

Surveillance Satellite Attitude Control Design Using RCS Jets and Reaction Wheels

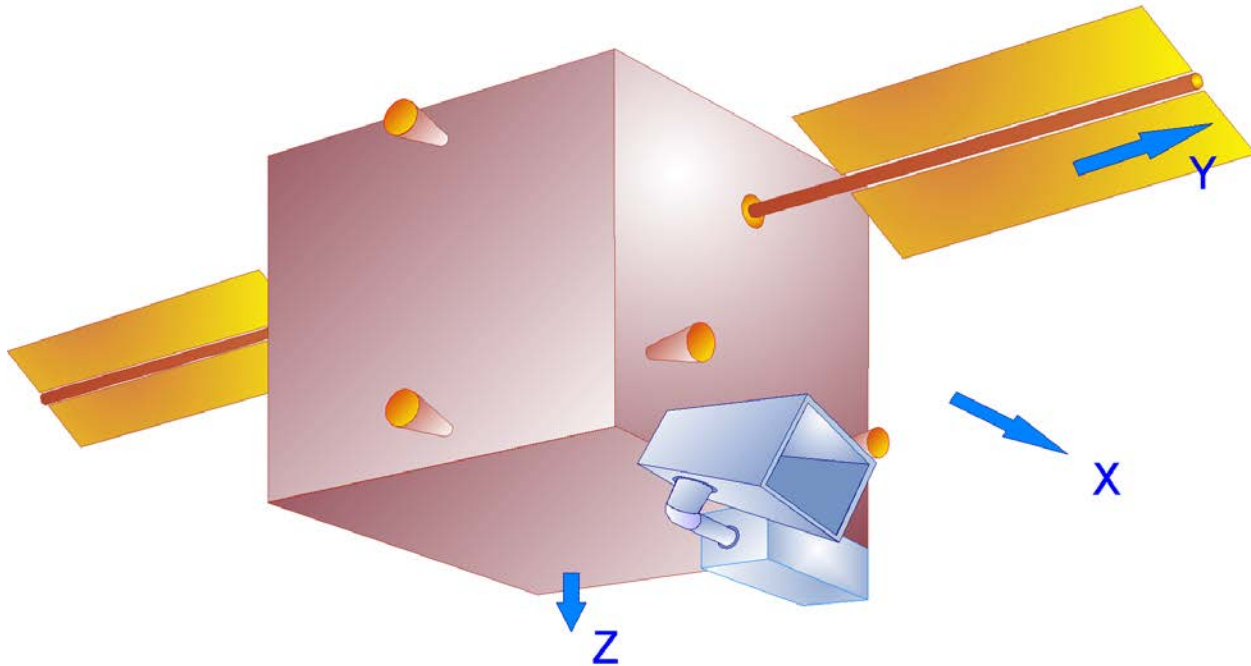


Figure 1 Surveillance Spacecraft with Reaction Wheels and a Rotating Telescope

The spacecraft in this example is a typical satellite with a pair of solar arrays and an optical instrument attached. The instrument can rotate in two directions (azimuth and elevation) relative to the spacecraft. The spacecraft includes 3 wheels for attitude control which are mounted as shown in figure 1.1. Two of the wheels, RW#2 & RW#3, are reaction wheels. Their spin axes are tilted 20° from horizontal and they can provide control torques only in pitch and yaw directions. Wheel #1 is a momentum wheel and it spins at constant rate. It is not actively used for attitude control but it provides a constant momentum of -40 (ft-lb-sec) in the pitch direction to provide passive roll/ yaw stabilization. The momentum bias provides a stiffening effect in the out-of-plane directions but it produces a nutation resonance that couples the roll and yaw axes. The lateral RW control law takes advantage of this dynamic coupling and dampens the nutation resonance. By stabilizing the roll axis, it also stabilizes yaw due to the gyroscopic coupling between the two axes. The spacecraft also includes 7 RCS jets for attitude control and momentum desaturation.

For attitude measurements the spacecraft uses horizon sensors which provide accurate pitch and roll attitude with respect to the local vertical local horizontal (LVLH) axes. The attitude control error requirement in pitch and roll is ± 1.5 (deg). Yaw control is allowed to be more relaxed during RW control, up to 7 (deg) of yaw error. Yaw attitude data are not required for attitude control purposes. There is, however, a slow and less accurate derived yaw estimate which is used to correct yaw drifts during momentum desaturations. External disturbance torques cause the RW momentum to build up and the accumulated momentum stored in the two reaction wheels is taken out by firing the reaction control jets. During desaturation the RCS jets control also the spacecraft attitude.

The following analysis focuses in a variety of typical satellite control design issues:

1. Designing a Reaction Wheel Attitude Control System for a Momentum Biased Spacecraft
2. Designing an RCS Attitude Control and Momentum Desaturation System
3. Designing a Telescope Gimbal Positioning Control System
4. Creating a Multi-Body Spacecraft Model, Controlling it, and Analyzing Jitter
5. Modeling and Stabilizing Structural Flexibility Modes, and
6. Creating Linear, Multi-Body, Flexible, Spacecraft Models and Analyzing Stability and Jitter Sensitivity to External Disturbances.

The ACS design and control analysis are presented systematically by separating them into seven sections. The complexity of the models and the analytic details increase from section to section. Different tools, models and simulations are employed to analyze various control and performance issues.

In Section 1 we derive the RW control laws for the momentum biased satellite that maintains an LVLH attitude as it orbits around the earth. In Section 2 we develop a rigid-body simulation model in Matlab for the orbiting spacecraft in LVLH attitude. The model includes both: reaction wheel and RCS control modes, and the loops are closed. The simulation includes a logic to switch between the two modes of operation. We simulate a pitch attitude maneuver using the RW control mode, followed by RCS control with momentum desaturation using the jets. We also analyze the RW stability of this rigid-body model.

In Section 3 we use the Flixan “Flexible Spacecraft” modeling program to create state-space systems for the flexible spacecraft structure from a Finite Element Model (FEM) which includes the rigid-body modes implemented as structure modes. The FEM also includes data to combine the spacecraft with the gimbaling telescope. We create a simple Simulink model to simulate this flexible spacecraft system using closed-loop RCS control. We also create gimbal controls for the telescope to position it in elevation and azimuth angles and we analyze its sensitivity to spacecraft disturbance.

In Section 4 we use Simulink to combine the non-linear rigid body model of Section 2 which is implemented as a Matlab function in parallel with the flex structure model created in Section 3. We simulate its response to environmental disturbances and analyze the combined system stability. We also design flex filters to attenuate some of the structural modes. In Section 5 we focus on linear analysis. We begin with the linear equations of motion which are implemented in a Simulink block. The linear block is connected in parallel with a flexible structure block and we analyze this system’s stability and performance as in Section 4.

In Section 6 we introduce the dynamics of the gimbaling telescope which rotates in two directions (elevation, and azimuth) relative to the spacecraft bus. A non-linear 3-body dynamic model is created in Matlab to simulate the spacecraft dynamics and the relative motion of the 3 bodies (spacecraft, telescope, and telescope yoke). The Solar Arrays are not gimbaling but they are assumed to be rigidly attached to the bus. Translational orbital motion of the spacecraft in the ECI frame is included in the simulation. The 3-body rigid spacecraft model is also combined with a flex model and the previous Section-4 analysis is repeated using the multi-body vehicle model. A simple position control system for the telescope gimbals is included and the stability and sensitivity of the telescope gimbal loops (elevation & azimuth) are analyzed.

In Section 7 we create a different state-space system for the spacecraft using the Flixan “Flight Vehicle Modeling” Program. This is a linear model in the LVLH attitude. It includes the RWs, the two telescope gimbals, the RCS jets, Gravity-Gradient, disturbance torques, plus flexibility. We also used this model to validate previous models by analyzing stability and Line-of-Sight (LOS) sensitivity to spacecraft disturbances.

1.0 Spacecraft Attitude Control System

The surveillance satellite is in circular orbit around the earth and it is maintaining a local vertical, local horizontal (LVLH) attitude, which is the z-axis pointing towards the center of the earth and the x-axis along the velocity vector. The orbital rate is $\omega_o=0.00113$ (rad/sec) so the spacecraft has a steady negative pitch rate equal to $(-\omega_o)$. There are three wheels mounted on the spacecraft for attitude control and stabilization. Wheel #1 in the middle is a Momentum Wheel (MW). Its spin axis is horizontal and it is rotating about the spacecraft -y axis in negative pitch direction, maintaining at a constant rate -500 (deg/sec) by a motor speed controller that provides -40 (ft-lb-sec) momentum bias to the spacecraft. This is in addition to the momentum due to negative spacecraft rotation at orbital rate. Wheel #1 is not actively used for attitude control but it provides passive roll/yaw stabilization. The other two are reaction wheels (RW#2 and RW#3). They are tilted $\pm 20^\circ$ with respect to the spacecraft y axis and they provide active pitch and yaw control by additive and differential wheel accelerations. There is no RW momentum component in the x direction for controlling roll directly, but the spacecraft is stabilized gyroscopically in the out of plane directions by the pitch momentum bias that couples the rotations in roll and yaw. The purpose of the attitude control system is to control the spacecraft attitude close to the LVLH attitude and to allow small pitch maneuvers. The ACS allows up to 1.5° error in pitch and roll and up to 7° in yaw. The spacecraft is excited by environmental disturbance torques in pitch and yaw, which are both cyclic with a steady bias component (secular) and they create attitude errors. They are due to aerodynamic and gravity gradient torques. Secular disturbances require steady torques which increases the RW momentum and need frequent desaturation when the momentum approaches saturation levels. There are 7 RCS jets of 0.05 (lbf) thrust each, used for attitude control and RW momentum desaturation. There are 3 jets thrusting in the velocity (+x) direction used for pitch control and orbit re-boost. There are also 4 jets pointing in the $\pm y$ direction for roll and yaw control. In addition to attitude control the RCS jets are mainly used to desaturate the reaction wheel momentum which is only in pitch and yaw since there is no RW component in the x direction.

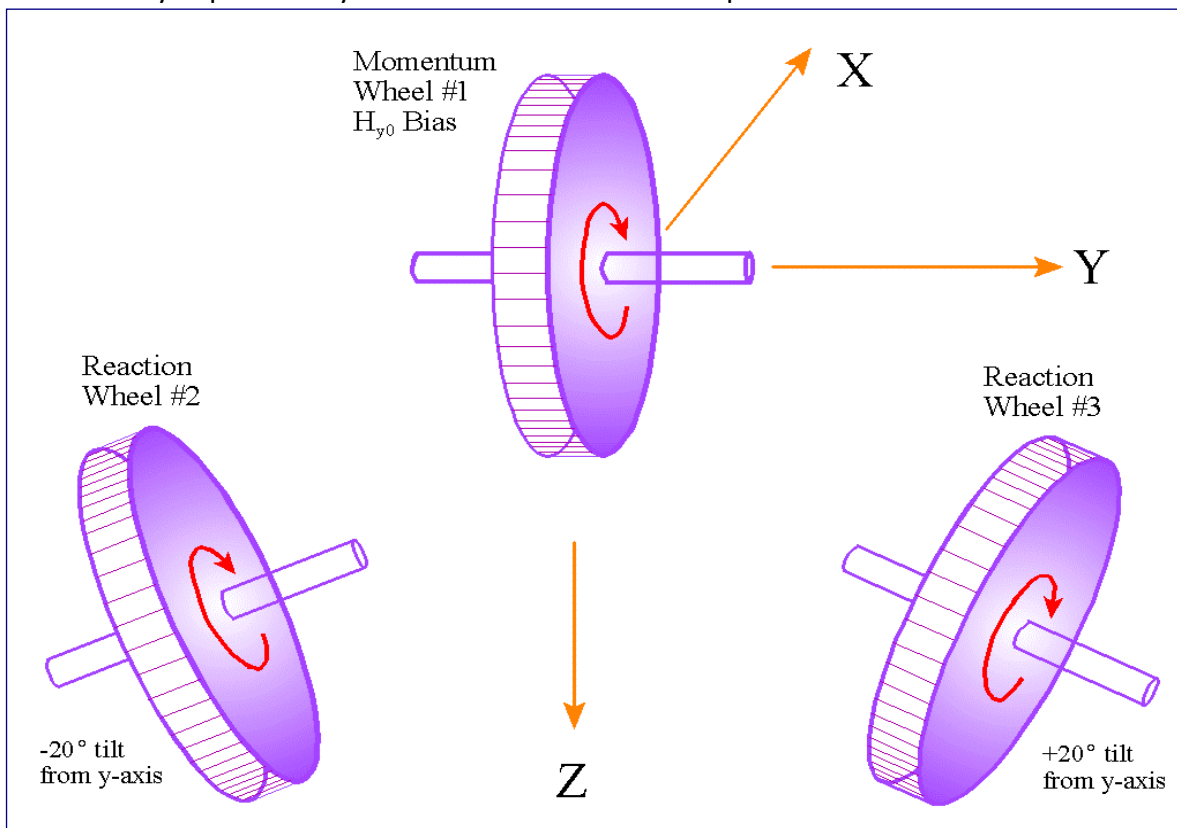


Figure 1.1 Momentum Wheel and 2 Reaction Wheels Configuration

1.1 Attitude Control Design

The attitude control system (ACS) operates in two modes: the RW mode and the RCS mode. In the RW mode the RWs are used to control attitude until the RW momentum exceeds a certain amount relative to the nominal bias level, and when it happens, jets are fired to desaturate the wheels. In fact, the attitude control system switches to the RCS mode and it is stabilized by the RCS while the wheels are torqued in the direction that zeros the RW (#2 and #3) momentum. The duration of the RCS operation is much shorter because there is more torque availability. Telescope operations occur only during RW control periods because the jets generate jitter that corrupts the image quality. During RCS control RW #1 is continuously driven to maintain the -40 (ft-lb-sec) bias momentum. The attitude control system is designed based on the attitude equations of motion of a spacecraft in the LVLH frame. The linearized equations of motion about the spacecraft principal axes are:

$$I_X \ddot{\phi} + \omega_0 H'_{WY} \phi + H'''_{WY} \dot{\psi} - \omega_0 H_{WZ} + \dot{H}_{WX} = T_{dX} + T_{cX}$$

$$I_Y \ddot{\theta} + 3\omega_0^2 (I_X - I_Z) \theta + \dot{H}_{WY} = T_{dY} + T_{cY}$$

$$I_Z \ddot{\psi} + \omega_0 H''_{WY} \psi + H_{WY} \dot{\phi} + \omega_0 H_{WX} + \dot{H}_{WZ} = T_{dZ} + T_{cZ}$$

where :

$$H'_{WY} = 4\omega_0 (I_Y - I_Z) + H_B$$

$$H''_{WY} = \omega_0 (I_Y - I_X) + H_B$$

$$H'''_{WY} = \omega_0 (I_Y - I_X - I_Z) + H_B$$

- (ϕ, θ, ψ) attitude angles in the LVLH frame about (x, y, z), respectively
- (ω_0) is the spacecraft orbital rate (rad/sec)
- (H_B) is the bias momentum in the pitch axis (positive along $-y_b$)
- (T_d) are the environmental disturbance torques
- (T_c) are the reaction wheel control torques

The pitch equation which is in the orbital plane, is decoupled from the roll/ yaw (out-of-plane) dynamics allowing the three-axis control problem to be reduced to two separate systems: a pitch axis and a lateral axis. The control system attempts to minimize the attitude perturbations produced by the environmental torques. The gains are designed directly from the equations of motion.

Pitch Control

The pitch axis is a standard PID reaction wheel attitude control system designed to provide a bandwidth of 0.02 (rad/sec), and damping $\zeta=0.8$. The rate of change of pitch wheel momentum is commanded as a shaped function of the measured pitch attitude in order to remove the pitch attitude errors and to dampen the pitch motion.

Out-of-Plane Control Law

Roll and yaw control in this spacecraft is accomplished gyroscopically by virtue of the pitch momentum bias. From the roll and yaw equations, assuming only pitch momentum bias and ignoring the slow orbital rate, we can obtain an open-loop solution for the roll and yaw rates which are coupled by the nutation frequency (ω_n). Passive damping is used to attenuate the nutation oscillations amplitude after being excited by jet firing (not shown).

$$\dot{\phi} = A \cos(\omega_n t)$$

$$\dot{\psi} = A \sqrt{\frac{I_X}{I_Z}} \sin(\omega_n t); \text{ where: } \omega_n = \frac{H_B}{\sqrt{I_X I_Z}}$$

By taking advantage of the gyroscopic coupling between roll and yaw, the yaw momentum is commanded as a function of the measured roll attitude error. After combining the yaw and roll equations together and ignoring the small orbital rate we obtain

$$I_X \ddot{\phi} + \frac{H_B^2}{I_Z} \phi - \frac{H_B}{I_Z} H_{WZ} = T_{dX} + T_{cX} - \frac{H_B}{I_Z} \int (T_{dX} + T_{cX}) dt$$

Controlled damping of the roll and yaw nutational motion can be accomplished by commanding the yaw momentum H_{WZ} as a function of roll rate. In addition, to reduce the roll attitude offsets in response to external disturbances, the yaw momentum is also commanded as a function of the integral of roll attitude. Finally, since the roll rate is not measured directly but it is derived by lead shaping of the measured roll attitude, a roll attitude error term will also be present in the control law for commanding yaw momentum as a function of roll attitude, that is

$$H_{WZC} = -[K_1 \dot{\phi} + K_2 \phi + K_3 \int \phi dt]$$

After substitution the characteristic equation can be simplified to a third order in the following form

$$\left[I_X \lambda^2 + \frac{K_1 H_B}{I_Z} \lambda + \frac{H_B}{I_Z} (K_2 + H_B) \right] \left(\lambda + \frac{K_3}{K_2 + H_B} \right) \approx 0$$

The complex pair of roots can be characterized by a natural frequency and damping ratio

$$\omega_c = \sqrt{\frac{H_B (K_2 + H_B)}{I_X I_Z}} ; \quad \zeta = \frac{K_1}{2} \sqrt{\frac{H_B}{I_X I_Z (K_2 + H_B)}}$$

The objective in gain selection is to achieve the desired nutation damping by the proper choice of K_1 gain. The nutation frequency increases with K_2 . The integrator root should be more than 1/10 the real part of the complex root pair. A good choice of gains is

$$K_1 = \frac{0.1 \zeta^2 I_X I_Z}{H_B} + \sqrt{\frac{0.01 \zeta^4 I_X^2 I_Z^2}{H_B^2} + 4 \zeta^2 I_X I_Z}$$

$$K_2 = 0.05 K_1$$

$$K_3 \leq 0.1 \zeta (K_2 + H_B) \sqrt{\frac{H_B}{I_X I_Z}}$$

2.0 Rigid Body Simulation

In this Section we will develop a non-linear simulation model of an orbiting spacecraft that is maintaining a local-vertical local-horizontal (LVLH) attitude and we will linearize this model to analyze stability. We begin by describing the non-linear rigid-body equations, the vehicle dynamics, the control system, the Simulink models that implement these functions, and present simulation and stability analysis results. The Simulink files for this example are in “\Examples\10-Surveillance Satellite React-Wheels\1-Rigid-Body Sim”.

2.1 Non-Linear Dynamic Equations

The linearized equations of motion in Section 1 are used for the derivation of attitude control gains. The attitude control system attempts to keep the spacecraft at constant attitude with respect to the LVLH. The LVLH frame rotates at orbital rate. The spacecraft x axis is towards the velocity vector, the z axis is pointing towards the center of the earth, and the y axis is perpendicular to the x-z plane towards the right solar array. The following equations describe the non-linear dynamic motion of a spacecraft with Reaction Wheels with respect to the LVLH frame.

$$\begin{aligned} I\dot{\underline{\omega}} &= -(\underline{\omega} \times I\underline{\omega}) + 3\omega_o^2(\underline{c} \times I\underline{c}) + \underline{T}_{RCS} + \underline{T}_d + \underline{T}_{RW} \\ \dot{\underline{H}}_{RW} &= -\underline{T}_{RW} - (\underline{\omega} \times \underline{H}_{RW}) \end{aligned} \quad (2.1)$$

If we assume that the reaction wheel torque T_{RW} consists of the control torque plus a term that cancels out the gyroscopic torque $(\omega \times H_{RW})$

$$\underline{T}_{RW} = \underline{T}_{WC} - (\underline{\omega} \times \underline{H}_{RW})_{estim} \quad (2.2)$$

Then the equations simplify in the following form

$$\begin{aligned} I\dot{\underline{\omega}} &= -(\underline{\omega} \times \underline{H}_{sys}) + 3\omega_o^2(\underline{c} \times I\underline{c}) + \underline{T}_{RCS} + \underline{T}_d + \underline{T}_{WC} \\ \dot{\underline{H}}_{RW} &= -\underline{T}_{WC} \\ \underline{H}_{sys} &= I\underline{\omega} + \underline{H}_{RW} \end{aligned} \quad (2.3)$$

Where:

T_{WC} is only the control part of the RW torque, excluding the gyroscopic torque

H_{RW} is the reaction wheel momentum, and

H_{sys} is the system momentum

$\underline{\omega}$ is the spacecraft body rate and ω_o is its circular orbit rate (0.0011 rad/sec). In the top equation, the first two non-linear terms on the RHS of the moment equation are the gyroscopic and gravity gradient torques respectively. T_{RCS} , T_{WC} and T_D are the RCS torques, the reaction wheel control torques, and the disturbance torques respectively applied in the body axes. The state-vector is initialized in the LVLH attitude, which has an initial pitch rate equal to $(-\omega_o)$. The attitude kinematics equation calculates the Euler angles (ϕ, θ, ψ) with respect to the LVLH frame by integrating the transformed body rates $\underline{\omega}$. The bottom equation in equations 2.1 calculates the rate of change in the reaction wheel momentum in body axis as a function of the RW torque T_{RW} . The spacecraft attitude control system is designed by taking into consideration the constant pitch bias in the system momentum. The 3 wheels are initialized at $H_{RW} = (-40, 0, 0)'$ (ft-lb-sec).

$$I = \begin{bmatrix} I_{XX} & I_{XY} & I_{XZ} \\ I_{XY} & I_{YY} & I_{YZ} \\ I_{XZ} & I_{YZ} & I_{ZZ} \end{bmatrix}; \quad c = \begin{bmatrix} -\sin \theta \cos \psi \\ \cos \phi \sin \theta \sin \psi + \sin \phi \cos \theta \\ -\sin \phi \sin \theta \sin \psi + \cos \phi \cos \theta \end{bmatrix}$$

$$\begin{pmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{pmatrix}_{LVLH} = \omega_{LVLH} = C_B^L \underline{\omega} + \begin{pmatrix} 0 \\ \omega_o \\ 0 \end{pmatrix} \quad (2.4)$$

$$\text{where: } C_B^L = \frac{1}{\cos \psi} \begin{bmatrix} \cos \psi & -\cos \phi \sin \psi & \sin \phi \sin \psi \\ 0 & \cos \phi & -\sin \phi \\ 0 & \sin \phi \cos \psi & \cos \phi \cos \psi \end{bmatrix}$$

The Matlab simulation model is in folder "... \Examples\10-Surveillance Satellite React-Wheels\1-Rigid-Body Sim". The Simulink model is "NonLinear_Sim.mdl", is shown below in Figure 2.1. The non-linear equations 2.1 are coded in Matlab function "NonLin-Vehi-Dynamics.m" which is implemented in the subsystem block "Spacecraft Non-Linear Dynamics" in the Simulink model, Figure 2.1. There is a pitch attitude command on the left side. The roll and yaw commands are zero.

Spacecraft with Reaction Wheels, RCS Jets and Pitch Momentum Bias, Non-Linear Simulation

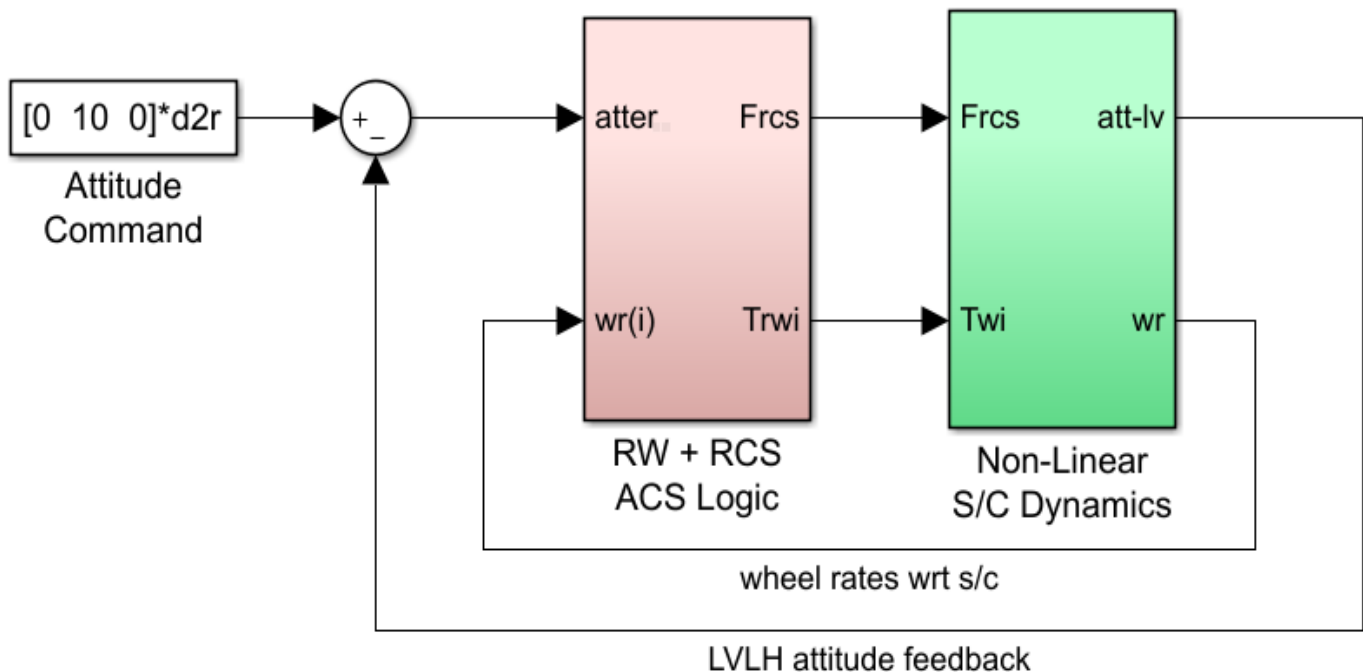


Figure 2.1 Rigid-Body Simulation Model in file "NonLinear_Sim.slx"

Non-Linear Spacecraft Dynamics

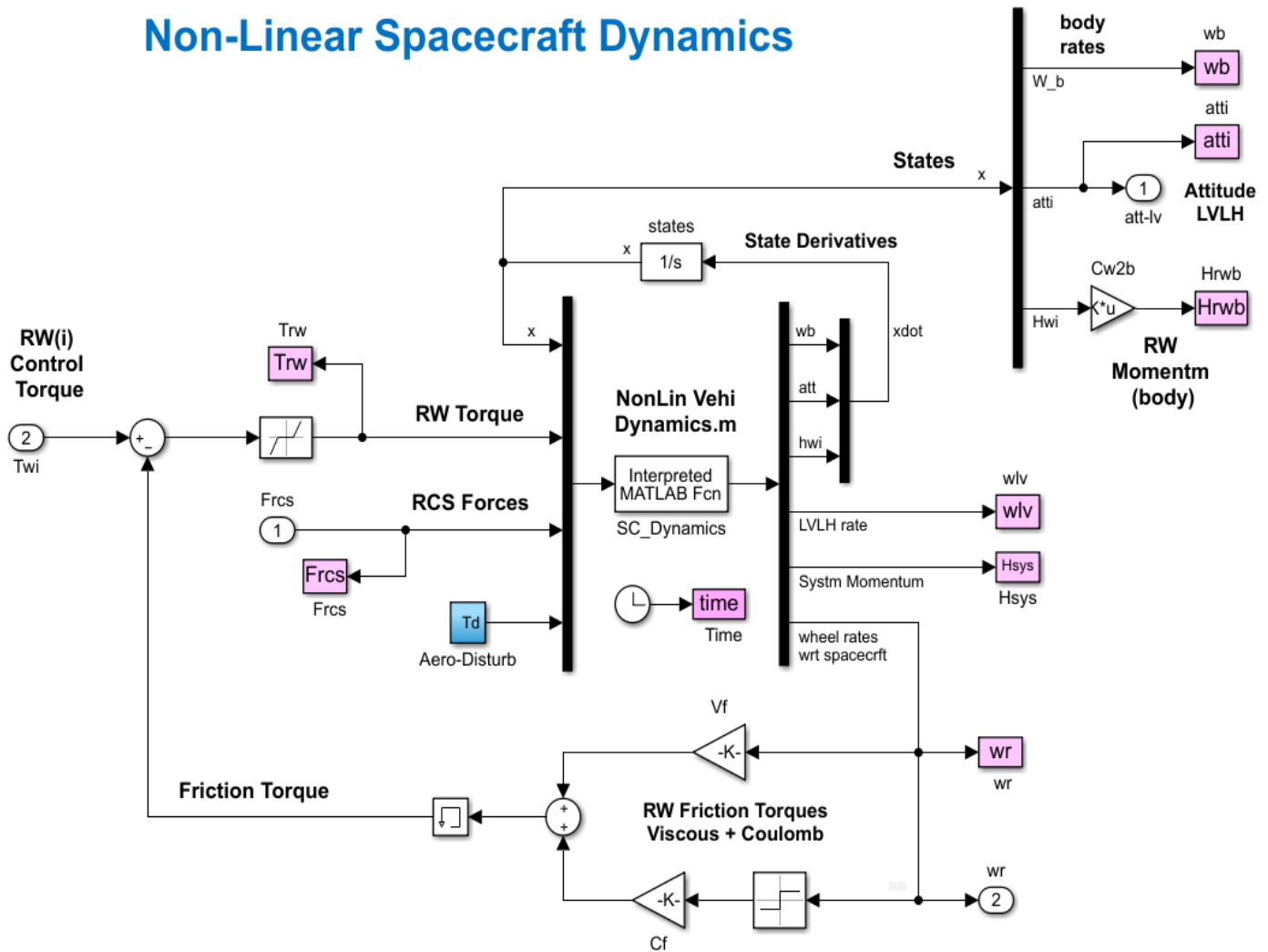


Figure 2.2 Spacecraft Dynamics block that includes Matlab function “NonLin_Vehi_Dynamics.m”

Figure 2.2 shows the spacecraft dynamics block that includes the vehicle equations of motion implemented as a Matlab function “NonLin-Vehi-Dynamics.m”, see Fig.2.2b. The inputs to the spacecraft model are: 9 state updates, 3 reaction-wheel control torques (T_{RW}), the first one is a small torque against friction to maintain a steady rate. There are also 7 RCS jet forces, and an external aero disturbance torque (T_d) in pitch and yaw. The dynamics block calculates the derivative of the state-vector (9 states) which is updated by an integrator loop around the Matlab function. The gravity-gradient torques are calculated internally as a function of the LVLH Euler angles. There is a mechanical feedback loop that calculates the RW friction torque as a function of the wheel speeds. It consists of viscous plus coulomb friction components. The motor torque for each wheel must exceed the Coulomb friction before the wheels begin to accelerate. The state vector consists of spacecraft body rates, LVLH attitude, and momentum for the 3 reaction wheels. There are additional outputs used in the simulation, such as: rates with respect to the LVLH, combined spacecraft and RW system momentum, individual wheel rates relative to spacecraft, and the reaction wheel momentum resolved in body axes. The transformation matrix CB2L is used to transform the vehicle attitude and rate from body to LVLH coordinates and it is included in the equations of motion. The vehicle parameters and integrators are initialized by the Matlab script “run.m”.


```

function out= NonLin_Vehi_Dynamics(x,Twi,f,Td) % Non-Linear Spacecraft Model
global J JI Iw Cw2b cg nt Jloc Jdir CB2L wo
% State Variables (x):
% x(1-3) = Body rates (wb) (rad/sec)
% x(4-6) = Wheel rates rel to s/c (wr) (rad/sec)
% x(7-9) = Reaction Wheel (i) Momentum (hwi) (ft-lb-sec)
% Inputs :
% Twi(3) = Reaction Wheel (i) Torques (ft-lb)
% f(nt) = RCS Forces (lbf)
% Td(3) = Disturbance Torque

xdot=zeros(9,1); wr=zeros(3,1); % Initialize
wb = x(1:3); % body rates (rad/sec)
the = x(4:6); % LVLH Attitude vector (rad)
hwi = x(7:9); % React-Wheel (i) momentum
Hsys= J*wb + Cw2b*hwi; % System Momentum (s/c+wheels)

cphi= cos(the(1)); sph= sin(the(1)); % Euler Angles
cthe= cos(the(2)); sthe= sin(the(2));
cps= cos(the(3)); sps= sin(the(3));

c= [-sthe * cps; ... % Gravity Gradient terms
    cphi * sthe * sps + sph * cthe; ...
    -sph * sthe * sps + cphi * cthe];

CB2L= [cps, -cphi*sps, sph*sps; ... % Body to LVLH Transform matrix
       0, cphi, -sph; ...
       0, sph*cps, cphi*cps]/cps;

% Thruster Forces and Moments
Tr= zeros(3,1);
for i=1:nt
    ma= Jloc(:,i) - cg; % Jet moment arms (ft)
    Tr= Tr + f(i)*cross(ma,Jdir(:,i)); % RCS Torques (ft-lb)
end

xdot(1:3)= JI*(Tr +Td - Cw2b*Twi ... % Vehi rotational accelerat
            + 3*wo^2*cross(c,J*c) - cross(wb,Hsys) );
wlv= CB2L*wb + [0, wo, 0]'; % rate of Euler rates wrt LVLH
xdot(4:6)= wlv; % rate of Euler angls wrt LVLH
xdot(7:9)= Twi; % rate of Reaction Wheel Momentum

for i=1:3; wr(i)= (hwi(i)/Iw) -dot(Cw2b(:,i),wb); end % Measured Wheel Rates wrt Spacecraft
out=[xdot; wlv; Hsys; wr];

```

Figure 2.2b Spacecraft Dynamics Function “NonLin_Vehi_Dynamics.m”

The spacecraft motion is also excited in pitch and yaw by an external aerodynamic disturbance torque T_d , which consists of secular and cyclic components. The cyclic components are mainly due to the rotation of the solar arrays at orbital rate (ω_o) and the variation in atmospheric density between the bright and dark sides of the earth. There is also disturbance torques occurring at twice the orbital rate ($2\omega_o$) because the satellite has less aero drag when the arrays are horizontal and more drag when they are vertical. There are secular disturbances in both pitch and yaw due to lack of aerodynamic symmetry (the satellite center of pressure is above the CG, and there is also an optical instrument on the right side). This biases the RW control torque which eventually saturates the RW momentum and a regular momentum desaturation with the RCS jets is needed.

2.2 Reaction Wheels

A simplified model of a reaction wheel is shown in figure 2.3. The torque applied to the spacecraft is equal to the torque generated by the RW motor minus the friction torque. The friction torque consists of two components: viscous friction which is proportional to the wheel rate plus Coulomb friction which opposes the motion at a constant magnitude. The wheel does not accelerate until the applied torque exceeds the Coulomb friction which is represented by a small dead-zone. This model is implemented in the Simulink file "RW.mdl". The momentum wheel device is almost identical to the reaction wheels. It has the same moment of inertia as the RW and its speed is maintained at constant rate 4770 (rpm). It does not accelerate and does not produce any torque about the spin direction but only gyroscopic torques in the orthogonal directions due to $(\omega \times H)$ coupling with the spacecraft rate.

Reaction Wheel Dynamics

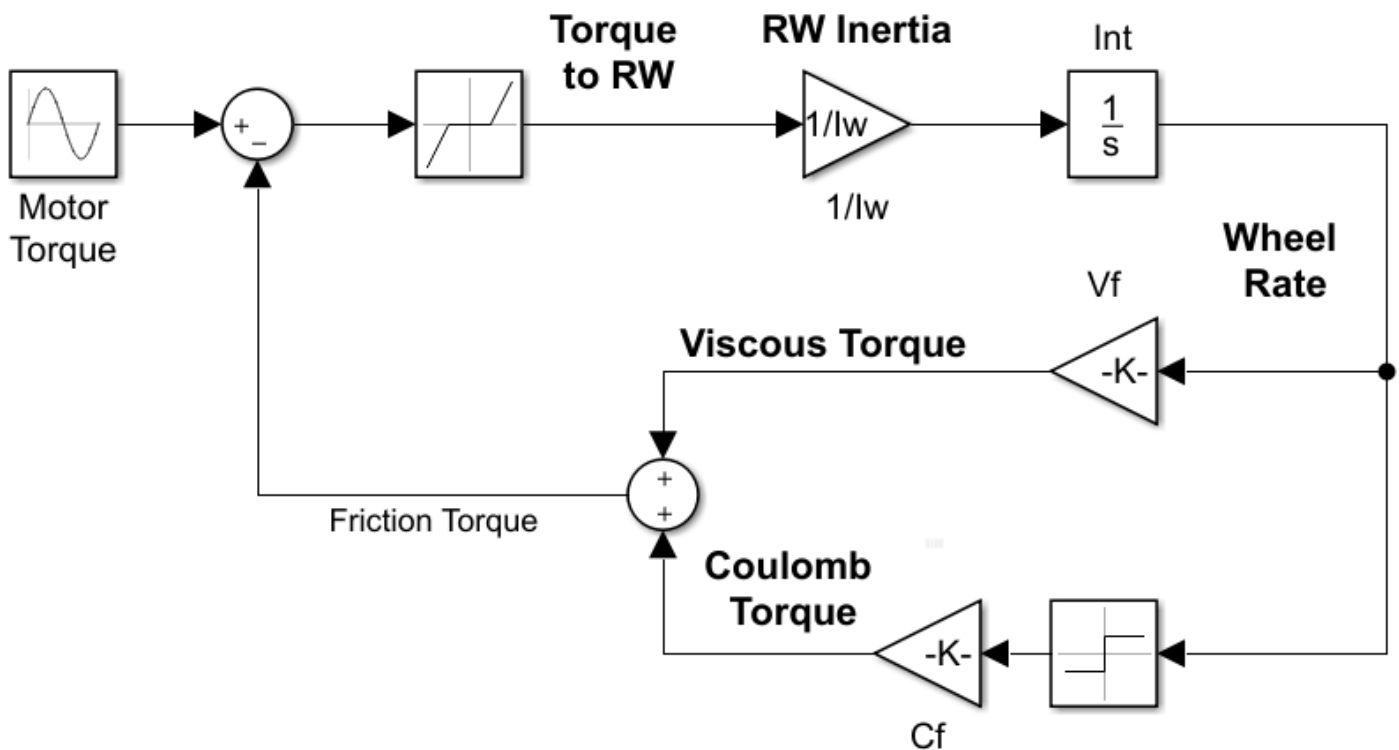


Figure 2.3 Reaction Wheel Dynamic Model

2.3 Attitude Control System

The combined attitude control and momentum desaturation system is shown in Figure 2.4. It includes both, RW and RCS control laws operating in two separate modes. There is a mode switching logic that turns on the RCS attitude controller when the RW momentum approaches saturation. During RCS control the wheels are torqued in the direction that nulls the RW momentum while the RCS maintains the desired attitude.

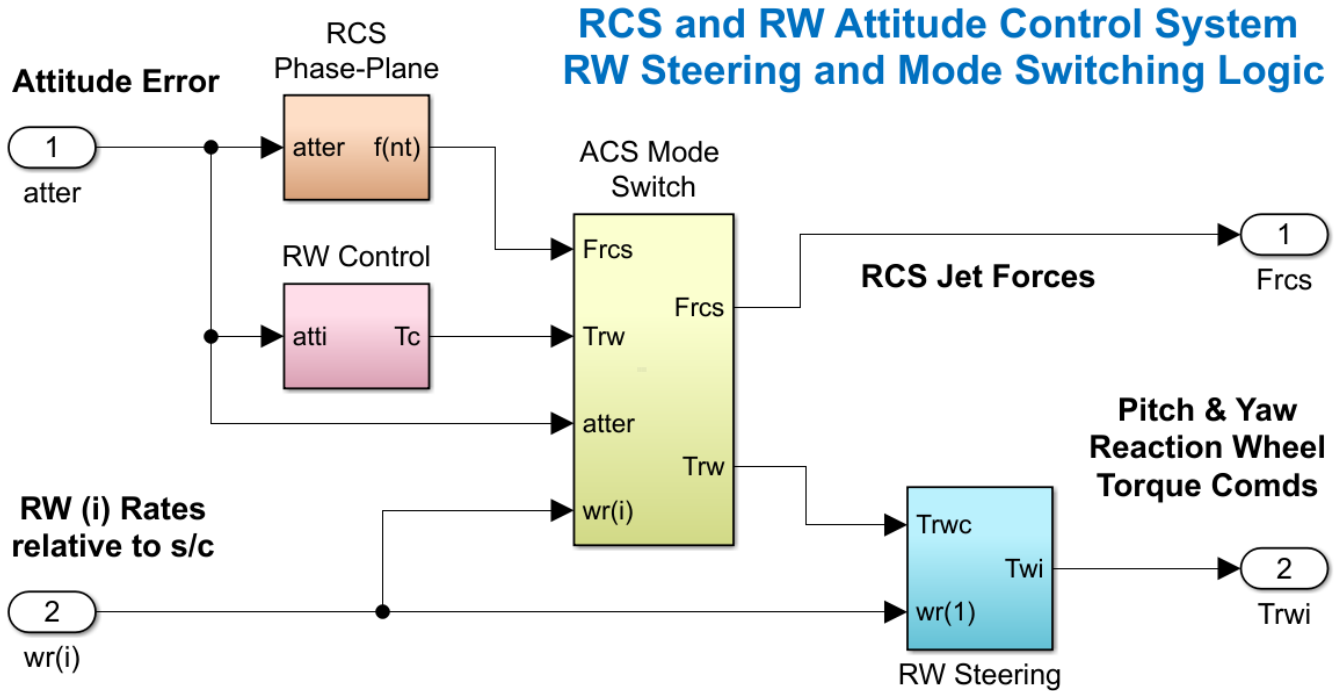


Figure 2.4 Combined Reaction Wheel plus RCS Attitude Control System

2.3.1 Reaction Wheel Control System

The derivation of the reaction wheel control law was described in Section 1.1. The inputs are roll and pitch LVLH attitude errors and the outputs are pitch and yaw torque commands to the reaction wheels. Roll is controlled gyroscopically by yaw commands by taking advantage of the pitch momentum bias. The coupling between roll and yaw also provides some degree of yaw stabilization.

Reaction Wheel Control Law

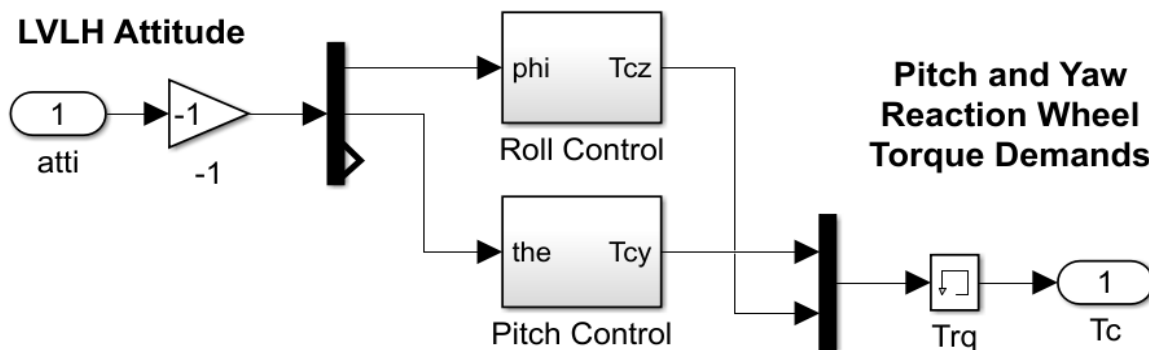


Figure 2.5 Reaction Wheel Control Law

Pitch Control Logic

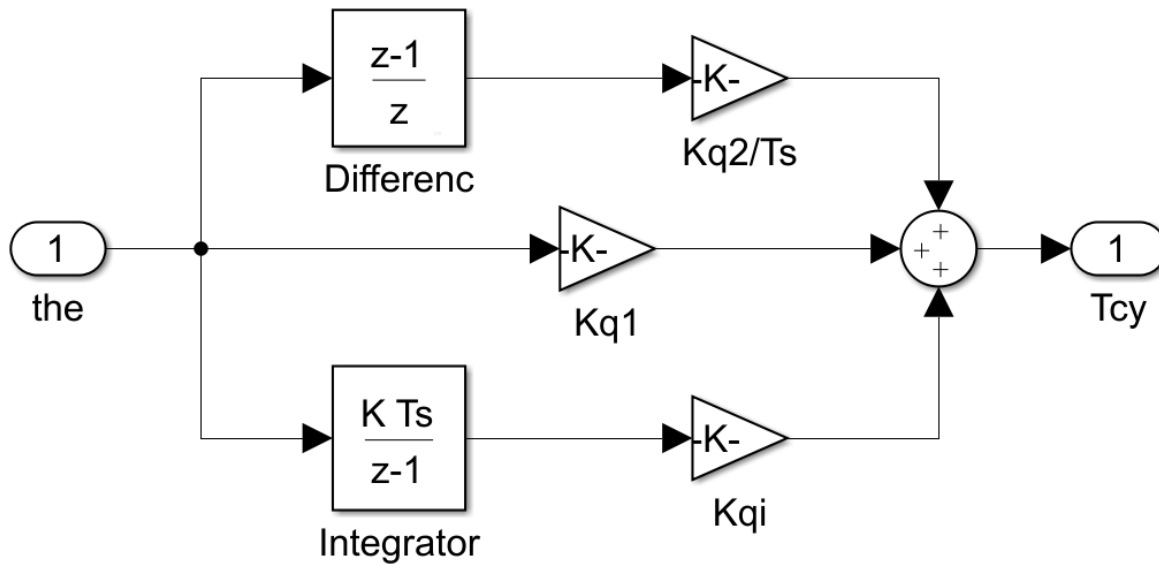


Figure 2.5.1 Pitch Reaction Wheel PID Control Law

Roll/ Yaw Control Logic

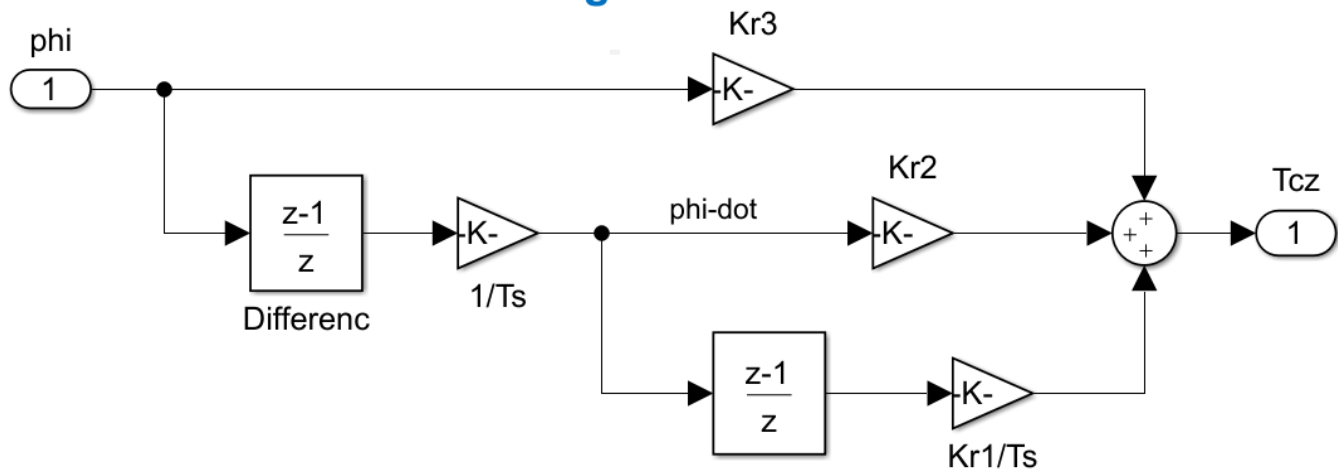


Figure 2.5.2 Out-of-Plane Reaction Wheel Control Law

2.3.2 Reaction Wheel Steering Logic

The RW steering logic performs two functions. The first function is to transform the pitch and yaw torque commands from the RW attitude control system into RW#2 and RW#3 torque commands. As we described earlier the average momentum in RW#2 and RW#3 should be zero and they provide pitch and yaw control torque to the spacecraft. An electric motor accelerates or decelerates the wheels about their spin axis and it produces a torque. The max torque magnitude that each RW produces is approx. 0.05 (ft-lb). There is a limiter in the steering logic that saturates the commanded wheel torques magnitude, so that their torque does not exceed the max torque capability. During torque limiting, the maneuver maintains the commanded eigenaxis direction. The steering logic subsystem also regulates the speed of wheel #1 by providing the necessary torque to overcome RW#1 friction and to maintain constant rate -500 (rad/sec) relative to the spacecraft. Wheel #1 provides momentum biasing to the spacecraft in the pitch direction for passive roll/ yaw stabilization. The total pitch momentum of the spacecraft system consists of wheel plus spacecraft momentum and they are both in the negative direction.

