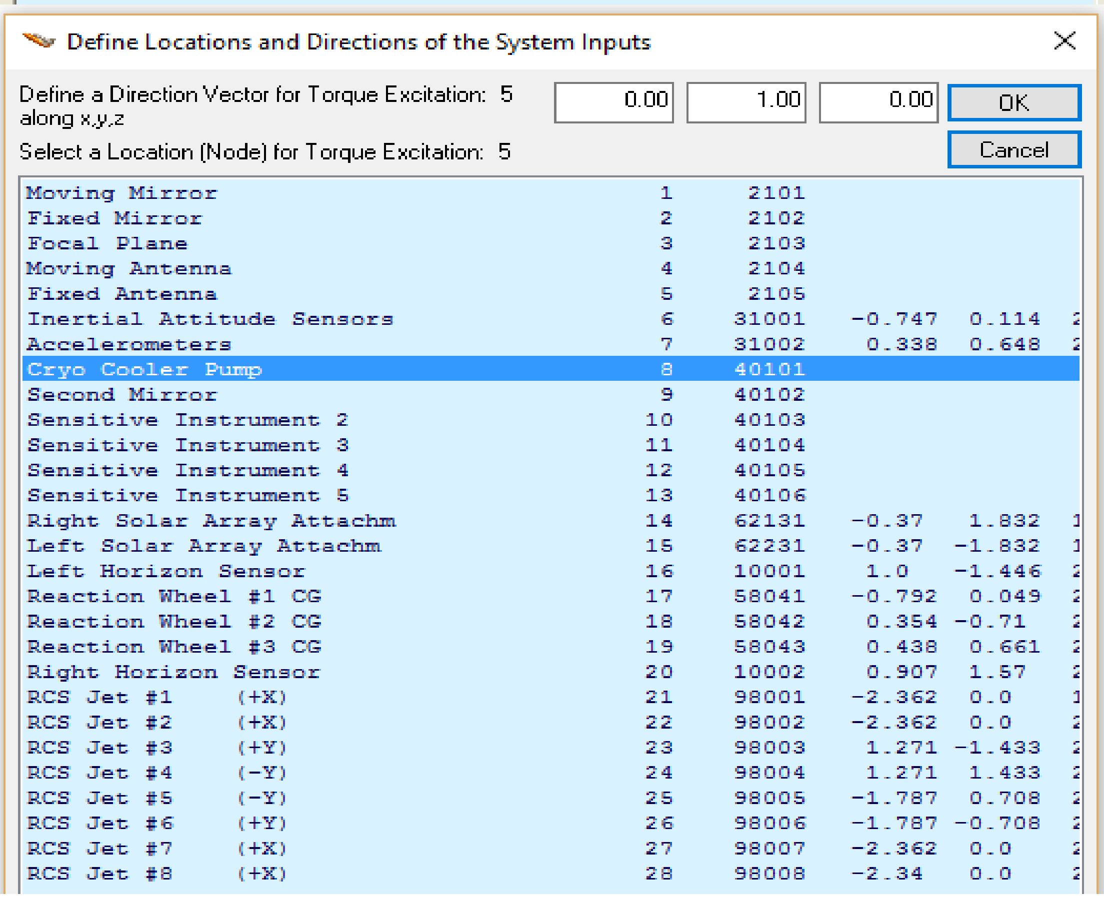
We must also select 3 structural locations for the cryo-cooler disturbance torques. The cryo-cooler is located at node #8. The disturbance torques, (4, 5, and 6) are applied in roll, pitch, and yaw respectively. Only the roll and pitch disturbance torque selections are shown below. Roll is (1, 0, 0), pitch is (0, 1, 0) and yaw is (0, 0, 1). All 3 torques are applied at the same node #8 location.



Define a Direction Vector for Torque Excitation: 4 along x,y,z — 1.00 — 0.00 — 0.00 — OK

Select a Location (Node) for Torque Excitation: 4 — Cancel

Moving Mirror	1	2101			
Fixed Mirror	2	2102			
Focal Plane	3	2103			
Moving Antenna	4	2104			
Fixed Antenna	5	2105			
Inertial Attitude Sensors	6	31001	-0.747	0.114	2
Accelerometers	7	31002	0.338	0.648	2
Cryo Cooler Pump	8	40101			
Second Mirror	9	40102			
Sensitive Instrument 2	10	40103			
Sensitive Instrument 3	11	40104			
Sensitive Instrument 4	12	40105			
Sensitive Instrument 5	13	40106			
Right Solar Array Attachm	14	62131	-0.37	1.832	1
Left Solar Array Attachm	15	62231	-0.37	-1.832	1
Left Horizon Sensor	16	10001	1.0	-1.446	2
Reaction Wheel #1 Spin Axis	17	58041	-0.792	0.049	2
Reaction Wheel #2 Spin Axis	18	58042	0.354	-0.71	2
Reaction Wheel #3 Spin Axis	19	58043	0.438	0.661	2
Right Horizon Sensor	20	10002	0.907	1.57	2
RCS Jet #1 (+X)	21	98001	-2.362	0.0	1
RCS Jet #2 (+X)	22	98002	-2.362	0.0	2
RCS Jet #3 (+Y)	23	98003	1.271	-1.433	2
RCS Jet #4 (-Y)	24	98004	1.271	1.433	2
RCS Jet #5 (-Y)	25	98005	-1.787	0.708	2
RCS Jet #6 (+Y)	26	98006	-1.787	-0.708	2
RCS Jet #7 (+X)	27	98007	-2.362	0.0	2
RCS Jet #8 (+X)	28	98008	-2.34	0.0	2



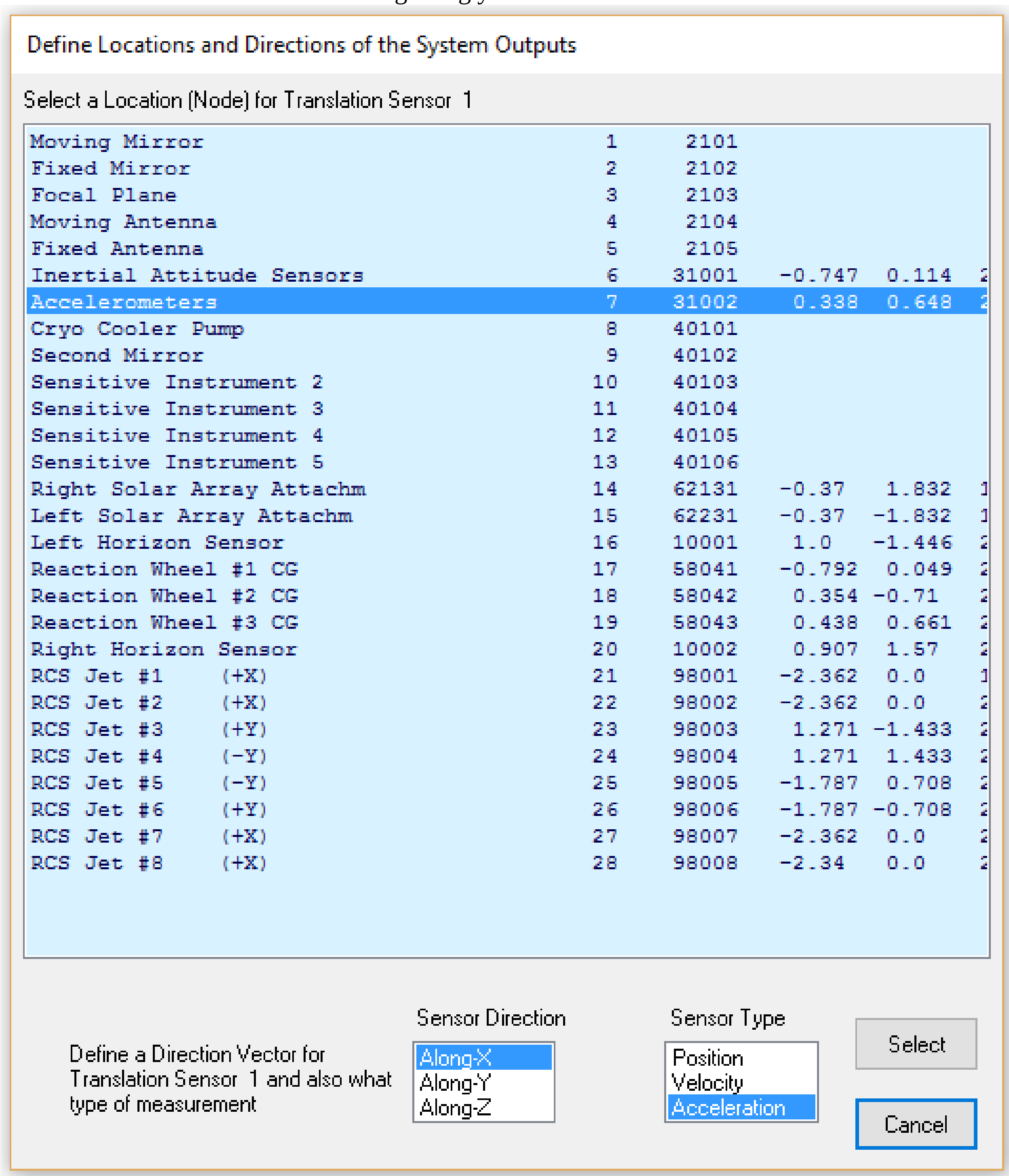
Define Locations and Directions of the System Inputs

Define a Direction Vector for Torque Excitation: 5 along x,y,z — 0.00 — 1.00 — 0.00 — OK

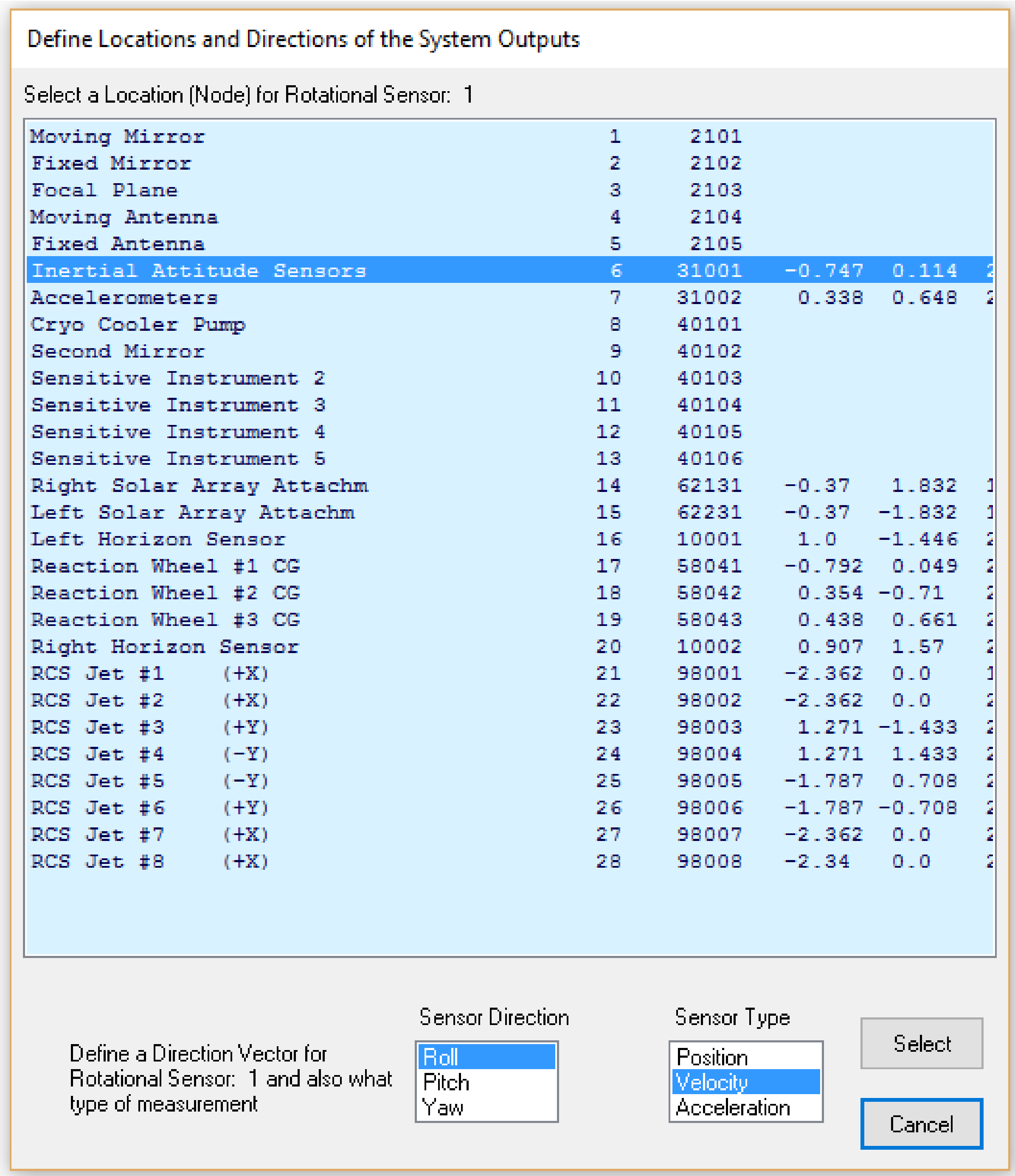
Select a Location (Node) for Torque Excitation: 5 — Cancel