Reaction Wheel Steering Logic

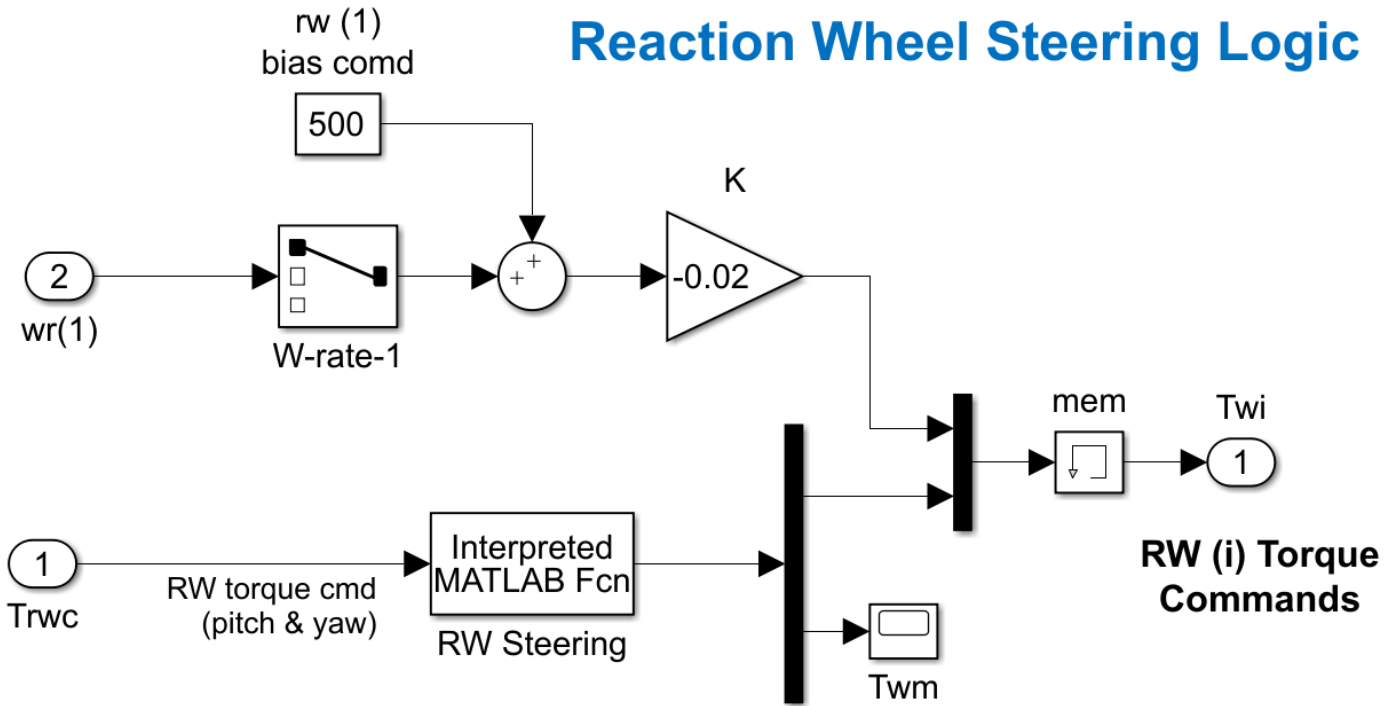


Figure 2.6 Reaction Wheel Steering and Wheel #1 Speed Control

```
function out = RW_Steering(Tc)
global Cb2w Tmax
% Converts the Torque Commands from s/c Body to Wheel torques
% Tc      = Torque Command (ft-lb)

Twc=zeros(3,1);
Twc= Cb2w*Tc;                                % Wheel(2,3) Torque command= Cb2w*(Tc + cross(wb,Hsys))
Twm= sqrt(Twc'*Twc);                          % Magnitude of torque commd
if Twm>Tmax; Twc= Tmax*Twc/Twm; end           % Limit Torque Command
out= [Twc; Twm];                             % Torque Commands for wheels 2 & 3, Torq magn
```

2.3.3 RCS Phase-Plane/ Jet Selection Attitude Control System

Figure 2.7 shows the RCS attitude control system (orange block in figure 2.4) which is a phase-plane with jet selection logic operating on the attitude and rate errors. It is implemented in the Matlab function “Phase-Plane.m”. The inputs to the phase-plane logic are spacecraft attitude and rate errors. Since only attitude measurements are available and not rates, the rates are obtained by differentiating the LVLH attitude errors in the z-domain. The phase-plane calculates the ideal direction of rotation eigenvector and calls the jet-selection logic (implemented in function “Jet_Select_dot.m”) to determine the jets to be fired. The jet-selection logic fires either one or two jets in order to rotate the spacecraft about an axis that is close to the commanded direction. The selection of jets is determined by calculating the dot-product contribution of each thruster in the commanded direction. Then, either one or two jets are selected to fire in order to provide maximum acceleration in that direction. The outputs of the phase-plane block are the 7 jet thrusts and the unit vector direction of the vehicle rotation.

Phase-Plane and Jet Selection

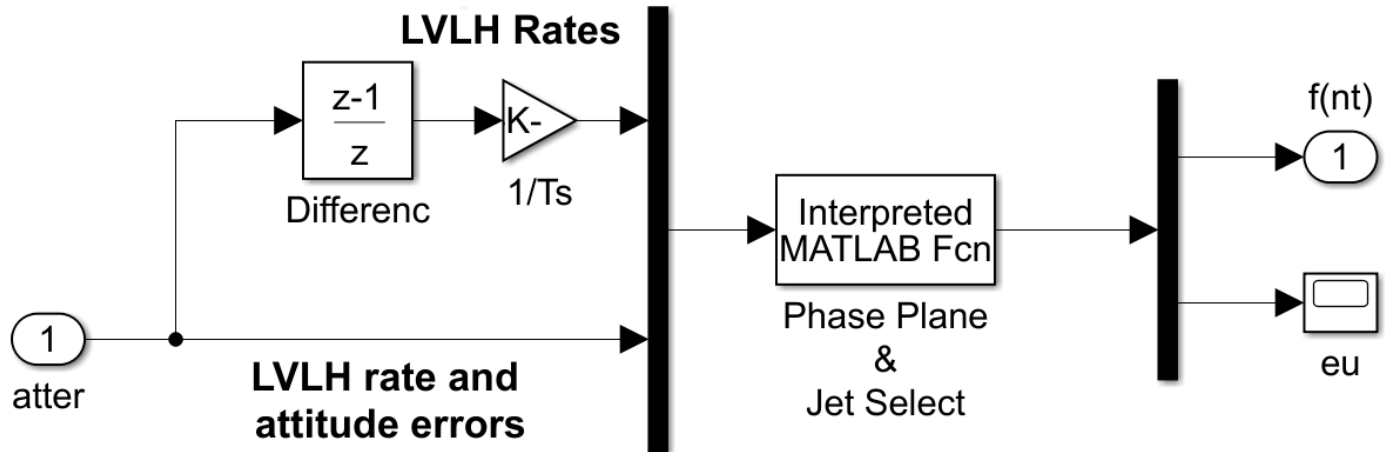


Figure 2.7 Phase-Plane and RCS Jet Selection Logic

2.3.4 ACS Mode Switching Logic for Momentum Desaturation

The ACS mode switching block (the yellow block in figure 2.4) is shown in Figure 2.8. It is used to switch between the RW and RCS attitude control modes of operation. When the magnitude of the combined RW#2 and RW#3 momentum is below 10 (ft-lb-sec), the spacecraft remains in the RW mode and it does not fire any jets. Pitch and roll attitudes are controlled more accurately than yaw. Yaw errors can drift to larger magnitudes due to greater yaw aero disturbances but they are maintained below 7° due to the stiffening effect of momentum biasing. The surveillance system can tolerate large attitude errors because the telescope is able to gimbal. When the RW momentum exceeds the threshold the logic switches to RCS attitude control in order to maintain the commanded LVLH attitude, and the yaw attitude error is reduced by the RCS to within the RCS dead-band. The two reaction wheels are then torqued in the direction that reduces the accumulated RW momentum. The commanded RW torque during desaturation is maintained below max torque and the torque is applied in the direction that reduces the accumulated momentum in order to bring it to zero in both directions in unison. The jet forces are stronger and they overpower the RW desaturation torques. When the magnitude of the RW momentum drops below (1 ft-lb-sec) the logic switches back to RW control. This logic is implemented in Matlab function "Mode-Switch.m". In Section 6 we replaced it with a Matlab/ State-flow switching logic.

Mode Switching Logic

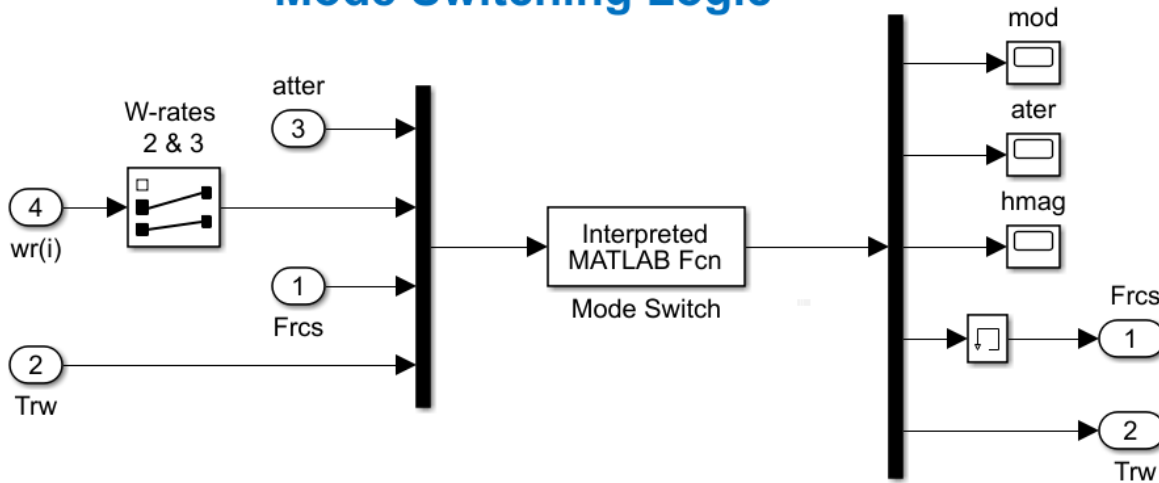


Figure 2.8 Reaction Wheel/ RCS Mode Switching Logic

```

function out= Mode_Switch(atter,wr, fi,Tci)
global Cw2b Jw Mode r2d Hmax Tmax nt
% atter = Attitude Errors (rad)
% wr(2) = Wheel rates (2,3) relat to s/c (rad/sec)
% fi(nt)= RCS Forces (lbf)
% Tc(2) = Torque cmd (pitch,yaw) (ft-lb)

wi=zeros(2,1);
for i=1:2
    wi(i)=wr(i); %+dot(Cw2b(:,i+1),[0,-wo,0]');
end % Inertial wheel rate (wheel+s/c)

hrwa=Cw2b(2:3,2:3)*Jw(2:3,2:3)*wi; % Reaction Wheel Momentm (y,z) in Body
hmag=sqrt(hrwa'*hrwa); % Momentum Magnitude
if hmag==0, Mode=0; end
aterm=sqrt(atter'*atter)*r2d; % Attitude Error (deg)

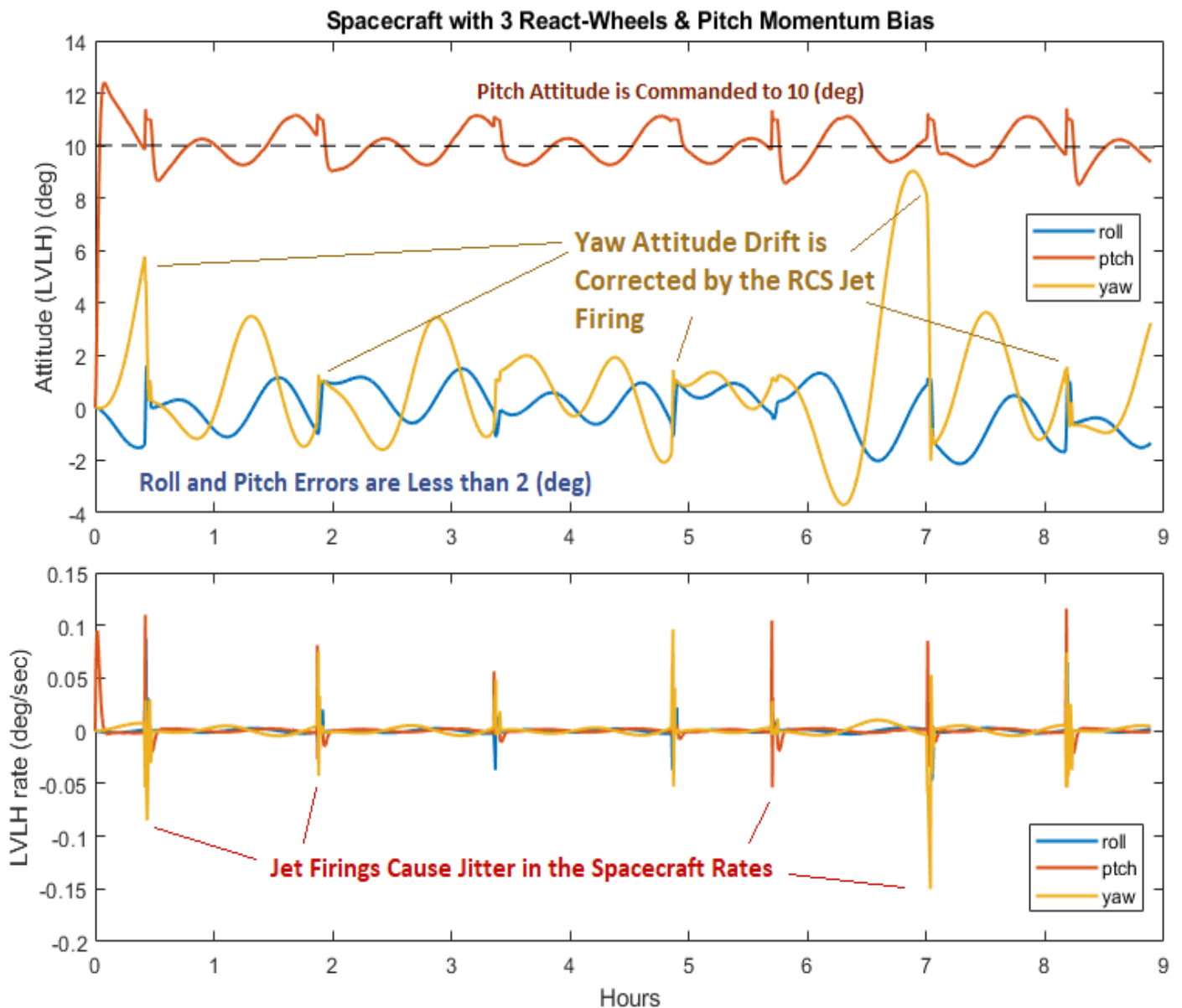
if Mode==0 & hmag<Hmax, % Remain in RW Mode
    Mode=0; f=zeros(nt,1); Tc=Tci; % Zero RCS thrust
else, Mode=1; f=fi; % Switch to RCS Control
    if hmag>Hmax/10; Tc= -hrwa*Tmax/hmag; % RCS with Desaturat
    else; Tc=[0 0]'; end % RCS without Desaturat
end

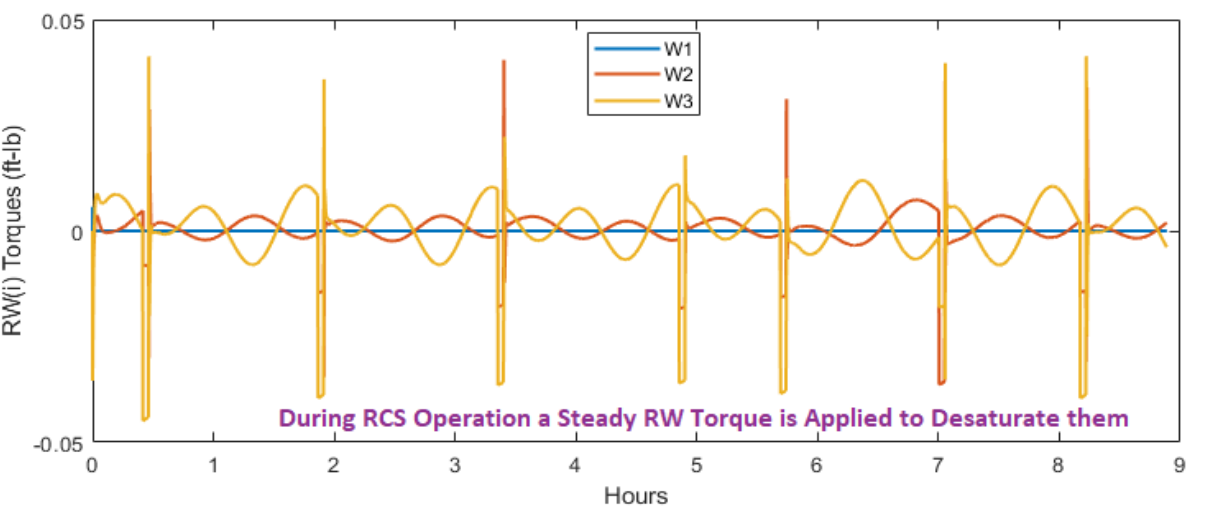
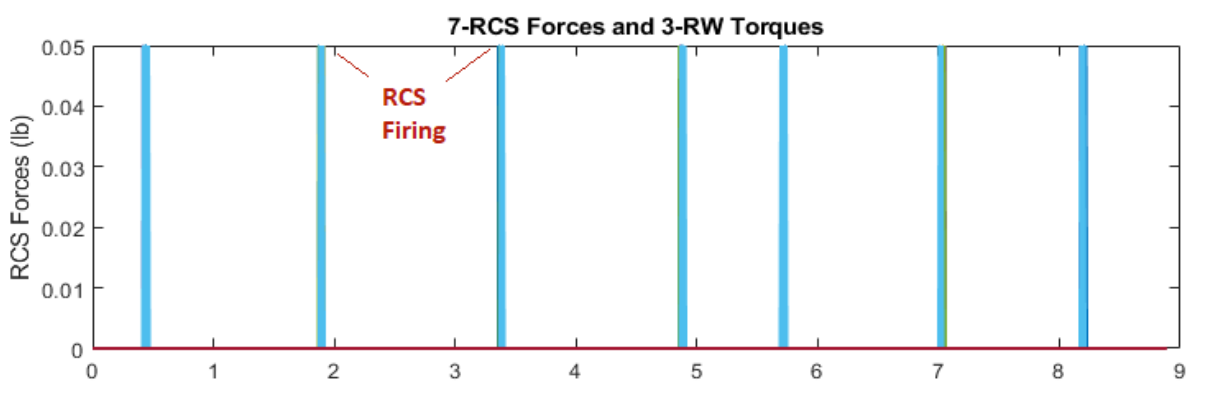
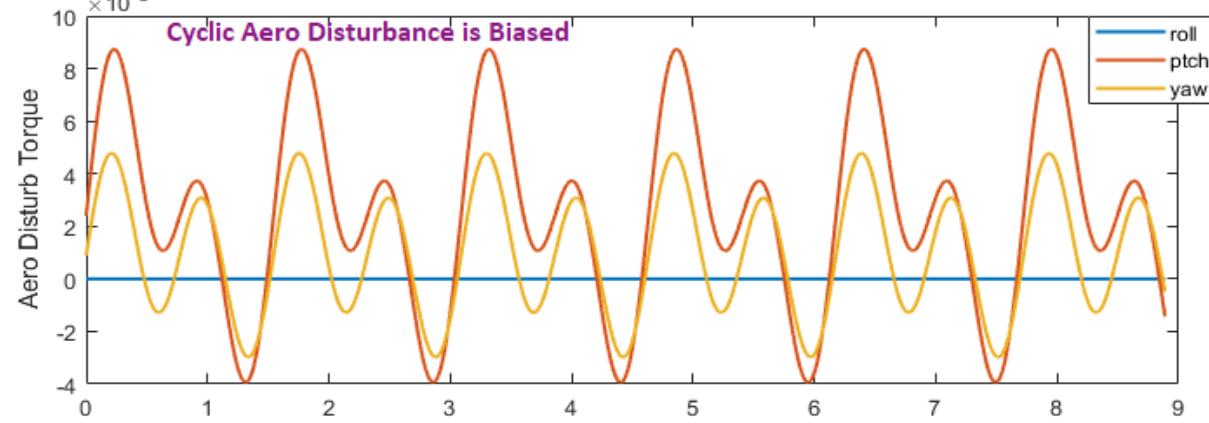
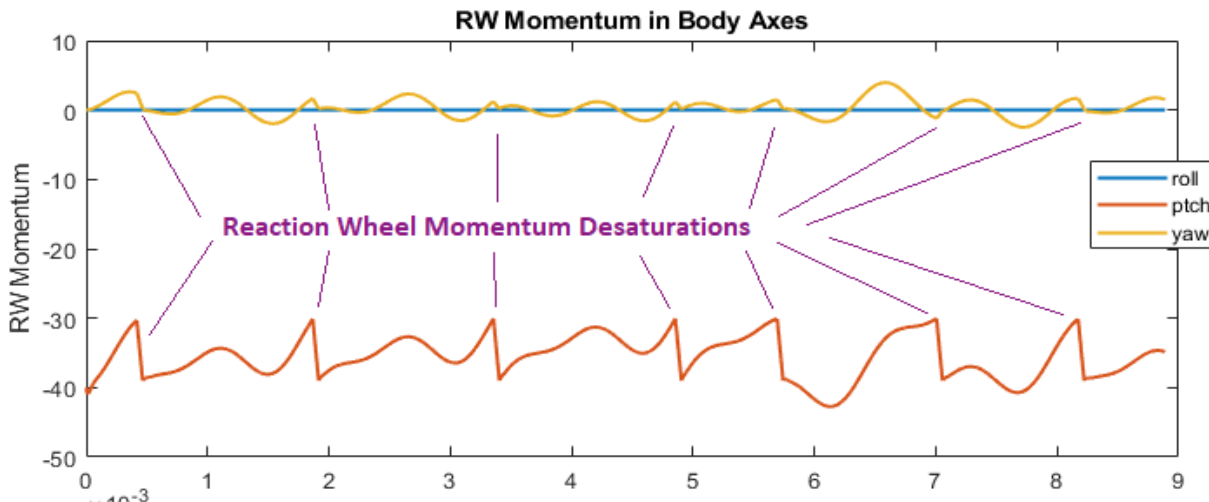
if Mode==1 & hmag>=Hmax/10, % if atterm or Hmag are big
    Mode=1; f=fi; % Remain in RCS Mode
    if hmag>=Hmax/10; Tc= -hrwa*Tmax/hmag; % RCS with Desaturat
    else; Tc= [0 0]'; end % RCS without Desaturat
else, Mode=0; f=zeros(nt,1); Tc=Tci; % Switch to RW Control
end

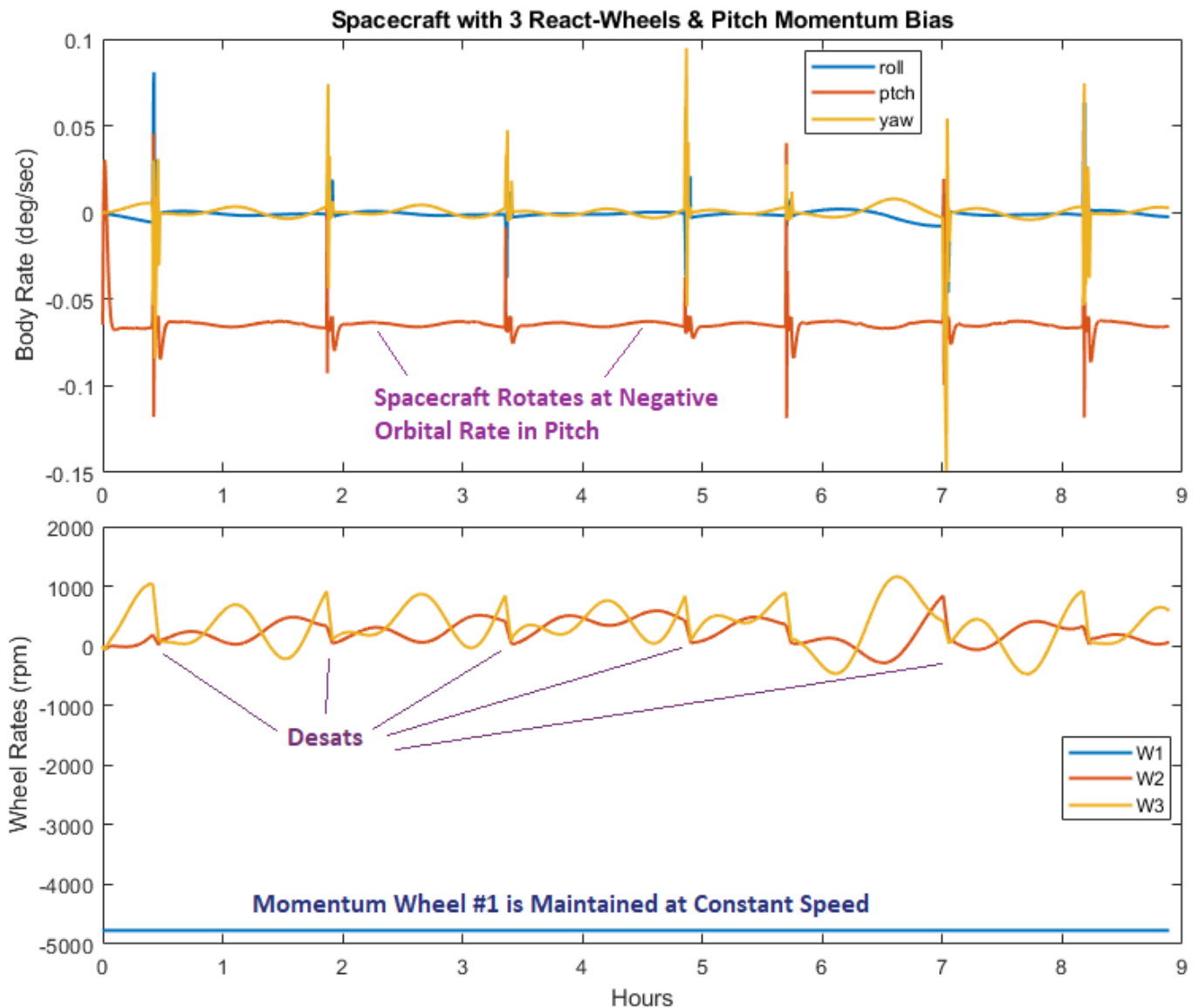
out=[Mode; aterm; hmag; f; Tc];
    
```

2.3 Simulation Results

The following results are obtained from the rigid body simulation model described using the equations of Section 2.1. The simulation is commanded to maneuver to 10° in pitch attitude and it achieves this attitude using reaction wheel control. The spacecraft does not maneuver in roll and yaw and the commands are zero. Cyclic aerodynamic torques are applied as inputs in pitch and yaw. Gravity-gradient torques are also included in the equations. The reaction wheels are reacting against the external torques and it causes the RW momentum to increase. When the RW momentum exceeds the desaturation threshold the logic switches to RCS control and uses the jets to maintain the LVLH attitude while at the same time it torques the reaction wheels #2 and #3 to de-saturate the accumulated momentum. The desaturation periods are short in comparison with the RW control periods and they occur approximately every 1.5 hours. During RW control the spacecraft maintains good pitch and roll control within 1.5 (deg) of attitude error. The yaw error in the RW mode can drift as high as $\pm 8^\circ$ and it is corrected when it switches to the RCS control mode.



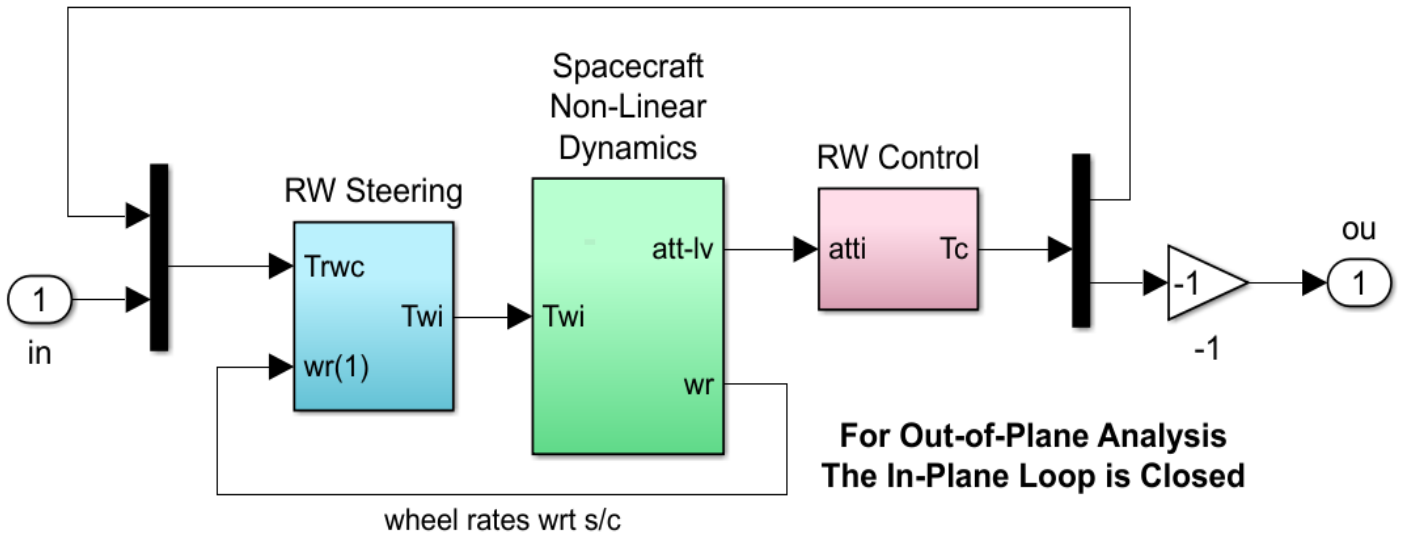




2.4 Reaction Wheel Stability Analysis

The Simulink model "Lin_Anal.slx" is used for analyzing the Reaction Wheel control system stability in the in-plane (pitch) and in the out-of-plane (lateral) axes, one axis at a time. One of the loops is closed (pitch loop shown in this case) and the other out-of-plane loop is opened. The Matlab script "Linanal.m" linearizes the Simulink model and calculates the frequency response across the opened loop. The out-of-plane loop has a strong nutation mode at 0.055 (rad/sec) caused by the pitch momentum wheel #1 biasing and the control system bandwidth is 0.18 rad/sec. The bandwidth of the in-plane loop is 0.035 (rad/sec). Both loops have plenty of phase and gain margins.

Linear Analysis Model



```
run
[Ao,Bo,Co,Do]=dlinmod('Lin_Anal',Ts);           % Discrete Open-Loop Analysis Model
[nr,nc]=size(Ao); E=diag(ones(nr,1));
sys=dss(Ao,Bo,Co,Do,E,Ts);                       % Prepare discrete SS model for
w=logspace(-2.4,1.6,30000);                       % frequency response analysis
figure(2); bode(sys,w); grid on
figure(3); nichols(sys,w)                          % for stability margins
```

Figure 2.9 Linear Model “Lin_Anal.slx” used by Script “Linanal.m” to Calculate the Frequency Response of the Reaction Wheel System for Stability Analysis

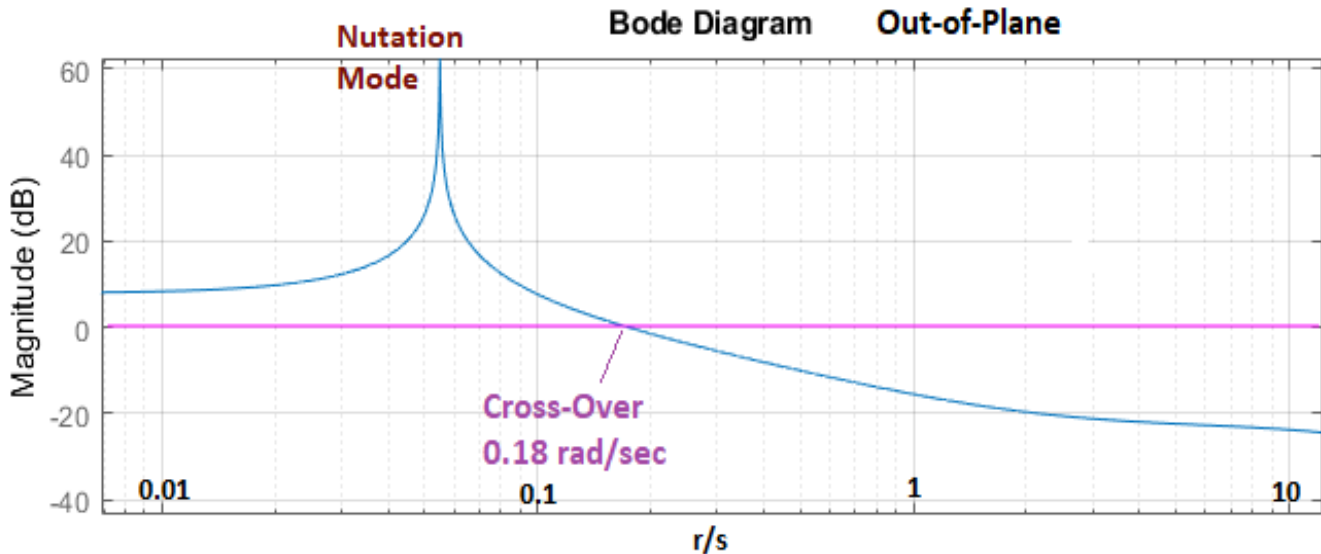


Figure 2.10 Out-of-Plane Open-Loop Frequency Response Shows the Nutation Mode and the Cross-Over Frequency

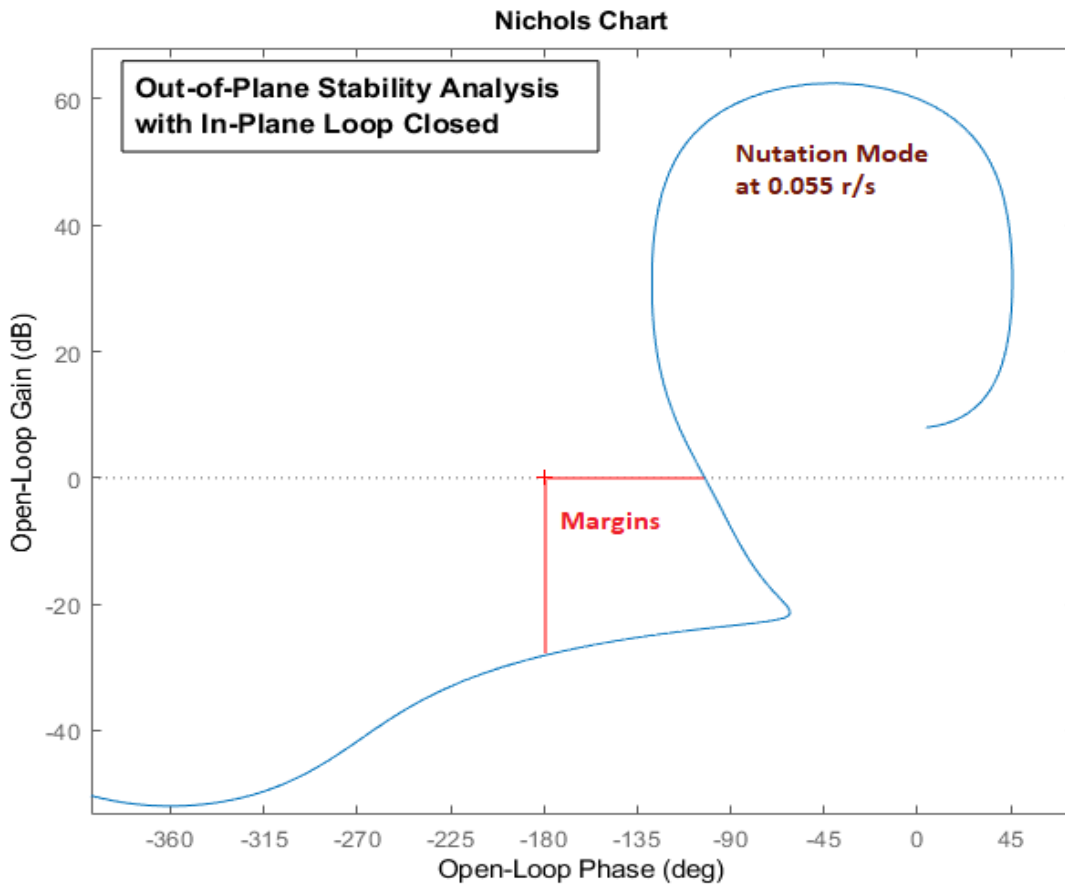
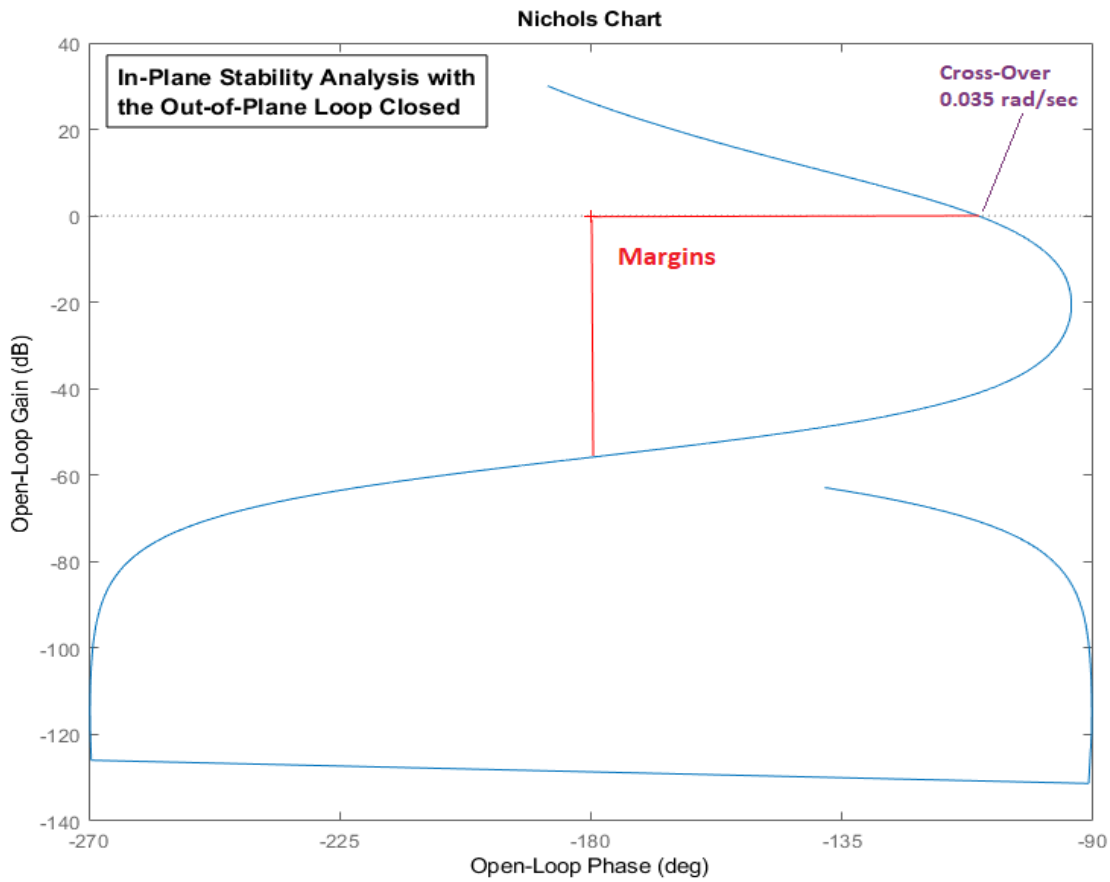


Figure 2.11 Stability Analysis of the In-Plane and Out-of-Plane Reaction Wheel Control Loops

3.0 Flexible Spacecraft Modeling Using Modal Data

This section describes the construction of flexible spacecraft state-space systems which are entirely derived from a finite elements model (FEM) of the spacecraft mechanical structure by means of mode shapes and frequency data. The modal data from the finite elements program consists of a huge number of mode frequencies and mode shapes at multiple locations, also known as structural nodes. The linear dynamic models are created by processing the modal data using the Flixan Flex Spacecraft Modeling program. The FEM contains many flex modes and most of them are not included in the analysis model. Only the strong modes are selected based on a mode selection process and the original FEM data set is reduced to a smaller modal data file for the Flixan program. In this example, the state-space system created consists of 67 modes from which the first six are rigid-body modes at zero frequency that define the rigid-body behavior of the spacecraft and the rotating appendages. The remaining 61 modes are structural flexibility modes associated with structural oscillations. The files for this analysis are in directory “/Examples/10-Surveillance Satellite React-Wheels”.

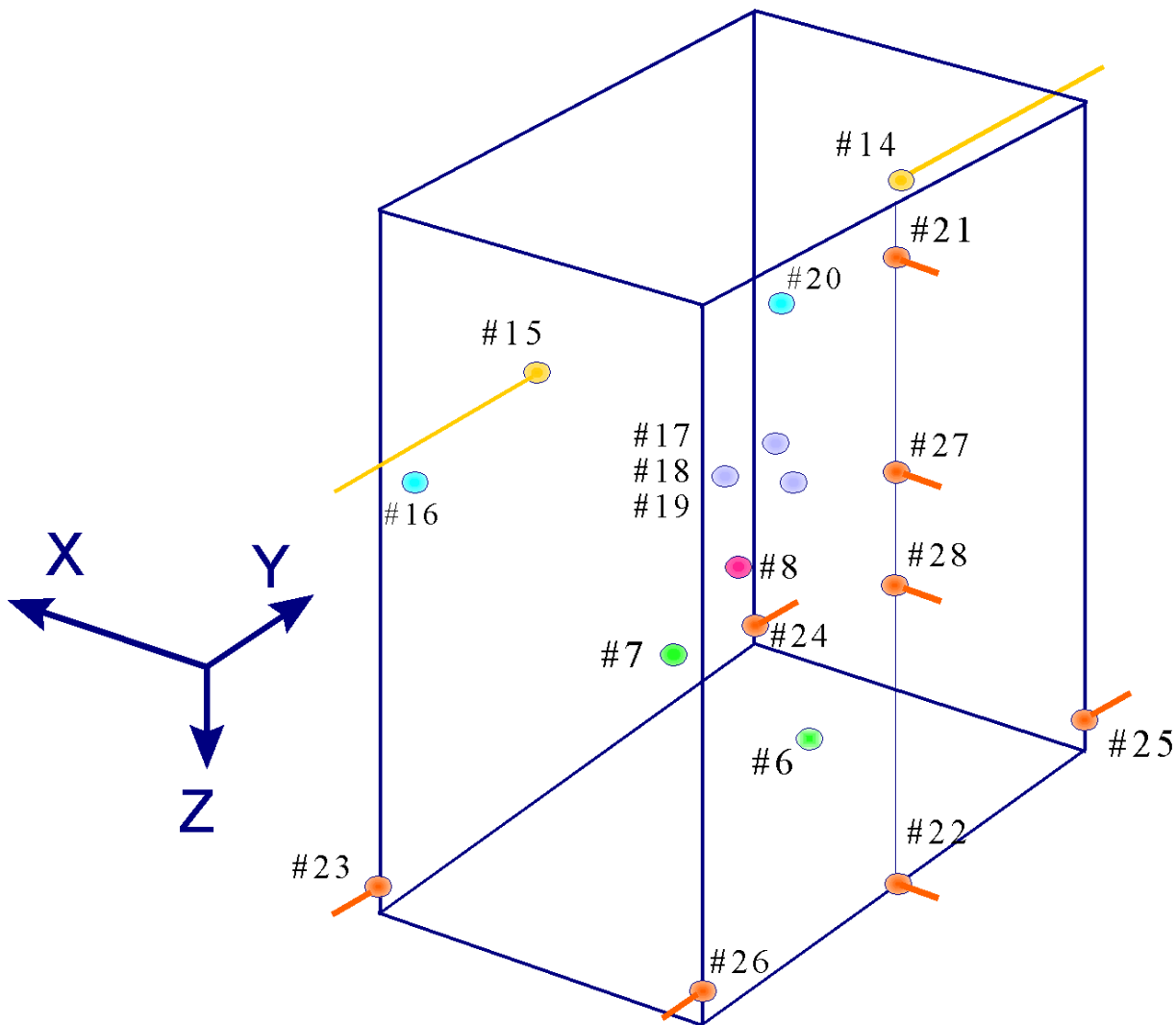


Figure 3.1 Some Important Node Locations on the Spacecraft Bus

The reduced modal data file is “*Surveillance-Sat.Mod*” and it contains only the first 100 modes at 28 useful locations or nodes. From the 100 modes in this file, we will use the “Mode Selection” process of the Flixan program to select 67 modes (6 rigid and 61 flex) that will be included in the spacecraft state-space system. The 28 nodes which are included in the modal data file are listed in a nodes map file “*Surveillance-Sat.Nod*”, see Table 3.1, that includes a title, a short description of each node, node numbers (1-28), the FEM id numbers, and the location coordinates of each node. Figure 3.1 shows the locations of some of the nodes on the spacecraft bus. By using mode selection, we remove the mode resonances that do not participate much in energy transfer between certain excitation points (such as actuators and disturbances) and measurements points (such as measurements or sensitive locations) on the spacecraft. The mode selection process displays the nodes file in menus to help the user to select the desired locations.