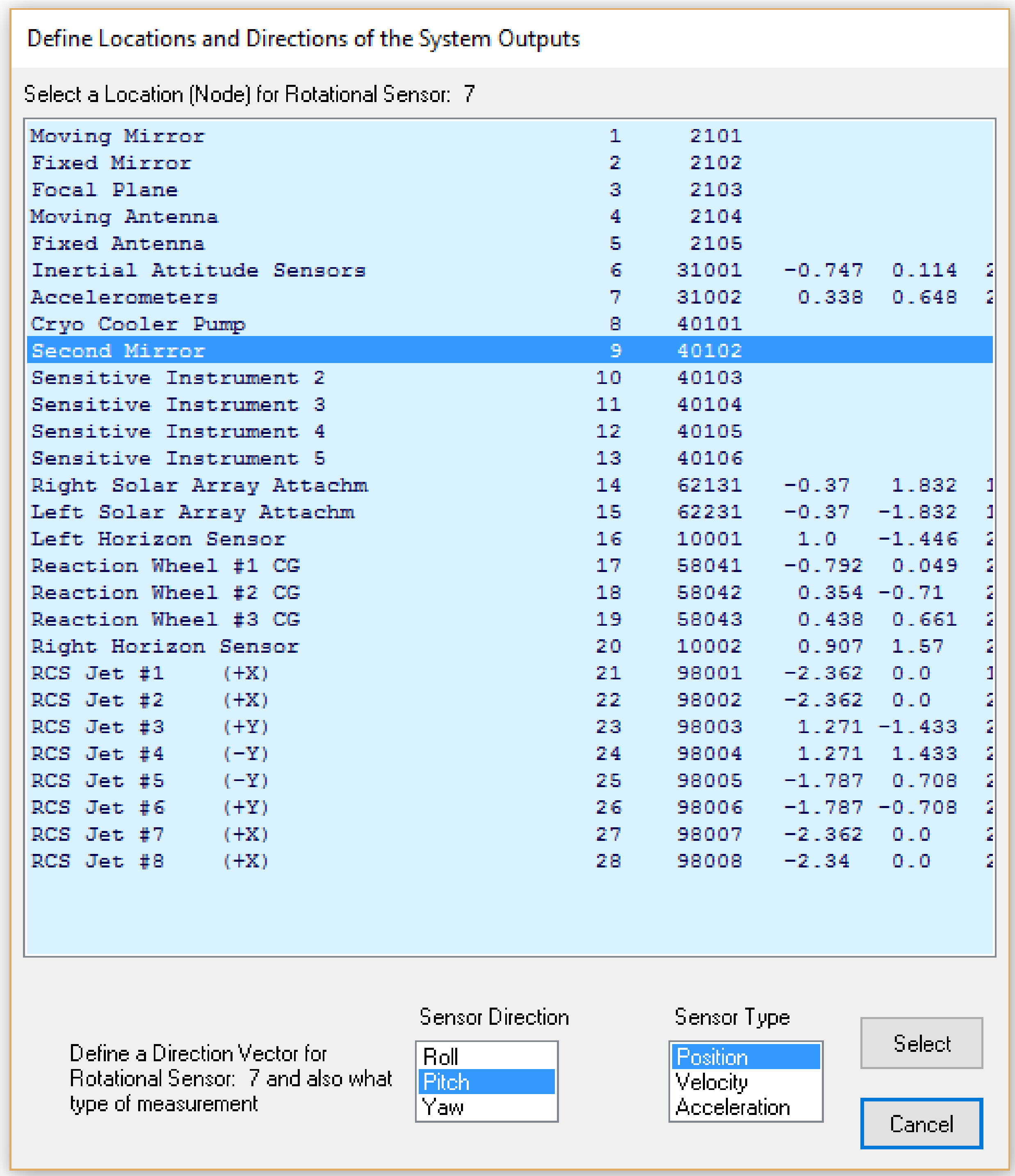
Moving Mirror	1	2101			
Fixed Mirror	2	2102			
Focal Plane	3	2103			
Moving Antenna	4	2104			
Fixed Antenna	5	2105			
Inertial Attitude Sensors	6	31001	-0.747	0.114	2
Accelerometers	7	31002	0.338	0.648	2
Cryo Cooler Pump	8	40101			
Second Mirror	9	40102			
Sensitive Instrument 2	10	40103			
Sensitive Instrument 3	11	40104			
Sensitive Instrument 4	12	40105			
Sensitive Instrument 5	13	40106			
Right Solar Array Attachm	14	62131	-0.37	1.832	1
Left Solar Array Attachm	15	62231	-0.37	-1.832	1
Left Horizon Sensor	16	10001	1.0	-1.446	2
Reaction Wheel #1 CG	17	58041	-0.792	0.049	2
Reaction Wheel #2 CG	18	58042	0.354	-0.71	2
Reaction Wheel #3 CG	19	58043	0.438	0.661	2
Right Horizon Sensor	20	10002	0.907	1.57	2
RCS Jet #1 (+X)	21	98001	-2.362	0.0	1
RCS Jet #2 (+X)	22	98002	-2.362	0.0	2
RCS Jet #3 (+Y)	23	98003	1.271	-1.433	2
RCS Jet #4 (-Y)	24	98004	1.271	1.433	2
RCS Jet #5 (-Y)	25	98005	-1.787	0.708	2
RCS Jet #6 (+Y)	26	98006	-1.787	-0.708	2
RCS Jet #7 (+X)	27	98007	-2.362	0.0	2
RCS Jet #8 (+X)	28	98008	-2.34	0.0	2

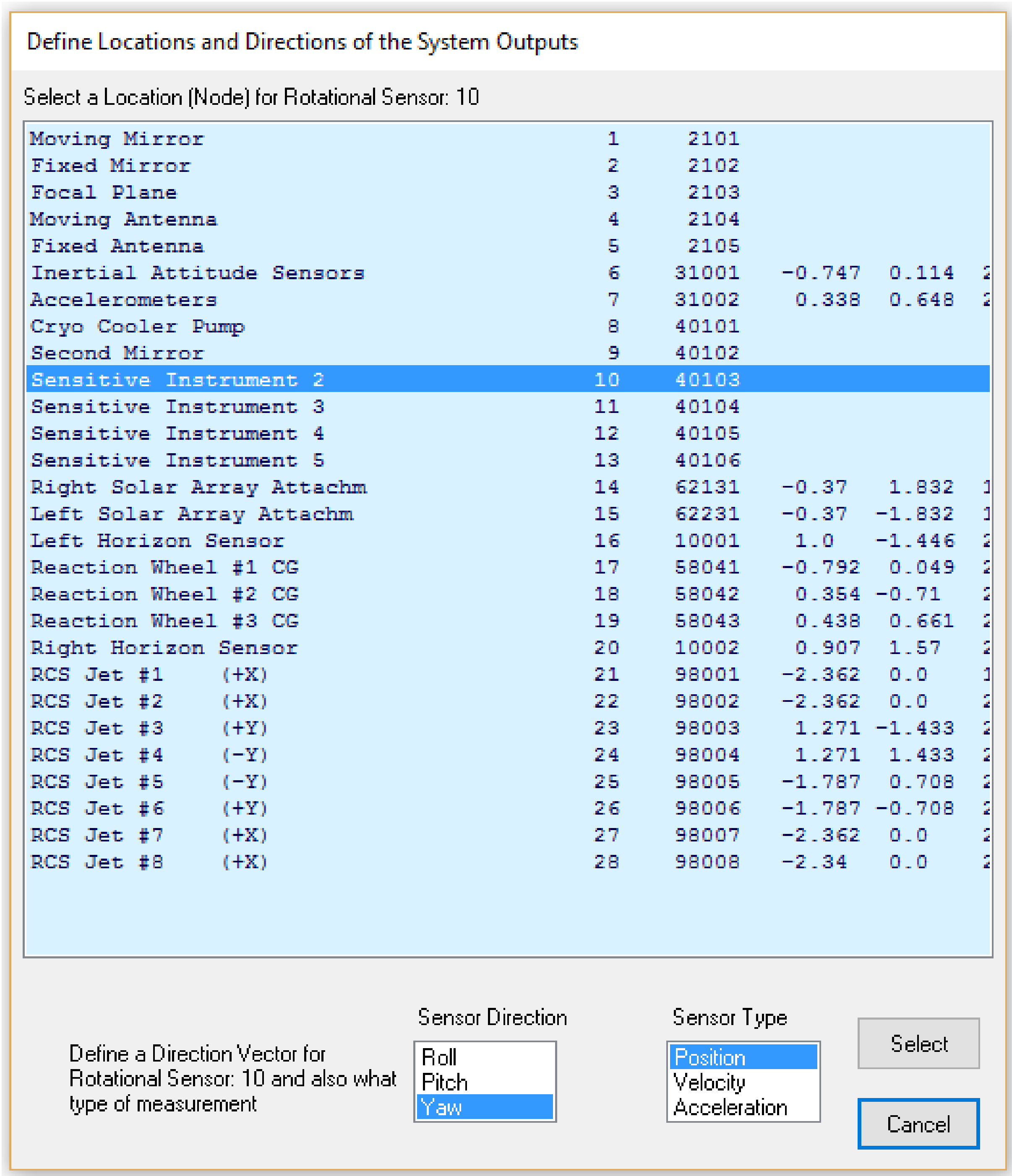
The sensors are also defined by the node number, the direction of measurement (roll, pitch, yaw) or along (x, y, z), and the type of measurement (position, rate, or acceleration). For the translational sensors (1 and 2) we select node #7 to define the location of two accelerometers measuring along the x and y axes respectively. The selection of the first accelerometer measuring in the x direction is shown below. The second accelerometer is measuring along y.