Table (3.1) Nodes Map “*Surveillance-Sat.Nod*”

NODE IDENTIFICATION TABLE FOR SURVEILLANCE SATELLITE WITH SOLAR ARRAYS AND OPTICAL SENSOR					
Node Description	Node No	FEM ID	Location X,Y,Z (feet) cg=[-0.05, 0.1, 22.625]		
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

The spacecraft configuration and its flex mode properties are specified by a set of data in the Flixan input file “*Surveillance-Sat.Inp*”. The title of the spacecraft dataset is “*Flex Spacecraft with Gimbaling Telescope and Reaction Wheels (67-modes)*”. Parameters such as input forces, torques, measurements and other sensors, locations and directions are defined in that dataset. The preparation of this dataset is an interactive process during which the modal strengths of all modes are calculated and a selected set of modal data is extracted and it is included at the bottom of the input dataset. After creating the spacecraft dataset in the input file, the Flex Spacecraft modeling program reads the dataset, processes it, and it creates the state-space model in file: “*Surveillance-Sat.Qdr*”.

3.1 Gimbaling Appendages

The rotating appendages increase the complexity of the dynamic model. The surveillance spacecraft in this example includes four gimbaling bodies that can be rotated with respect to the spacecraft by applying torques at the corresponding hinges. There is an optical sensor that gimbals in two orthogonal directions, and two solar arrays that rotate about the y axis. The mode shapes and frequencies are initially created in the FEM by assuming that all gimbals are locked and they do not rotate. The relative motion between the spacecraft and the rotating appendages is captured in the equations by means of the inertial coupling coefficients, or otherwise known as H-parameters. The H-parameters is a matrix of data that is also created by the finite element modeling program and it is extracted from the mass matrix. They provide dynamic coupling between the flex equations and the rotational equations of the gimbaling bodies, as shown in equations 3.1. They are included in a separate file “*Surveillance-Sat.Hpr*”. This file begins with the vehicle title, the number of modes (100), which should correspond to the number of modes in the modal data file “*Surveillance-Sat.Mod*”, and also the number of gimbaling body degrees-of-freedom (4). The H-parameters matrix has 100 rows of and 4 columns that correspond to the four hinges (telescope rotations in elevation and azimuth, left solar array, and right solar array rotations respectively). If the original modal data in file “*Surveillance-Sat.Mod*” had to be rescaled during mode selection (fortunately they did not have to be modified in this example), the units in the H-parameters file should also be scaled to match the modified modal data. At the bottom of the H-parameters file, the (4x4) moments of inertia matrix of the four appendages is also included in the corresponding order. Each element in the H-parameters matrix couples with a bending mode. The modes are excited with the rotational acceleration of an appendage. The H-parameters data also determine the relative rotation at a hinge, which is due to both: rigid-body motion and flexibility. The flex spacecraft modeling program reads the H-parameters file and it introduces the additional DOFs and the equations to unlock the gimbals.

With H-parameters, the flex spacecraft dynamics is represented by three sets of equations 3.1. The first set of equations describes how the structure modes ($\underline{\eta}$) are excited by the external forces and torques (F and T). The modes are also excited by the relative rotational accelerations at the hinges ($\underline{\ddot{\alpha}}$) via the H-coefficients. The second set of equations calculate the relative rotational acceleration ($\underline{\ddot{\alpha}}$) between the two bodies at the hinge as a function of the control torque T_α at the appendage gimbal. Structural flexibility ($\underline{\ddot{\eta}}$) also affects the relative gimbal acceleration via the same H-coefficients. The third set of equations represents the measurements for both, translation and rotation sensors. The interaction between the modes and the rotating appendages is defined by the inertial coupling coefficients matrix (H). This linear, multi-body model is very useful for servo control design and stability analysis purposes, and also for evaluating sensitivity and attitude control system performance with respect to commands and disturbances (jitter analysis, payload pointing, etc.). It can be used for to up to 5° of gimbal rotation and not intended for large angle slewing.

$$M_G \left(\underline{\ddot{\eta}} + 2\zeta \Omega \underline{\dot{\eta}} + \Omega^2 \underline{\eta} \right) + H \underline{\ddot{\alpha}} = \Phi^T \begin{bmatrix} F \\ T \end{bmatrix} \quad (3.1)$$

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

Where:

- $\underline{\eta}$ is the modal displacements vector of dimension (n) where (n) is the number of modes
- M_G is a (n x n) diagonal matrix of the modal masses (from FEM)
- Ω is a (n x n) diagonal matrix whose elements are the mode frequencies in (rad/sec)
- ζ is the modal damping coefficient of each mode, typically ($\zeta=0.005$)
- $\underline{\alpha}$ is a vector of dimension (m) representing the relative rotations 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) that couples the motion of the gimbaling bodies with modal displacements vector (η)
- Φ^T is the mode shapes matrix of size (n x 6) containing the generalized displacements at the nodes where control forces, torques, and disturbances are applied to the structure.
- \underline{F} is a vector of the externally applied forces along the vehicle x, y, and z axes
- \underline{T} is a vector of the externally applied torques about axes x, y, and z
- I_α is an (m x m) moments of inertia matrix of the (m) gimbaling bodies about their axis of rotation in (ft-lf-sec²)
- \underline{T}_α is a vector of size (m) representing the control torques in (ft-lb) at the payload gimbals.

The moments of inertia matrix (I_α) and the coupling coefficients matrix (H) are extracted from the mass matrix of the finite elements model. The measured displacement or rotation vector \underline{X}_s at a sensor point (s) on the structure is a linear combination from all the modes, that is, rigid body modes plus flexible modes.

$$\underline{X}_s = \Phi_s \underline{\eta}$$

Where:

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

During the preparation of the input dataset, the flex spacecraft modeling program interacts with the user who defines the spacecraft configuration and it saves the spacecraft parameters in file "*Surveillance-Sat.Inp*". In the absence of an H-parameters file the program ignores the gimbals. It assumes that the appendages are rigidly attached to the spacecraft and the state model will not include inputs for the gimbal torques and gimbal rotation outputs, like in our Space Station example, where we did not include an (.Hpr) file. The H-parameters file "*Surveillance-Sat.Hpr*" should match the modal data file "*Surveillance-Sat.Mod*". The H matrix should have 100 rows that correspond to the 100 modes in the modal data file, and 4 columns for the 4 hinges. When fewer than the max number of modes are selected (as in this case) the program will read only the H-parameters that correspond to the selected modes and it will ignore the unused modes data. When the dataset preparation is complete the program saves the spacecraft data and the selected modal data in file "*Surveillance_Sat.Inp*". The flex spacecraft modeling program will then process the spacecraft dataset from the input file and generate the state-space system in file "*Surveillance-Sat.Qdr*". The last statement in the input dataset includes the following line that references the H-parameters filename "*Surveillance-Sat.Hpr*" to be also processed by the program.

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

If this line is not included, but the spacecraft data set ends with the selected modal data, the program will assume that the spacecraft hinges are locked and the appendages are not rotating. In this case the state model will not include the additional states, inputs, and outputs associated with the gimbaling bodies. Note, that the modal data created by the FEM must have all the gimbals locked. The presence of H-parameters unlocks the gimbals by introducing additional state variables in the model.

```

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
-1.552249126E+00  4.562218814E-02  8.266835010E-02  -8.049545571E-03
-2.859227958E-01  -9.592453899E-02  8.001701164E-02  -2.275344254E-01
-4.599791855E-02  -1.623105364E-01  3.126333627E-03  1.393672876E-02
 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 FOR THE ROTATING BODIES (slug-ft^2)
 6.3954598075    -0.049079742633    0.000000000E+00    0.000000000E+00      Payload Inertia (elevation)
-0.049079742633    1.889057024167    0.000000000E+00    0.000000000E+00      Payload Inertia (azimuth)
 0.000000000E+00    0.000000000E+00    3.170436278333    0.000000000E+00      Right Solar Array
 0.000000000E+00    0.000000000E+00    0.000000000E+00    3.1704239175        Left Solar Array

Masses for the 4 Gimbal Appendages (slugs): Payload Elevation, Azimuth, 2 Solar Arrays
 2.2            0.88            1.4            1.4

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

Appendage Pivot Point Locations (feet) for Payload Elevation, Azimuth, 2 Sol-Arrays
 0.06           0.06           -0.372         -0.372
 0.1            0.13           -1.8           +1.8
 25.0           25.2           17.0           17.0

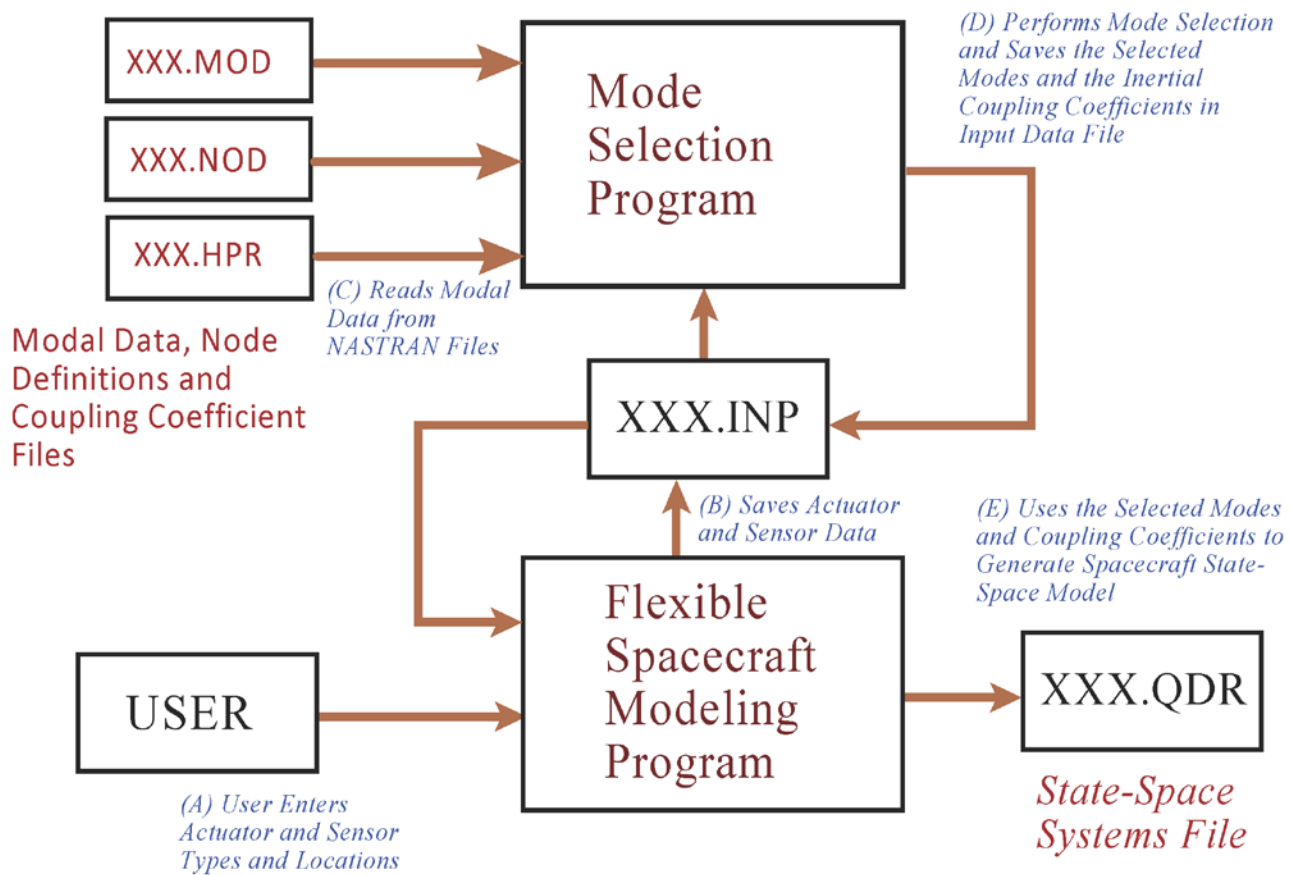
Appendage Center Mass Locations (feet) for Payload Elevation, Azimuth, 2 Sol-Arrays
 0.06           0.06           -0.372         -0.372
 0.14           0.14           -7.2           +7.2
 25.9           25.9           17.0           17.0

```

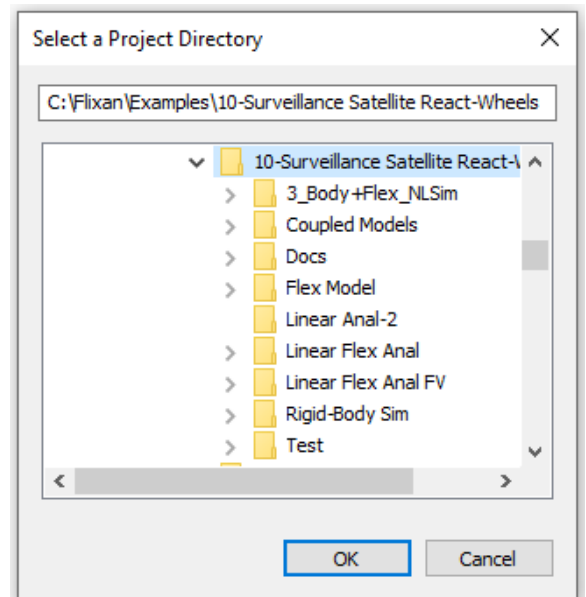
Table 3.2 H-Parameters File “Surveillance-Sat.Hpr”

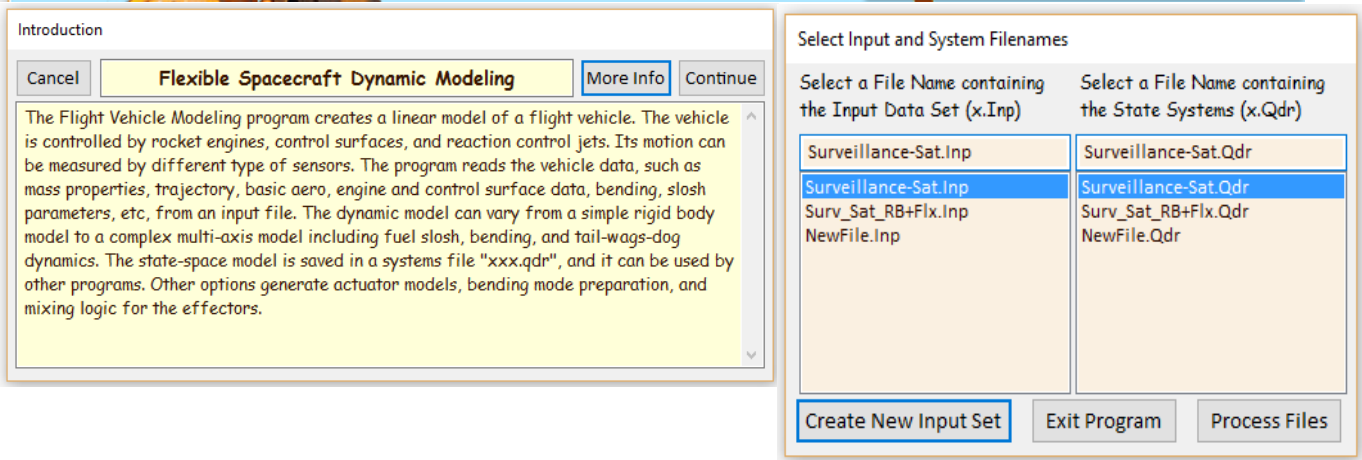
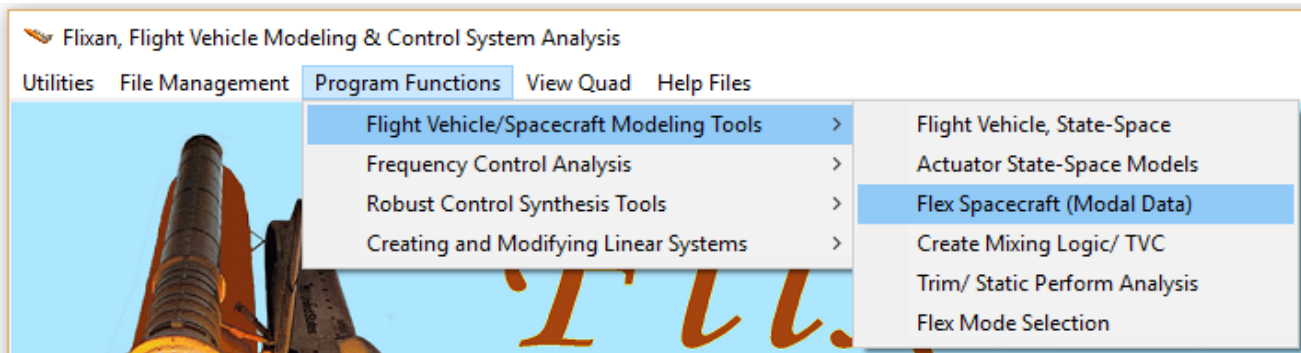
3.2 Generating the Flex Spacecraft State-Space Model

The flex spacecraft modeling program can process an already existing flex spacecraft dataset from an input file. However, if the “flex spacecraft” dataset is missing from an input file, the program will create a dataset from the existing modal data files (.Mod, .Nod, .Hpr) and the user guidance via an interactive utility. The block diagram below highlights this process and the data files involved.

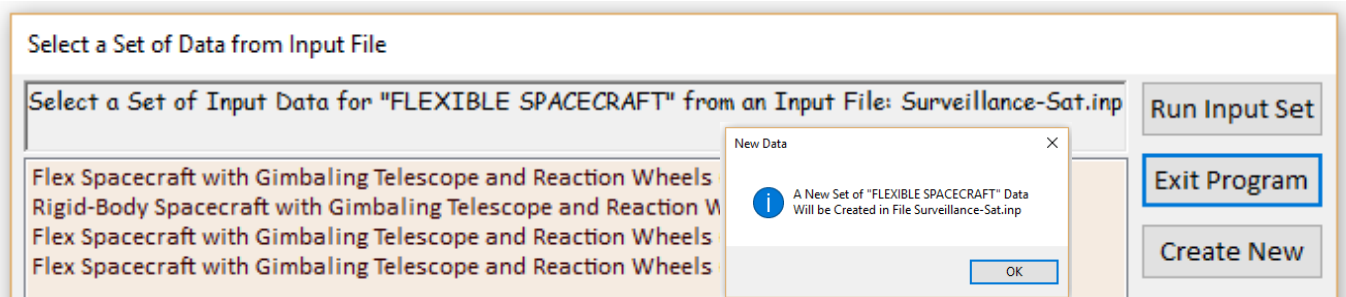


We will now present step by step instructions on how to create the input dataset for the flexible spacecraft including the process of selecting a set of strong modes. This is an interactive process of defining the inputs, outputs, flex modes, and the rotating appendages of the flex spacecraft model. That is, locations and directions of the RCS jets, reaction wheels, and disturbance inputs. We must also define locations and directions of sensors, such as, attitude control gyros, accelerometer sensors and other locations on the structure that determine instrument sensitivity to jitter. Start the Flixan program and select the project directory "C:\Flixan\Examples\ 10-Surveillance Satellite React-Wheels" as shown. Then go to Flixan main menu, "Program Functions", "Flight Vehicle/Spacecraft Modeling Tools", and select the option "Flexible Spacecraft from Modal Data", as shown below. You must also select an input filename that will contain the spacecraft dataset to be created and a systems filename for saving the state-space model.

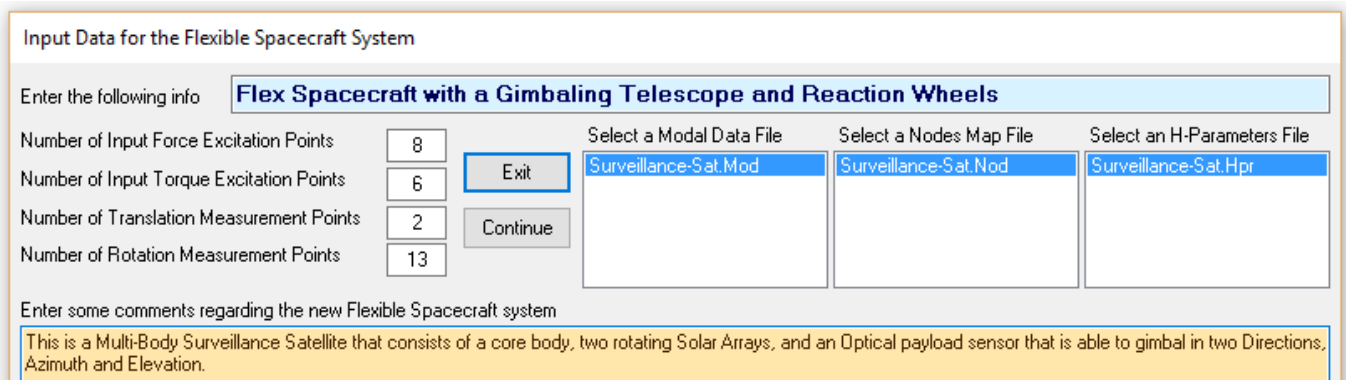




The following menu shows the titles of the flexible spacecraft data-sets which are already saved in the input file. There are four flex spacecraft sets already there but in this demo we will create a new dataset, so we do not select any, but click on "Create New" to create a new dataset from scratch.



In the next dialog you must enter the new spacecraft title and the number of inputs and outputs that define the spacecraft configuration. In this case we have 8 input RCS forces, 6 torque excitation inputs, that is: 3 reaction wheel control torques and 3 disturbance torques.



We also define 2 translational acceleration measurements and 13 rotational measurements, that is: control measurements plus other sensitivity measurements. Use the 3 menus on the right to select the necessary file names: the modal data file *“Surveillance-Sat.Mod”*, the nodes file *“Surveillance-Sat.Nod”*, and the H-parameters file *“Surveillance-Sat.Hpr”* that includes the 4 gimbaling appendages. We may also enter a short paragraph in the orange field at the bottom that describes the flexible spacecraft model that will appear as comments in the data files, below the title.

After defining the configuration inputs and outputs the next step is to define structural locations for the input and output points specified. That is, to associate the 8 RCS jet forces, the 6 torque application points, the two accelerometer measurements, and the 13 rotational sensors defined in the above dialog with structural locations in the modal data file. The next two dialogs show how to select nodes and directions for the RCS jet forces. The excitation locations are defined by the node number, and the direction is defined by a unit vector. Node numbers #21 through #28 are chosen to correspond to RCS forces 1 through 8. Node #21 is selected for force excitation #1, corresponding to RCS #1, where the force direction is along x, that is unit vector: (1, 0, 0). Similarly, force excitation #2 is RCS jet #2 corresponding to node #22 which is also along x: (1, 0, 0). Force excitation #5 is RCS jet #5 that corresponds to node #25 which is along y: (0, -1, 0). Force excitation #7 is RCS jet #7 that corresponds to node #27 which is along x: (1, 0, 0), etc.

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	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

Define Locations and Directions of the System Inputs ✕

Define a Direction Vector for Force Excitation : 2 along x,y,z

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

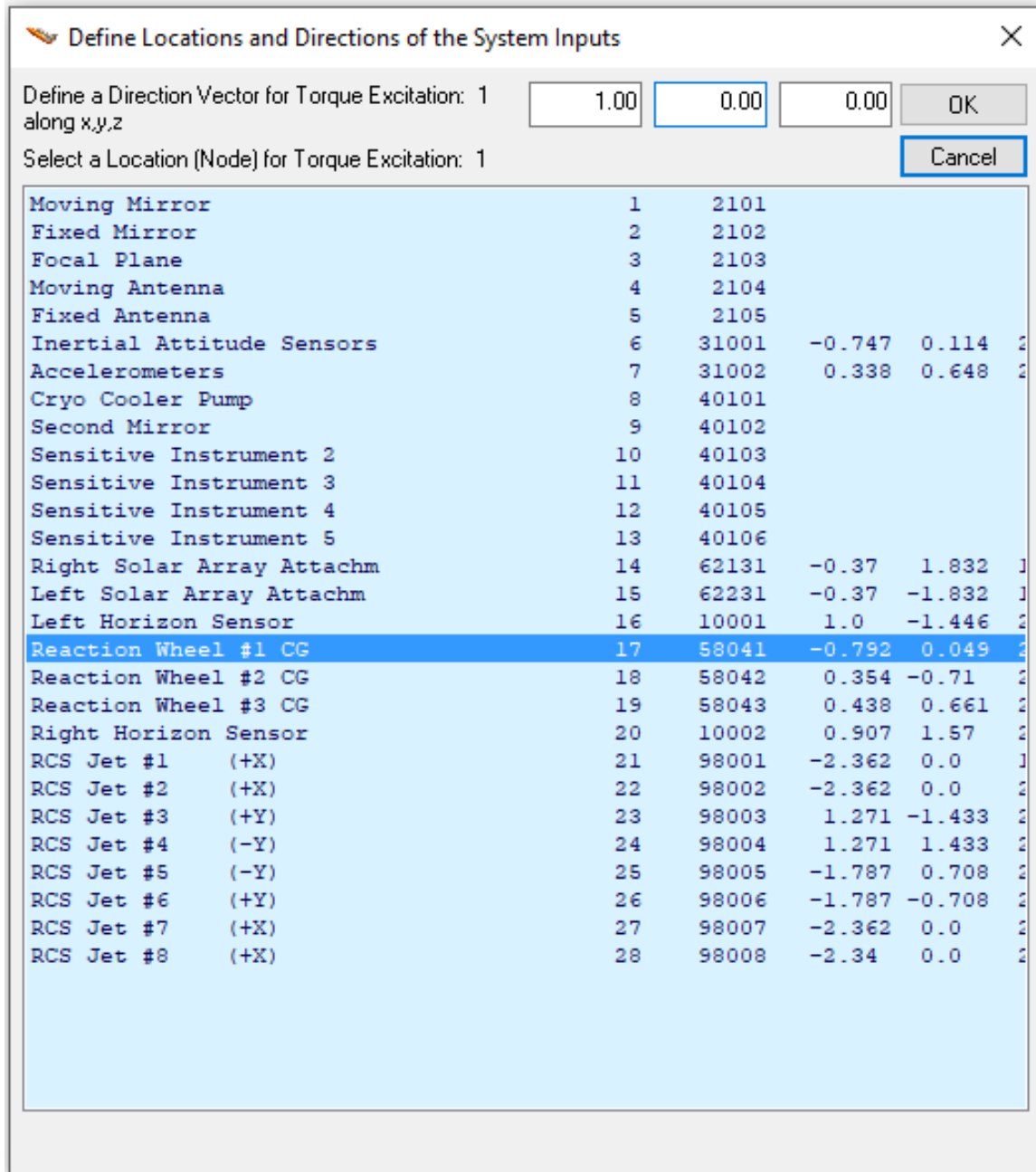
Define Locations and Directions of the System Inputs ✕

Define a Direction Vector for Force Excitation : 5 along x,y,z

Select a Location (Node) for Force Excitation : 5

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

In the next three dialogs we must select locations and directions for the first 3 torques which are the reaction wheel assembly torques. Nodes #17, #18, #19, correspond to roll, pitch and yaw RW torques which are all centrally located. The torque directions in body axes are about x, y, and z respectively. The dialog below is used to select the first torque excitation on wheel #1 about x-axis. The next two are selected from similar dialogs in wheels #2 and #3 in pitch and yaw respectively. The wheels are very near to each other and mounted inside a solid structure. A single node is therefore sufficient for the RW 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 at the same node #8 in roll, pitch, and yaw respectively. The roll and pitch disturbance torque definitions are shown below. The roll vector is (1, 0, 0), pitch is (0, 1, 0) and yaw is (0, 0, 1).

Define Locations and Directions of the System Inputs ✕

Define a Direction Vector for Torque Excitation: 4 along x,y,z

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

Select a Location (Node) for Torque Excitation: 5

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

The sensor locations are also defined by their node number, the direction of measurement (roll, pitch, yaw for rotational) or along (x, y, z for translational), and also 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.

Define Locations and Directions of the System Outputs

Select a Location (Node) for Translation Sensor 1

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

Define a Direction Vector for Translation Sensor 1 and also what type of measurement

Sensor Direction

Along-X
 Along-Y
 Along-Z

Sensor Type

Position
 Velocity
 Acceleration

Select

Cancel

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. All 6 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 3 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: 1

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

Define a Direction Vector for Rotational Sensor: 1 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: 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	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

Define a Direction Vector for Rotational Sensor: 7 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: 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	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

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	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

Define a Direction Vector for Rotational Sensor: 12 and also what type of measurement

Sensor Direction

- Roll
- Pitch
- Yaw

Sensor Type

- Position
- Velocity
- Acceleration

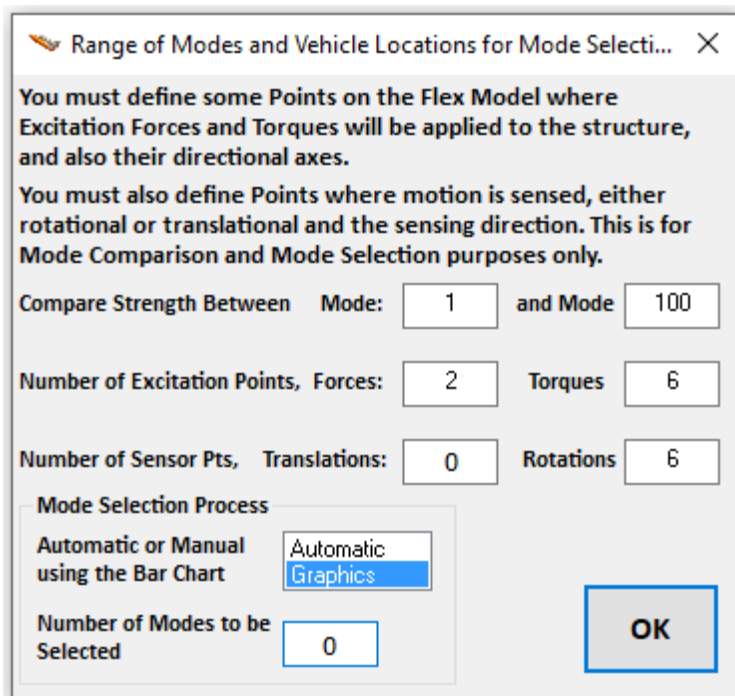
Select

Cancel

The previous light-blue colored menus were used to associate the vehicle model inputs and outputs with locations that correspond to the FEM. We must now define some excitation and sensor points (structure nodes) to be used strictly for mode selection purposes. The locations of these nodes may not necessarily be the same as those defined in the spacecraft model, but they could be any, typically fewer points, used only for mode strength comparison. The mode selection program uses the nodes map file "Surveillance-Sat.Nod" that describes the node locations which are included in the modal data file "Surveillance-Sat.Mod". It is used by menus for selecting effector and sensor locations. We will now use similar menu dialogs to select locations for mode strength comparison. This is for analyzing the modal strength between locations in order to select some of the strongest modes for the flex model. The menus are similar to the previously used dialogs, the background color, however, is different (amber) to avoid mix-up with the spacecraft modeling menus. The excitation locations are defined by the node number and their direction is

defined by a unit vector. The sensors are also defined by the node number, the direction of measurement is roll, pitch, yaw for rotations or along (x, y, z) for translations, and also the type of measurement (position, rate, or acceleration) must be included.

Use the following dialog to enter the parameters for mode selection. The range of modes to be compared is from 1 to 100. In this case we select the full range of modes including rigid modes. The mode strength will be calculated between two force excitation points, 6 torque excitation points, and 6 rotational measurement points. There are no translational measurements used in the mode selection process. Select the "Graphic" option to manually select the modes from the bar plot and click "OK". In the following dialog choose not to modify or rescale the modal data because the units and x, y, z directions are acceptable for analysis and they don't have to be rescaled.



Range of Modes and Vehicle Locations for Mode Selection

You must define some Points on the Flex Model where Excitation Forces and Torques will be applied to the structure, and also their directional axes.

You must also define Points where motion is sensed, either rotational or translational and the sensing direction. This is for Mode Comparison and Mode Selection purposes only.

Compare Strength Between Mode: and Mode

Number of Excitation Points, Forces: Torques

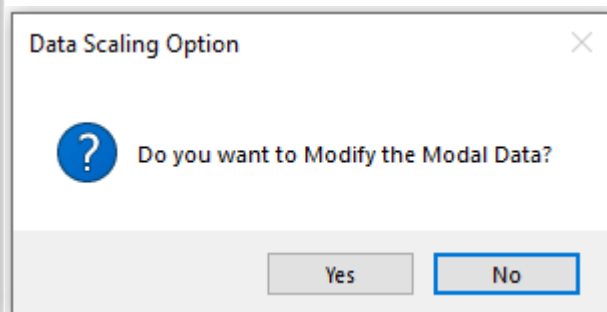
Number of Sensor Pts, Translations: Rotations

Mode Selection Process

Automatic or Manual using the Bar Chart:

Number of Modes to be Selected:

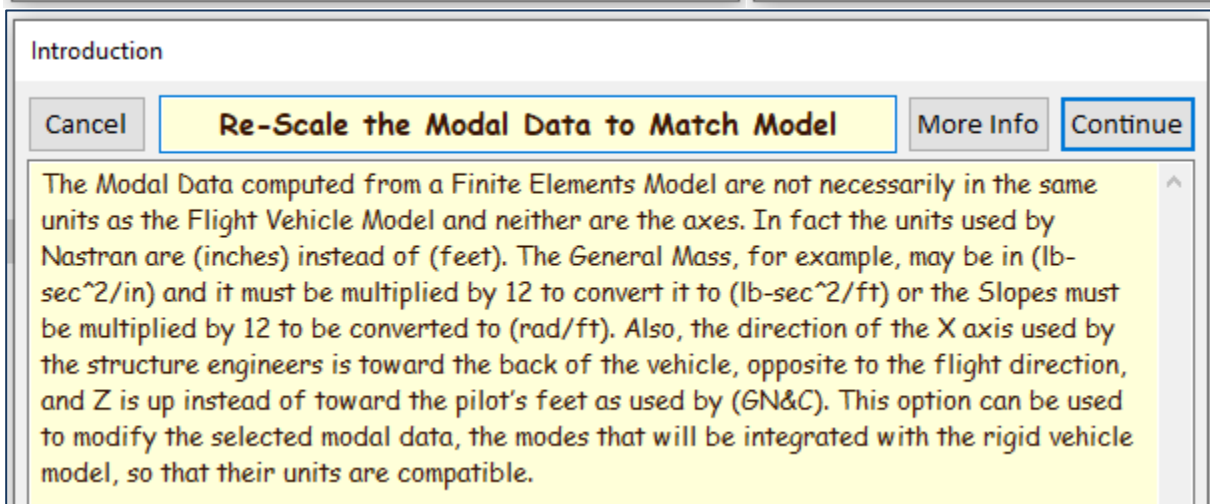
OK



Data Scaling Option

Do you want to Modify the Modal Data?

Yes No



Introduction

Cancel **Re-Scale the Modal Data to Match Model** More Info Continue

The Modal Data computed from a Finite Elements Model are not necessarily in the same units as the Flight Vehicle Model and neither are the axes. In fact the units used by Nastran are (inches) instead of (feet). The General Mass, for example, may be in (lb-sec²/in) and it must be multiplied by 12 to convert it to (lb-sec²/ft) or the Slopes must be multiplied by 12 to be converted to (rad/ft). Also, the direction of the X axis used by the structure engineers is toward the back of the vehicle, opposite to the flight direction, and Z is up instead of toward the pilot's feet as used by (GN&C). This option can be used to modify the selected modal data, the modes that will be integrated with the rigid vehicle model, so that their units are compatible.

The menu below shows the spacecraft structure locations in the order they appear in the modal data file. It is created from the nodes file and is used for mode comparison and mode selection purposes. We will use it to select nodes where we shall apply the two excitation forces specified in the previous dialog. In this case, node #21 is selected to apply a force in the +X direction, and node #26 is selected (not shown) to apply the second force in the +Y direction.

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

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

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

OK
Cancel

Axis
Along-X
Along-Y
Along-Z

Direction
+ (positive)
- (negative)

Similarly, we must select six points to apply torques for mode selection 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.

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 Accelerometers	6	31001	-0.747	0.114	25.572
	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

OK

Cancel

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.

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 Accelerometers	6	31001	-0.747	0.114	25.572
	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

OK

Cancel

Axis

Roll
Pitch
Yaw

Direction

+ (positive)
- (negative)

We must also select nodes and directions for the 6 rotational sensors that were defined earlier 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.

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

Node Description	Node Number	Nastran Node ID Number	Location Coordinates [X, Y, Z]
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]

Select a Location (Node) for Rotational Sensor: 6

Node Description	Node Number	Nastran Node ID Number	Location Coordinates [X, Y, Z]
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

Axis: Roll, Pitch, Yaw

Direction: + (positive), - (negative)

At this point the program calculates the mode strength and displays a bar chart that shows the mode numbers in the horizontal axis and the corresponding relative mode strength in the vertical axis in logarithmic scale. The chart can be used for manual mode selection. Initially all the modes appear in red. The user can select some of the strong modes by clicking on the corresponding bar with the mouse 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 to be used in different analysis. When the mode selection is complete the user must press the "Enter" key to complete the creation of the spacecraft dataset that will be saved in file "Surveillance-Sat.Inp".

The flex spacecraft program will process it and will generate the state-space model. It displays a menu of spacecraft titles that already exist in the input data file, including the latest one from our demo. The user selects one of the titles and clicks on "Run Input Set" to process it and compute the flex spacecraft state-space system in file "Surveillance_Sat.Qdr".

Mode Strength (use mouse to select the strongest modes in the specified axis)

Select Dominant Modes of: Flex Spacecraft with Gimbaling Telescope

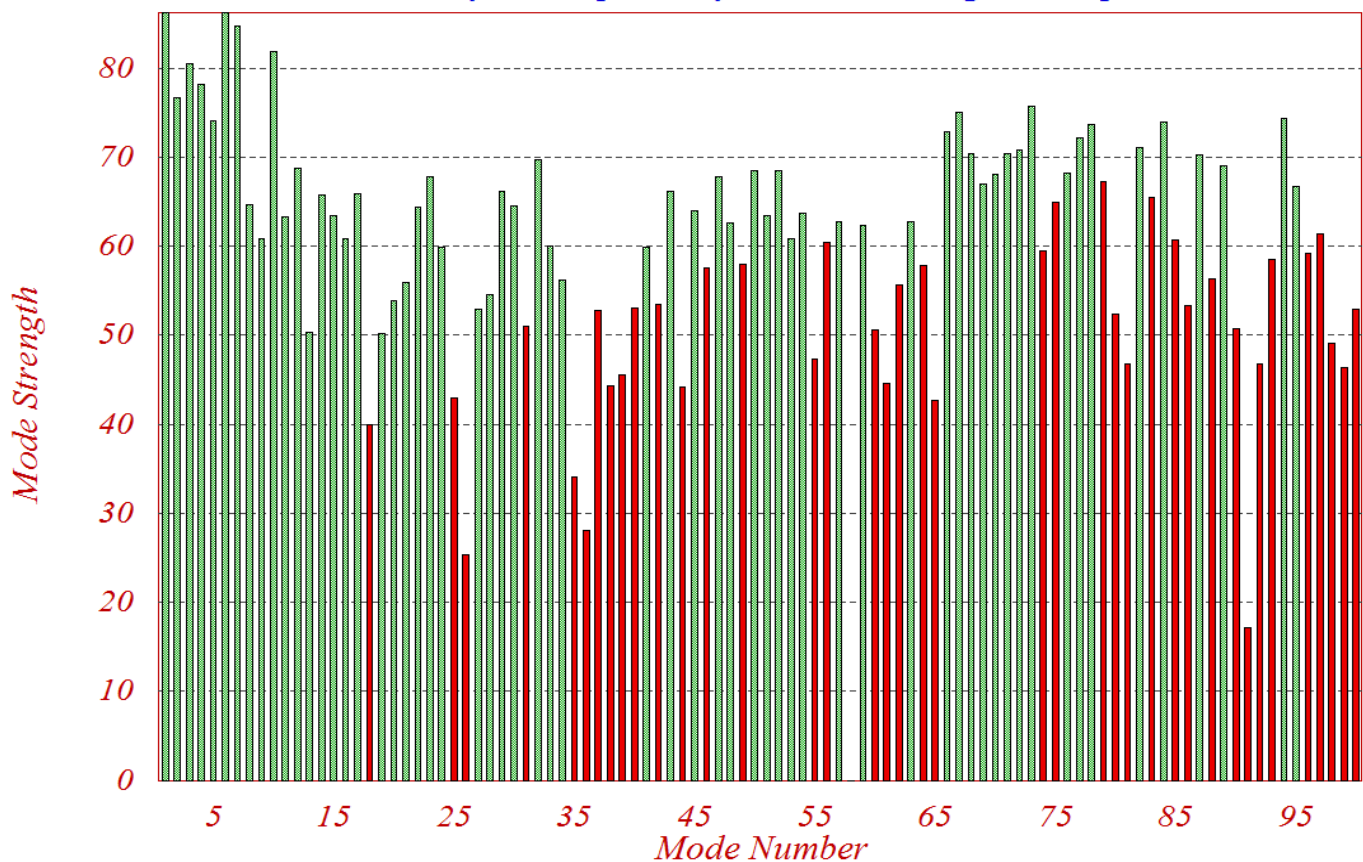
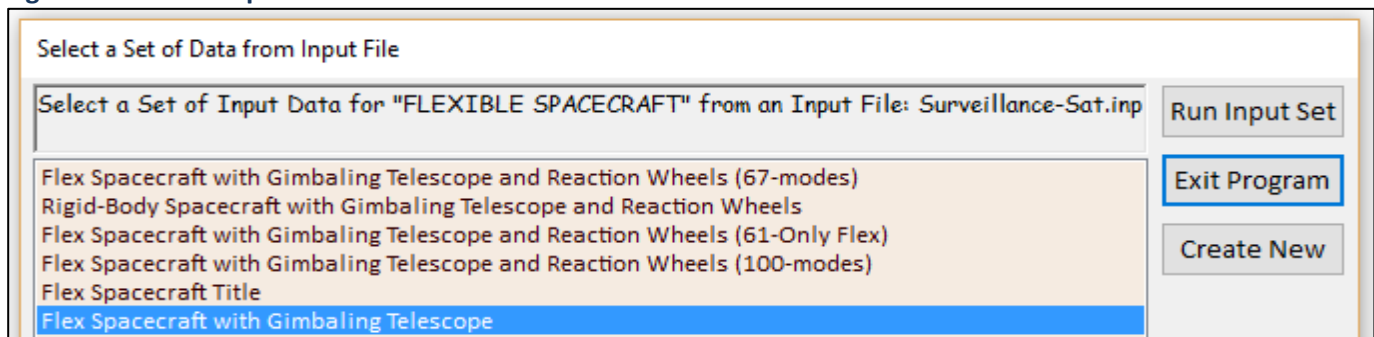


Figure 3.1 Flexible Spacecraft Mode Selection Bar-Chart



The Spacecraft Input File

This file contains the datasets to be processed by the Flixan program. It begins with a batch dataset "Batch to Create the Flex Surveillance Satellite Models" that includes datasets for 4 spacecraft configurations. It also includes the corresponding Matlab conversion datasets.

```
BATCH MODE INSTRUCTIONS .....
Batch to Create the Flex Surveillance Satellite models
! This batch creates flex models for a surveillance spacecraft that includes four
! gimbaling appendages. The Inertial Coupling Coefficients of the appendages are included
! in a separate file "Surveillance-Sat.Hpr" which is also processed by the Flixan
! Flexible Spacecraft Modeling Program
!
Flex Spacecraft : Rigid-Body Spacecraft with Gimbaling Telescope and Reaction Wheels (6-modes)
Flex Spacecraft : Flex Spacecraft with Gimbaling Telescope and Reaction Wheels (67-modes)
Flex Spacecraft : Flex Spacecraft with Gimbaling Telescope and Reaction Wheels (61-Only Flex)
Flex Spacecraft : Flex Spacecraft with Gimbaling Telescope and Reaction Wheels (100-modes)
!
To Matlab Format : Rigid-Body Spacecraft with Gimbaling Telescope and Reaction Wheels (6-modes)
To Matlab Format : Flex Spacecraft with Gimbaling Telescope and Reaction Wheels (67-modes)
To Matlab Format : Flex Spacecraft with Gimbaling Telescope and Reaction Wheels (61-Only Flex)
To Matlab Format : Flex Spacecraft with Gimbaling Telescope and Reaction Wheels (100-modes)
-----
```

The following dataset "Flex Spacecraft with Gimbaling Telescope and Reaction Wheels (67-modes)" is used to create the flexible spacecraft system, including 4 gimbaling appendages. The system includes 6 rigid-body modes and 61 flex modes. Only 2 modes are shown, the first and the last. The name of the H-parameters file "Surveillance-Sat.Hpr" is included at the bottom of the dataset.

```
FLEXIBLE SPACECRAFT FE MODEL ...
Flex Spacecraft with Gimbaling Telescope and Reaction Wheels (67-modes)
! The following flex vehicle is a multi-body Space Surveillance satellite consisting of
! a core spacecraft body, two rotating Solar Arrays, and an optical payload that can
! gimbal in two directions: azimuth and elevation. It has 3 reaction wheels for applying
! attitude control torques, 8 RCS jets for control and desaturating the reaction wheels,
! and 4 servos to control the 4 gimbals, two for 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
 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	0.42404D+00	-0.27679D+00	-0.14051D+00	-0.44087D-02	-0.65808D-01	0.13421D+00
RCS Jet #2	(+X)	22	-0.10290D-01	-0.24769D+00	-0.14051D+00	-0.44078D-02	-0.65808D-01	0.13421D+00
RCS Jet #3	(+Y)	23	0.17370D+00	0.24048D+00	0.10491D+00	-0.44083D-02	-0.65807D-01	0.13421D+00
RCS Jet #4	(-Y)	24	-0.21102D+00	0.24048D+00	0.92270D-01	-0.44087D-02	-0.65807D-01	0.13421D+00
RCS Jet #5	(-Y)	25	-0.10535D+00	-0.17053D+00	-0.10580D+00	-0.44088D-02	-0.65808D-01	0.13421D+00
RCS Jet #6	(+Y)	26	0.84773D-01	-0.17053D+00	-0.99551D-01	-0.44087D-02	-0.65808D-01	0.13421D+00
RCS Jet #7	(+X)	27	0.20194D+00	-0.26187D+00	-0.14051D+00	-0.44644D-02	-0.65806D-01	0.13408D+00
RCS Jet #8	(+X)	28	0.18000D+00	-0.25736D+00	-0.13903D+00	-0.44644D-02	-0.65806D-01	0.13408D+00

		Node Numb	Modal Data at the 6 Torque Application Points					
Reaction Wheel #1 Spin Axis		17	0.18591D+00	-0.50452D-01	-0.37350D-01	-0.44086D-02	-0.65808D-01	0.13421D+00
Reaction Wheel #2 Spin Axis		18	0.28777D+00	0.10320D+00	0.41342D-01	-0.44084D-02	-0.65808D-01	0.13421D+00
Reaction Wheel #3 Spin Axis		19	0.10377D+00	0.11459D+00	0.40882D-01	-0.44086D-02	-0.65808D-01	0.13421D+00
Cryo Cooler Pump		8	0.11375D+00	0.81339D-01	0.24904D-01	-0.44083D-02	-0.65808D-01	0.13421D+00
Cryo Cooler Pump		8	0.11375D+00	0.81339D-01	0.24904D-01	-0.44083D-02	-0.65808D-01	0.13421D+00
Cryo Cooler Pump		8	0.11375D+00	0.81339D-01	0.24904D-01	-0.44083D-02	-0.65808D-01	0.13421D+00

		Node Numb	Modal Data at the 2 Linear Translation Measurement Points					
Accelerometers		7	-0.15620D+00	0.11872D+00	0.34365D-01	-0.44084D-02	-0.65808D-01	0.13421D+00
Accelerometers		7	-0.15620D+00	0.11872D+00	0.34365D-01	-0.44084D-02	-0.65808D-01	0.13421D+00

		Node Numb	Modal Data at the 13 Rotation Measurement Points					
Inertial Attitude Sensors		6	-0.84672D-01	-0.26885D-01	-0.34682D-01	-0.44084D-02	-0.65808D-01	0.13421D+00
Inertial Attitude Sensors		6	-0.84672D-01	-0.26885D-01	-0.34682D-01	-0.44084D-02	-0.65808D-01	0.13421D+00
Inertial Attitude Sensors		6	-0.84672D-01	-0.26885D-01	-0.34682D-01	-0.44084D-02	-0.65808D-01	0.13421D+00
Inertial Attitude Sensors		6	-0.84672D-01	-0.26885D-01	-0.34682D-01	-0.44084D-02	-0.65808D-01	0.13421D+00
Inertial Attitude Sensors		6	-0.84672D-01	-0.26885D-01	-0.34682D-01	-0.44084D-02	-0.65808D-01	0.13421D+00
Second Mirror		9	0.32795D-01	0.86594D-01	0.24822D-01	-0.44084D-02	-0.65808D-01	0.13421D+00
Second Mirror		9	0.32795D-01	0.86594D-01	0.24822D-01	-0.44084D-02	-0.65808D-01	0.13421D+00
Sensitive Instrument 2		10	-0.34485D+00	0.43255D-01	-0.88348D-02	-0.44084D-02	-0.65808D-01	0.13421D+00
Sensitive Instrument 2		10	-0.34485D+00	0.43255D-01	-0.88348D-02	-0.44084D-02	-0.65808D-01	0.13421D+00
Sensitive Instrument 3		11	-0.21043D+00	0.11532D+00	0.30918D-01	-0.44084D-02	-0.65808D-01	0.13421D+00
Sensitive Instrument 4		12	-0.24461D+00	0.13119D+00	0.37577D-01	-0.44084D-02	-0.65808D-01	0.13421D+00
Sensitive Instrument 5		13	-0.23529D+00	0.12195D+00	0.33354D-01	-0.44084D-02	-0.65808D-01	0.13421D+00

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

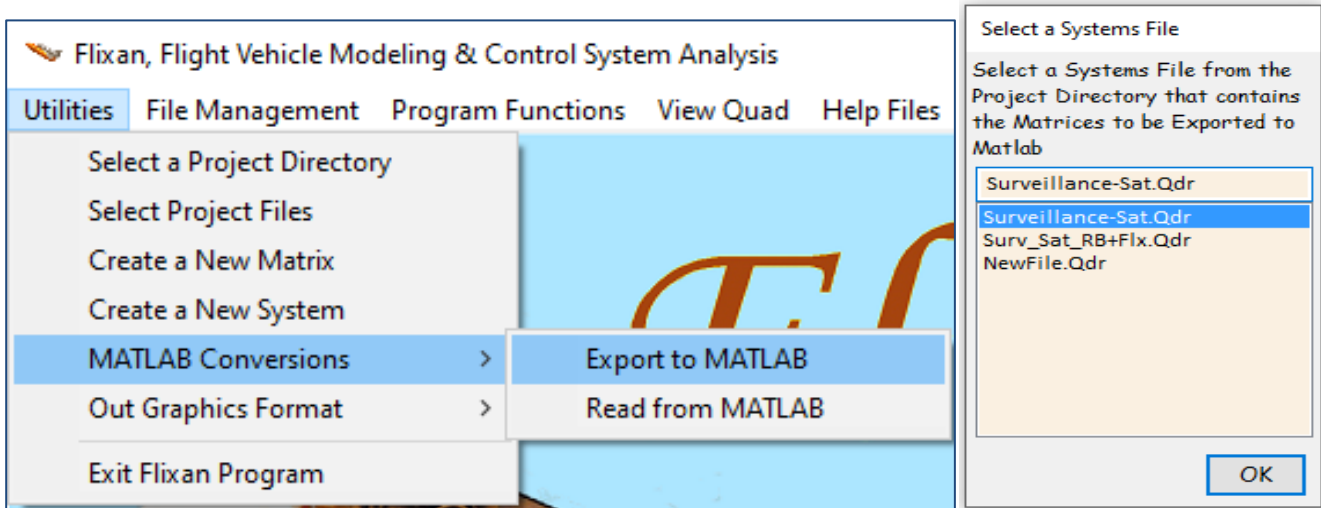
		Node Numb	Modal Data at the 2 Linear Translation Measurement Points					
Accelerometers		7	0.54855D-02	-0.25231D-01	-0.31773D-01	-0.57026D-01	-0.61675D-01	0.15947D-01
Accelerometers		7	0.54855D-02	-0.25231D-01	-0.31773D-01	-0.57026D-01	-0.61675D-01	0.15947D-01

		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
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

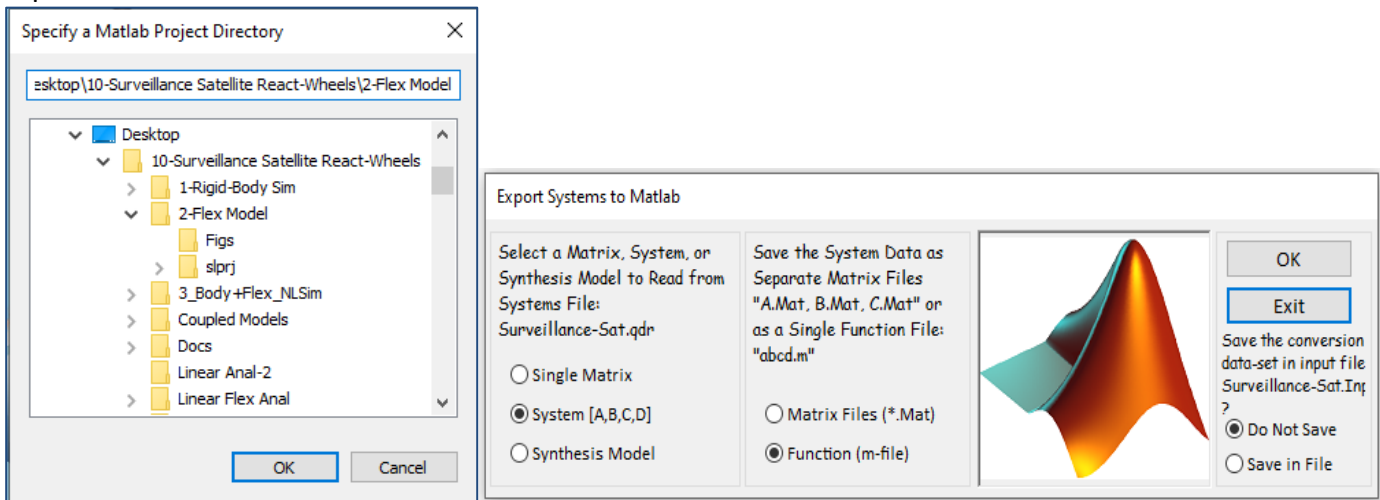
Inertial Coupling Coefficients (H-Parameters) File Name for the 4 gimbaling bodies : Surveillance-Sat.Hpr

3.3 Data Conversion to Matlab Format

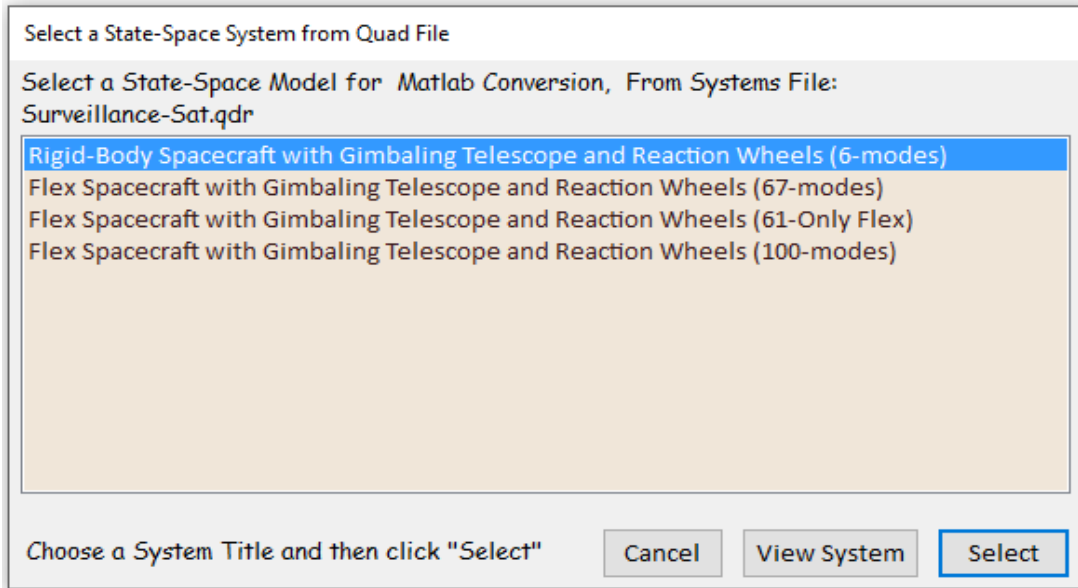
The flex spacecraft model will be analyzed in Matlab and we must, therefore, convert the state-space systems in file "Surveillance-Sat.Qdr" to a format that can be loaded into Matlab. The "Export to Matlab" utility program will be used for the data conversion. From the Flixan menu select "Utilities", "Matlab Conversions", and then "Export to Matlab". Select the current project folder "...\Examples\ 10-Surveillance Satellite React-Wheels\2-Flex Model", and from the filename selection menu (right) select the systems file "Surveillance-Sat.Qdr" and click "OK". Then define the folder where the m-file with the state-space system will be placed and this is where the Matlab analysis will be performed. That is, in folder "2-Flex Model" (show below). Click "OK" to continue.



In the Matlab conversion dialog below, you must specify that you are converting a state-space system into Matlab, rather than just a single matrix, and that it will be saved as a 4-matrix function m-file instead of 4 separate matrices.

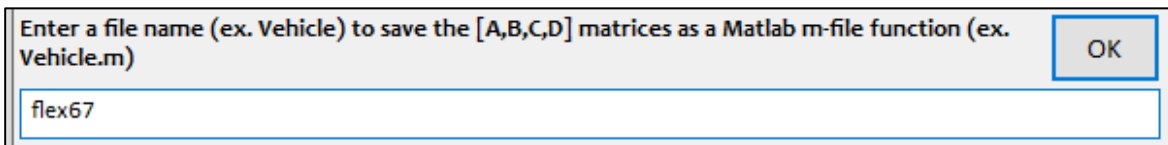


The following menu shows the titles of the systems which are saved in the systems file "Surveillance-Sat.Qdr". In this case there are four flex satellite systems. We must point to the second system that includes 67 modes and click on "Select" to read the system data.



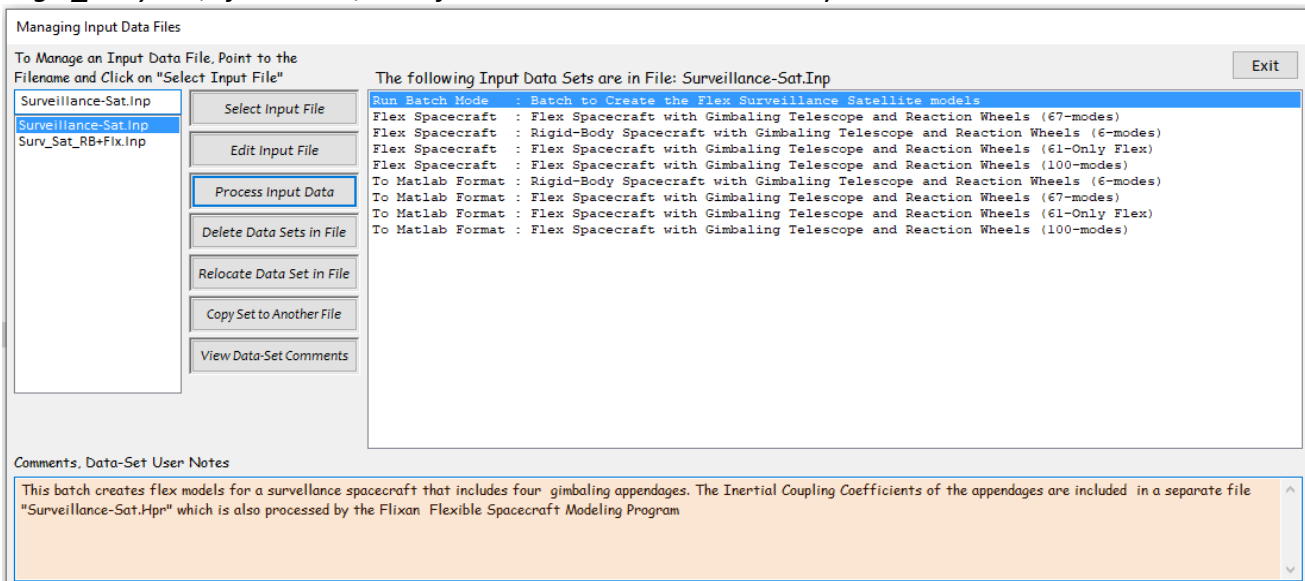
We must finally enter a filename where the four-matrix m-function will be saved in the chosen Matlab folder. Enter “flex67” without the (.m). The program reformats the data and saves it as a system function “flex67.m” in the destination folder. The system can be loaded into Matlab by executing the following statement in Matlab.