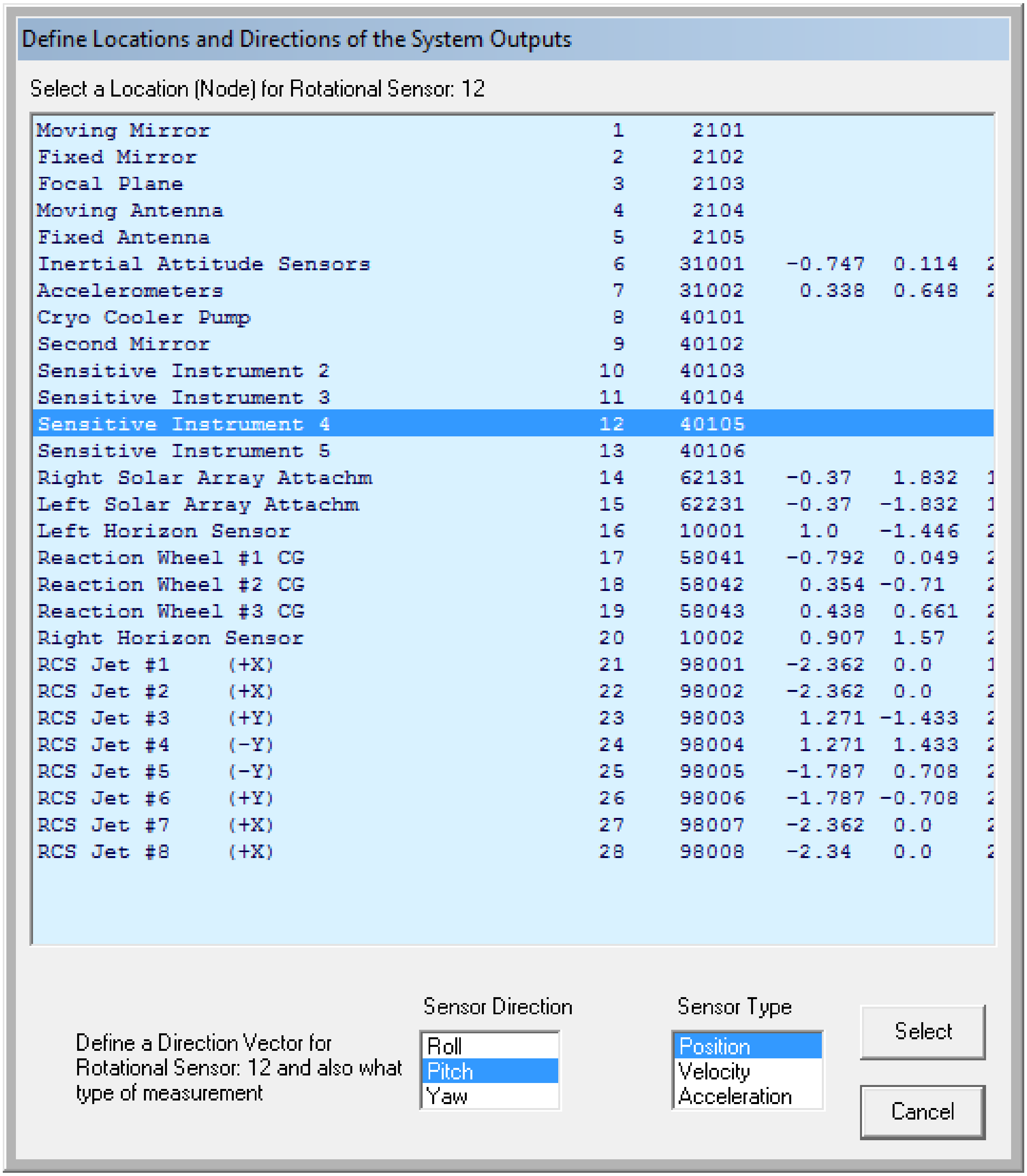


We must finally define locations and directions for our 13 rotational sensors. We have 3 rate gyros at node #6 measuring roll, pitch, and yaw rates, 3 gyro measurements also at node #6 measuring roll, pitch, and yaw rotation angles. They are used for attitude control. We also have two angular pitch and yaw measurements at node #9, two additional angular measurements in pitch and yaw at node #10, and three angular measurements at nodes #11, #12, and #13 measuring roll, pitch, and yaw respectively. They are used for measuring sensitivity at those locations. The following dialogs show the node selection for some of these 13 rotational sensors.