```
[Avf, Bvf, Cvf, Dvf]= flex67; % Load Flex Model from Flixan
```



Batch Mode

The file “Surveillance-Sat.Inp” includes a batch set “Batch to Create the Flex Surveillance Satellite Models” that can be used to speed up the systems generation process. This batch creates four systems in file “Surveillance-Sat.Qdr”, including a rigid model and a flex only model to be used later in the analysis. They are saved in folder “10-Surveillance Satellite React-Wheels”. The Matlab modified files “flex67.m”, “rigid_body.m”, “flex61.m”, and “flex100.m” are also created by the batch.



3.4 Flexible Spacecraft Simulation Analysis

In the previous section we used the flex spacecraft modeling program to create a 67-mode state-space system of the surveillance spacecraft in file *"Surveillance_Sat.Qdr"*. This multi-body spacecraft model is linear, at a fixed gimbal orientation, and it includes 6 rigid-body modes (3 rotations and 3 translations) implemented like the flex modes using modal data. The system actually includes more than 67 modes, because we introduced four additional gimbal modes which unlock the hinges of the four rotating appendages via the H-parameters which are included in file *"Surveillance_Sat.Hpr"*. The H-parameters create dynamic coupling between gimbal rotations and the flex modes. This model can be used for small angle analysis, for gimbal rotations up to 5 degrees or so. For large angle slewing we will obviously need a non-linear multi-body simulation. This will be studied later in Section 5. The linear model, however, is very useful for control design, stability analysis and sensitivity to disturbances. The total number of states in the linear model is 142. The last 8 states are rotations and rates at the four gimbals, which are: elevation and azimuth rotations of an optical sensor and two solar array gimbals. The spacecraft system title is *"Flex Spacecraft with Gimbaling Telescope and Reaction Wheels (67-modes)"*. It has 18 inputs: 8 RCS jet forces, 3 Reaction Wheel torques (roll, pitch, yaw), 3 disturbance torques at the cryo-cooler, and 4 torques at the appendage gimbals. It has 23 outputs: two accelerometers along X and Y, three rate gyros at the navigation platform, three rotational gyros also at the nav-base, four rotational gyros at nodes #9 and #10, and another 3 rotational gyros at nodes #11 to #13. They are locations for analyzing jitter sensitivity. The last 8 outputs are gimbal angles and gimbal rates at the 4 hinges.

We will now use this flexible state-space model to create a simulation model of the satellite with the gimbaling telescope and the solar array appendages. We will include the RCS and the telescope gimbal control systems and will analyze its performance to a pitch attitude command, gimbal commands and to disturbances from the solar array stepper-motor. The Matlab analysis files are in folder *"Examples\10-Surveillance Satellite React-Wheels\2-Flex Model"*. The Simulink model *"Flex_RCS.slx"* shown in Figure 3.3 is used to analyze the flexible spacecraft. The m-file script *"runf.m"* is used to initialize the model and the spacecraft state-space system is loaded from file *"flex67.m"*. Other parameters are also loaded into Matlab, such as: jet locations, jet directions and gimbal servo gains. The 100-mode system and the rigid-body system that were created in files: *"flex100.m"* and *"rigid_body.m"* are also included in this folder and they can be loaded instead using *"runf.m"*. The 100 flex modes model has 208 states. It was used for comparison purposes and it will not be discussed here.

The disadvantage of this linear FEM derived spacecraft model is that it is missing the nutation effects which is produced by the pitch momentum bias (H_{v0}) and it is coupling the roll and yaw axes. In the Section 4 we will couple the flex model with the previously described momentum biased non-linear model, but in this section, we shall analyze the linear flex model alone. This simulation model includes the RCS closed-loop controller and the two telescope gimbal loops are also closed via torque motors. The reaction-wheel ACS loop is not implemented because it cannot work efficiently in the lateral directions without the out-of-plane gyroscopic coupling. The flex spacecraft (cyan) and the gimbal control blocks (pink) are shown in detail in Figure (3.3 & 3.5). We will use this model to analyze attitude maneuvering and telescope gimbaling effects and also jitter effects from the solar array stepper motors.

Flex Spacecraft Simulation from Structural Model

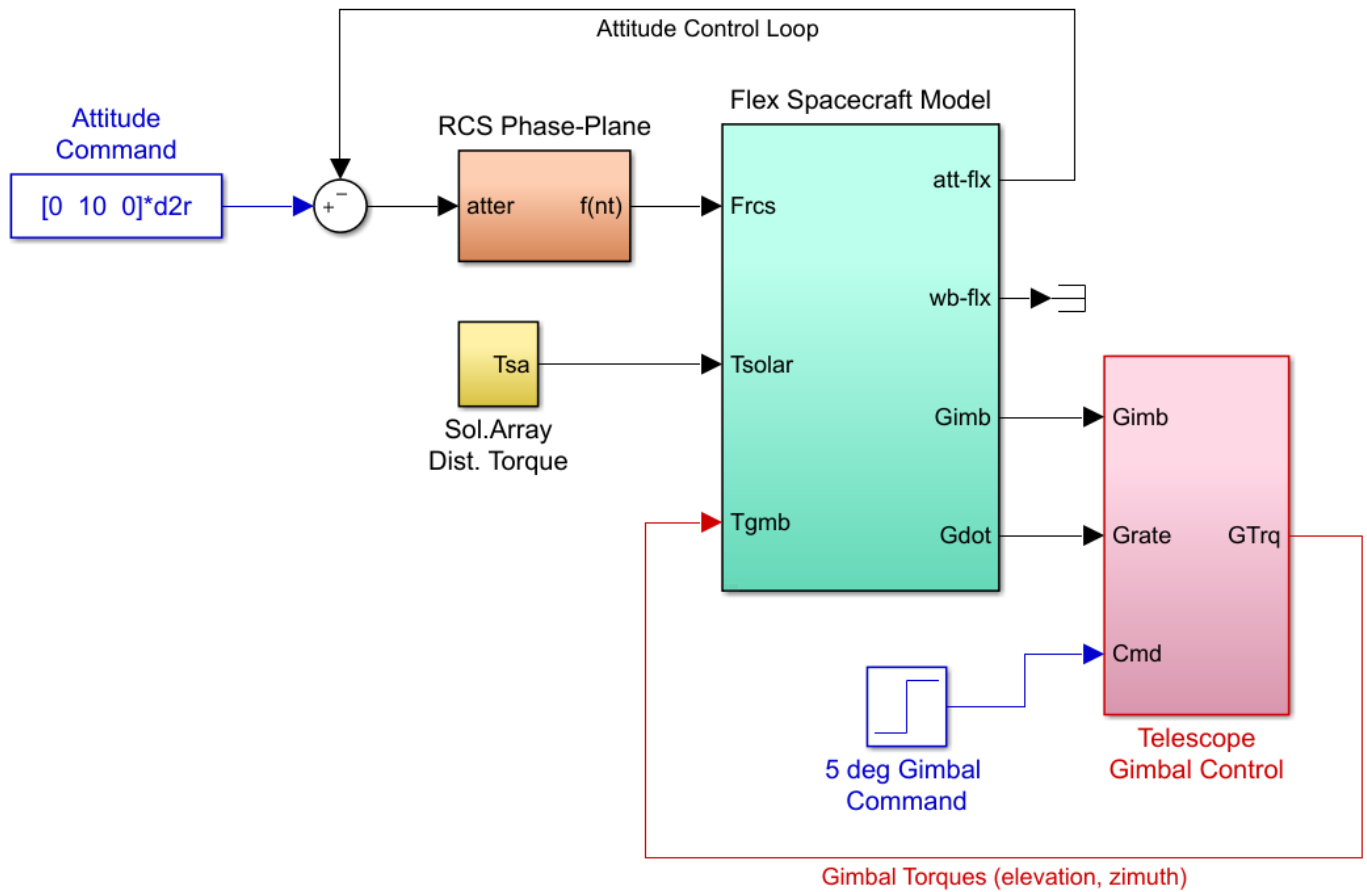


Figure 3.2 Simulink Model "Flex_RCS.slx" for Analyzing the Flex Spacecraft System with RCS and Gimbal Loops Closed

RCS Phase-Plane and Jet Selection Logic

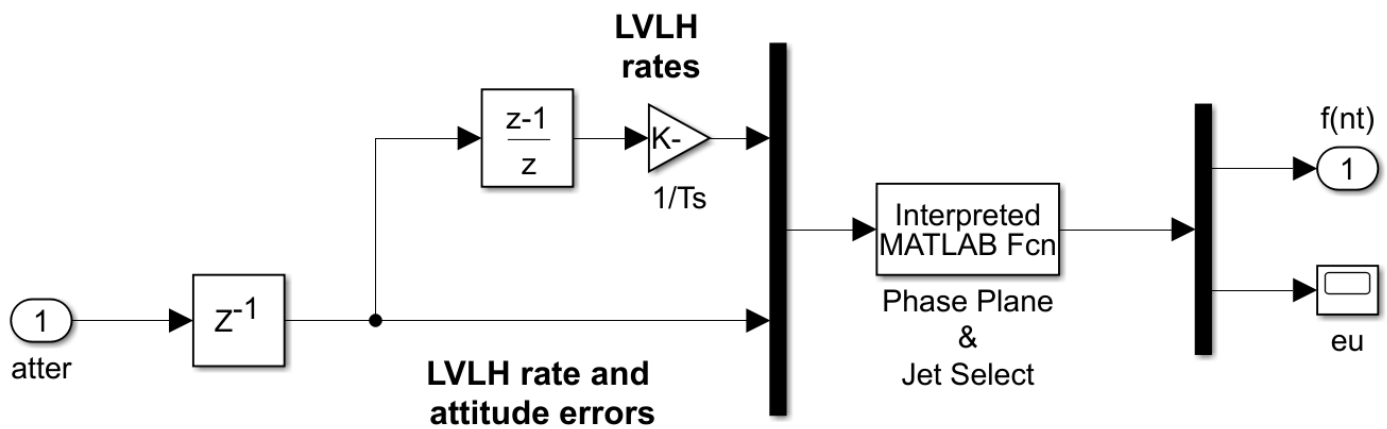


Figure 3.3 Phase-Plane RCS Control Logic

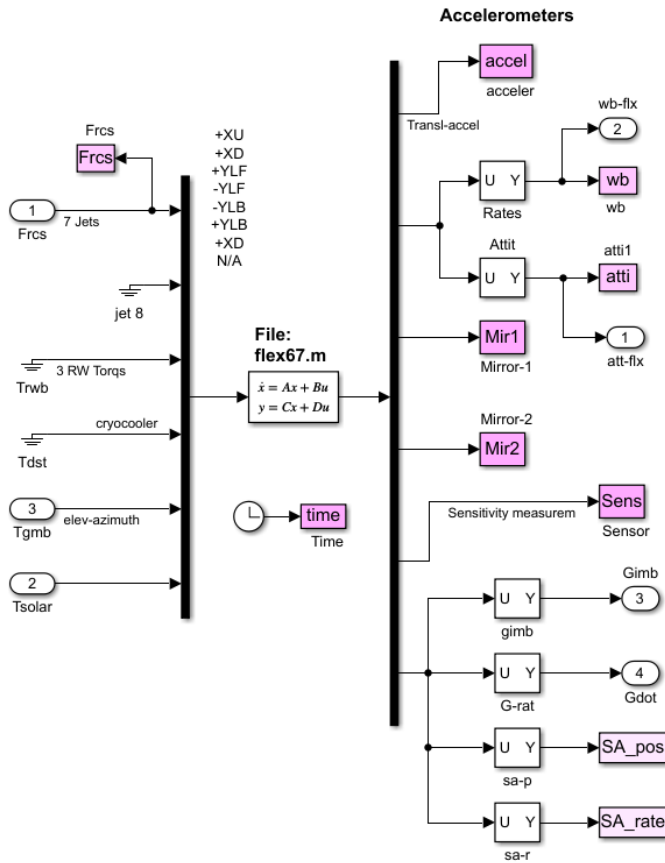
Finite Elements Spacecraft Model (6 Rigid-Body, 61 Flex Modes)

Inputs = 18

- 1 RCS Force No 1 at Node # 21 (lbf) +XU
- 2 RCS Force No 2 at Node # 22 (lbf) +XD
- 3 RCS Force No 3 at Node # 23 (lbf) +YLF
- 4 RCS Force No 4 at Node # 24 (lbf) -YLF
- 5 RCS Force No 5 at Node # 25 (lbf) -YLB
- 6 RCS Force No 6 at Node # 26 (lbf) +YLB
- 7 RCS Force No 7 at Node # 27 (lbf) +XD
- 8 RCS Force No 8 at Node # 28 (lbf) +X n/a

- 9 RW Torque No 1 at Node # 17 (ft-lb) roll
- 10 RW Torque No 2 at Node # 18 (ft-lb) ptch
- 11 RW Torque No 3 at Node # 19 (ft-lb) yaw
- 12 Dist Trque No 4 at Node # 8 (ft-lb) roll
- 13 Dist Trque No 5 at Node # 8 (ft-lb) ptch
- 14 Dist Trque No 6 at Node # 8 (ft-lb) yaw

- 15 Elevation Trque at Gimbal No 1 (ft-lb)
- 16 Azimuth Torque at Gimbal No 2 (ft-lb)
- 17 Rght SA Torque at Gimbal No 3 (ft-lb)
- 18 Left SA Torque at Gimbal No 4 (ft-lb)



Outputs = 23

- 1 X-Accelerat. Sensed at Node # 7 (ft/sec2)
- 2 Y-Accelerat. Sensed at Node # 7 (ft/sec2)

- 3 X-Rot. Rate Sensed at Node # 6 (radian)
- 4 Y-Rot. Rate Sensed at Node # 6 (radian)
- 5 Z-Rot. Rate Sensed at Node # 6 (radian)
- 6 X-Rotation Sensed at Node # 6 (radian)
- 7 Y-Rotation Sensed at Node # 6 (radian)
- 8 Z-Rotation Sensed at Node # 6 (radian)

- 9 Y-Rotation Mirror at Node # 9 (radian)
- 10 Z-Rotation Mirror at Node # 9 (radian)

- 11 Y-Rotation Instrum-2 Node # 10 (radian)
- 12 Z-Rotation Instrum-2 Node # 10 (radian)

- 13 X-Rotation Instrum-3 Node # 11 (radian)
- 14 Y-Rotation Instrum-4 Node # 12 (radian)
- 15 Z-Rotation Instrum-5 Node # 13 (radian)

- 16 Rotation Angle at Elevati Gimbal No 1
- 17 Rotation Rate at Elevati Gimbal No 1
- 18 Rotation Angle at Azimuth Gimbal No 2
- 19 Rotation Rate at Azimuth Gimbal No 2
- 20 Rotation Angle at Rght SA Gimbal No 3
- 21 Rotation Rate at Rght SA Gimbal No 3
- 22 Rotation Angle at Left SA Gimbal No 4
- 23 Rotation Rate at Left SA Gimbal No 4

Figure 3.4 Flex Spacecraft Block from file: Flex67.m" Consisting of 61 Flex Modes and 6 Rigid Modes

Telescope Gimbal Control

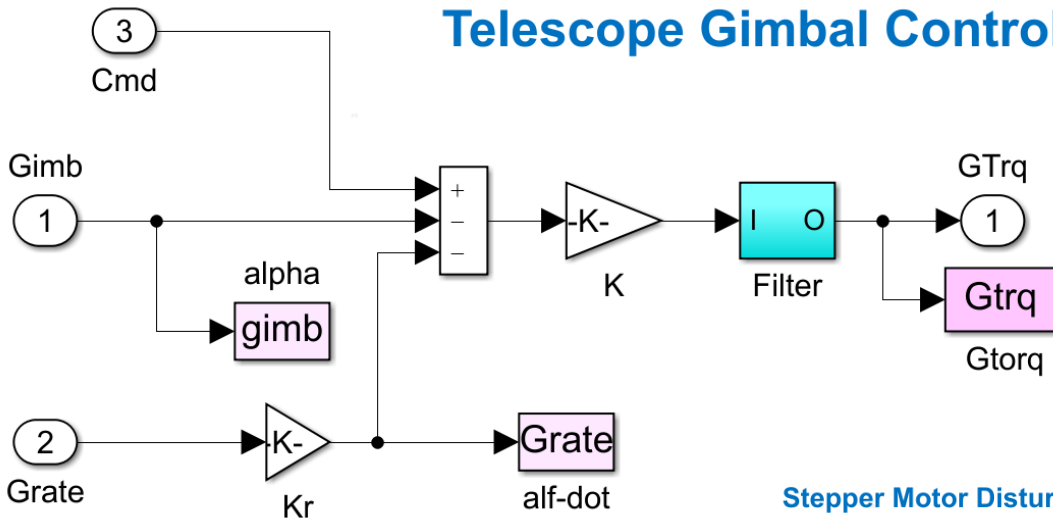
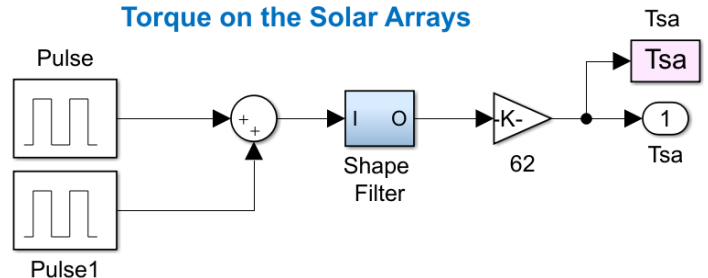


Figure 3.5 Telescope Gimbal Control System

Stepper Motor Disturbance Torque on the Solar Arrays



The following results are obtained by commanding the RCS attitude control system to perform a 10° rotation in pitch. The elevation and azimuth gimbals of the telescope are also commanded 20 seconds later to perform 5° slew rotations. Figure 3.6 shows the spacecraft attitude and rate responses during the maneuvers. The attitude response is rate limited by the phase-plane logic. Flex oscillations are observed in the rate measurement in response to gimbaling and jet firing. Figure 3.7 shows the azimuth and elevation gimbal responses to 5° commands. The gimbals respond much faster than the RCS. Figure 3.9 shows the Solar Arrays motion relative to the spacecraft. They are not constrained and they rotate negative because the spacecraft rotates +10° in pitch. Relative flex motion at the SA gimbals is excited by the telescope slewing and the jet firing.

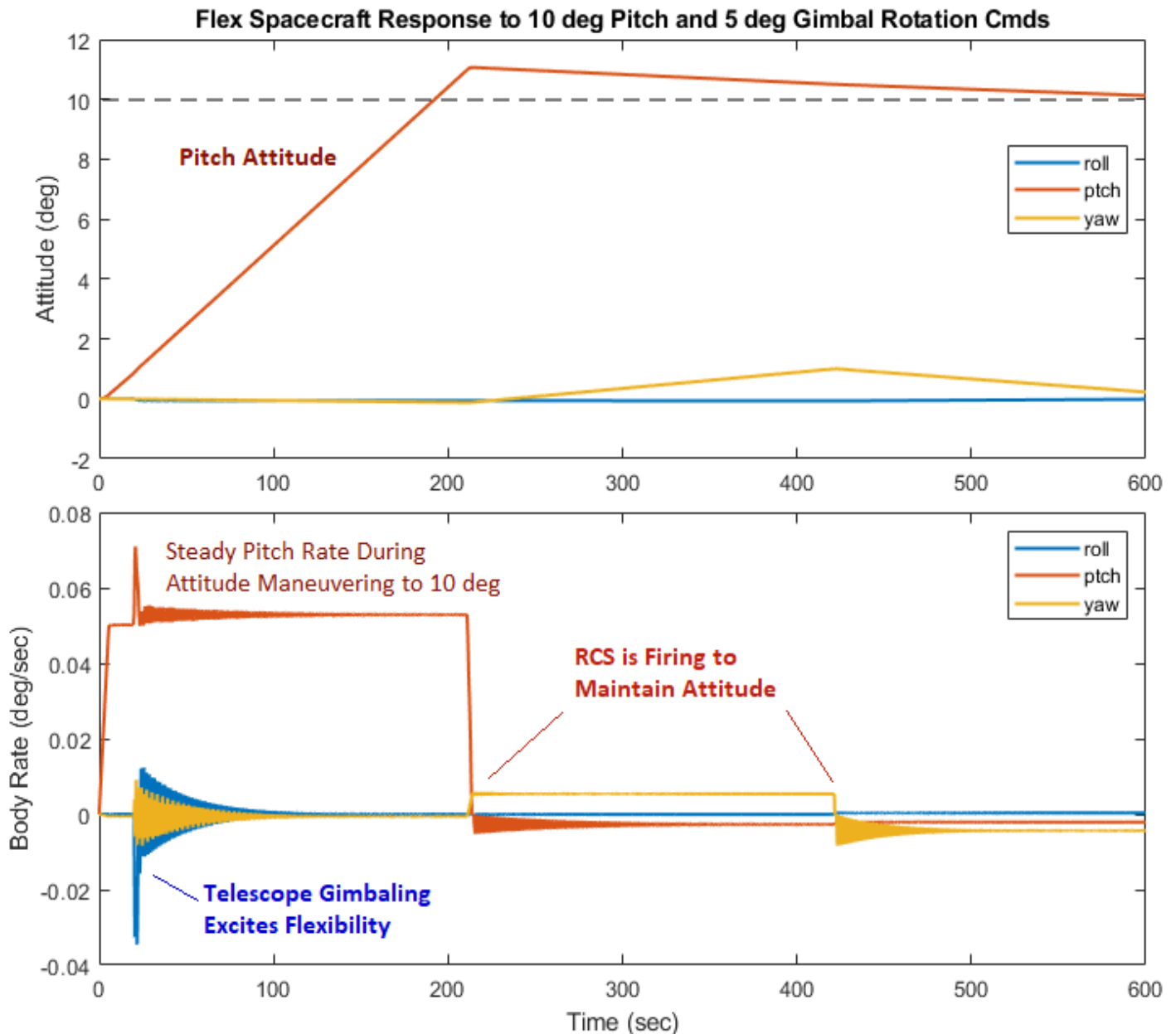


Figure 3.6 Flex Spacecraft Attitude and Rate Response to Attitude and Gimbal Commands

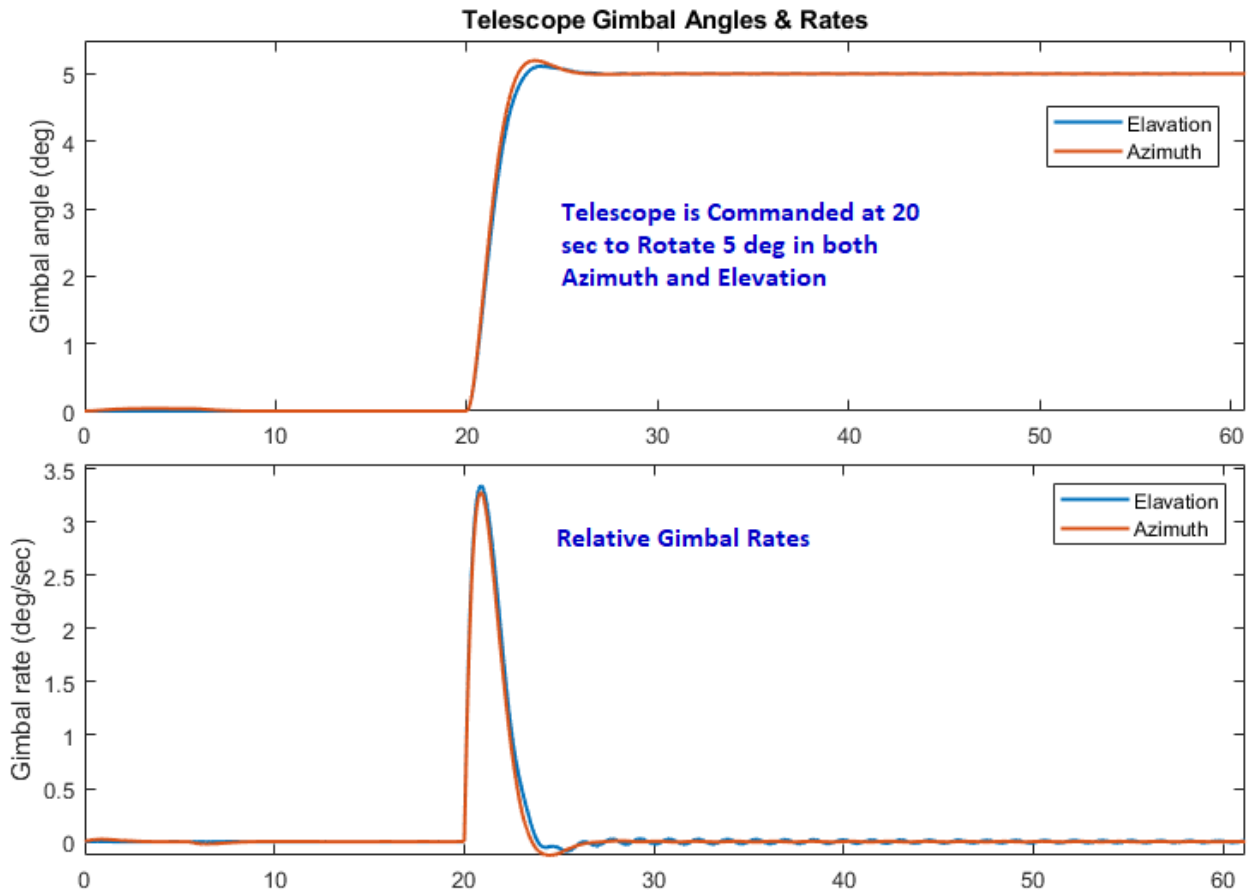


Figure 3.7 Elevation and Azimuth, Position and Rate, Gimbal Responses to Commands

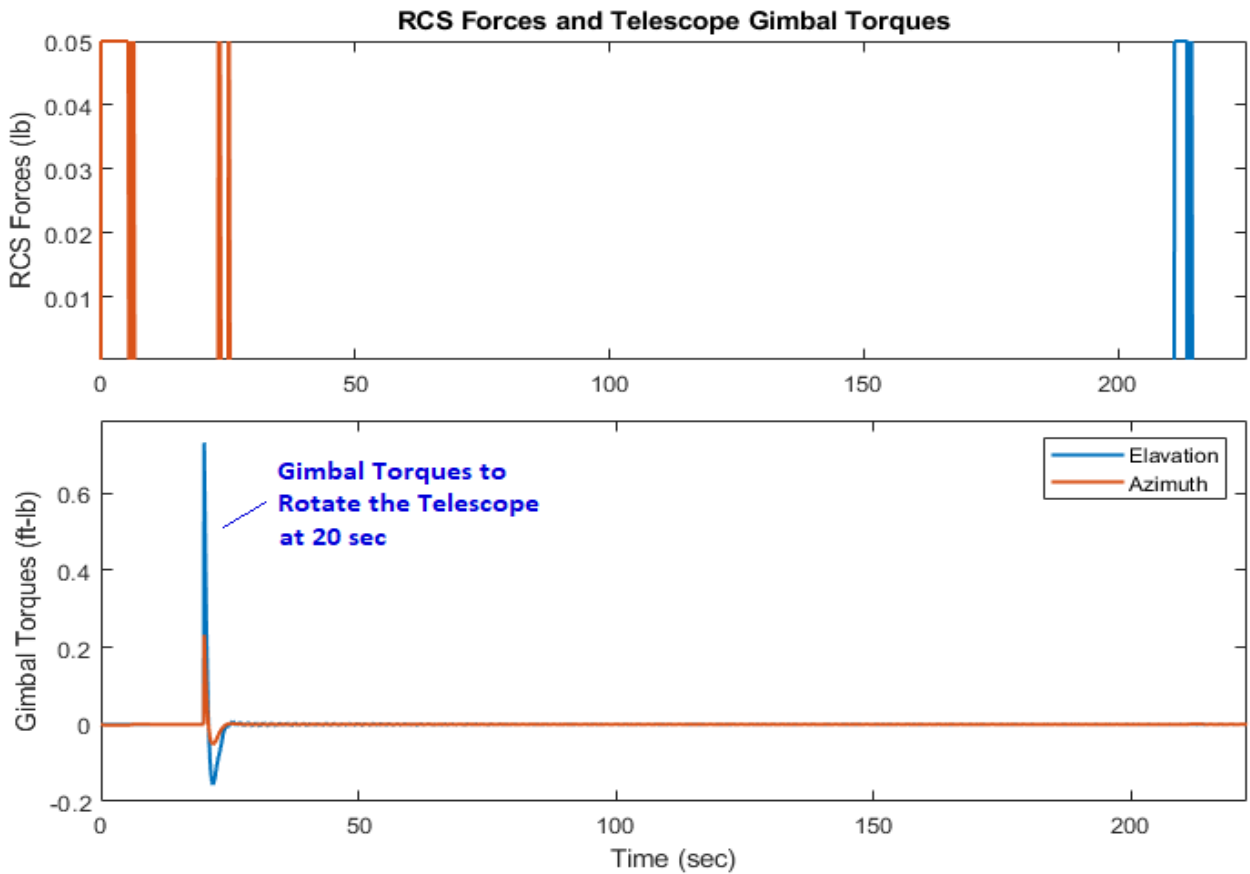


Figure 3.8 RCS Forces and Gimbal Torques During Maneuvering

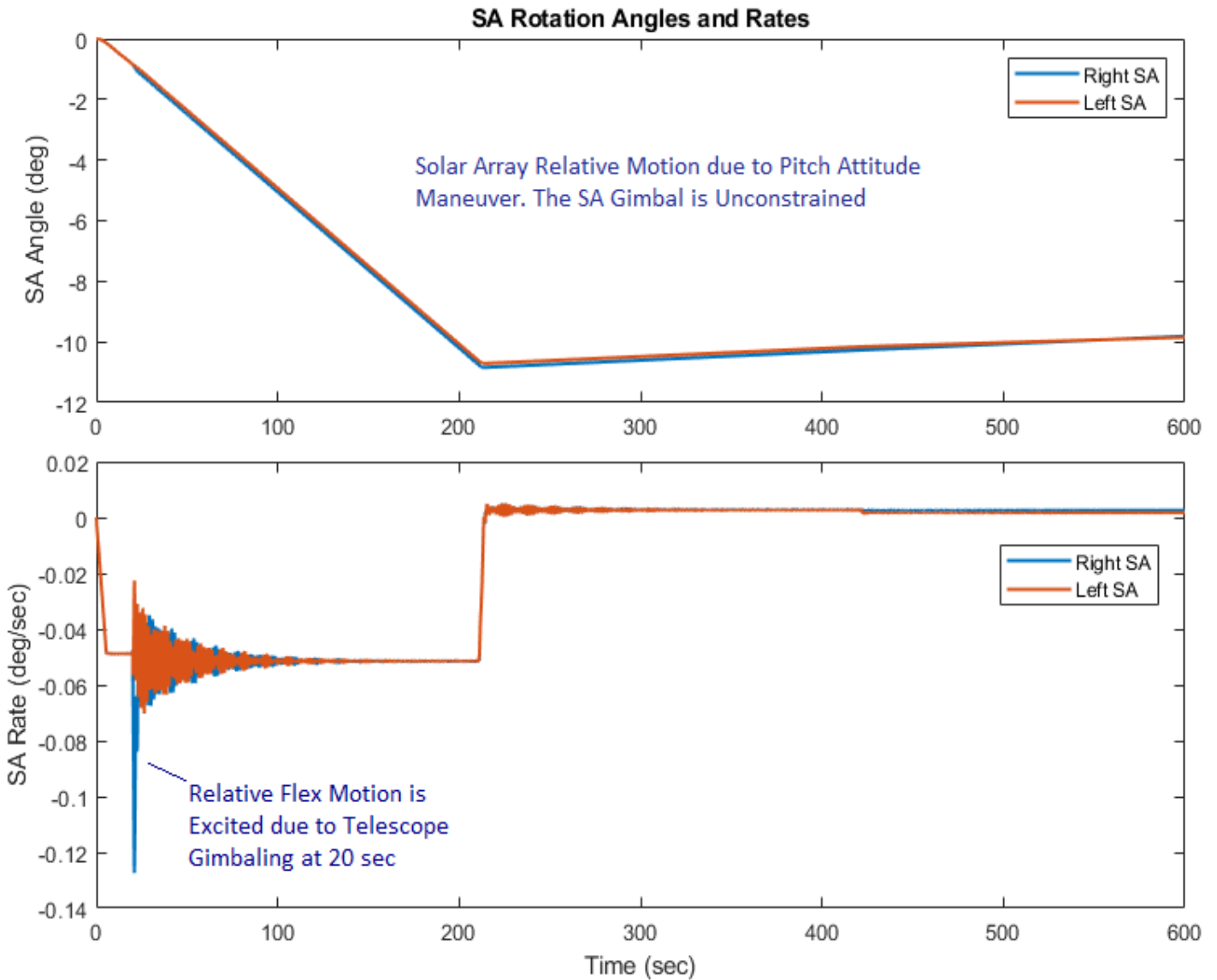


Figure 3.9 Solar Array Rotation Angles and Rates Relative to Spacecraft

3.5 Gimbal Sensitivity to Solar Array Stepper Motor Disturbances

The two solar arrays rotate about the spacecraft y axis and they perform a 360° rotation with respect to the spacecraft for every orbit. The rotation is controlled by stepper motors at the solar array joints which generate a train of torque pulses that rotate the arrays at constant rate. The frequency of the pulses is 2 Hz and they consist of a 0.08 (ft-lb) positive torque pulse followed by a similar negative pulse. The pulses, however, generate disturbances on the spacecraft that degrade the telescope image because of jitter in the Line-of-Sight (LOS). We will now use the simulation to perform sensitivity analysis by introducing the stepper motor torque pulses at the solar array joints and observe the effect on the azimuth and elevation jitter at the telescope gimbals. Only the gimbal control loops are closed in this case because the RCS generates much bigger disturbances and it is typically not active during telescope operations.

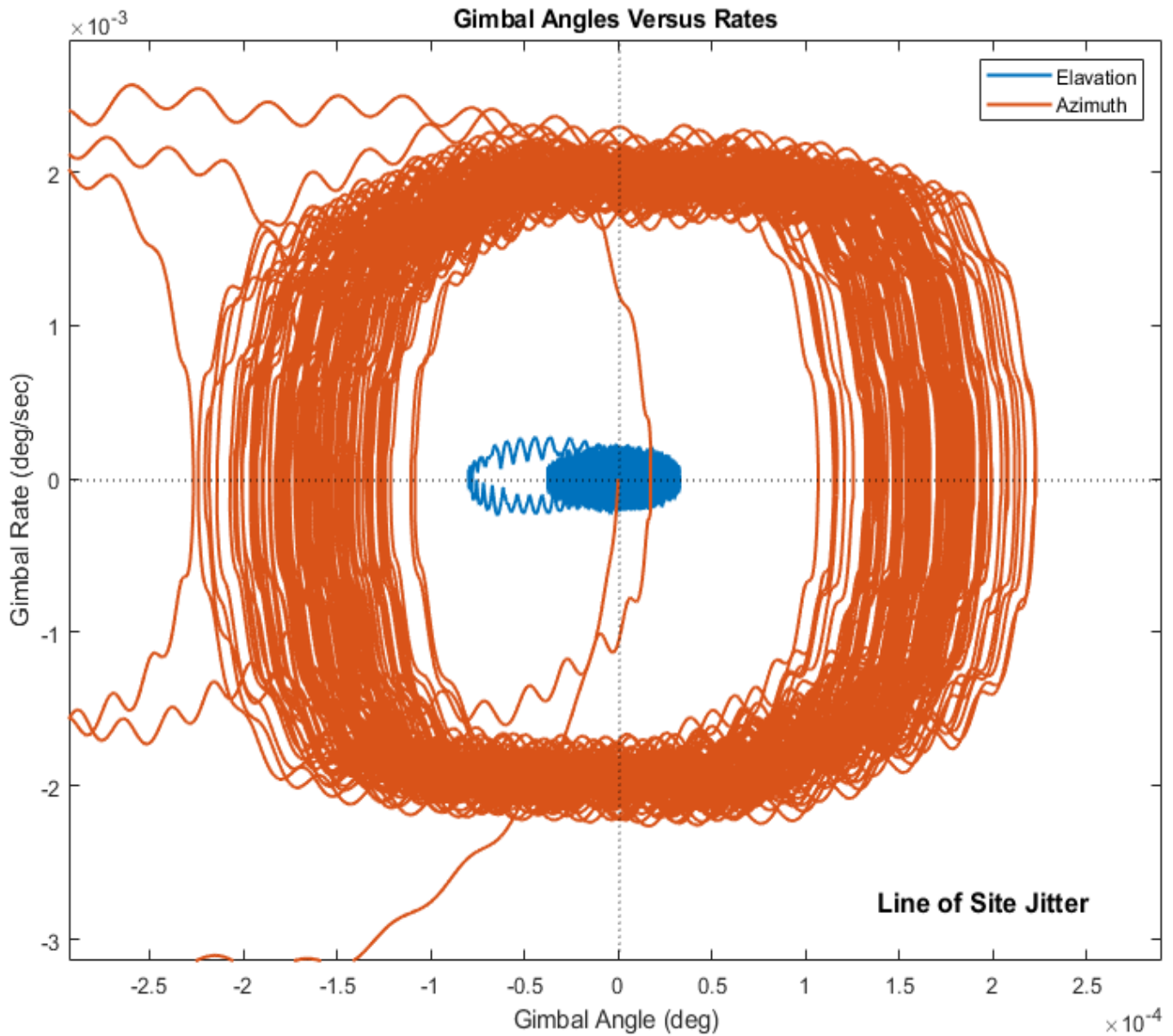


Figure 3.10 Azimuth and Elevation Jitter on the Telescope Line-of-Sight

Figure 3.10 shows the jitter effect on the telescope LOS, gimbal rates versus rotation error in both: elevation and azimuth. The azimuth direction is more affected by the disturbances because the pulses from the SA gimbals are in pitch and the telescope is pointing along Y. Figure 3.11 shows the solar array rotation angles and rates. The average rate is equal to orbital rate 0.063 (deg/sec). The rate oscillations are caused by the stepper motor pulses. Figure 3.12 shows the effect of the disturbance torque on the telescope gimbal torques.

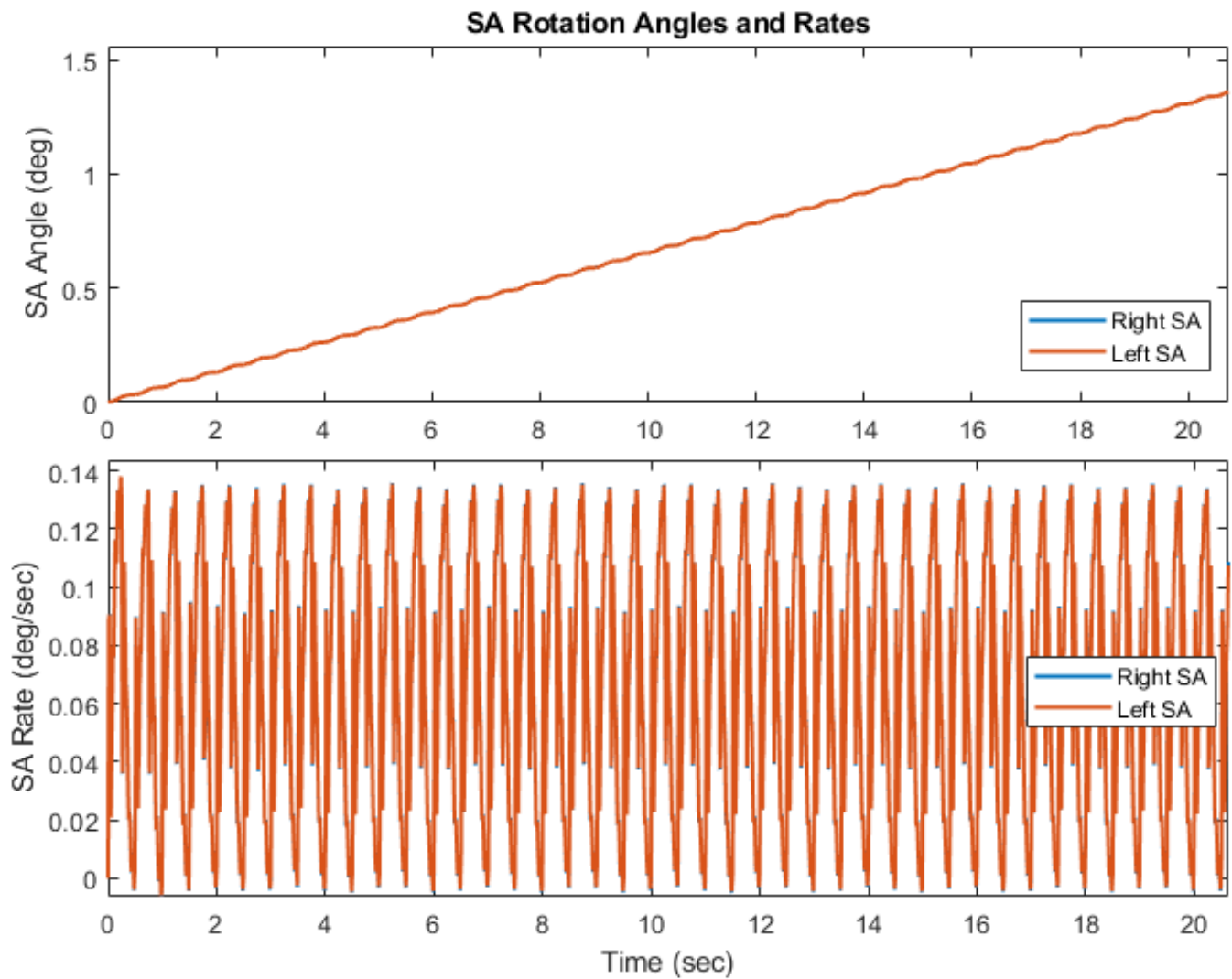


Figure 3.11 Solar Array Rotation Angle in (rad) and Rate in (rad/sec)

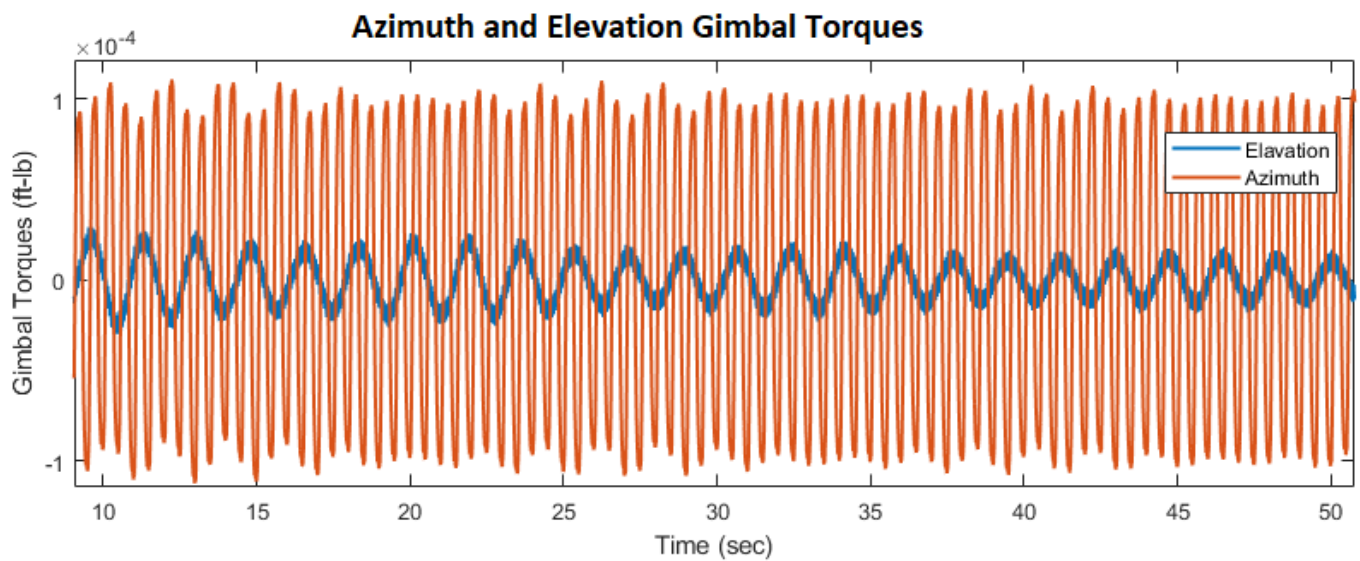


Figure 3.12 Azimuth and Elevation Gimbal Torques due to the Stepper-Motor Disturbances

4.0 Analyzing the Non-Linear Rigid-Body and the Flexible Systems Combined

In Section 2 we created a non-linear simulation model of the orbiting spacecraft in the LVLH frame. In Section 3 we created 3 flexible spacecraft systems from modal data. That is, a flex system that includes the rigid-body modes (flex67.m), a system that has only the 6 rigid modes (rigid_body.m), and a system that includes only flex modes without the 6 rigid modes. This flex only system contains 61 flex modes starting from mode #7 and it will be used in this Section and in Section 5. Its title is “Flex Spacecraft with Gimbaling Telescope and Reaction Wheels (61-Only Flex)” and it was saved in Matlab m-function “flex61.m”. It will be combined in parallel with the non-linear rigid-body model to capture both: flexibility and non-linear dynamics. The Matlab analysis in this section is performed in subdirectory: “\Examples\10-Surveillance Satellite React-Wheels\3-Coupled Models”.

4.1 Non-Linear Simulation Model, Rigid + Flex

Figure 4.1 shows the non-linear simulation model with flexibility “NonLinear-Flex-Sim.Slx”. The spacecraft dynamics block is shown in Figure 4.1b. It consists of the non-linear spacecraft dynamics block connected in parallel with the flexibility block which includes the state-space system “flex61.m”. Both systems receive the same RCS forces and RW torques, and their outputs are combined together to represent the measured rigid plus flex motion. The RW torques are calculated in body axes by the Wheel Dynamics block shown in Figure 4.1a, and implemented in function “Wheel_Dynamics.m”. It includes the gyroscopic effect due to body rate coupling with the bias momentum and also calculates the wheel rates relative to the spacecraft. The RW/RCS control law is identical to the one used in section 2. The file “run.m” initializes the simulation model.

Non-Linear Simulation of Flexible Spacecraft with Reaction Wheels, RCS Jets and Momentum Bias

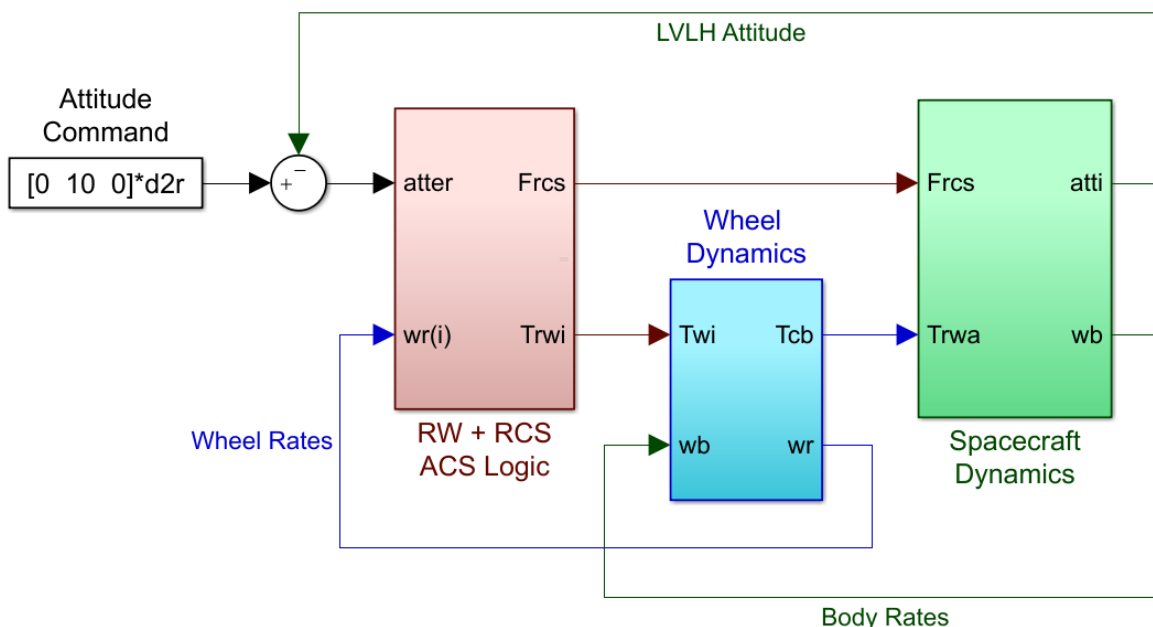


Figure 4.1 Non-Linear Simulation Model with Flexibility “NonLinear_Flex_Sim.Slx”

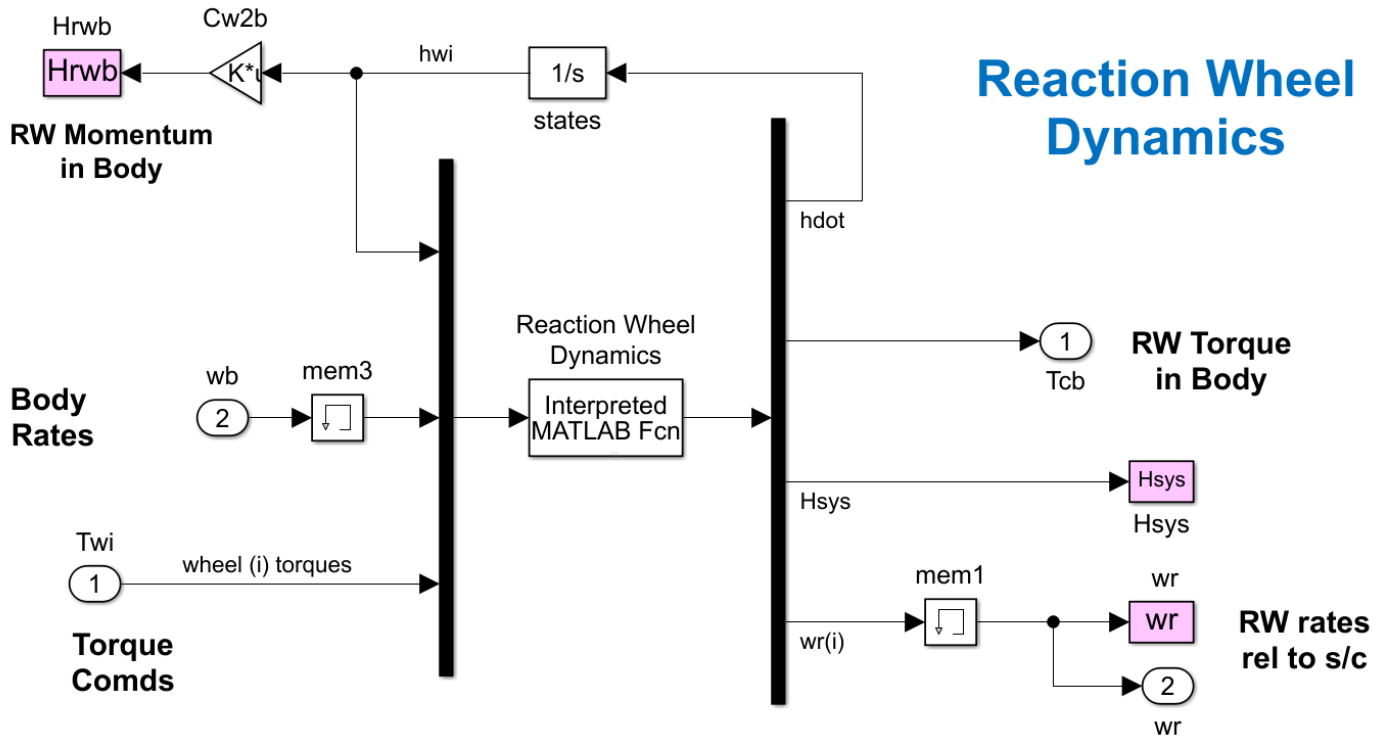


Figure 4.1a Reaction Wheel Dynamics Block Calculates the RW Torques in Body Coordinates

Non-Linear Spacecraft Model In Parallel with the Flex Model

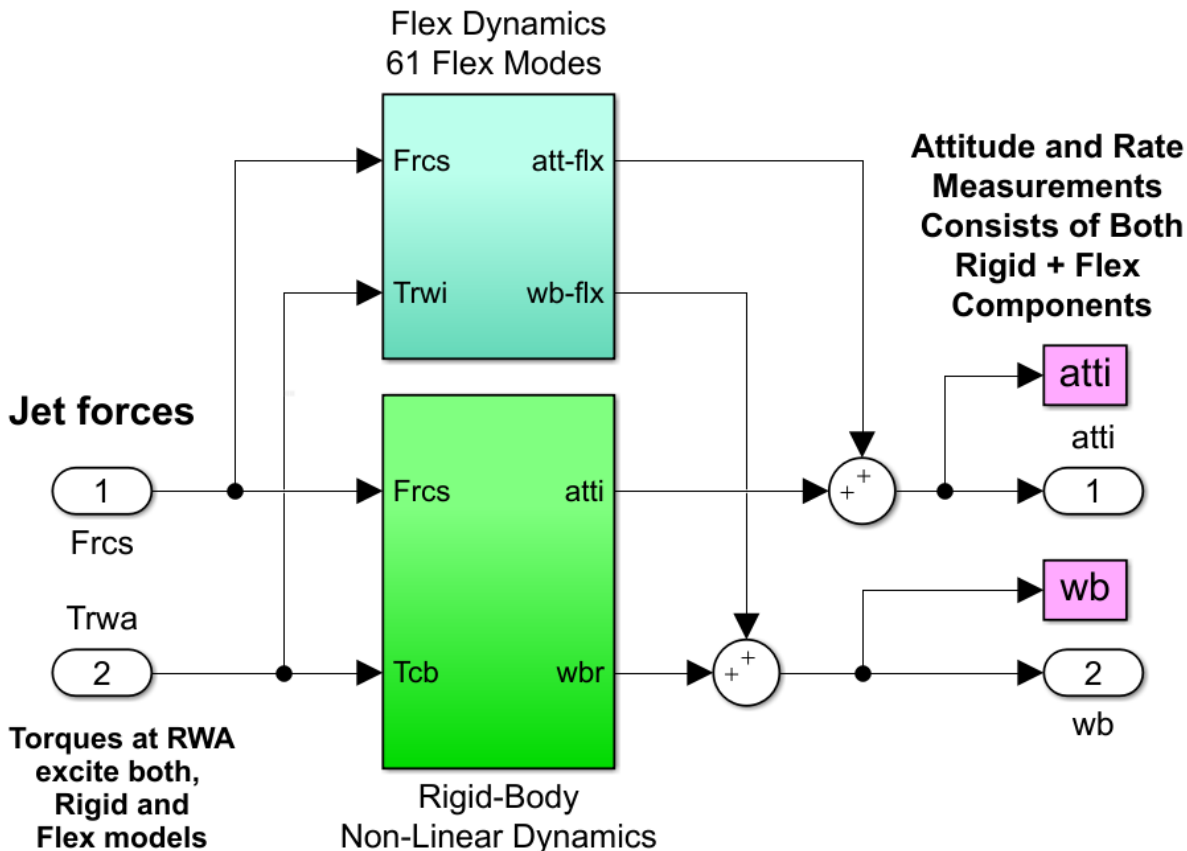


Figure 4.1b Spacecraft Dynamics Consisting of Flex System in Parallel with the Non-Linear Model

RCS and RW Attitude Control System RW Steering and Mode Switching Logic

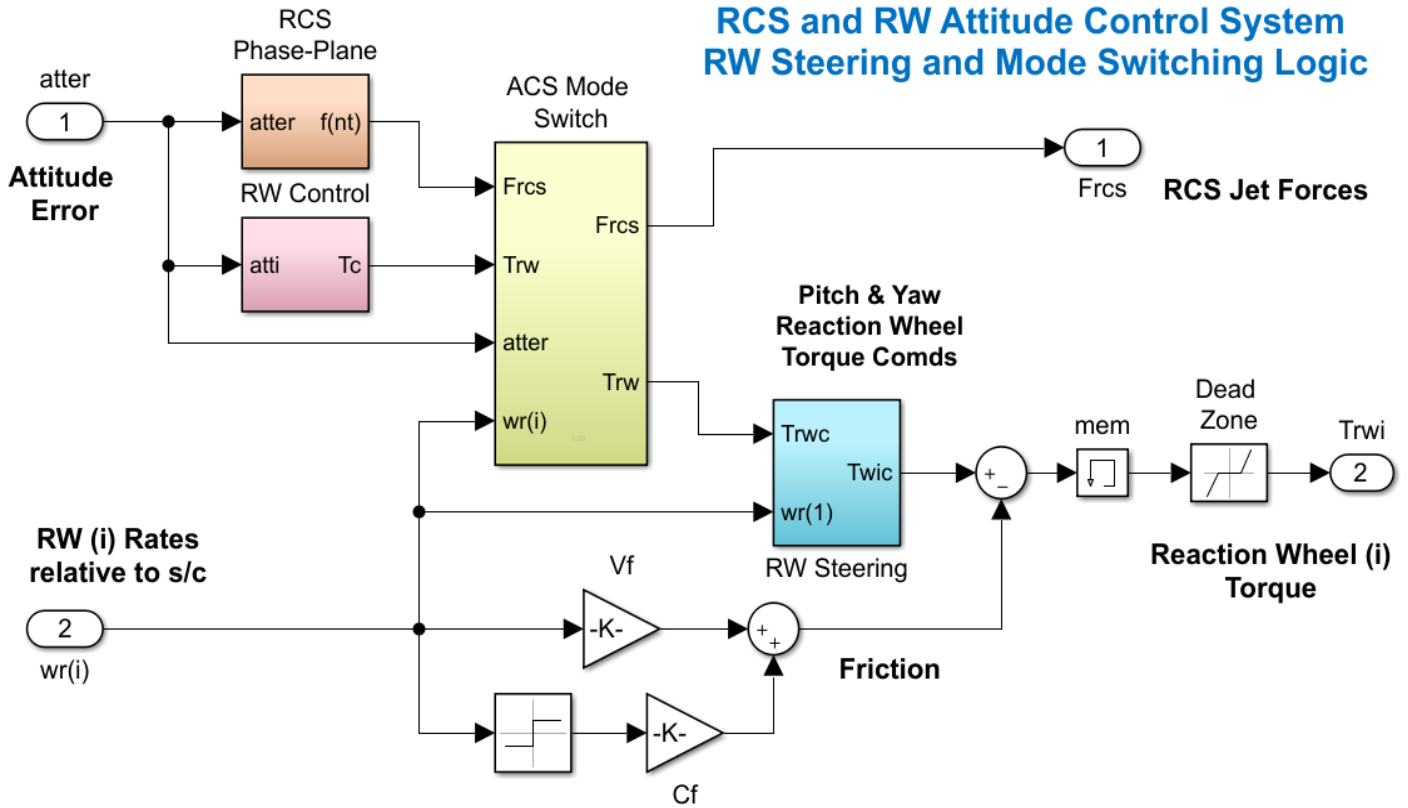


Figure 4.1c RCS and RW Control Logic, Including Mode Switching and RW Steering Logic

Spacecraft Non-Linear Dynamics

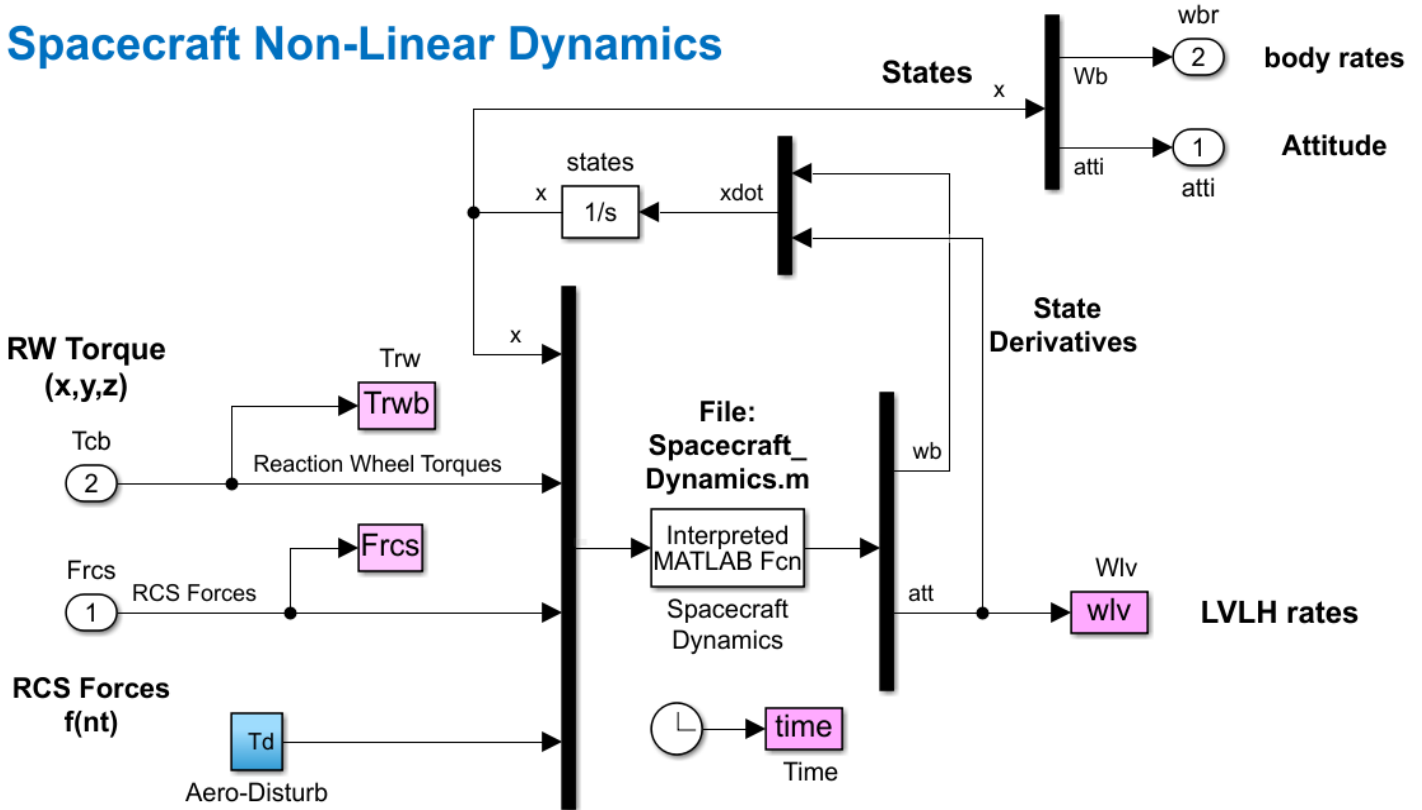


Figure 4.1d Spacecraft Non-Linear Rigid-Body Dynamics, Includes Function "Spacecraft_Dynamics.m"

Finite Elements Spacecraft Model (61 Flex Modes, No Rigid-Body)

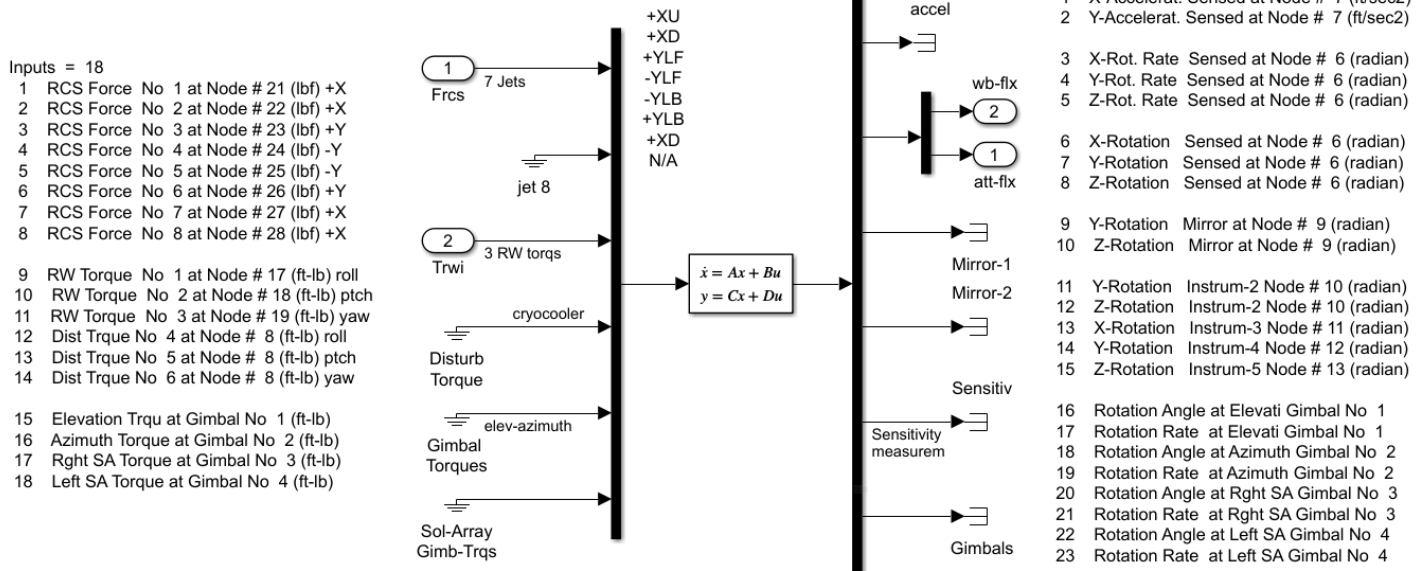
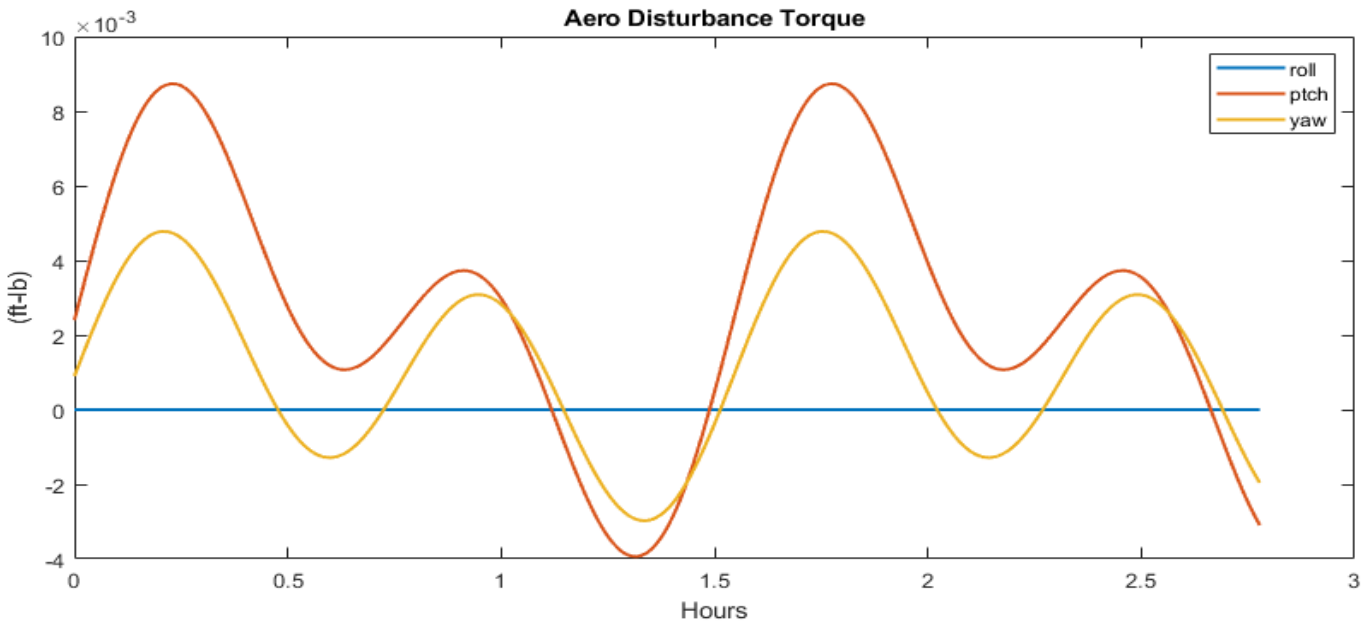


Figure 4.1e Spacecraft Structural Flexibility Dynamics, Includes Function “flex61.m”

Figures 4.2a through 4.2d show simulation results using the Simulink model “NonLinear-Flex_Sim.Slx”. This model is obviously much slower than the rigid-body of Section-1 because it includes 60 flex modes. It is initialized at non-zero RW #2 and #3 rates to reduce the time to reach the momentum saturation. The pitch attitude is commanded to 10° rotation. The maneuver begins by using the reaction wheels #2 and #3. Wheel #1 is maintained at constant speed to provide the -40 (ft-lb-sec) bias by a small torque to overcome gimbal friction. The external disturbance torques on the spacecraft cause the momentum to drift. When the magnitude exceeds 10 (ft-lb-sec) the ACS switches to the RCS mode in order to maintain the commanded attitude while the RW #2 and #3 are torqued in the direction to reduce their rates back towards zero. When the momentum dump is complete, the logic switches back to the RW control mode.



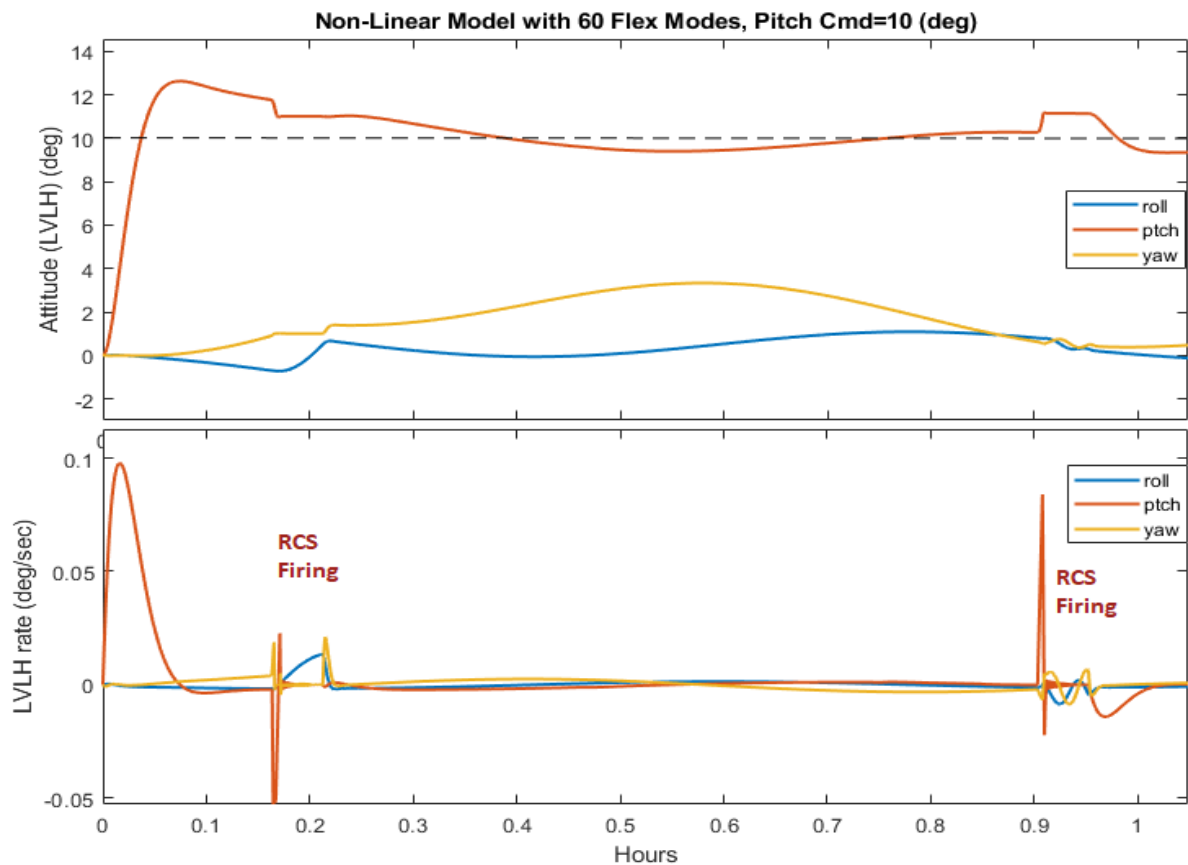


Figure 5.2a Spacecraft Attitude and Rate Relative to the LVLH frame with a 10° Command in Pitch

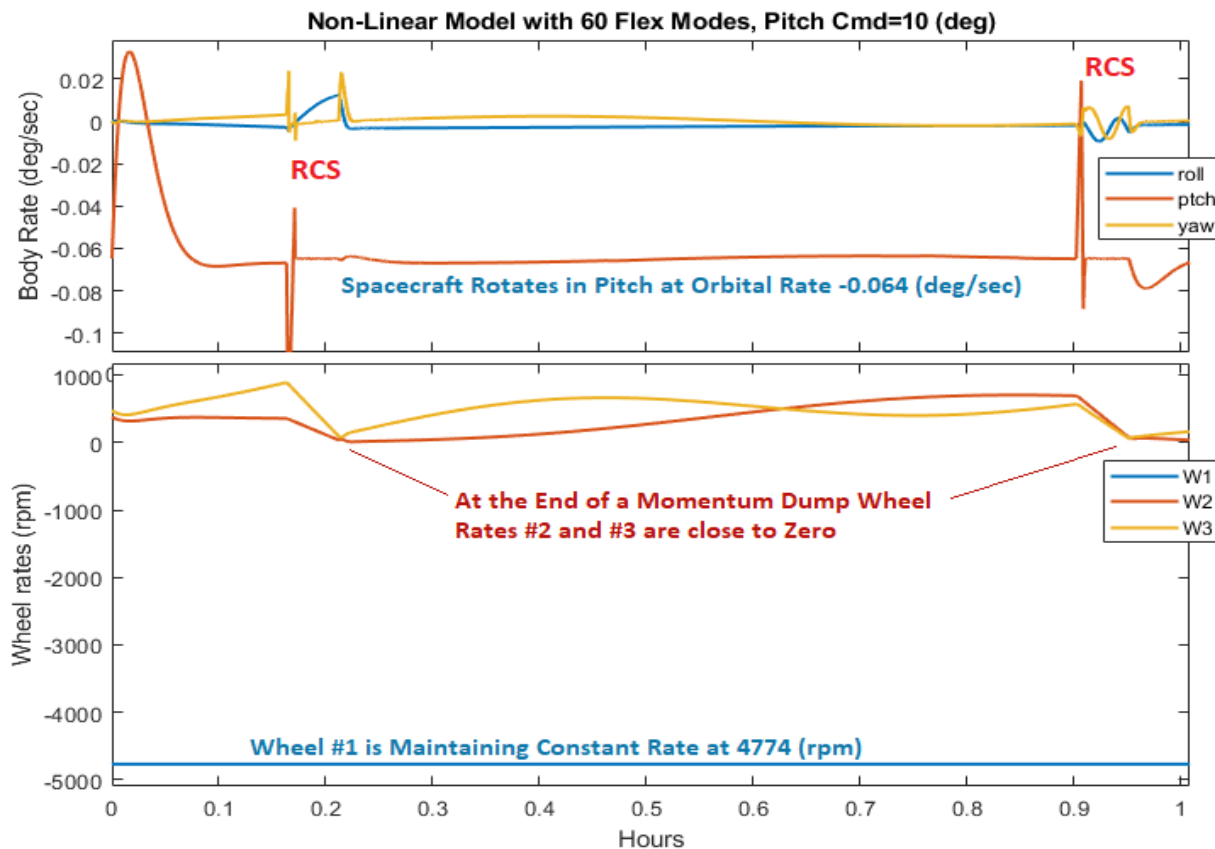


Figure 4.2b During RCS Control the Wheels are torqued to reduce their Roll and Yaw Momentum to Zero and the Pitch Momentum steady at -40 (ft-lb-sec). Wheel #1 (blue) is commanded a small torque to overcome internal friction and to maintain a constant speed.

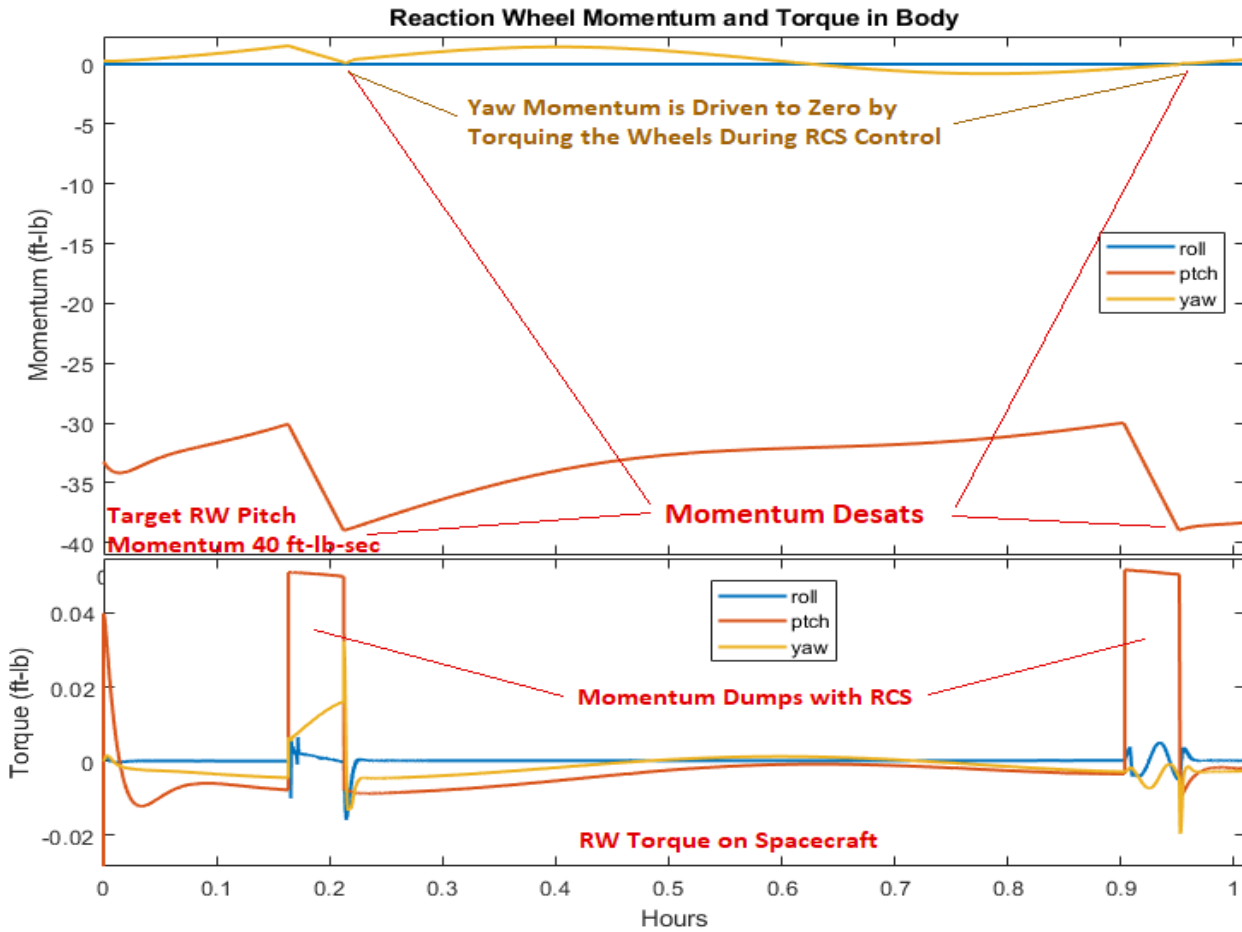


Figure 4.2c During RCS control Wheels #2 and #3 are torqued in the direction to bring their speeds to zero in unison. The RW Desaturation Torque is mostly in the Pitch direction. The Roll torque (blue) is gyroscopic in nature due to yaw body rate coupling with the pitch momentum.

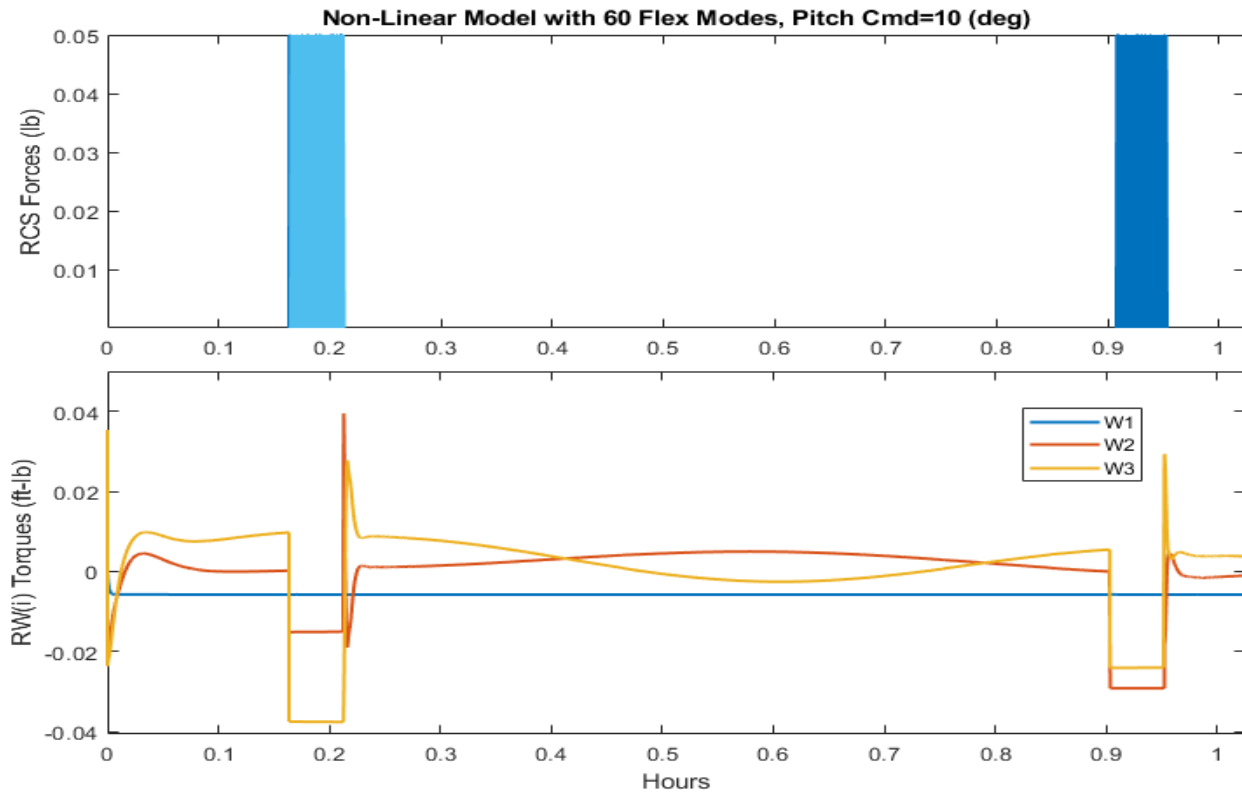


Figure 4.2d During RW Control Wheels #2 and #3 are torqued to control attitude by overcoming the external disturbances. During RCS Control they produce steady torque in the direction to drive the RW momentum to zero in unison

5.0 Linear Analysis of the Combined Rigid Spacecraft and Flexible Systems

For linear stability analysis we will combine again the 61-flex-mode state-space system which includes only flex modes in parallel with a linearized model of the spacecraft dynamics. We will ignore the RCS stability for now and focus mainly on analyzing the stability of the RW system. We will create two linear models: a closed-loop and an open-loop model and perform linear analysis. The work files for this section are included in subdirectory: "Examples\10-Surveillance Satellite React-Wheels\5-Linear Flex Anal".

5.1 Linearized Rigid-Body Equations of Motion

The following equations describe the linear motion of the spacecraft in circular orbit around the earth relative to the LVLH frame. The angular acceleration is a function of various external torques, as follows:

$$I \dot{\omega}_b = -\omega_b \times I \omega_b + T_{sc} + T_{gg} + T_d + T_{bias}$$

Where: the first term on the RHS is the gyroscopic torque on spacecraft

T_{sc} is the torques on the spacecraft from the RWA

T_{gg} is the gravity gradient torques on the spacecraft as a function of attitude

T_d is the aerodynamic torque

T_{sc} is a bias torque due to linearization

ω_0 is the orbital rate in (rad/sec)

The linearized gyroscopic term is:

$$-\omega_b \times I \omega_b = \omega_0 \begin{bmatrix} I_{XZ} & 2I_{YZ} & I_{ZZ} - I_{YY} \\ -I_{YZ} & 0 & I_{XY} \\ I_{YY} - I_{XX} & -2I_{XY} & I_{XZ} \end{bmatrix} \begin{pmatrix} \omega_x \\ \omega_y \\ \omega_z \end{pmatrix} + \omega_0^2 \begin{pmatrix} -I_{YZ} \\ 0 \\ I_{XY} \end{pmatrix}_{bias}$$

The torque applied on the spacecraft from the reaction wheel assembly consists of: reaction torques due to rotor acceleration plus lateral gyroscopic torques due to pitch momentum bias. In this case we only have H_{Y0} .

$$T_{sc} = \begin{bmatrix} \omega_z H_{Y0} - \omega_y H_{Z0} + \omega_0 H_z \\ \omega_x H_{Z0} - \omega_z H_{X0} \\ \omega_y H_{X0} - \omega_x H_{Y0} - \omega_0 H_x \end{bmatrix}_{gyro} - C_w^b T_{wi}$$

The rate of change in reaction wheel momentum in body frame is a function of the applied RW torques:

$$\begin{pmatrix} \dot{H}_{RWX} \\ \dot{H}_{RWY} \\ \dot{H}_{RWZ} \end{pmatrix} = \begin{pmatrix} T_{RWX} \\ T_{RWY} \\ T_{RWZ} \end{pmatrix}$$

The gravity gradient torque is a function of the LVLH attitude

$$T_{gg} = 3\omega_0^2 \begin{bmatrix} I_{ZZ} - I_{YY} & I_{XY} & 0 \\ I_{ZZ} & I_{ZZ} - I_{XX} & 0 \\ -I_{XZ} & -I_{YZ} & 0 \end{bmatrix} \begin{pmatrix} \phi \\ \theta \\ \psi \end{pmatrix}_{LVLH} + \omega_0^2 \begin{pmatrix} -I_{YZ} \\ 3I_{XZ} \\ -2I_{XY} \end{pmatrix}_{bias}$$

The combined bias term after linearization from the gyroscopic and the gravity gradient equations is

$$T_{bias} = \omega_0^2 \begin{pmatrix} -2I_{YZ} \\ 3I_{XZ} \\ -I_{XY} \end{pmatrix}$$

The LVLH attitude is obtained by integrating the following equations:

$$\begin{pmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{pmatrix}_{LVLH} = \begin{pmatrix} \omega_x + \omega_0\psi \\ \omega_y + \omega_0 \\ \omega_z - \omega_0\phi \end{pmatrix}$$

5.2 Linear Closed-Loop Simulation Model

We will examine the in-plane and out-of-plane systems stability of the spacecraft using linear models and design filters to attenuate the structural modes. The folder “5-Linear Flex Anal” contains a linear simulation model “Sim_Flex.slx”, shown in Figure 5.1. It consists of three blocks, the spacecraft dynamics, the reaction wheel dynamics and the RW control law that was described earlier. In this model, the Matlab function “Wheel_Dynamics.m” calculates the linearized wheel momentum in body axes and the total torque that is applied to the spacecraft at the reaction wheels assembly. The output torque T_{cb} from the RW dynamics block is in the body frame. It consists of two components: the control torques due to the RW #2 & #3 rotor accelerations and also the out-of-plane gyroscopic torques generated by the coupling of the 40 (ft-lb-sec) pitch wheel #1 momentum bias with the body rate ($\omega_b \times H_{rw}$). The torque T_{cb} drives both: rigid and flex subsystems. The green spacecraft block in Figure 5.1, consists of two blocks in parallel, the rigid-body and the flex dynamics, shown in Figure 5.2.

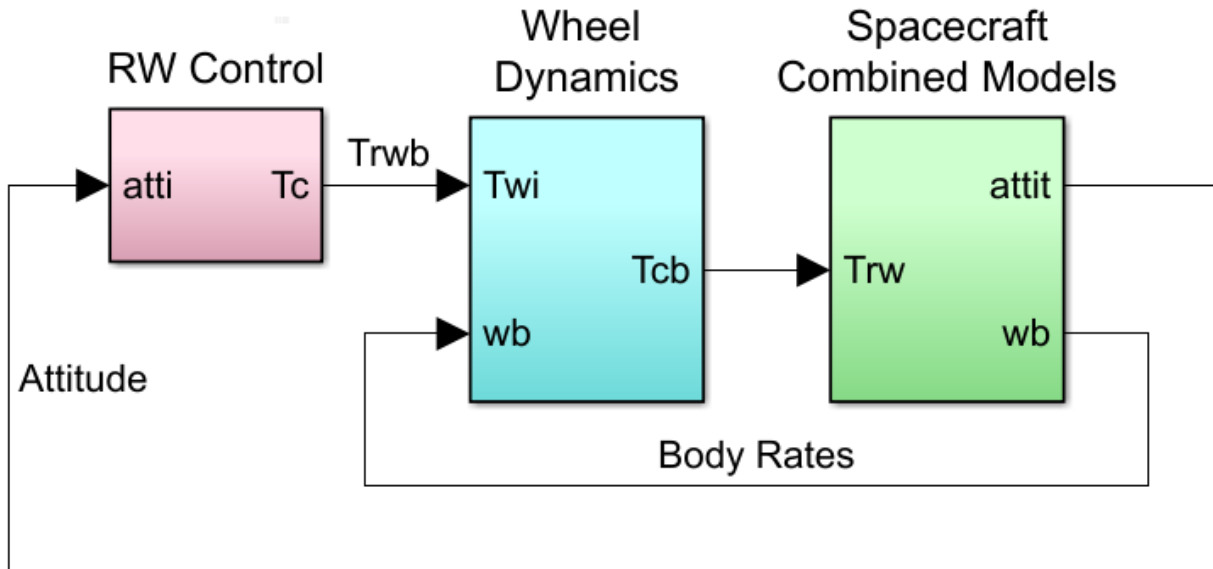


Figure 5.1 Linear Closed-Loop Simulation of the Reaction-Wheel Control System in file “*Sim_Linear.slx*”. Spacecraft Model Includes Both: Rigid and Flex Subsystems

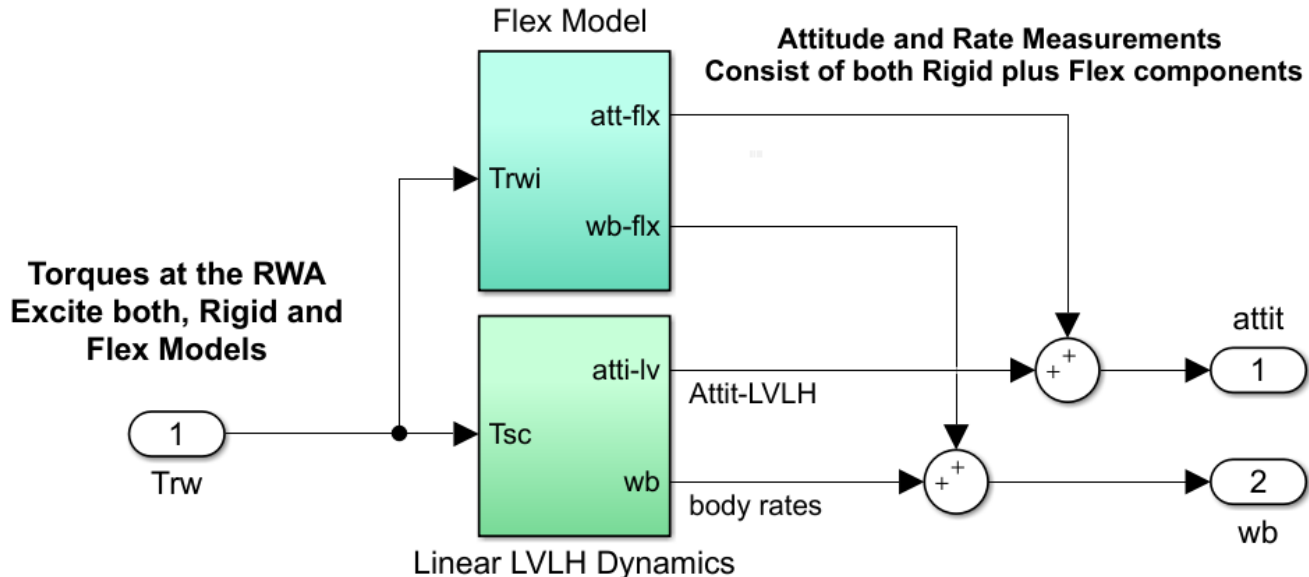
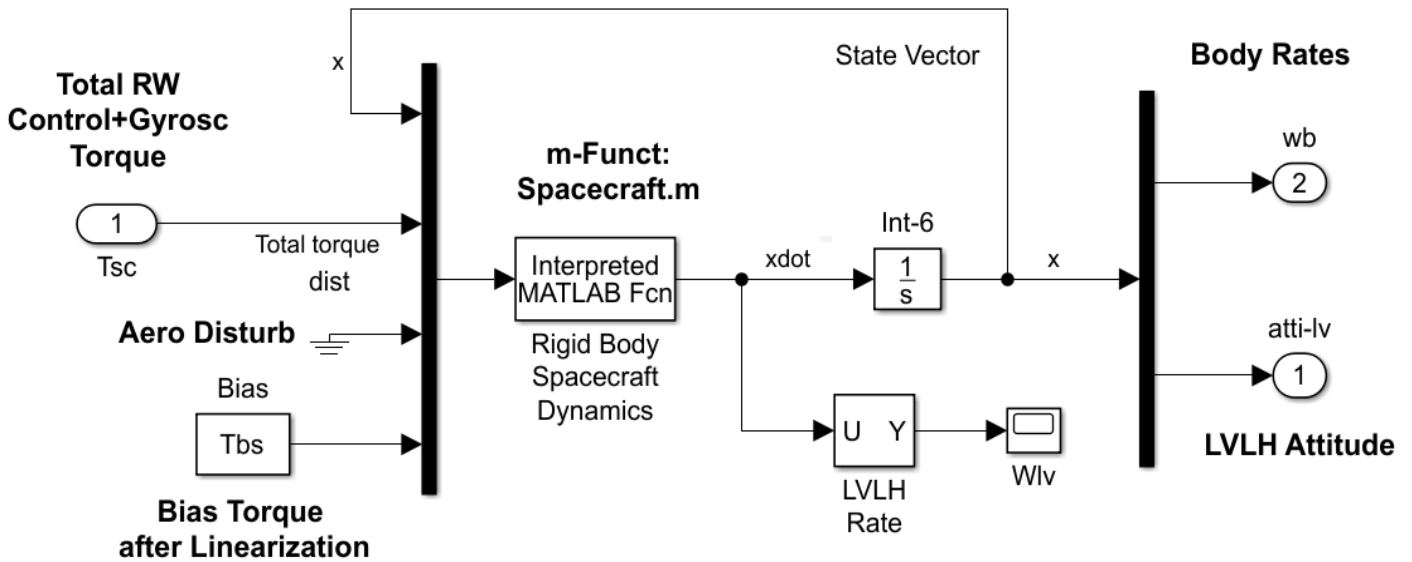


Figure 5.2 Combined Spacecraft Dynamics Consisting of Linear Rigid plus Flex Subsystems in Parallel

The rigid spacecraft subsystem is shown in Figure 5.3. It is linearized with respect to the LVLH frame, as described in Section 5.1. The equations are implemented in Matlab function “*Spacecraft.m*”, which produces the body rates and the spacecraft LVLH attitude as a function of the torques applied in the RWs. The gravity-gradient and the linearized spacecraft gyroscopic torques ($\omega_b \times J\omega_b$) are calculated as a function of attitude and body rate by means of matrices (M_{gg} and M_1), which are calculated in file “*run.m*” as a function of mass properties. T_d and T_{bs} are disturbance and bias torques respectively. The torque T_{sc} in function “*Spacecraft.m*” is the torque coming from the RW cluster and it includes also the gyroscopic effects due to the bias momentum of wheel #1. The spacecraft model outputs are: body rates, and LVLH attitude.

Rigid-Body Spacecraft LVLH Dynamics



```
function dot= Spacecraft(x,Tsc,Td,Tbs) % s/c Dynamics with CMG
global JI Mgg Ml wo d2r r2d

% dot= Spacecraft(x,Tsc,Td,Tbs)
% Spacecraft Linearized Dynamics in the Local Vertical Local Horizontal plane
% State Variables (x)
% x(1-3) = vehicle body rates (rad/sec)
% x(4-6) = Attitude in LVLH
% Inputs:
% Tsc(3) = RW Total Torque [Trw_contr + gyrosc (wb x Hrw) ] (ft-lb)
% Td(3) = External Torque (ft-lb)
% Tbs(3) = Bias Torques (after linearization)

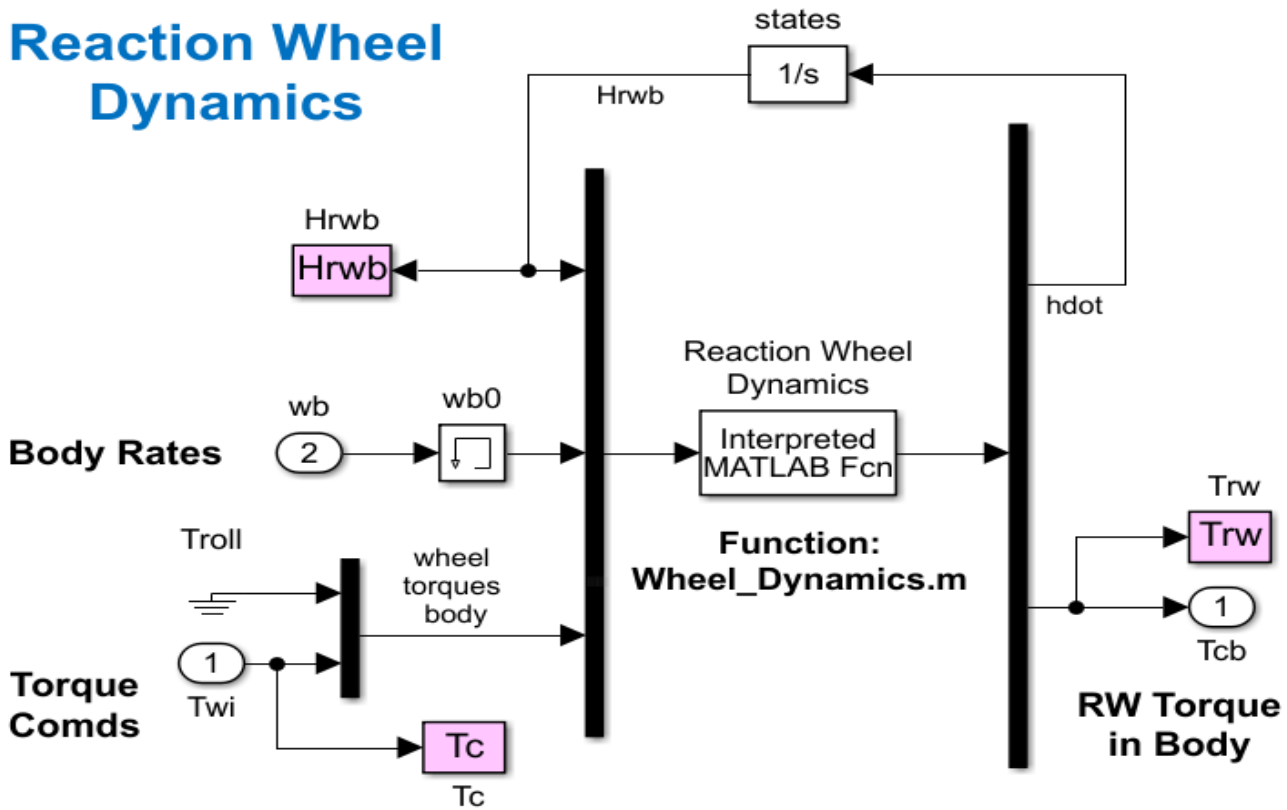
dot= zeros(6,1);
wb = x(1:3); % Vehicle body rates
the = x(4:6); % Vehicle Attitude LVLH

Tgg= Mgg*the; % Gravity Gradient Torque
Tgy= Ml*wb; % Spacecraft Gyrosc Torque
dot(1:3) = JI*(Tsc +Tgy +Td +Tgg +Tbs); % Body accelerations wb-dot
dot(4:6) = wb + wo*[the(3), 1, -the(1)]'; % LVLH Attitude -dot
```

Figure 5.3 Linearized Spacecraft Rigid-Body Dynamics Implemented in Function “Spacecraft.m”

The flex dynamics block is the same state-space system that was used in Section 4.1 from file “flex61.m” that has the 6 rigid-body modes taken out. The reason for replacing the FEM rigid-body modes with the spacecraft LVLH dynamics is because the FEM does not include the gyroscopic, gravity-gradient, and orbital effects. The rates and attitudes from the flex model are added to the rates and attitudes of the rigid-body model to simulate the sensor outputs which measure both: rigid and flex motion.

Reaction Wheel Dynamics



```
function out= Wheel_Dynamics (Hrw,wb,Trw)
global wo Hx0 Hy0 Hz0
% wb(3) = Body rates (wb) (rad/sec)
% hwi(3) = Reaction Wheel (i) Momentum (hwi) (ft-lb-sec)
% Trw(3) = Reaction Wheel (body torques (ft-lb)