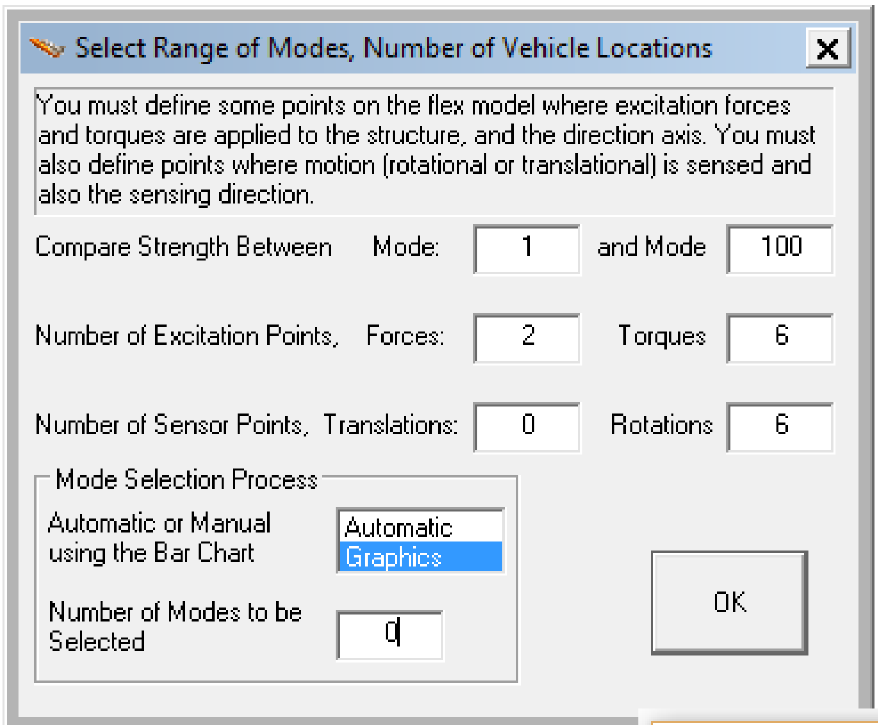

Define Locations and Directions of the System Outputs
Select a Location (Node) for Rotational Sensor: 7
Moving Mirror 1 2101
Fixed Mirror 2 2102
Focal Plane 3 2103
Moving Antenna 4 2104
Fixed Antenna 5 2105
Inertial Attitude Sensors 6 31001 -0.747 0.114
Accelerometers 7 31002 0.338 0.648
Cryo Cooler Pump 8 40101
Second Mirror 9 40102
Sensitive Instrument 2 10 40103
Sensitive Instrument 3 11 40104
Sensitive Instrument 4 12 40105
Sensitive Instrument 5 13 40106
Right Solar Array Attachm 14 62131 -0.37 1.832
Left Solar Array Attachm 15 62231 -0.37 -1.832
Left Horizon Sensor 16 10001 1.0 -1.446
Reaction Wheel #1 CG 17 58041 -0.792 0.049
Reaction Wheel #2 CG 18 58042 0.354 -0.71
Reaction Wheel #3 CG 19 58043 0.438 0.661
Right Horizon Sensor 20 10002 0.907 1.57
RCS Jet #1 (+X) 21 98001 -2.362 0.0
RCS Jet #2 (+X) 22 98002 -2.362 0.0
RCS Jet #3 (+Y) 23 98003 1.271 -1.433
RCS Jet #4 (-Y) 24 98004 1.271 1.433
RCS Jet #5 (-Y) 25 98005 -1.787 0.708
RCS Jet #6 (+Y) 26 98006 -1.787 -0.708
RCS Jet #7 (+X) 27 98007 -2.362 0.0
RCS Jet #8 (+X) 28 98008 -2.34 0.0
Sensor Direction
Sensor Type
Define a Direction Vector for Rotational Sensor: 7 and also what type of measurement
Roll
Pitch
Yaw
Position
Velocity
Acceleration
Select
Cancel

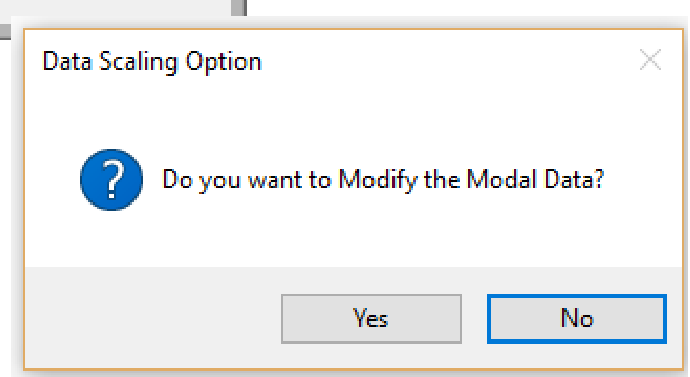

Define Locations and Directions of the System Outputs
Select a Location (Node) for Rotational Sensor: 10
Moving Mirror 1 2101
Fixed Mirror 2 2102
Focal Plane 3 2103
Moving Antenna 4 2104
Fixed Antenna 5 2105
Inertial Attitude Sensors 6 31001 -0.747 0.114
Accelerometers 7 31002 0.338 0.648
Cryo Cooler Pump 8 40101
Second Mirror 9 40102
Sensitive Instrument 2 10 40103
Sensitive Instrument 3 11 40104
Sensitive Instrument 4 12 40105
Sensitive Instrument 5 13 40106
Right Solar Array Attachm 14 62131 -0.37 1.832
Left Solar Array Attachm 15 62231 -0.37 -1.832
Left Horizon Sensor 16 10001 1.0 -1.446
Reaction Wheel #1 CG 17 58041 -0.792 0.049
Reaction Wheel #2 CG 18 58042 0.354 -0.71
Reaction Wheel #3 CG 19 58043 0.438 0.661
Right Horizon Sensor 20 10002 0.907 1.57
RCS Jet #1 (+X) 21 98001 -2.362 0.0
RCS Jet #2 (+X) 22 98002 -2.362 0.0
RCS Jet #3 (+Y) 23 98003 1.271 -1.433
RCS Jet #4 (-Y) 24 98004 1.271 1.433
RCS Jet #5 (-Y) 25 98005 -1.787 0.708
RCS Jet #6 (+Y) 26 98006 -1.787 -0.708
RCS Jet #7 (+X) 27 98007 -2.362 0.0
RCS Jet #8 (+X) 28 98008 -2.34 0.0
Define a Direction Vector for Rotational Sensor: 10 and also what type of measurement
Sensor Direction
Roll
Pitch
Yaw
Sensor Type
Position
Velocity
Acceleration
Select
Cancel


Define Locations and Directions of the System Outputs
Select a Location (Node) for Rotational Sensor: 12
Moving Mirror 1 2101
Fixed Mirror 2 2102
Focal Plane 3 2103
Moving Antenna 4 2104
Fixed Antenna 5 2105
Inertial Attitude Sensors 6 31001 -0.747 0.114
Accelerometers 7 31002 0.338 0.648
Cryo Cooler Pump 8 40101
Second Mirror 9 40102
Sensitive Instrument 2 10 40103
Sensitive Instrument 3 11 40104
Sensitive Instrument 4 12 40105
Sensitive Instrument 5 13 40106
Right Solar Array Attachm 14 62131 -0.37 1.832
Left Solar Array Attachm 15 62231 -0.37 -1.832
Left Horizon Sensor 16 10001 1.0 -1.446
Reaction Wheel #1 CG 17 58041 -0.792 0.049
Reaction Wheel #2 CG 18 58042 0.354 -0.71
Reaction Wheel #3 CG 19 58043 0.438 0.661
Right Horizon Sensor 20 10002 0.907 1.57
RCS Jet #1 (+X) 21 98001 -2.362 0.0
RCS Jet #2 (+X) 22 98002 -2.362 0.0
RCS Jet #3 (+Y) 23 98003 1.271 -1.433
RCS Jet #4 (-Y) 24 98004 1.271 1.433
RCS Jet #5 (-Y) 25 98005 -1.787 0.708
RCS Jet #6 (+Y) 26 98006 -1.787 -0.708
RCS Jet #7 (+X) 27 98007 -2.362 0.0
RCS Jet #8 (+X) 28 98008 -2.34 0.0
Define a Direction Vector for Rotational Sensor: 12 and also what type of measurement
Sensor Direction
Roll
Pitch
Yaw
Sensor Type
Position
Velocity
Acceleration
Select
Cancel