hdot= Trw; % Reaction Wheel Momentum -dot (body)
Tsc= -Trw + ... % RWA torque on spacecraft
    [Hy0*wb (3) -Hz0*wb (2) +wo*Hrw (3); % Gyroscopic Torques due to
     Hz0*wb (1) -Hx0*wb (3); % RW Momentum Bias and Body Rate
     Hx0*wb (2) -Hy0*wb (1) -wo*Hrw (1) ];
out= [hdot; Tsc];
```

Figure 5.4 Reaction Wheel Dynamics Subsystem Implemented in Function “Wheel_Dynamics”

Figure 5.5 is a simulation analysis of the linear model initialized from an LVLH attitude [2, 1, -2] degrees. It includes no aero disturbances only gravity gradient torque. The out-of-plane system maintains a zero-mean oscillation at orbital rate 0.00113 (rad/sec) because it is initialized at a non-zero attitude and the system has an undamped resonance at that frequency. The frequency, however, is very low and the RCS (not included here) would normally take out the roll and yaw attitude oscillation. The nutation mode at 0.055 (rad/sec) is well damped by the RW attitude control system. The structural modes are attenuated by the low-pass filter. The pitch LVLH attitude converges fast to zero and the pitch RW momentum is building up because of the gravity gradient torque. The simulation sampling rate T_s was set to 0.001 seconds.

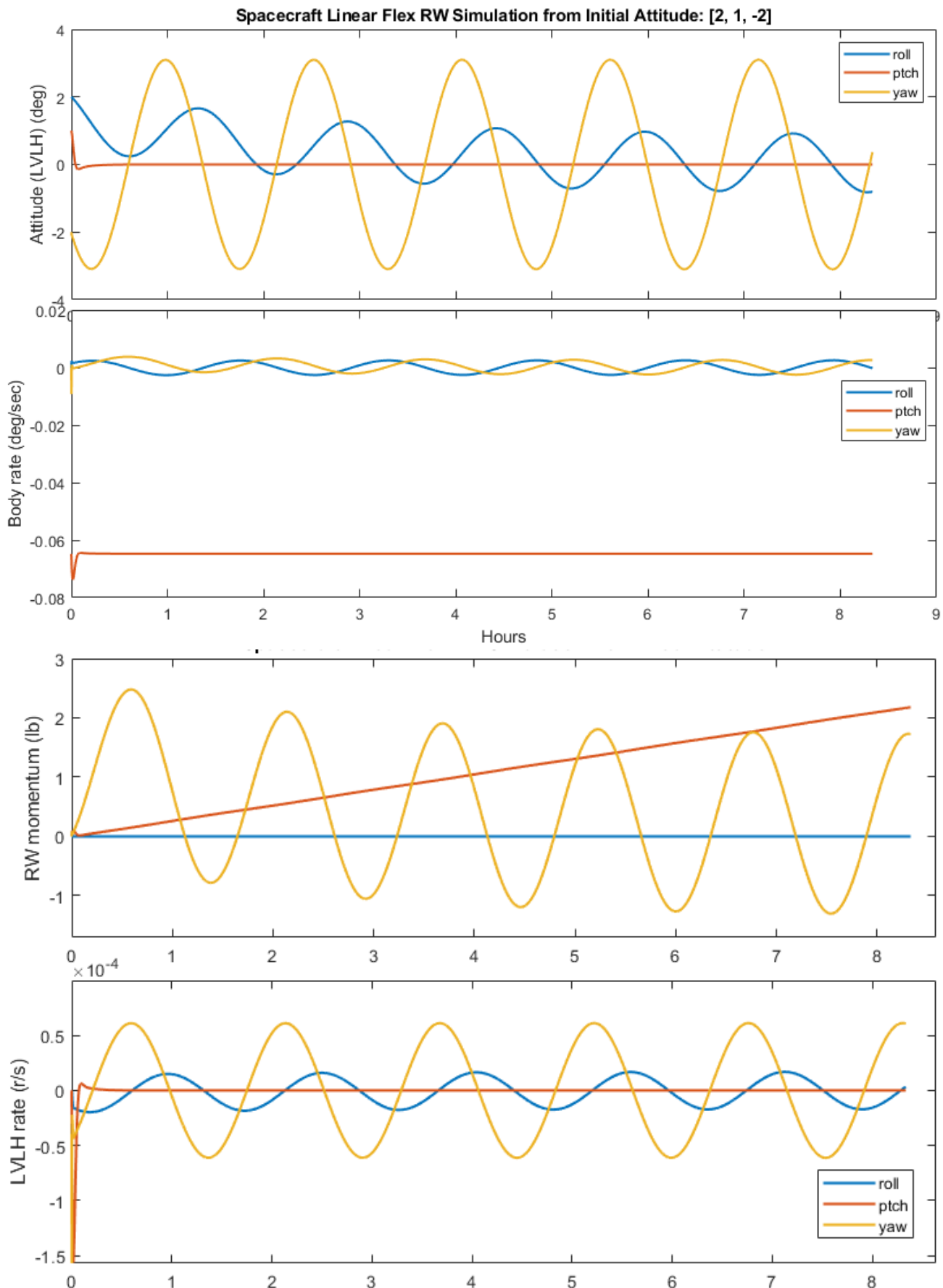


Figure 5.5a Linear Simulation using model "Sim_Flex.Mdl" shows spacecraft response from an initial LVLH attitude

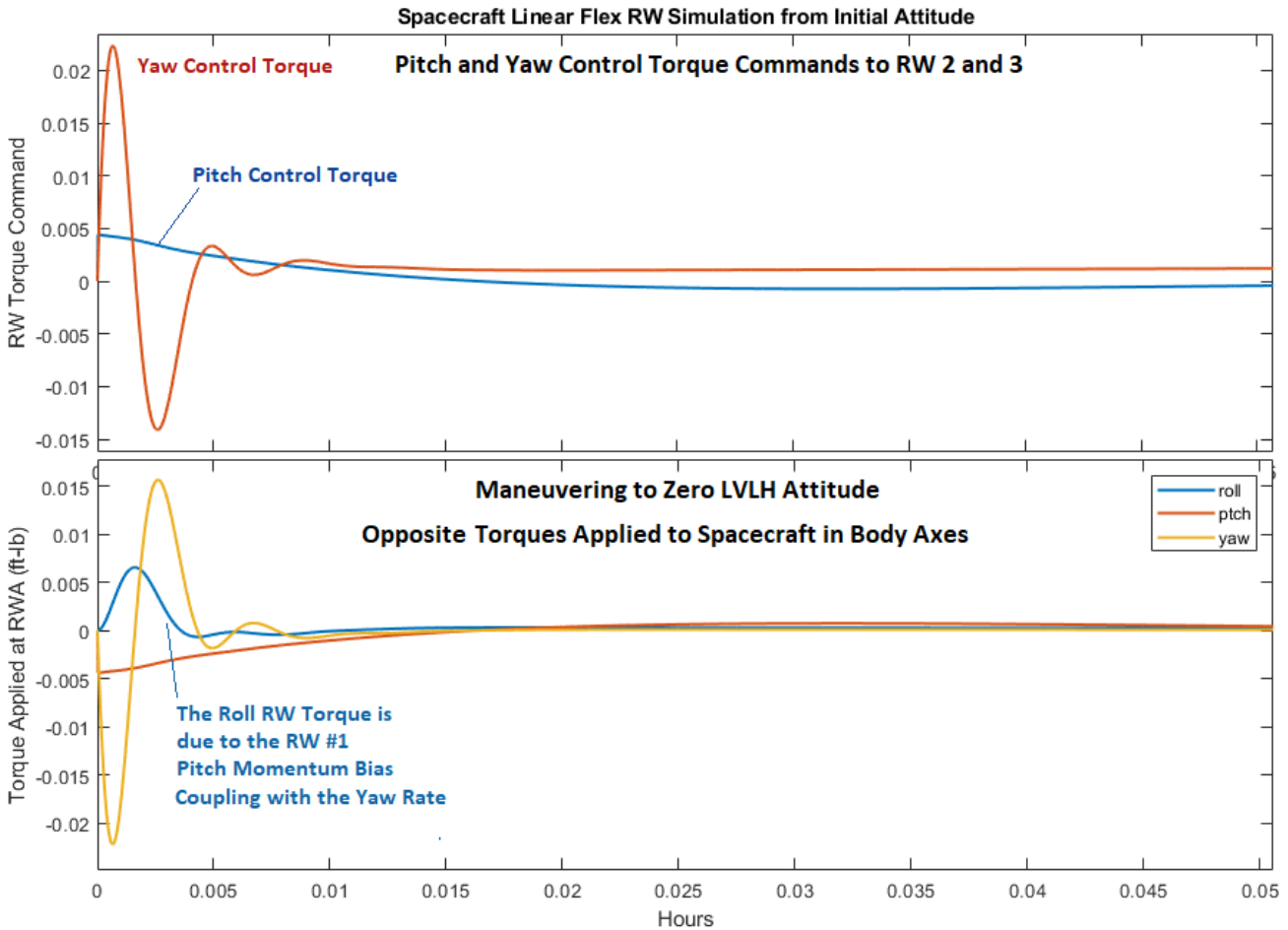


Figure 5.5b Reaction Wheel Torque Commands from ACS and the Actual Torques Applied to Spacecraft

5.3 Stability Analysis in Frequency Domain

Figure 5.6 is also a linear Simulink model "Open_Anal.slx" consisting of the same subsystems as Figure 5.1 and it is used for open-loop frequency response analysis. The controller consists of two loops, the in-plane pitch loop and the out-of-plane loop. The control loops are cut at the RW controller output, one loop at a time. The Matlab file "LinAnal.m" calculates the frequency response.

Open-Loop Linear React-Wheel Analysis

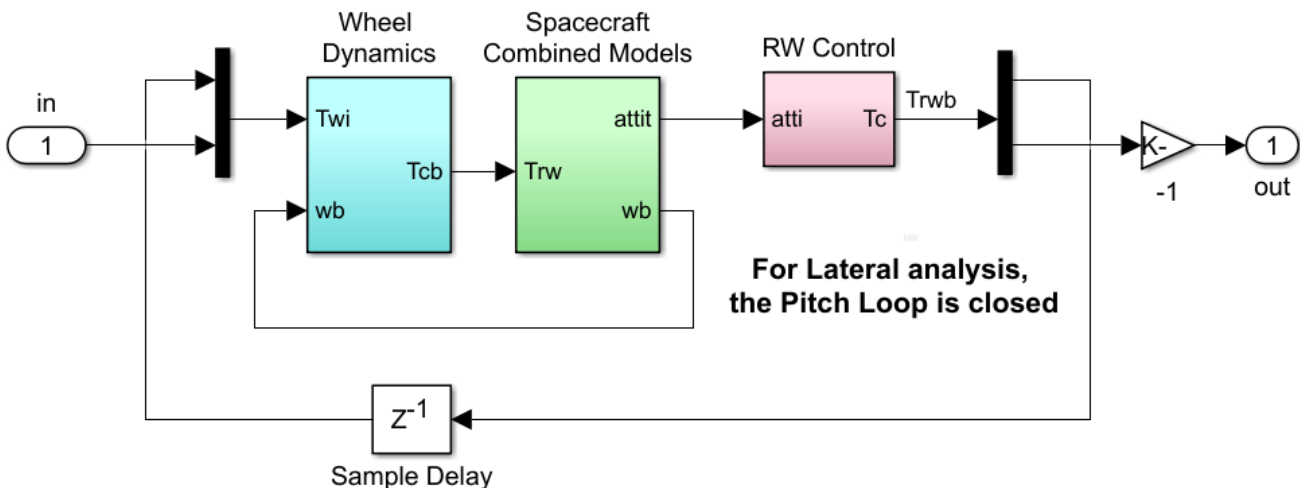


Figure 5.6 Simulink Model "Open_Anal.Slx" used for Frequency Response Stability Analysis

The configuration shown in Fig. 5.6 is for analyzing the out-of-plane stability with the pitch loop closed. Preliminary stability analysis predicts flex mode instability in the out-of-plane axis, as shown by the Bode plot in Figure 5.8. The instability, however, is attenuated by introducing a low pass filter in the out-of-plane RW control loop, as shown in Figure 5.10. The pitch axis stability is shown in figure 5.9, and it does not require any flex filtering.

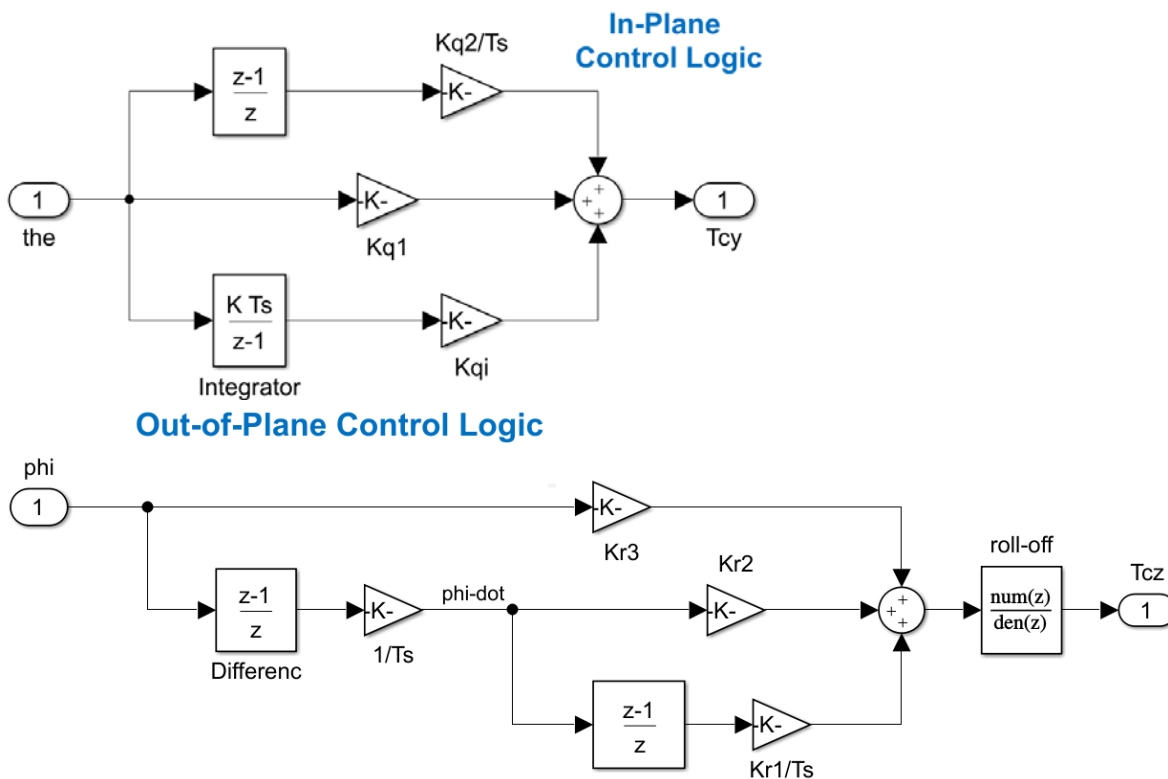


Figure 5.7 RW Control Law with additional low-pass filter to attenuate flex mode instability in roll

Lateral Axis Uncompensated Open-Loop Frequency Response

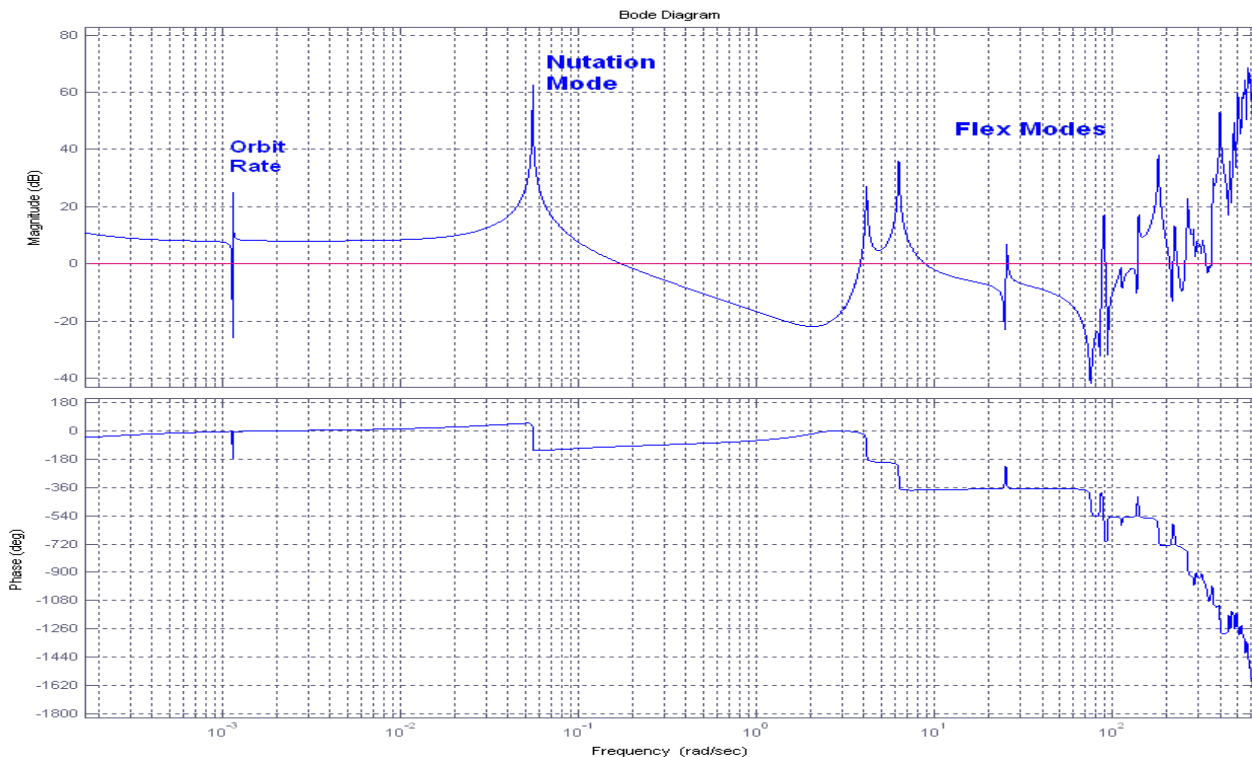
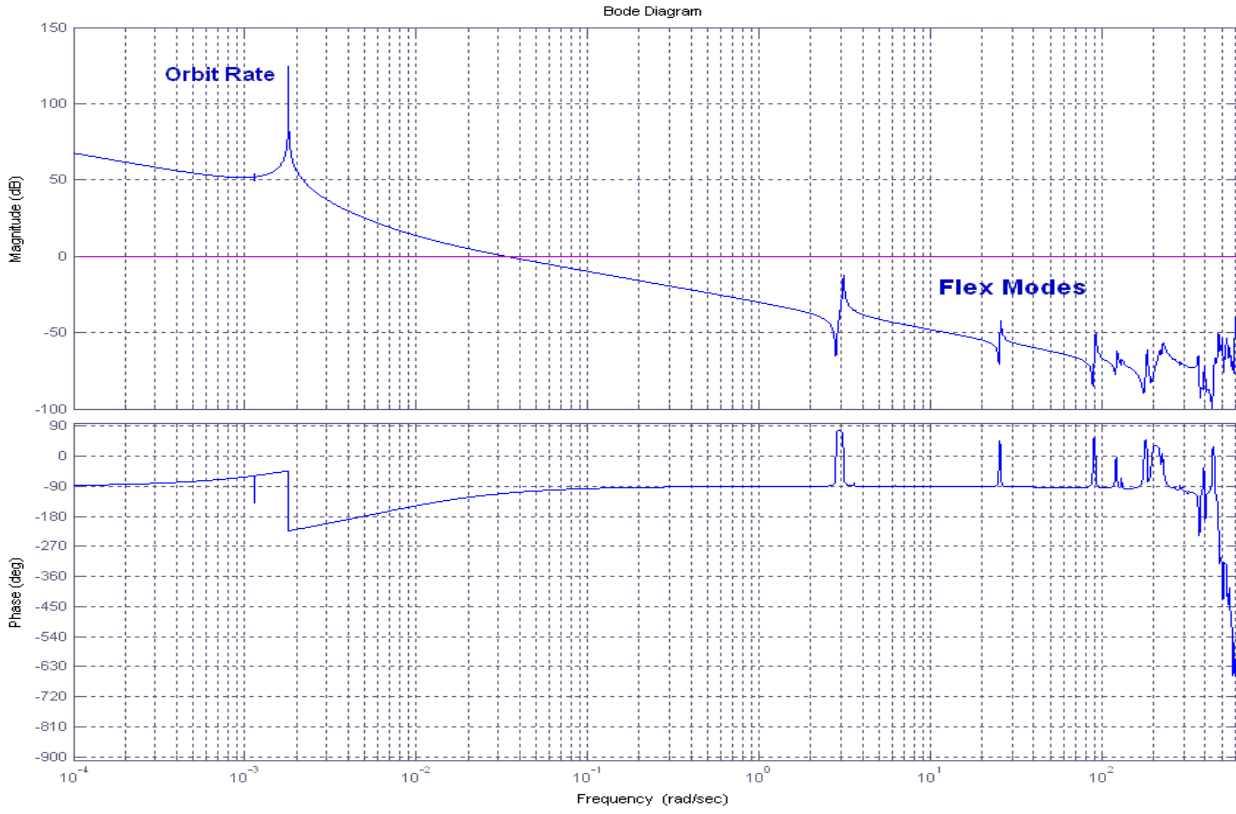


Figure 5.8 Flex Modes are Unstable in the Out-of-Plane Axis Without Compensation

Pitch Axis Open-Loop Frequency Response with Lateral Loop Closed



Pitch Axis Stability with Out-of-Plane Loop Closed

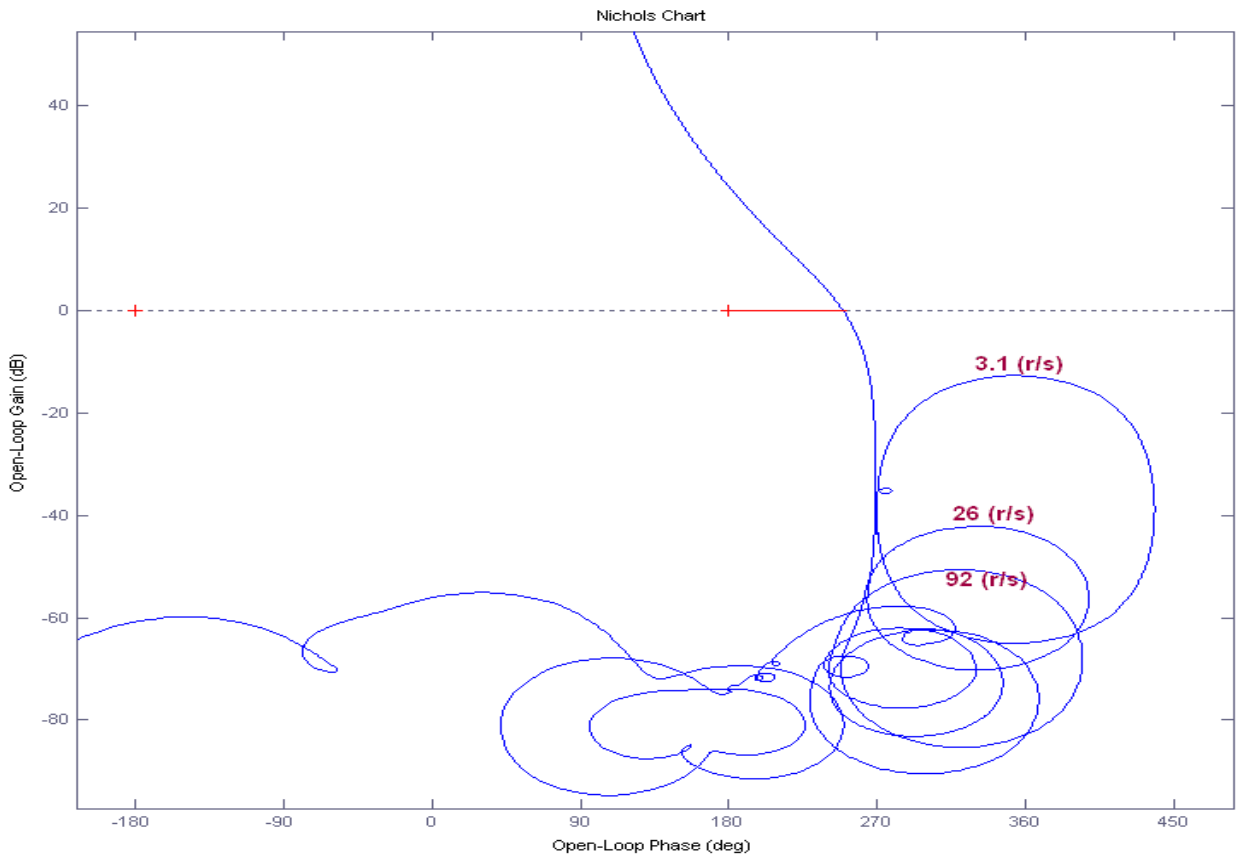


Figure 5.9 In-Plane Axis is Stable with Plenty of Margin

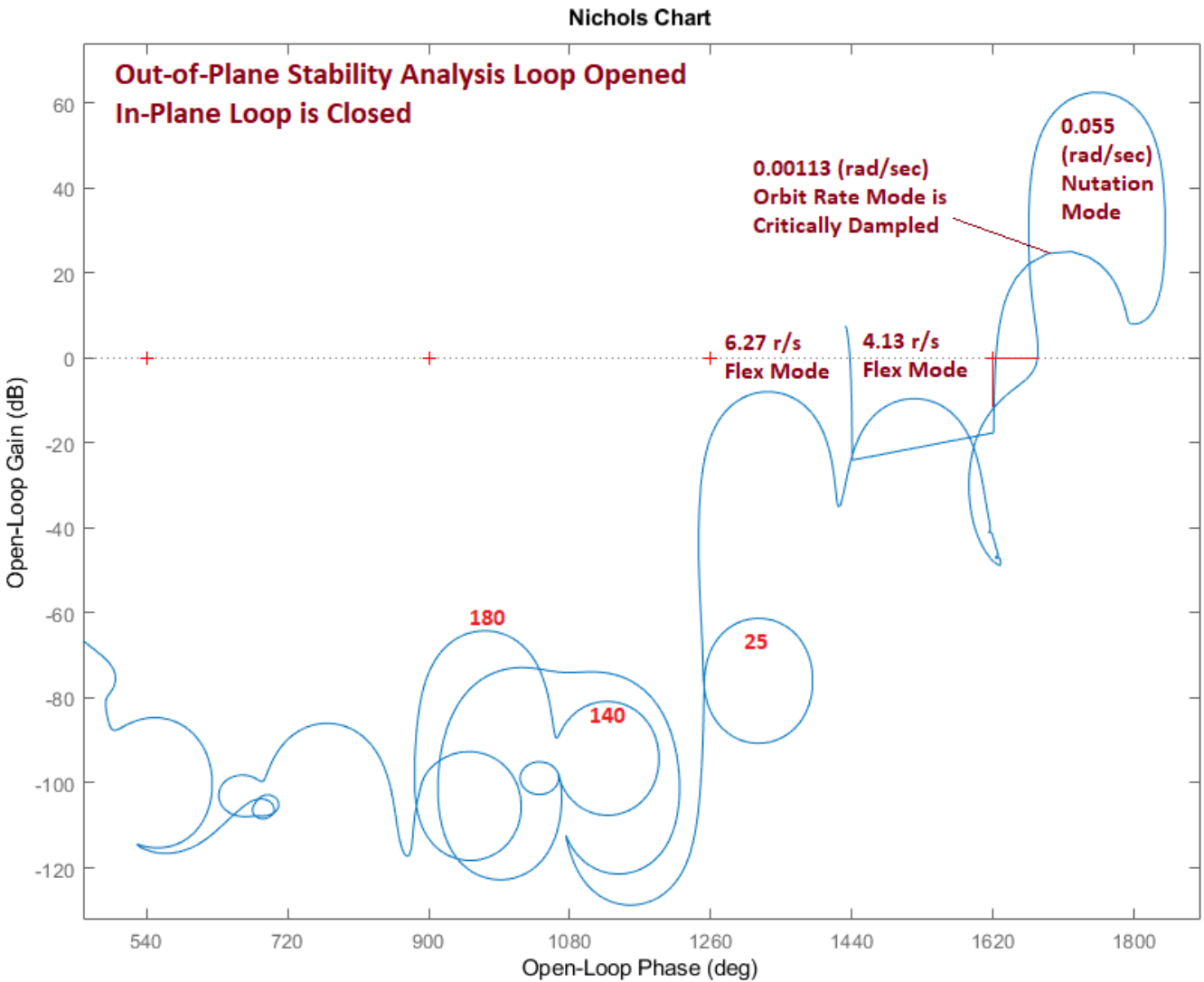
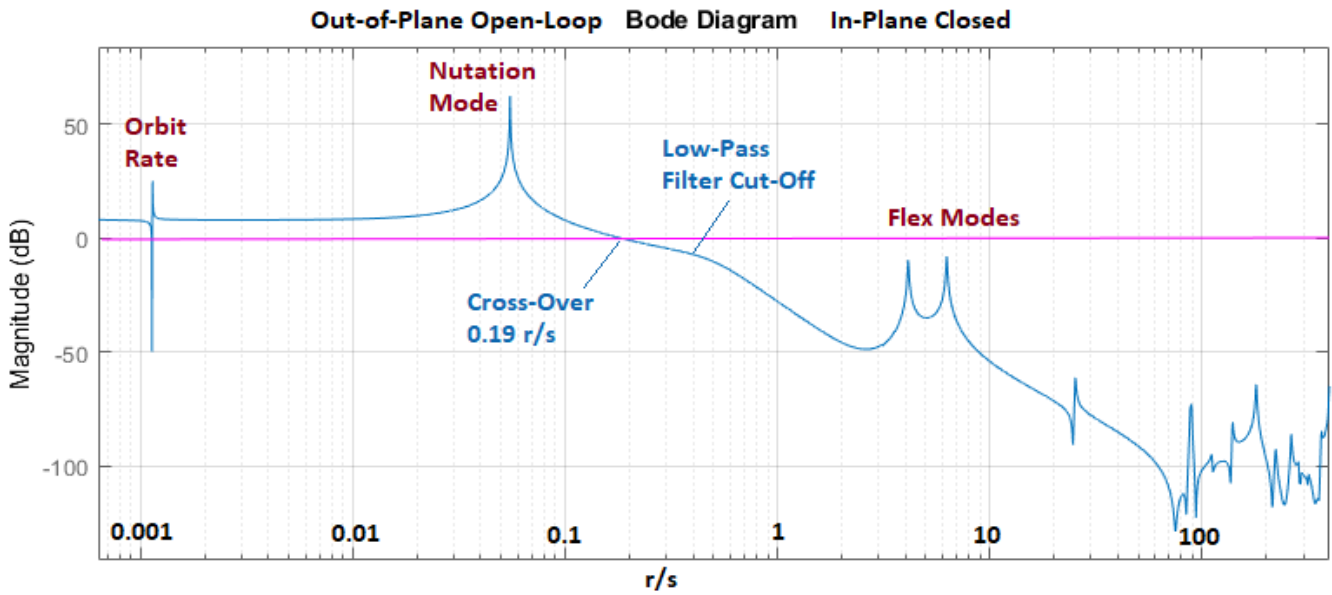
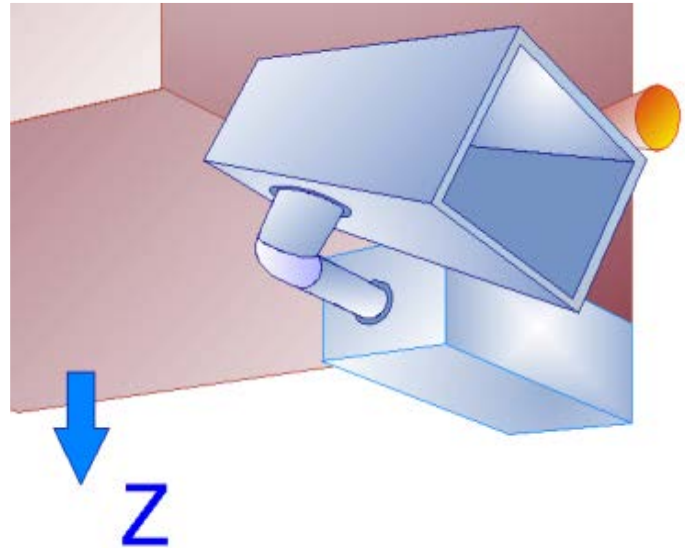


Figure 5.10 The Out-of-Plane Flex Instability is Corrected with Filters. The low frequency mode, however, at Orbital Rate ω_b remains Critically Damped. But we don't care, because it is at very low frequency and we don't excite that mode because we initialize at zero roll/ yaw attitude, and even if get an Out-of-Plane attitude error, it can be attenuated with the RCS.

6.0 Multi-Body Analysis

The next step in the analysis is to improve the dynamic model of the spacecraft by introducing two additional rotational degrees of freedom for the optical telescope. The telescope is attached to the spacecraft bus by means of a 2-hinge mechanical system that allows it to rotate about two orthogonal axes. The inner hinge is parallel to the spacecraft x axis. The outer hinge is orthogonal to the first hinge. When the hinges are at zero position the telescope is pointing towards the earth (+z) and the direction of the outer hinge is along the spacecraft -y axis. Typically, a multi-body non-linear simulation tool is used to simulate the relative motion between the satellite bus and the moving sensor, but in this case, we will use a 3-



rigid-body non-linear Simulink model and introduce the flexibility by coupling it in parallel with the flex model. We will also design simple PD control laws to stabilize the two gimbals, elevation (inner) and azimuth (outer) and analyze the system performance and stability using the attitude control laws that were designed in previous sections. We will first model the rigid-body dynamics for the 3-body system and simulate it in Matlab using the previously designed control laws. Then we will combine the 3-rigid-body model with the flex model in parallel and analyze flex stability and performance to gimbal commands. We will also analyze the telescope Line-of-Sight (LOS) sensitivity to mechanical disturbances.

6.1 Rigid-Body Simulation

The analysis data files for this section are in folder "...\\Flixan\\Examples\\10-Surveillance Satellite React-Wheels\\ 5-NLSim 3Body+Flex". The 3-body spacecraft dynamics is in file "Vehi-3B3W.m". The two solar arrays are not hinged in this model because their motion is very slow and do not create disturbances while rotating. Their masses and inertias were included in the mass properties of the spacecraft bus. The dynamic model consists of spacecraft attitude, gimbal dynamics, reaction wheels, orbital dynamics, reaction control jets, and gravity gradient effects. The model mass properties, hinge directions, etc. are initialized by running file "Dynamics-Data.m". The file "run.m" in addition to the "Dynamics-Data" it also initializes all the other parameters needed in this analysis. The wheels are initialized with -40 (ft-lb-sec) initial momentum in the pitch direction and the spacecraft has a negative pitch rate -0.00113 (rad/sec). The initial position and velocity are initialized for a 215 N-miles circular orbit. The flex state-space system "flex61.m" created from previous analysis and consisting of 61 flex modes (no rigid modes) is also loaded. The RCS, the reaction wheel parameters and the state-vector in the simulation (Int_IC) are also initialized. The inputs to this model are: RCS jet forces, reaction wheel torques for each individual wheel axes, 2 torques at the telescope gimbals, and disturbance torques. The outputs of the spacecraft model are: LVLH attitudes, body rates, RW momentum, RW rates relative to spacecraft, spacecraft position and velocity (ECI), altitude, telescope gimbal angles and rates.

The rigid-body rigid Simulink model is “*RigidBody3_Sim.Slx*”, shown in Figure 6.1. The 3-body spacecraft dynamics is implemented in function “*Vehi-3B3W.m*” and is included in the green spacecraft block. The attitude control logic has already been described in section 4. The spacecraft dynamics block is shown in detail in Figure 6.2.

Rigid Multi-Body Simulation

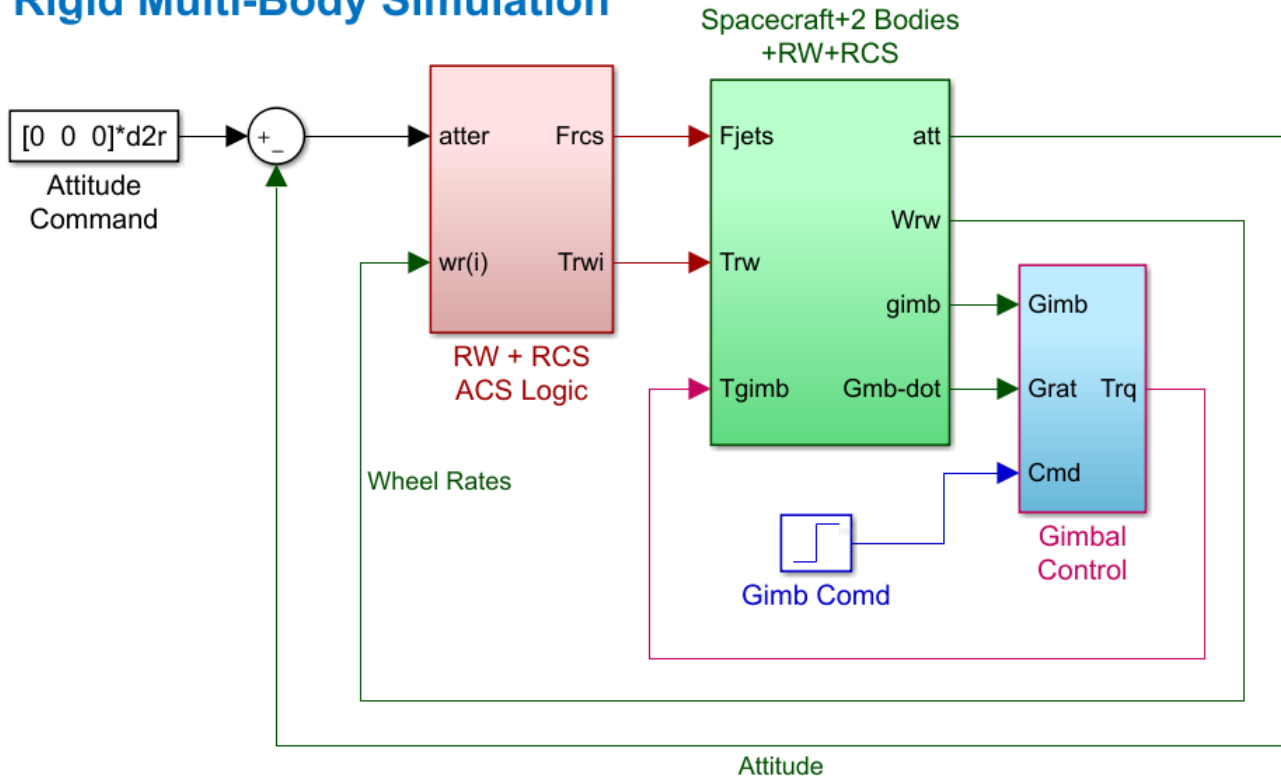


Figure 6.1 Rigid-Body 6-dof Simulation Model “*RigidBody3_Sim.Slx*”

The telescope gimbal servo system, shown in Figure 6.2, is a PD controller that rotates the gimbals at the commanded gimbal angles relative to the spacecraft. The gains are designed for a 0.25 Hz bandwidth. The telescope system includes an independent inertial navigation and guidance system to guide the telescope LOS. It is beyond the scope of this analysis which is to evaluate stability, performance and LOS sensitivity to disturbances.

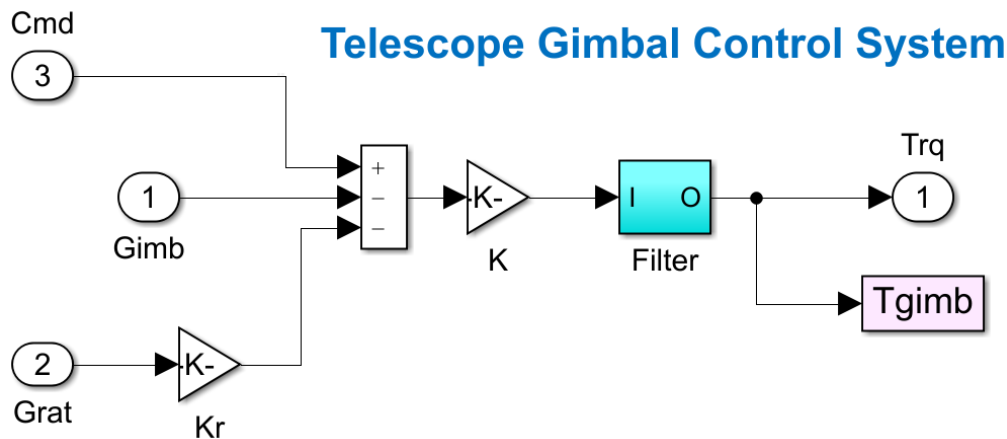


Figure 6.2 Telescope Gimbal Control System

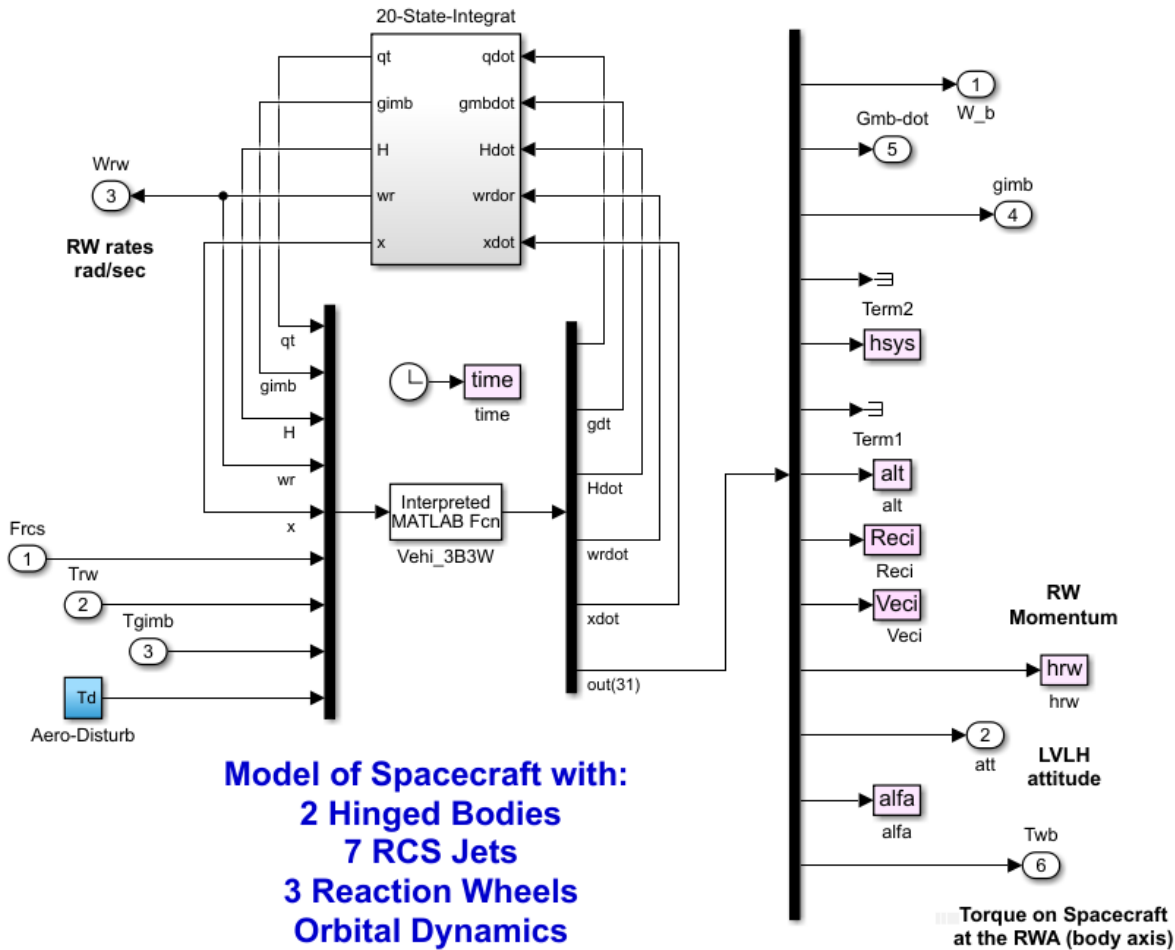
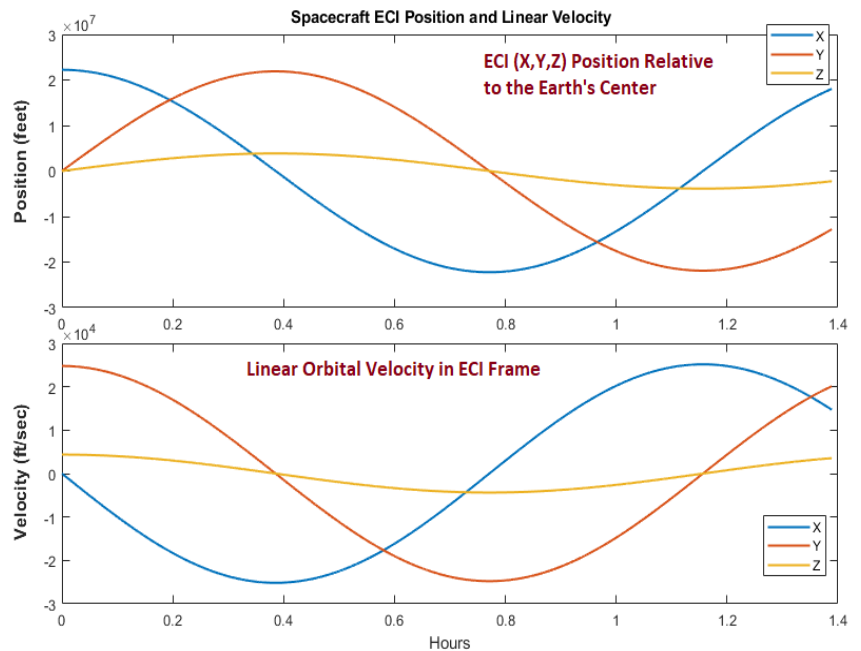


Figure 6.3 Rigid 3-Body Spacecraft Model Implemented in Function: "Vehi-3B3W.m"

6.2 Rigid-Body Analysis

Before including the spacecraft flexibility, we must first analyze the dynamic behavior of the 3-rigid-body model. We will therefore run the rigid model under the influence of external environmental torques (aero and gravity gradient disturbances) to make sure that the controls are functioning properly and verify that the model is stable and that the RW momentum desaturation works as expected when it exceeds a certain level (10 ft-lb-sec) from its nominal biased value. Then, we can go ahead and combine it with the flex model. Figure 6.4a shows the spacecraft attitude and rate. A yaw attitude error of 6° is within the acceptable range. Pitch and roll attitude are controlled more tightly at ±1.5° error.



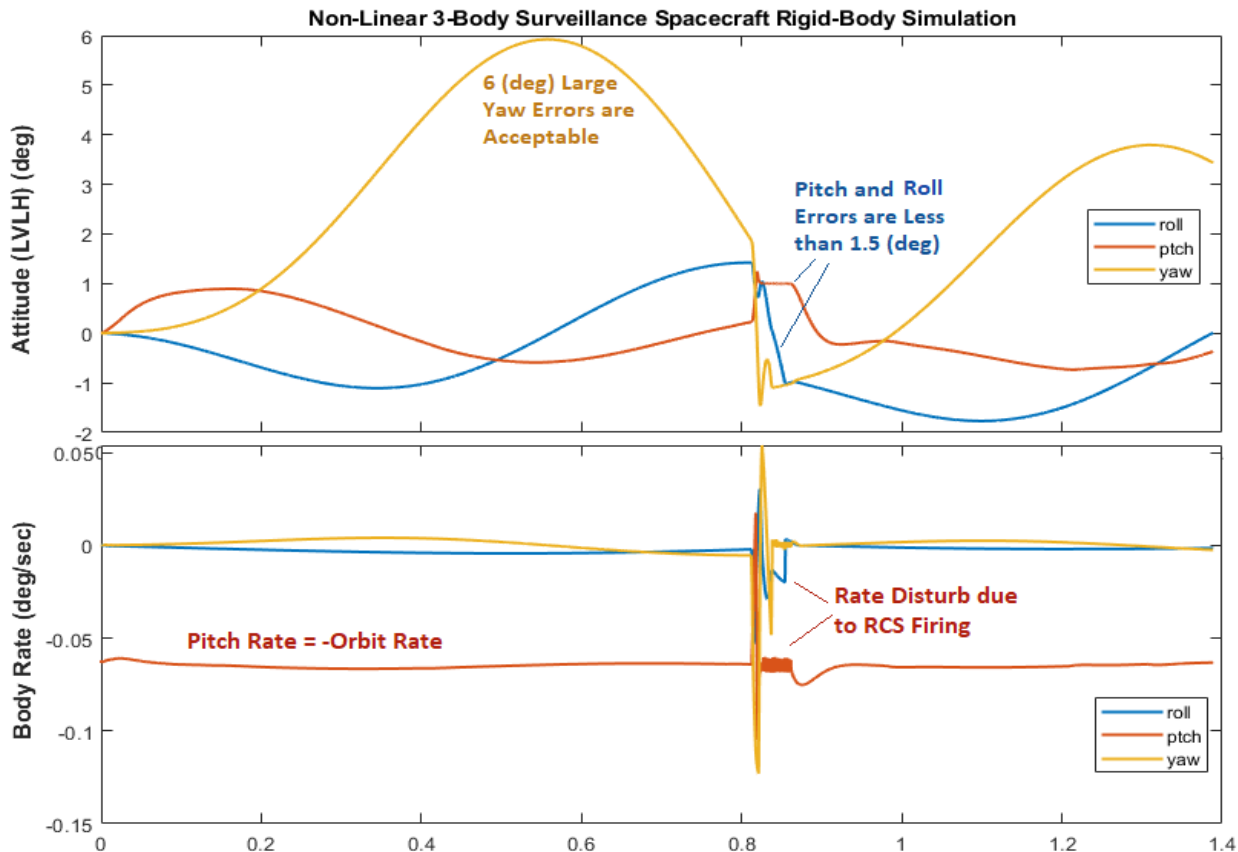


Figure 6.4a Spacecraft Attitude and Rate Response to Aero and Gravity Gradient Torques

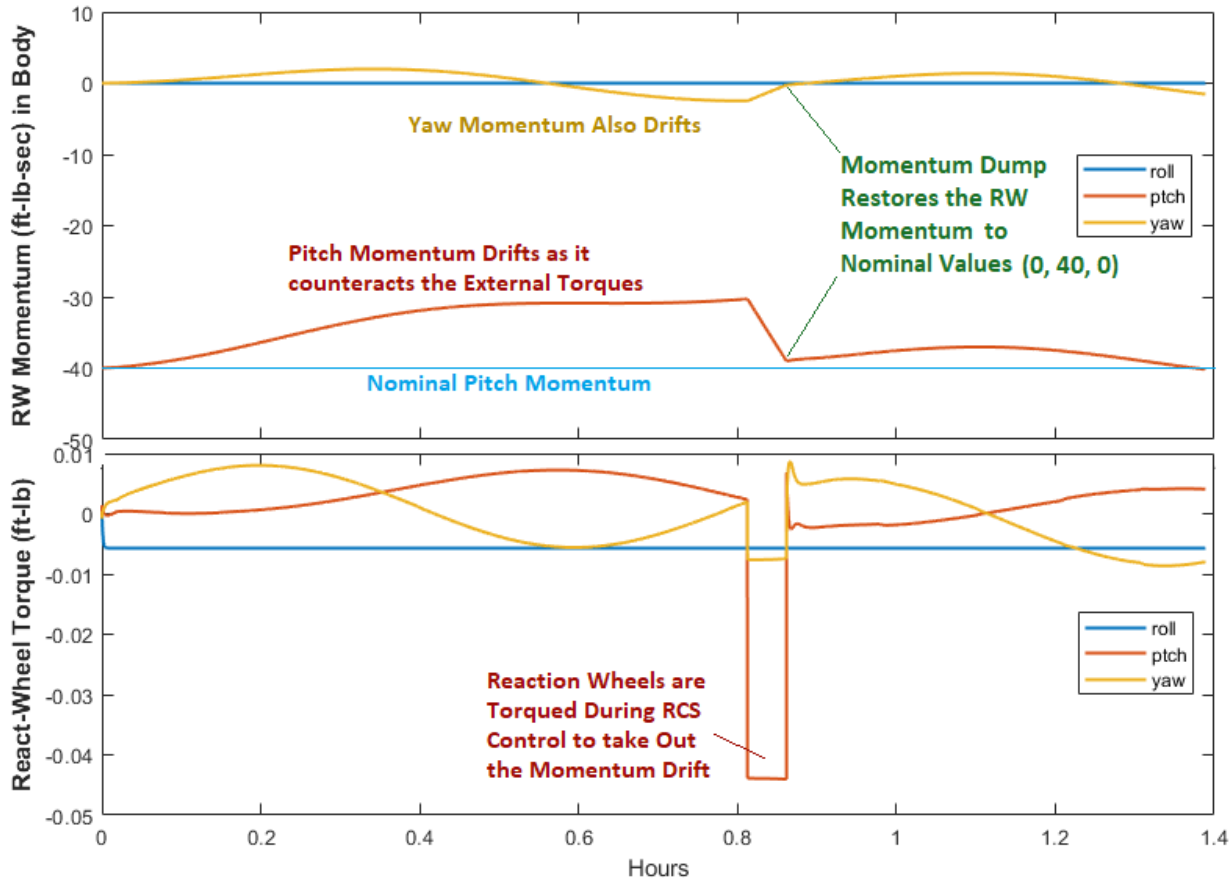


Figure 6.4b RW pitch and yaw torques are cycling to balance the biased aero torques. RW Momentum drifts during RW control. Desaturation brings it back near its nominal value

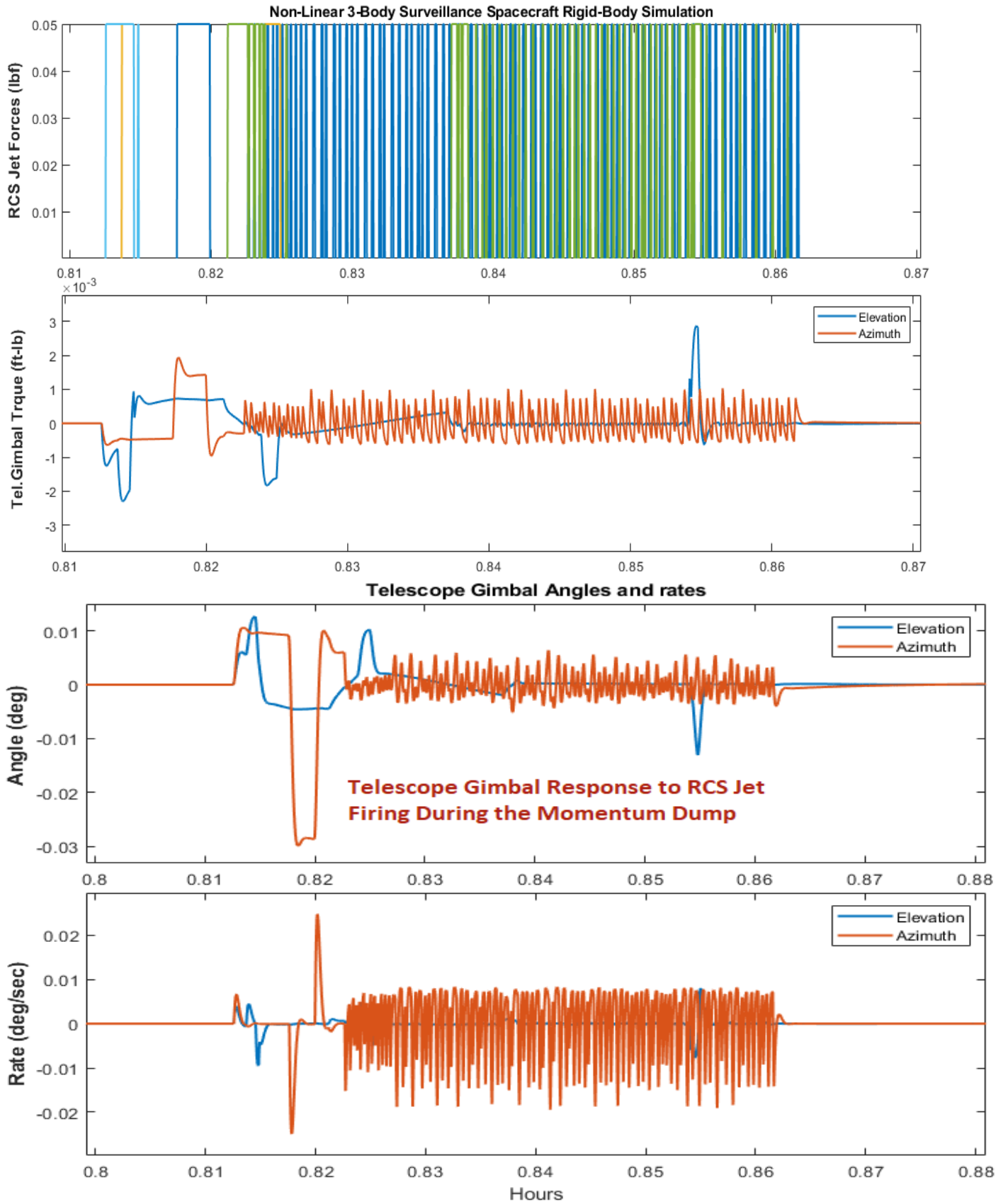


Figure 6.4e Telescope Gimbal Torques and Jitter at its Gimbals due to RCS Jets Firing

6.3 Flexible Multi-Body Simulation Model

The flex non-linear simulation model is in file "Body3_Flex_Sim.mdl" in folder "Examples\10-Surveillance Satellite React-Wheels\5-NLSim 3Body+Flex". It includes the spacecraft non-linear dynamics and the telescope implemented with 2 hinged appendages and rotating relative to the spacecraft. It is very similar to the rigid-body model "RigBody3_Sim.mdl", in Figure 6.1, but it includes the 61-mode flexible system from file "flex61.m" in parallel with the 3-rigid-body model, as shown in Figure 6.5. The flex system was derived in Section 3 and it does not include rigid-body modes. The same jet force inputs and gimbal torques are applied to both rigid and flex models. The RW input torques, however, are different. The rigid model requires the wheel control torques about each individual wheel axis which comes directly from the control law. The flex model requires the torque in body axes from the combined RW assembly. This torque also includes the gyroscopic effects due to the momentum bias coupling with the body rates. It is calculated in the rigid-body model (Twb) and is connected to the equivalent flex model input. The outputs from the two models are combined. Although this model includes also the low frequency orbital dynamics, the flex modes are slowing down the simulation because the sampling period is $T_s=0.001$ (sec), and we are therefore using it for shorter periods.

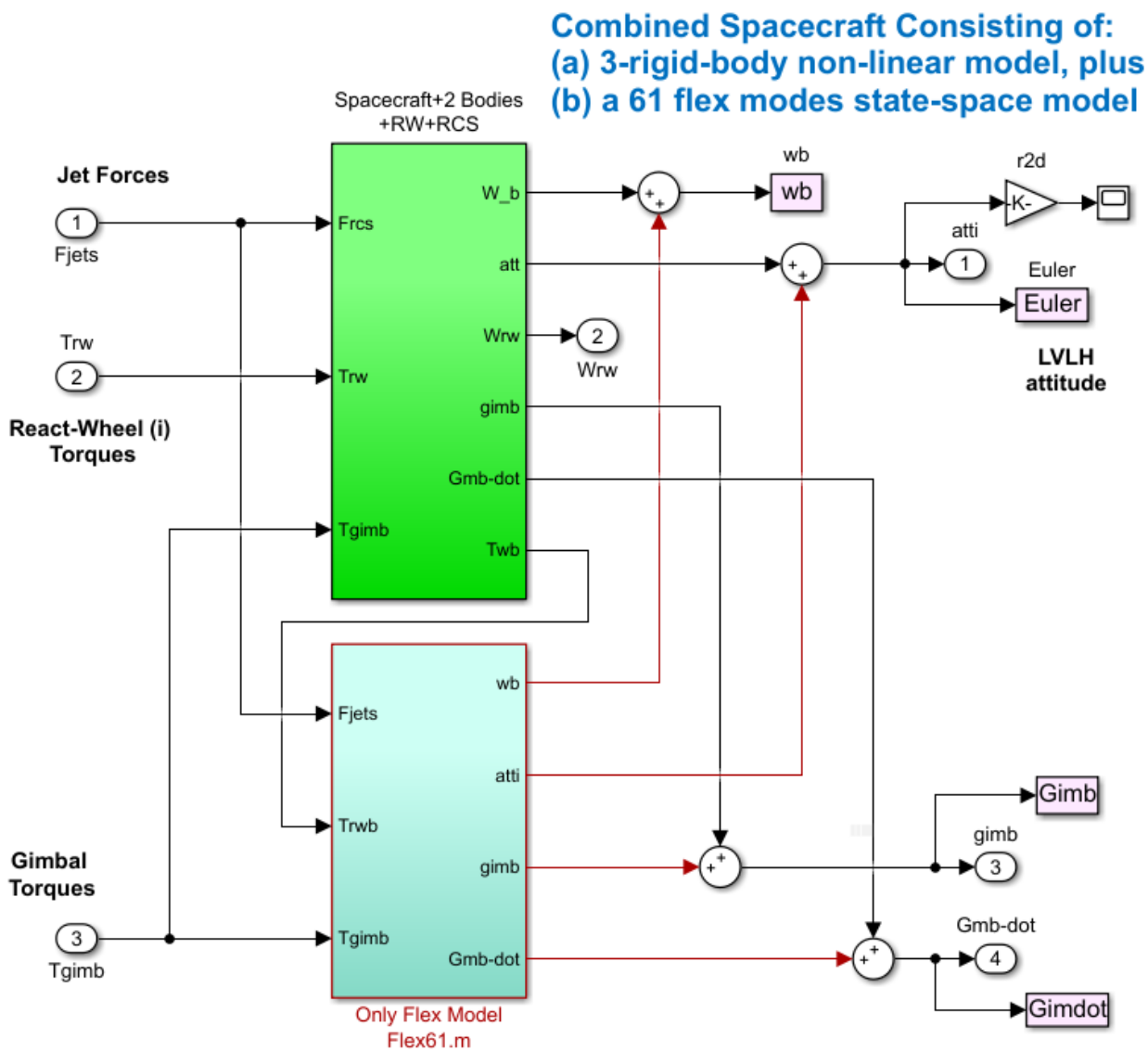


Figure 6.5 Rigid Multi-Body spacecraft dynamics combined in parallel with the 61-mode flex spacecraft system

6.4 Performance of the Gimbals Position Control System

The 3-body flex spacecraft model “*Body3_Flex_Sim.mdl*” is now used to analyze the spacecraft response to 5 (deg) gimbal commands in both, inner and outer gimbals. The gimbal torque reaches a peak value of 0.7 (ft-lb) that causes the reaction wheel torque to saturate. A torque limiter is needed here to soften the impact to the reaction wheel control system, but this is left as an exercise to the reader.

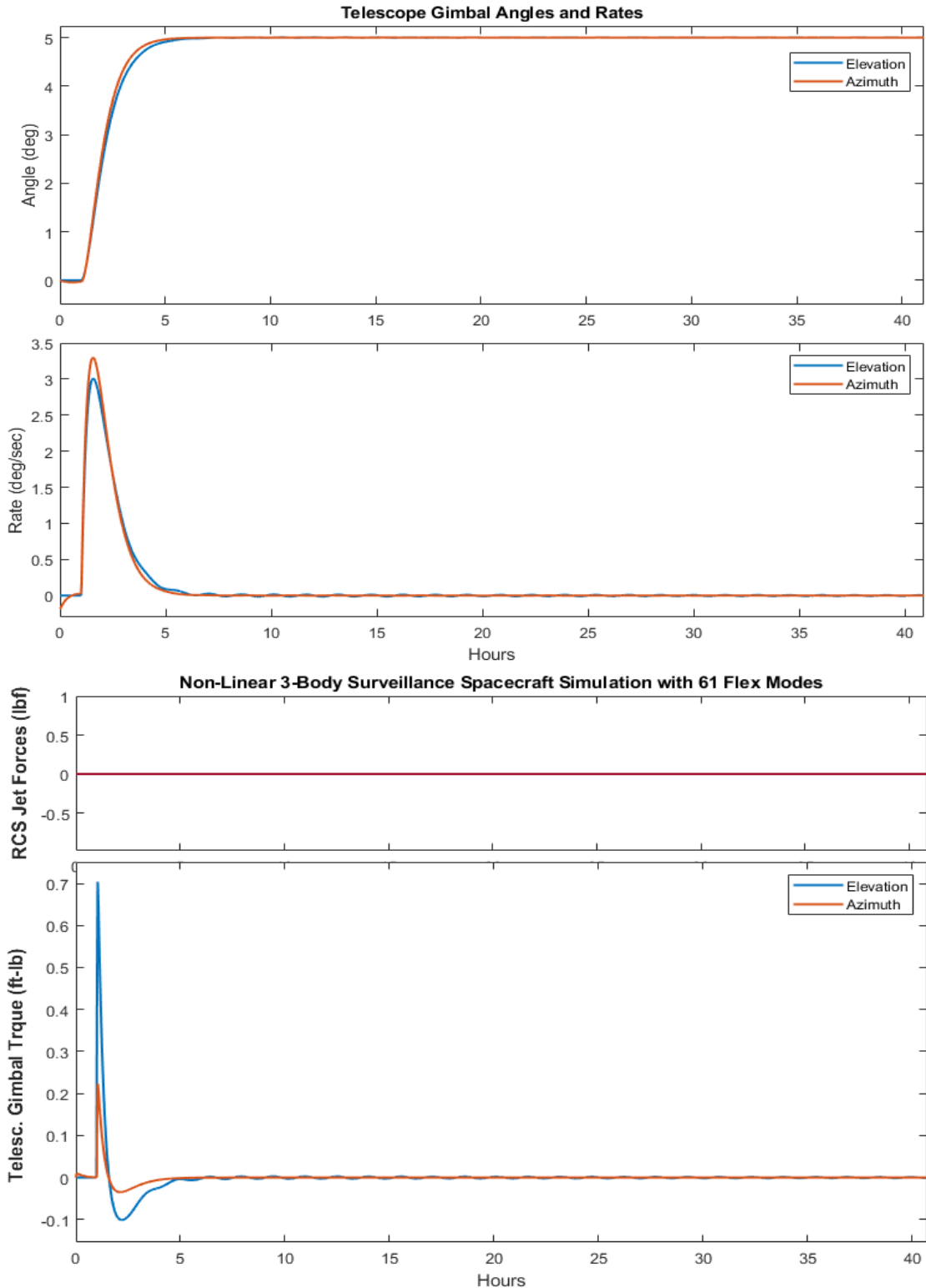


Figure 6.6a Telescope Gimbal Responses and Gimbal Torque to a 5 (deg) Azimuth and Elevation Command

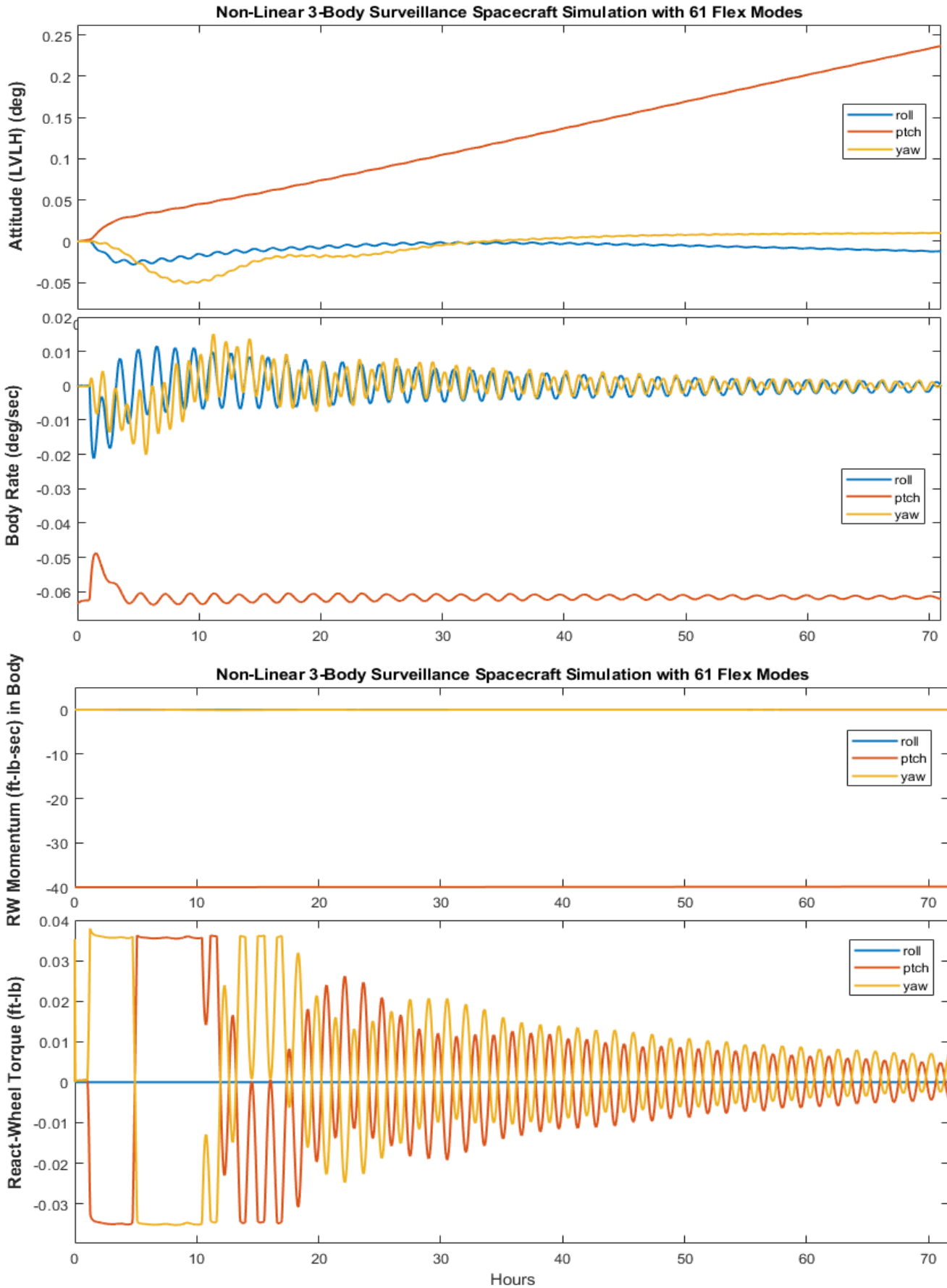


Figure 6.6b Effect of Telescope Gimbaling on the Spacecraft Rate and Reaction Wheel Torques

6.5 Stability Analysis of the RW System

Figure 6.7 shows a Simulink model “*Lin_Analysis.Slx*” which is used for analyzing the reaction wheel control system stability with frequency response. A similar analysis can be used to analyze stability of the RCS loops using the Describing Function method but it was already demonstrated in other examples and will not be shown here. The linear model includes the RW steering logic and controls, and the gimbal control loops of the telescope, which are closed. One of the two RW loops is opened at a time. To analyze the out-of-plane control loop stability this model calculates the frequency response across the opened lateral loop that feeds roll error into the yaw RW torque with the pitch loop closed, as shown in Fig. 6.7. The Matlab m-script “*LinAnal.m*” calculates the Bode and Nichols charts which are shown in Figures 6.8.

The results look similar to those obtained from the previous flex analysis in Fig. (5.9 & 5.10). The biggest difference is at low frequencies near the orbital range because of the additional orbital dynamics that have been included in this model. Figure 6.9 shows a similar plot after modifying the model in Figure 6.7, by closing the lateral loop and opening the pitch loop. Figures (6.10 and 6.11) show the stability analysis plots of the two gimbals, by opening one gimbal loop and closing all the other loops. It appears that the gimbal loops have plenty of stability margin.

Linear Analysis Model

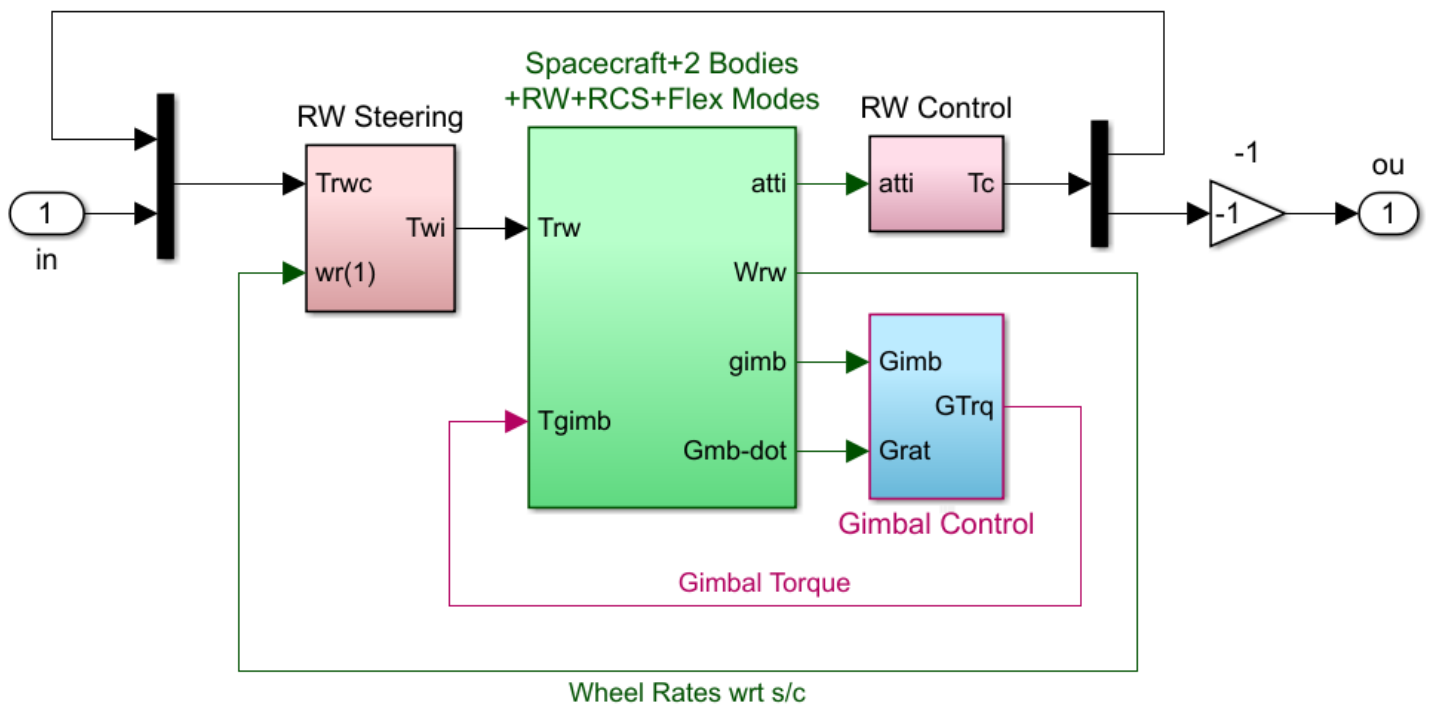
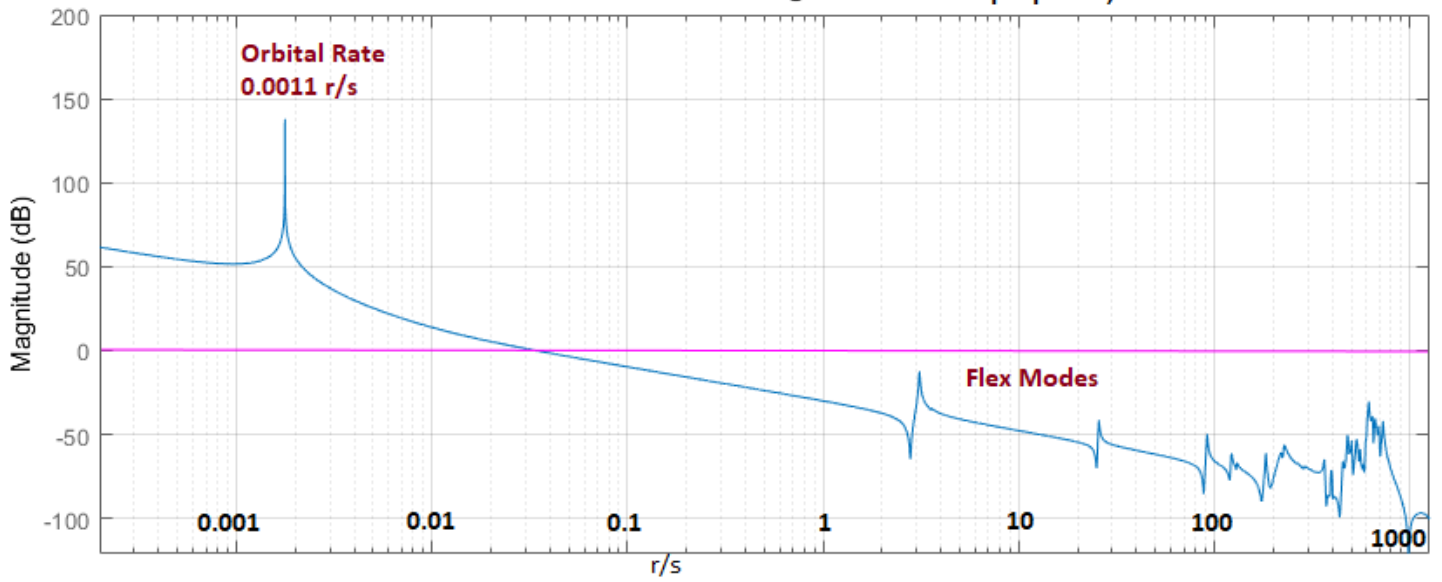


Figure 6.7 Linear Stability Analysis Simulink Model “*Lin_Analysis.Slx*”

Bode Diagram Pitch Loop Opened, Out-of-Plane Closed



Nichols Chart

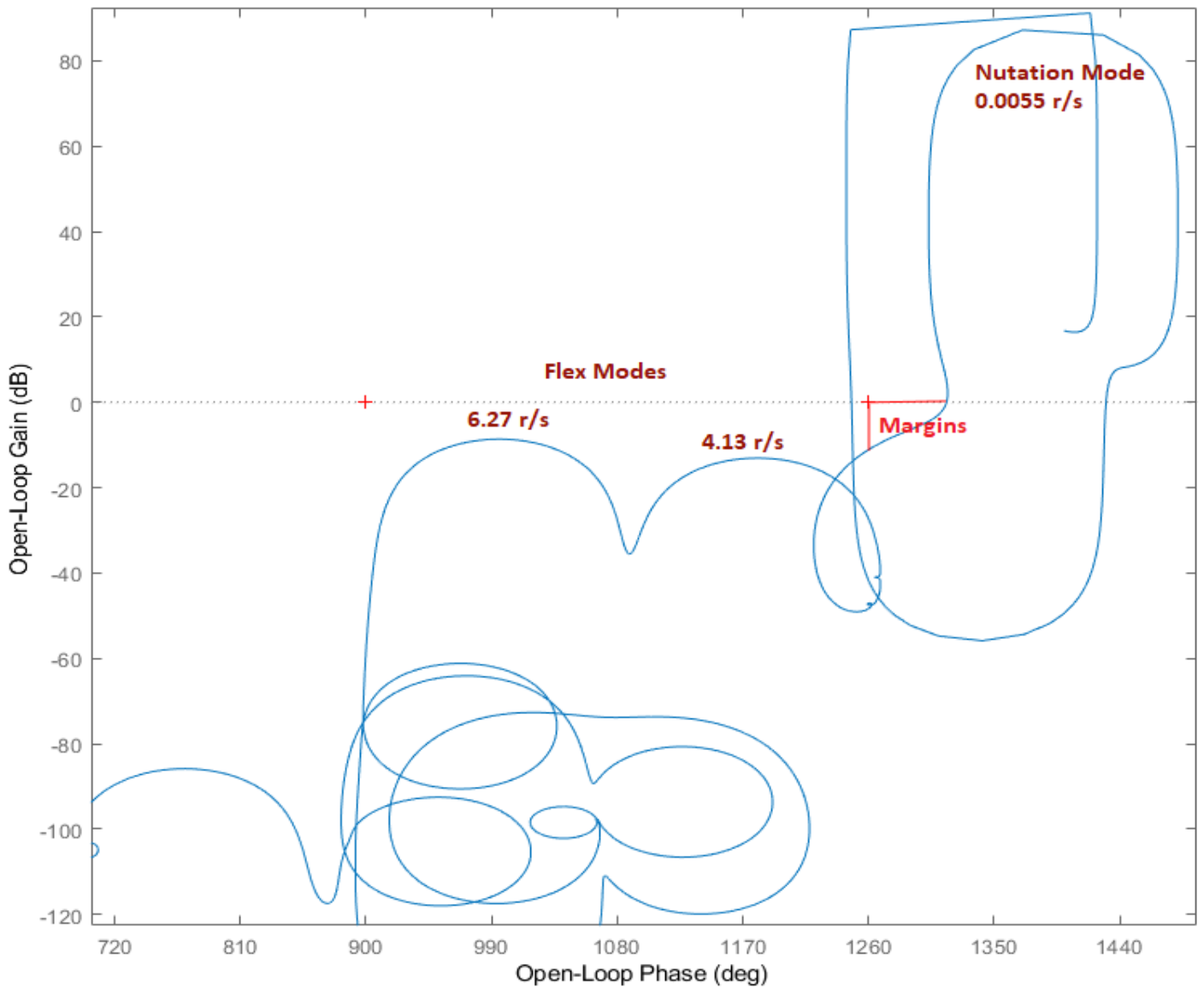


Figure 6.8 Bode and Nichols Plots show the RW System Stability in the Out-of-Plane Axis with the Pitch Loop Closed

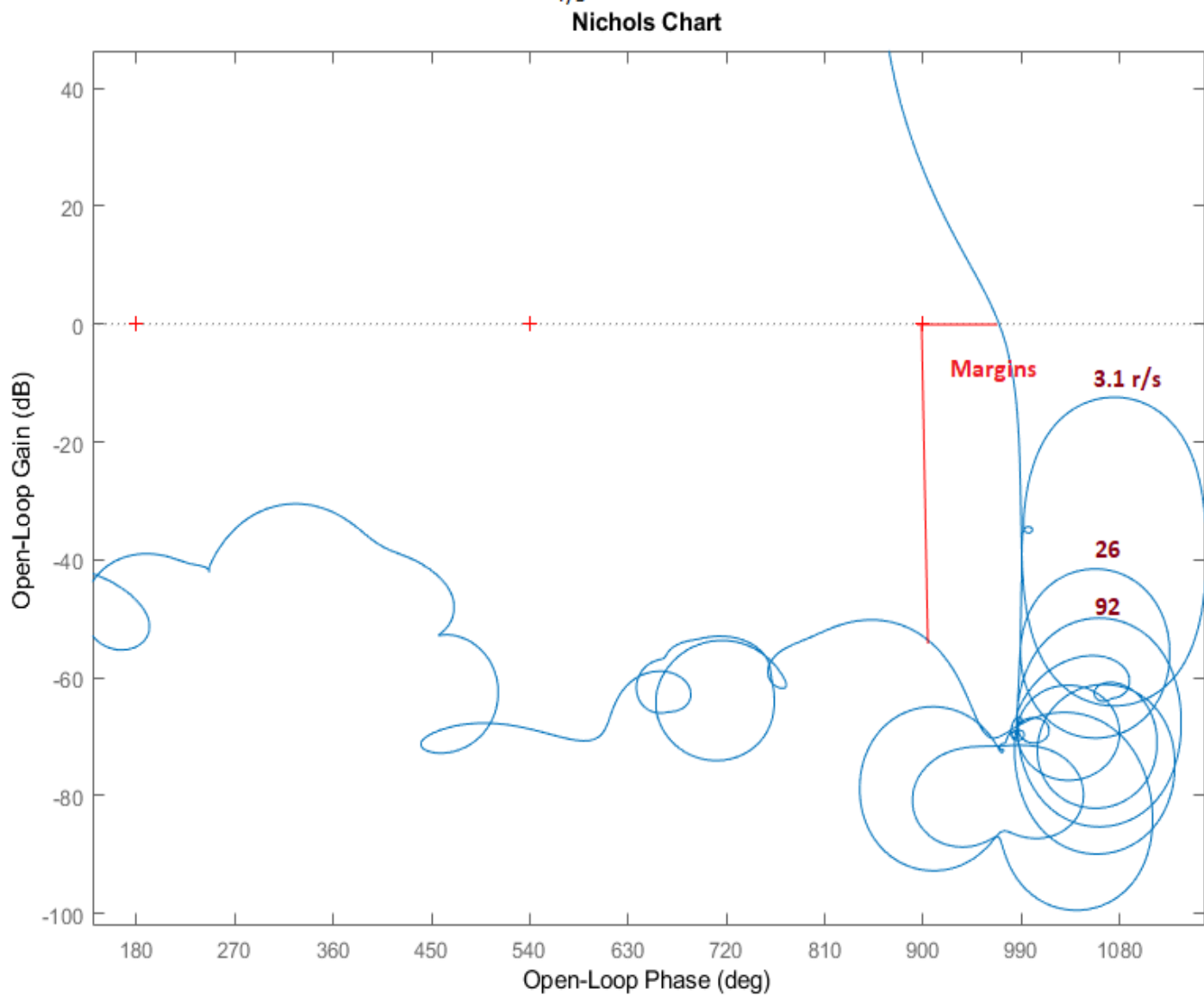
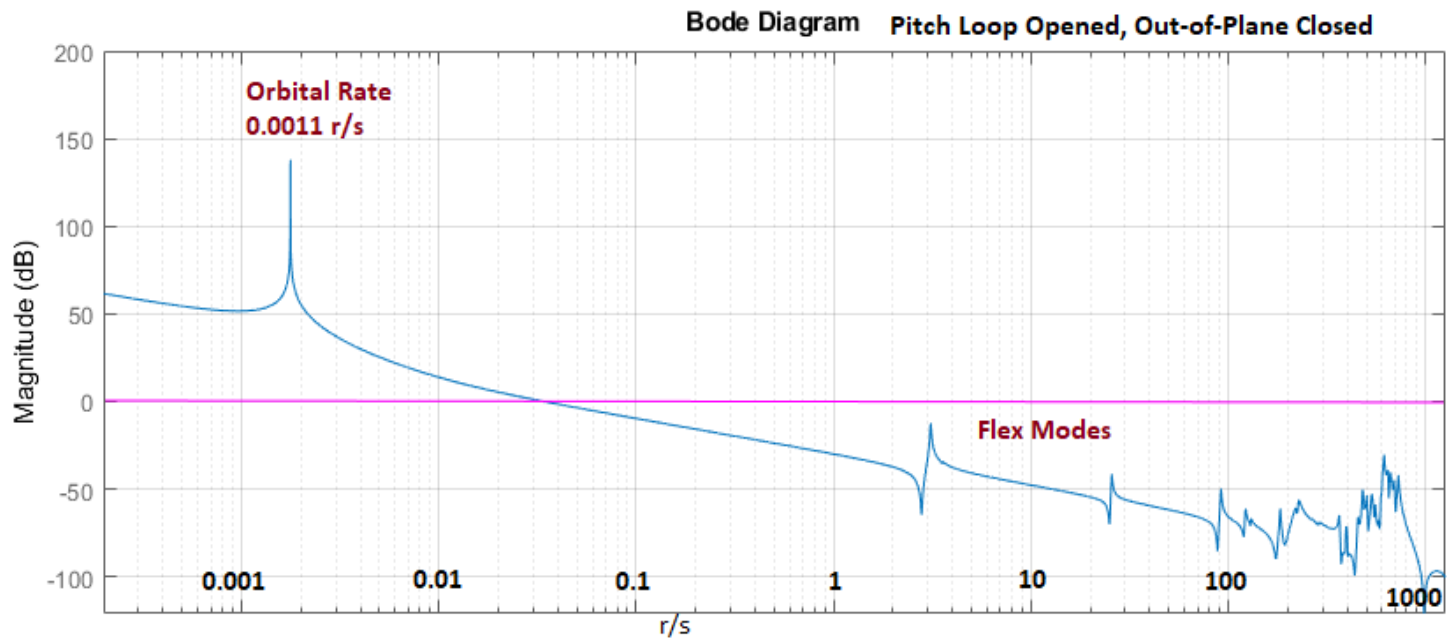


Figure 6.9 Bode and Nichols Plots show the RW System Stability in the Pitch axis with the Out-of-Plane Loop Closed

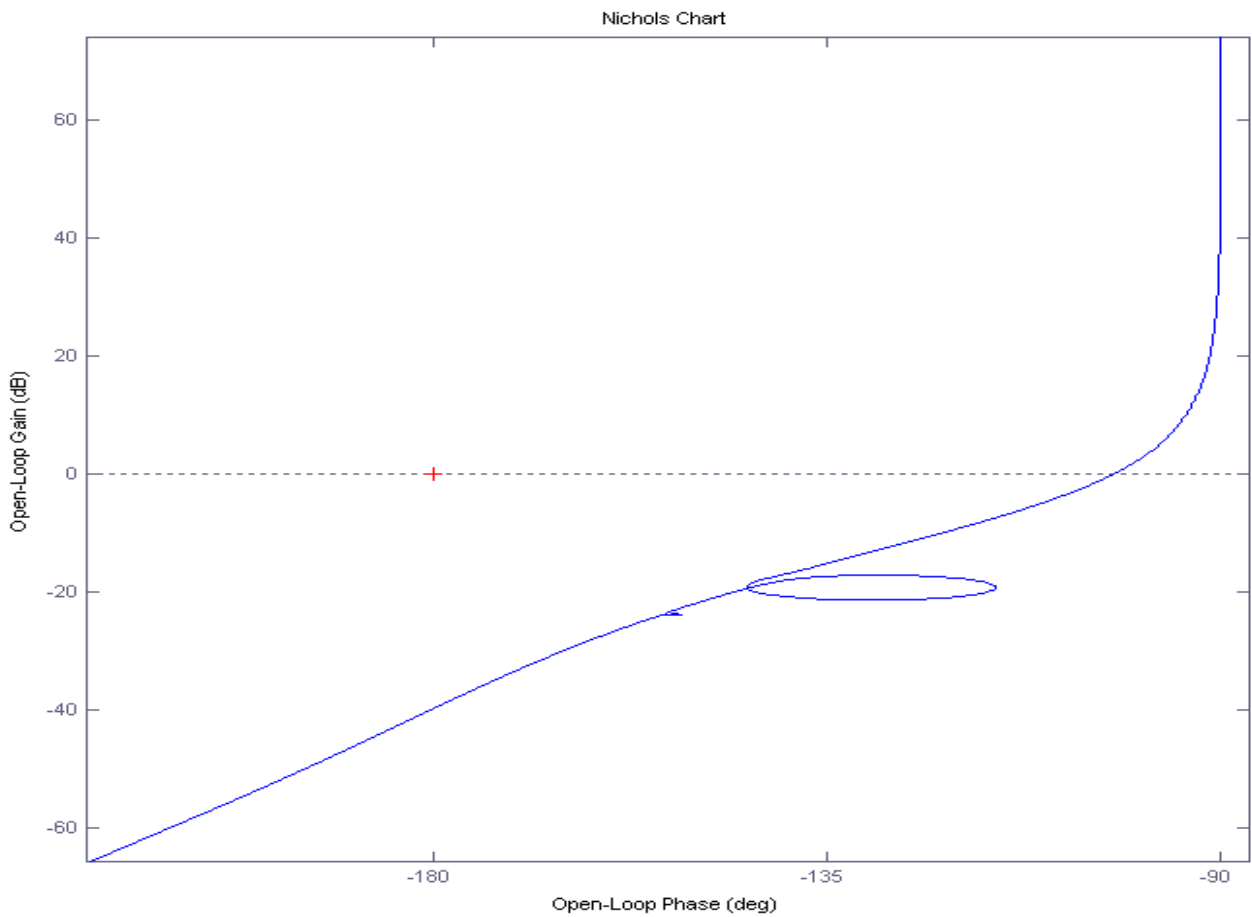
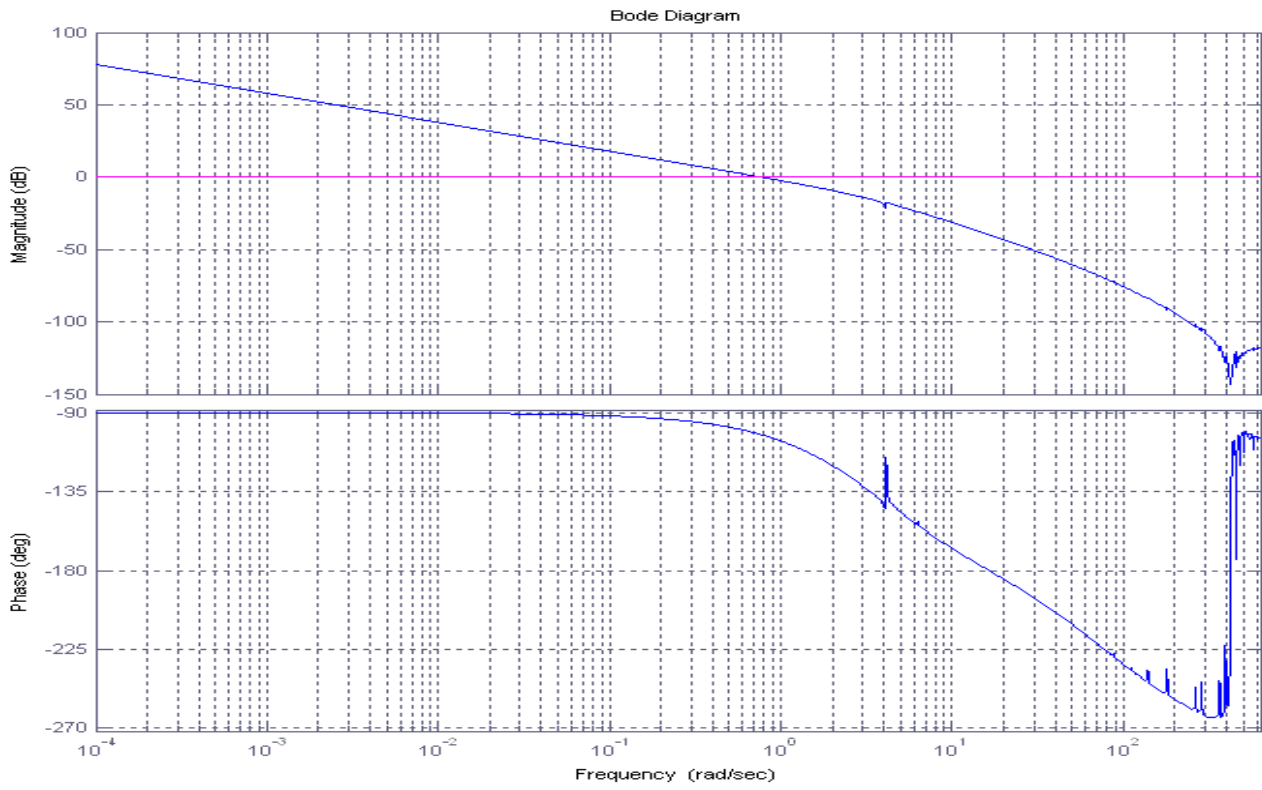


Figure 6.10 Bode and Nichols Plots show the Inner Gimbal system open-loop stability with all other loops closed

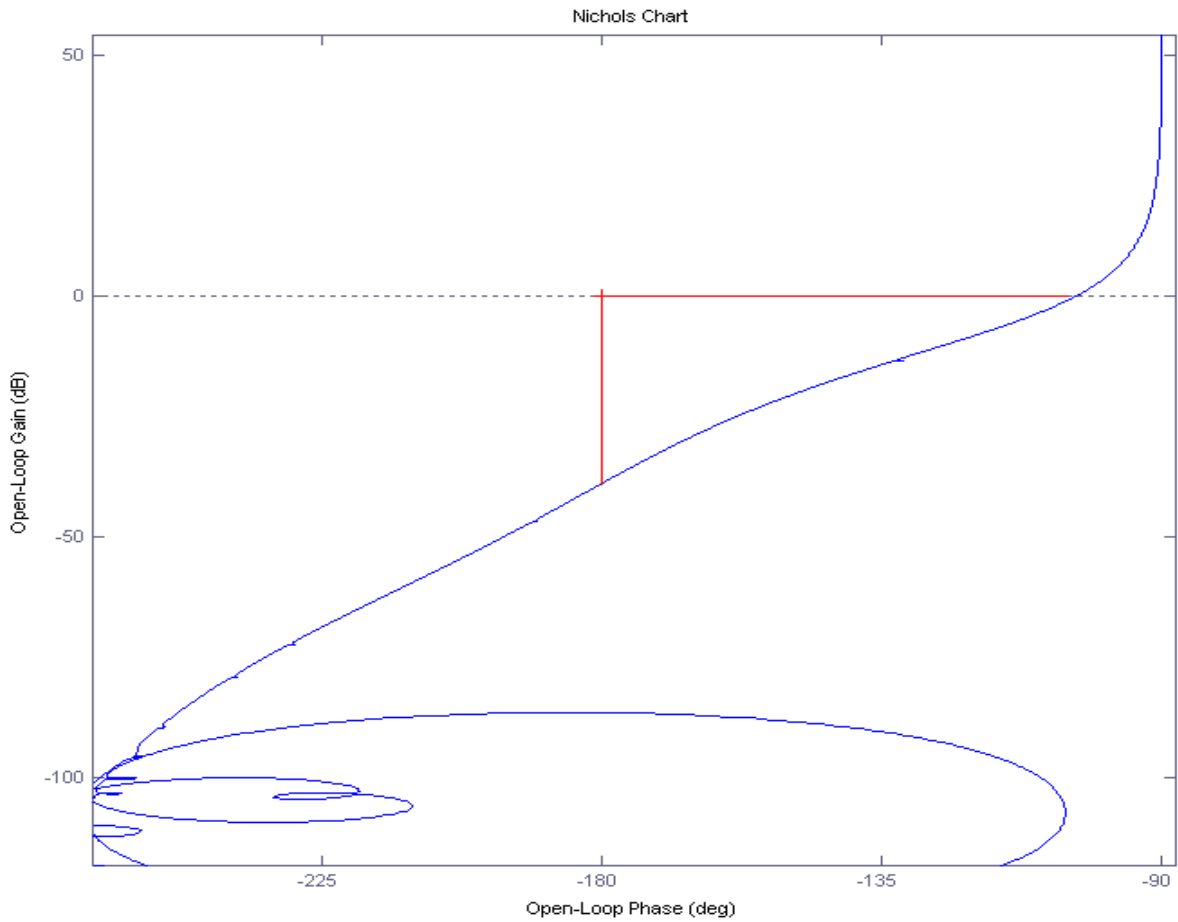
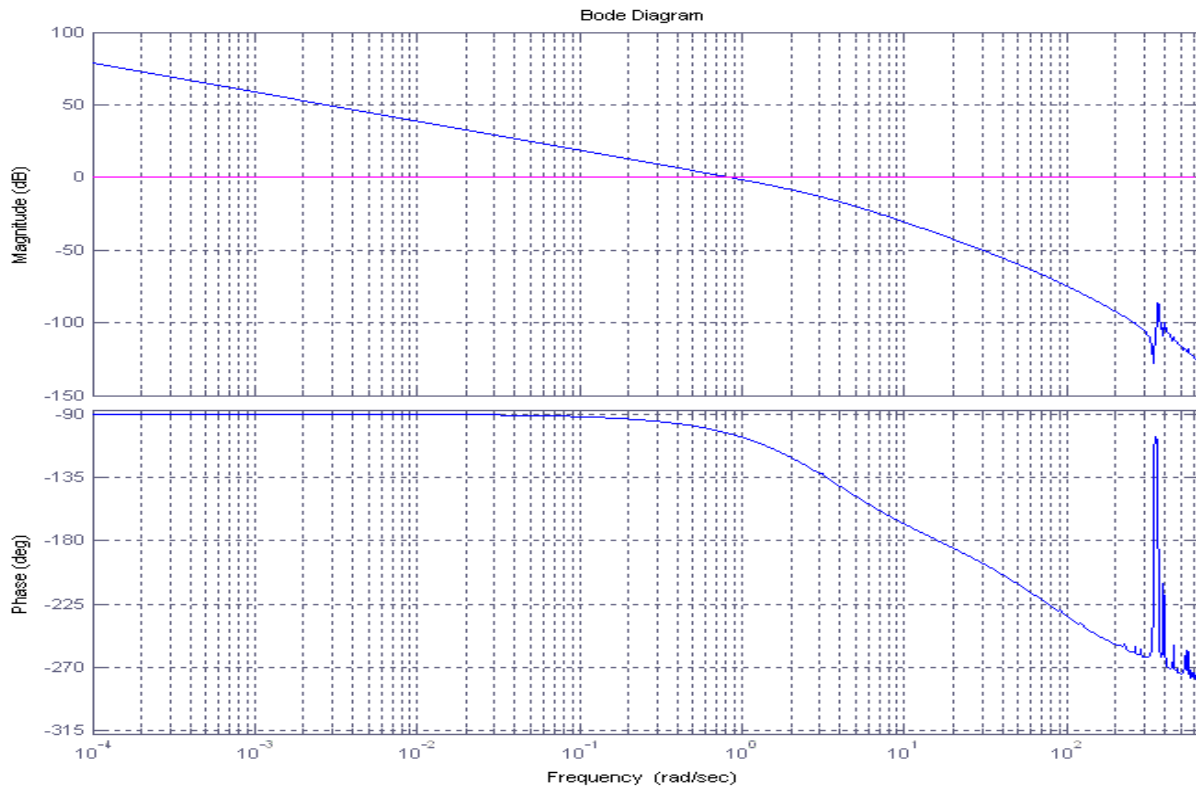
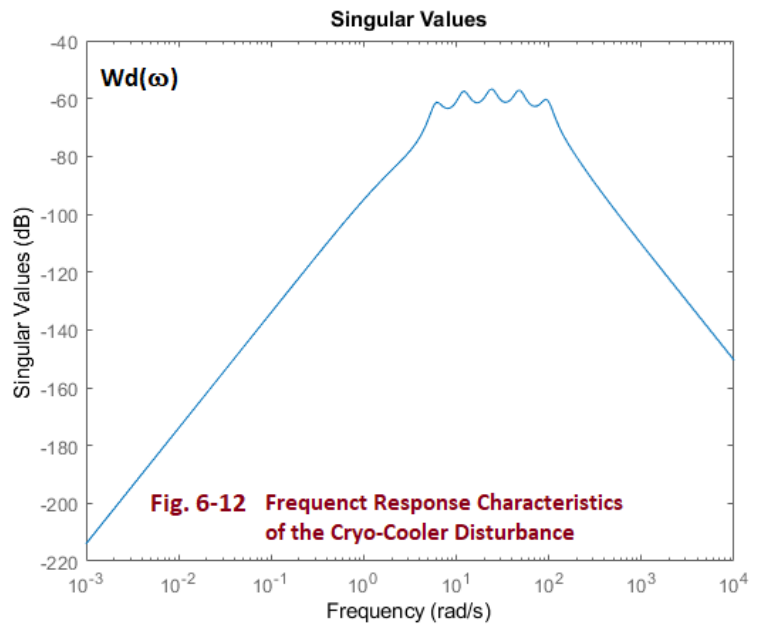


Figure 6.11 Bode and Nichols Plots show the Outer Gimbal system open-loop stability with all other loops closed

6.6 Jitter Sensitivity to Mechanical Disturbances

The spacecraft has several on board instruments that generate disturbances during RW control and they are causing jitter on the telescope image. The LOS jitter during jet firing is much bigger and for this reason the telescope is not being used during periods of RCS control. One of the main disturbance sources is the cryo-cooler, which is a pump that circulates a coolant fluid around the spacecraft. There are also disturbances coming from the reaction wheels. Figure 6.12 shows the frequency characteristics of the combined disturbance torque which can be represented as a transfer function $W_d(s)$ driven by noise.

The requirement for the LOS position error jitter in the presence of the disturbances must be less than 2 (micro-radians). If $S(s)$ is the sensitivity transfer function of the closed-loop spacecraft between the disturbance torque and the telescope gimbal angles, and e_{\max} is the maximum allowable line-of-sight error, then the equation $W_d(\omega)S(\omega) < e_{\max}$ must be satisfied at all frequencies ω . The Simulink model “*Sensitiv-Analysis.m*”, shown in Figure 6.13, is used to analyze the system LOS sensitivity to disturbances. Figure 6.14 shows the normalized sensitivity response which was obtained by running the Matlab script file “*LinAnal.m*”. It shows that the sensitivity function is less than 1 at all frequencies which satisfies the LOS jitter requirement.