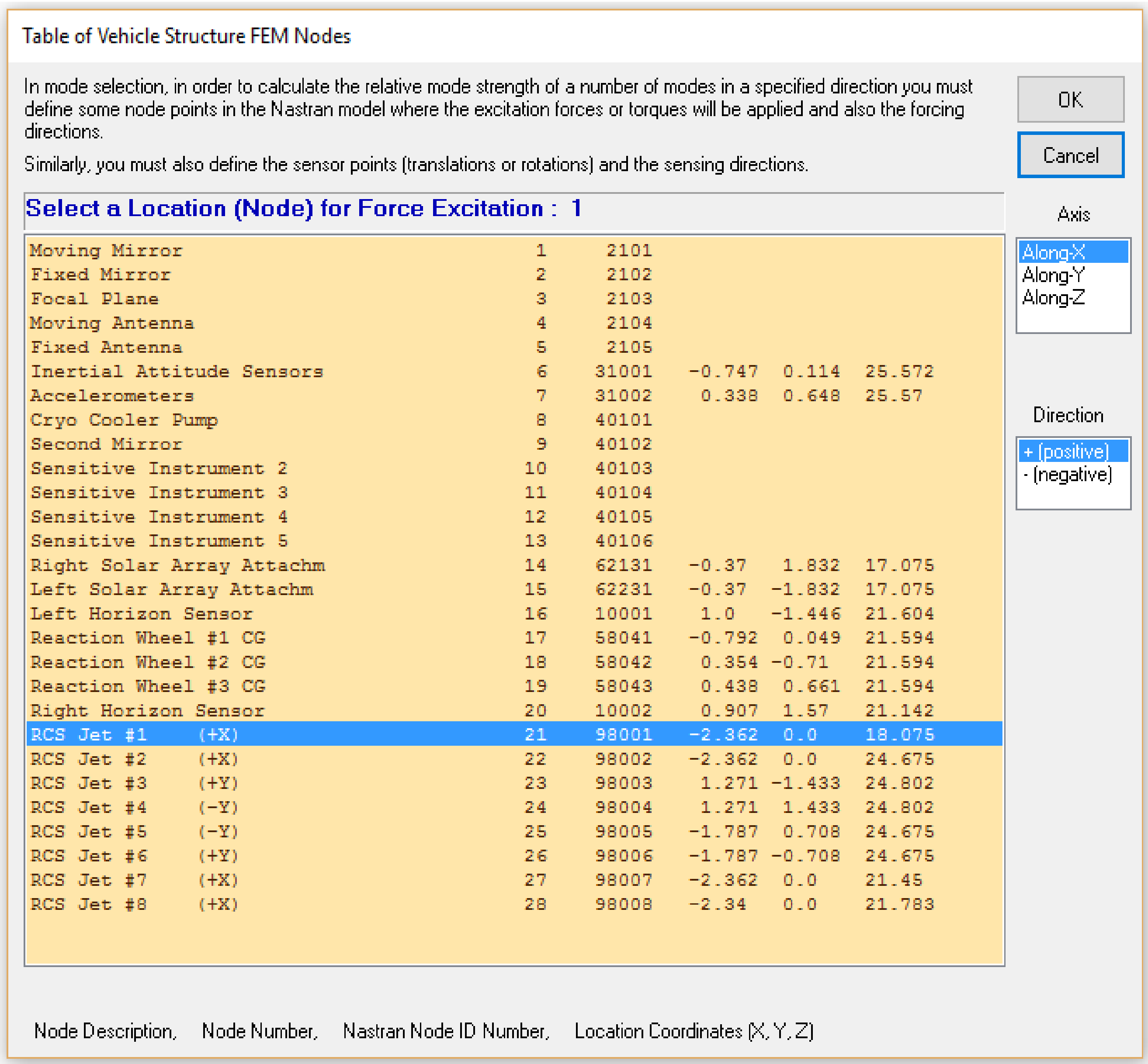
The previous light-blue menus were used to associate the vehicle model inputs and outputs with locations that correspond to the FEM. We must now use similar node menus to define excitation and sensor points (structure nodes) to be used by the mode selection program only for mode strength comparison. These locations are not necessarily the same as those defined in the spacecraft model, but they could be any nodes used only for mode selection purposes. The program calculates the modal strength between those inputs and outputs in order to select some of the strongest modes to represent the flexible spacecraft. The remaining modes are ignored.

Use the next dialog to enter some parameters for mode selection. The range of modes to be compared, in this case we include the full range from 1 to 100. The mode strength in this case is calculated between 2 force excitation points, 6 torque excitation points, and 6 rotational measurements. There are no translational measurements used in this mode selection case. Select the "Graphic" option to manually select the modes using the mode strength comparison plot and click "OK". In the next dialog choose not to modify or rescale the modal data because the units and x, y, z directions are acceptable.





The menu below is similar to the previous light-blue dialogs but has different (amber) background to avoid mix-up with the spacecraft modeling dialogs. It is also created from the nodes file showing the spacecraft structure locations in the order they appear in the modal data file, and is used to select the nodes where we shall apply the two excitation forces specified. In this case, node #21 is selected to apply a force in the +X direction, and node #26 is also selected (not shown) to apply the second force in the +Y direction. This is only for mode comparison and mode selection purposes.



Similarly, we must define six points where we shall apply torques for mode strength comparison purposes. We select 3 points, the reaction wheel nodes #17, #18, #19 to apply torques (1, 2, 3) in +roll, +pitch, and +yaw directions respectively. The next three torques: 4, 5, and 6 represent disturbances coming from a noisy cryo-cooler pump inside the spacecraft that is located at node #8. All 3 excitation torques are applied at the same node #8, in +roll, +pitch, and +yaw directions respectively, only for mode selection. Two of the torque definitions are shown below.

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.

OK

Cancel

Select a Location (Node) for Torque Excitation: 2

Moving Mirror	1	2101			
Fixed Mirror	2	2102			
Focal Plane	3	2103			
Moving Antenna	4	2104			
Fixed Antenna	5	2105			
Inertial Attitude Sensors	6	31001	-0.747	0.114	25.572
Accelerometers	7	31002	0.338	0.648	25.57
Cryo Cooler Pump	8	40101			
Second Mirror	9	40102			
Sensitive Instrument 2	10	40103			
Sensitive Instrument 3	11	40104			
Sensitive Instrument 4	12	40105			
Sensitive Instrument 5	13	40106			
Right Solar Array Attachm	14	62131	-0.37	1.832	17.075
Left Solar Array Attachm	15	62231	-0.37	-1.832	17.075
Left Horizon Sensor	16	10001	1.0	-1.446	21.604
Reaction Wheel #1 CG	17	58041	-0.792	0.049	21.594
Reaction Wheel #2 CG	18	58042	0.354	-0.71	21.594
Reaction Wheel #3 CG	19	58043	0.438	0.661	21.594
Right Horizon Sensor	20	10002	0.907	1.57	21.142
RCS Jet #1 (+X)	21	98001	-2.362	0.0	18.075
RCS Jet #2 (+X)	22	98002	-2.362	0.0	24.675
RCS Jet #3 (+Y)	23	98003	1.271	-1.433	24.802
RCS Jet #4 (-Y)	24	98004	1.271	1.433	24.802
RCS Jet #5 (-Y)	25	98005	-1.787	0.708	24.675
RCS Jet #6 (+Y)	26	98006	-1.787	-0.708	24.675
RCS Jet #7 (+X)	27	98007	-2.362	0.0	21.45
RCS Jet #8 (+X)	28	98008	-2.34	0.0	21.783

Axis

Roll
Pitch
Yaw

Direction

+ (positive)
- (negative)

Node Description, Node Number, Nastran Node ID Number, Location Coordinates (X, Y, Z)

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.

OK

Cancel

Select a Location (Node) for Torque Excitation: 3

Moving Mirror	1	2101			
Fixed Mirror	2	2102			
Focal Plane	3	2103			
Moving Antenna	4	2104			
Fixed Antenna	5	2105			
Inertial Attitude Sensors	6	31001	-0.747	0.114	25.572
Accelerometers	7	31002	0.338	0.648	25.57
Cryo Cooler Pump	8	40101			
Second Mirror	9	40102			
Sensitive Instrument 2	10	40103			
Sensitive Instrument 3	11	40104			
Sensitive Instrument 4	12	40105			
Sensitive Instrument 5	13	40106			
Right Solar Array Attachm	14	62131	-0.37	1.832	17.075
Left Solar Array Attachm	15	62231	-0.37	-1.832	17.075
Left Horizon Sensor	16	10001	1.0	-1.446	21.604
Reaction Wheel #1 Spin Axis	17	58041	-0.792	0.049	21.594
Reaction Wheel #2 Spin Axis	18	58042	0.354	-0.71	21.594
Reaction Wheel #3 Spin Axis	19	58043	0.438	0.661	21.594
Right Horizon Sensor	20	10002	0.907	1.57	21.142
RCS Jet #1 (+X)	21	98001	-2.362	0.0	18.075
RCS Jet #2 (+X)	22	98002	-2.362	0.0	24.675
RCS Jet #3 (+Y)	23	98003	1.271	-1.433	24.802
RCS Jet #4 (-Y)	24	98004	1.271	1.433	24.802
RCS Jet #5 (-Y)	25	98005	-1.787	0.708	24.675
RCS Jet #6 (+Y)	26	98006	-1.787	-0.708	24.675
RCS Jet #7 (+X)	27	98007	-2.362	0.0	21.45
RCS Jet #8 (+X)	28	98008	-2.34	0.0	21.783

Axis

Roll
Pitch
Yaw

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.

OK

Cancel

Select a Location (Node) for Torque Excitation: 4

Moving Mirror	1	2101			
Fixed Mirror	2	2102			
Focal Plane	3	2103			
Moving Antenna	4	2104			
Fixed Antenna	5	2105			
Inertial Attitude Sensors	6	31001	-0.747	0.114	25.572
Accelerometers	7	31002	0.338	0.648	25.57
Cryo Cooler Pump	8	40101			
Second Mirror	9	40102			
Sensitive Instrument 2	10	40103			
Sensitive Instrument 3	11	40104			
Sensitive Instrument 4	12	40105			
Sensitive Instrument 5	13	40106			
Right Solar Array Attachm	14	62131	-0.37	1.832	17.075
Left Solar Array Attachm	15	62231	-0.37	-1.832	17.075
Left Horizon Sensor	16	10001	1.0	-1.446	21.604
Reaction Wheel #1 CG	17	58041	-0.792	0.049	21.594
Reaction Wheel #2 CG	18	58042	0.354	-0.71	21.594
Reaction Wheel #3 CG	19	58043	0.438	0.661	21.594
Right Horizon Sensor	20	10002	0.907	1.57	21.142
RCS Jet #1 (+X)	21	98001	-2.362	0.0	18.075
RCS Jet #2 (+X)	22	98002	-2.362	0.0	24.675
RCS Jet #3 (+Y)	23	98003	1.271	-1.433	24.802
RCS Jet #4 (-Y)	24	98004	1.271	1.433	24.802
RCS Jet #5 (-Y)	25	98005	-1.787	0.708	24.675
RCS Jet #6 (+Y)	26	98006	-1.787	-0.708	24.675
RCS Jet #7 (+X)	27	98007	-2.362	0.0	21.45
RCS Jet #8 (+X)	28	98008	-2.34	0.0	21.783

Axis: Roll, Pitch, Yaw

Direction: + (positive), - (negative)

Node Description, Node Number, Nastran Node ID Number, Location Coordinates (X, Y, Z)

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.

OK

Cancel

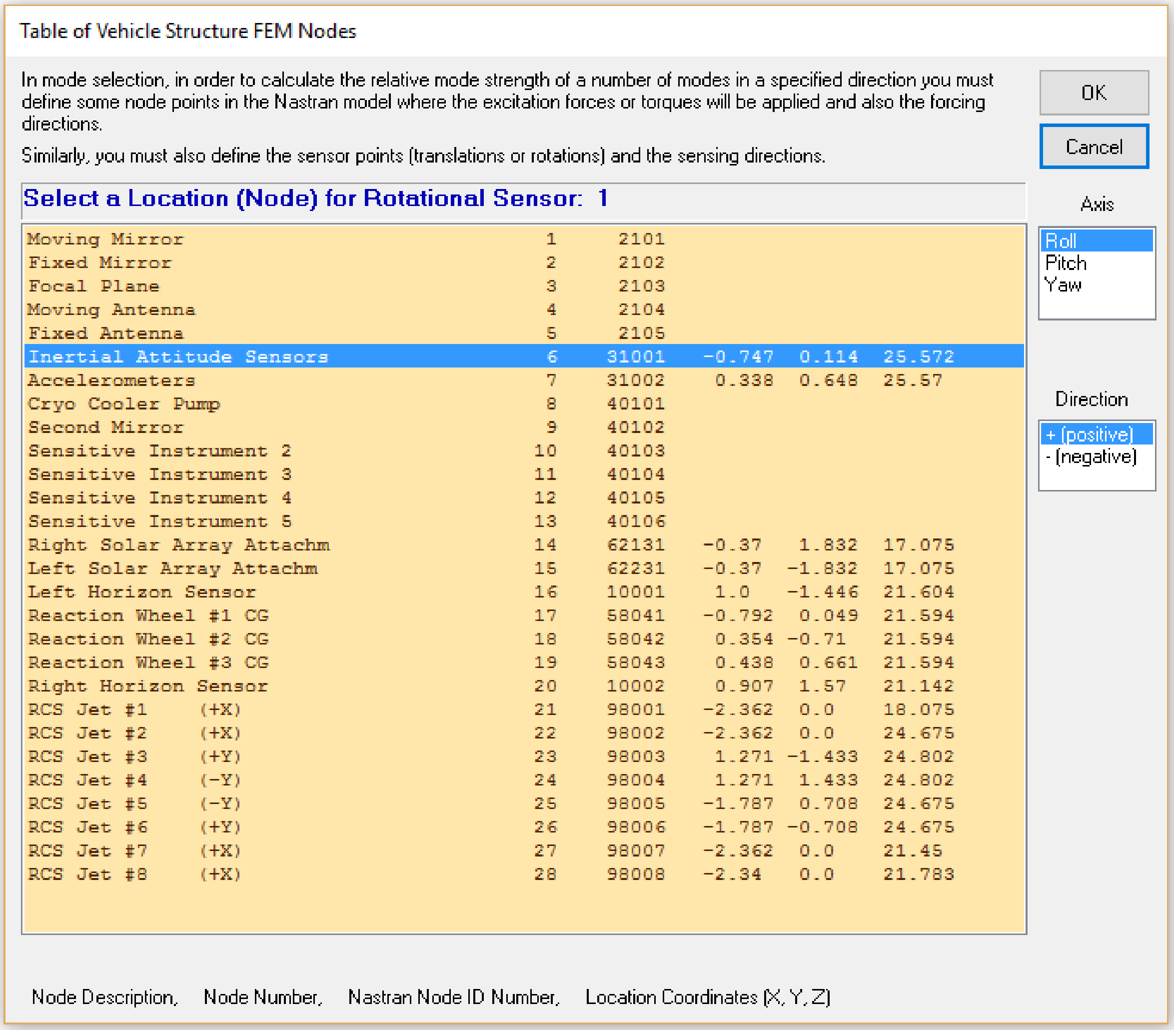
Select a Location (Node) for Torque Excitation: 6

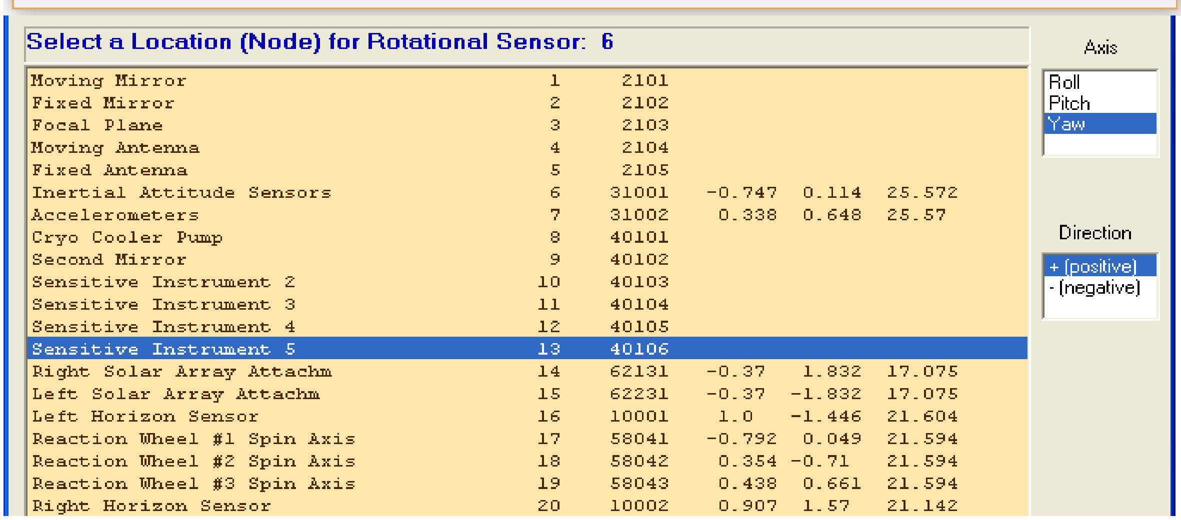
Moving Mirror	1	2101			
Fixed Mirror	2	2102			
Focal Plane	3	2103			
Moving Antenna	4	2104			
Fixed Antenna	5	2105			
Inertial Attitude Sensors	6	31001	-0.747	0.114	25.572
Accelerometers	7	31002	0.338	0.648	25.57
Cryo Cooler Pump	8	40101			
Second Mirror	9	40102			
Sensitive Instrument 2	10	40103			
Sensitive Instrument 3	11	40104			
Sensitive Instrument 4	12	40105			
Sensitive Instrument 5	13	40106			
Right Solar Array Attachm	14	62131	-0.37	1.832	17.075
Left Solar Array Attachm	15	62231	-0.37	-1.832	17.075
Left Horizon Sensor	16	10001	1.0	-1.446	21.604
Reaction Wheel #1 Spin Axis	17	58041	-0.792	0.049	21.594
Reaction Wheel #2 Spin Axis	18	58042	0.354	-0.71	21.594
Reaction Wheel #3 Spin Axis	19	58043	0.438	0.661	21.594
Right Horizon Sensor	20	10002	0.907	1.57	21.142
RCS Jet #1 (+X)	21	98001	-2.362	0.0	18.075
RCS Jet #2 (+X)	22	98002	-2.362	0.0	24.675
RCS Jet #3 (+Y)	23	98003	1.271	-1.433	24.802
RCS Jet #4 (-Y)	24	98004	1.271	1.433	24.802
RCS Jet #5 (-Y)	25	98005	-1.787	0.708	24.675
RCS Jet #6 (+Y)	26	98006	-1.787	-0.708	24.675
RCS Jet #7 (+X)	27	98007	-2.362	0.0	21.45

Axis: Roll, Pitch, Yaw

Direction: + (positive), - (negative)

We must also select nodes and directions for the 6 rotational sensors that were defined earlier, only for mode selection purposes. Node #6 was selected for the rotational sensors (1, 2, 3), measuring in the +roll, +pitch, and +yaw directions respectively. Similarly, nodes #11, #12, and #13 were selected to represent the rotational sensors (4, 5, 6), measuring in +roll, +pitch, and +yaw directions respectively.





At this point the program calculates the mode strength from all modes and it displays the mode strength comparison bar-plot showing the mode numbers in the horizontal axis and the corresponding relative mode strength on a vertical logarithmic scale. Initially all the modes appear in red. The user can select some of the strong modes by clicking on the corresponding bar and the color of the bar changes to green when the mode is selected. Notice, that in this demo the first 6 rigid-body modes are included in the model. We also created a flex model without the 6 rigid-body modes for different analysis. When the mode selection is complete the user must press the "Enter" key to complete the creation of the spacecraft dataset, and it will be saved in file "*Surveillance-Sat.Inp*". The program continues to process it, and it displays a menu that includes titles of spacecraft datasets already saved in the input file, including the latest one from our recent demo. The user selects one of the titles and clicks on "*Run Input Set*" to process it and to compute the flexible spacecraft state-space system in file "*Surveillance_Sat.Qdr*".