```

% Linear Analysis LinAnal.m
% Stability Analysis
[Ao,Bo,Co,Do]=dlinmod('Lin_Analysis',Ts);           % Discrete Open-Loop Analysis Model
[nr,nc]=size(Ao); E=diag(ones(nr,1));
sys=dss(Ao,Bo,Co,Do,E,Ts);                          % Prepare discrete SS model for
w=logspace(-3.7,3.1,180000);                          % frequency response analysis
figure(2); bode(sys,w); grid on
figure(3); nichols(sys,w)                             % for stability margins

% Sensitivity Analysis Calculations
[As,Bs,Cs,Ds]=dlinmod('Sensitiv_Analysis',Ts);       % Closed-Loop Sensit Analysis Model
[nr,nc]=size(As); E=diag(ones(nr,1));
sys2=dss(As,Bs,Cs,Ds,E,Ts);                          % Prepare discrete SS model for
w=logspace(-3,3,100000);                              % frequency response analysis
figure(4); sigma(sys2,w)                             % Singular values Plot

```

Sensitivity Analysis to Disturbances Model

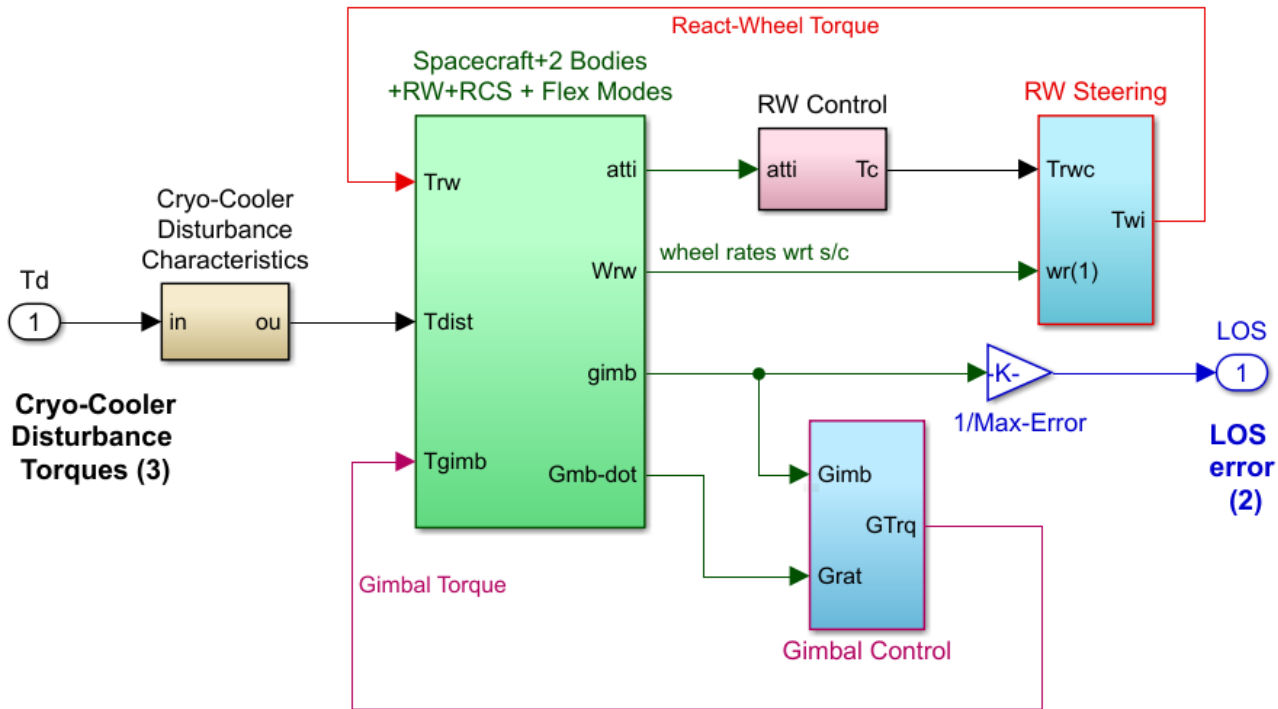


Figure 6.13 Sensitivity Analysis Model to Cryocooler Disturbances

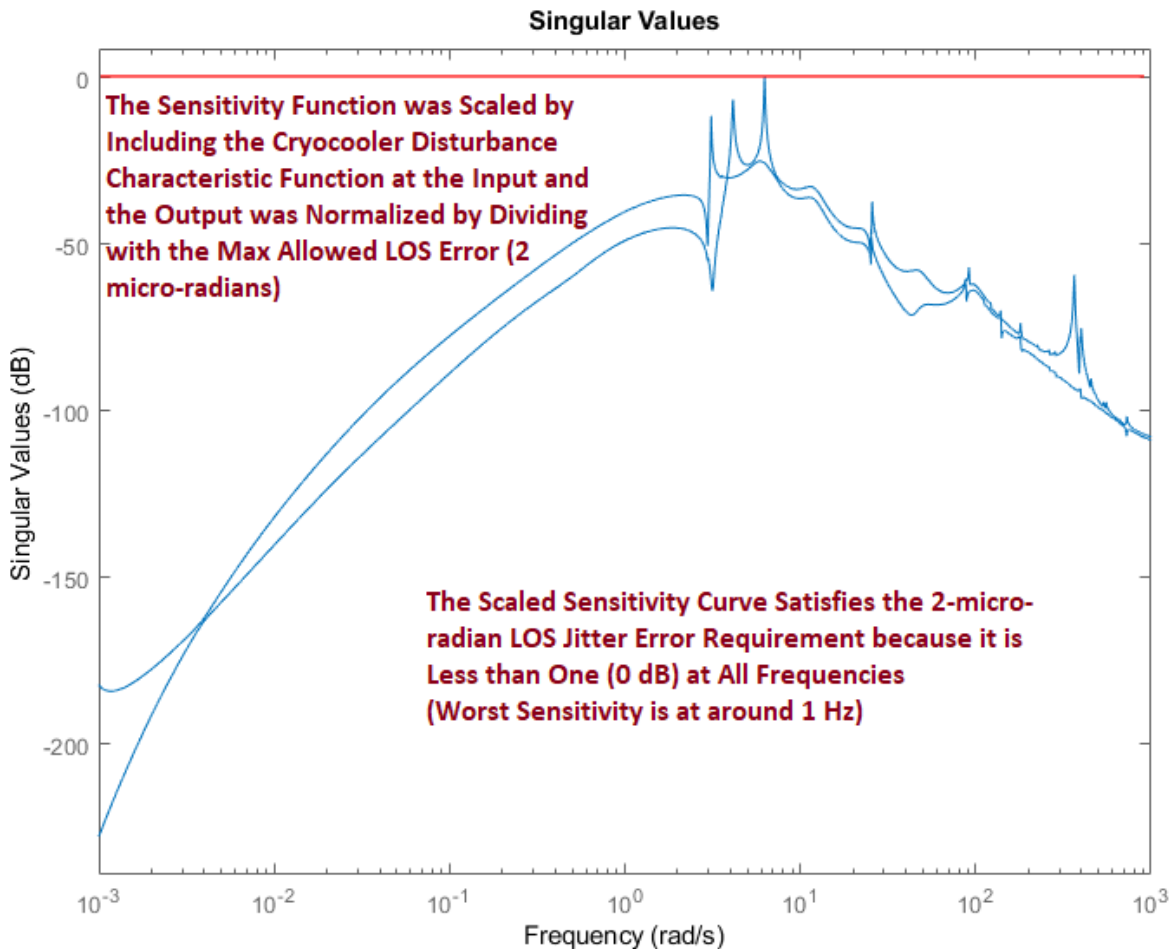


Figure 6.14 Scaled Sensitivity Response between Disturbance Torques and the LOS rotations, shows that the system barely meets the 2 (micro-radians) Jitter Requirement

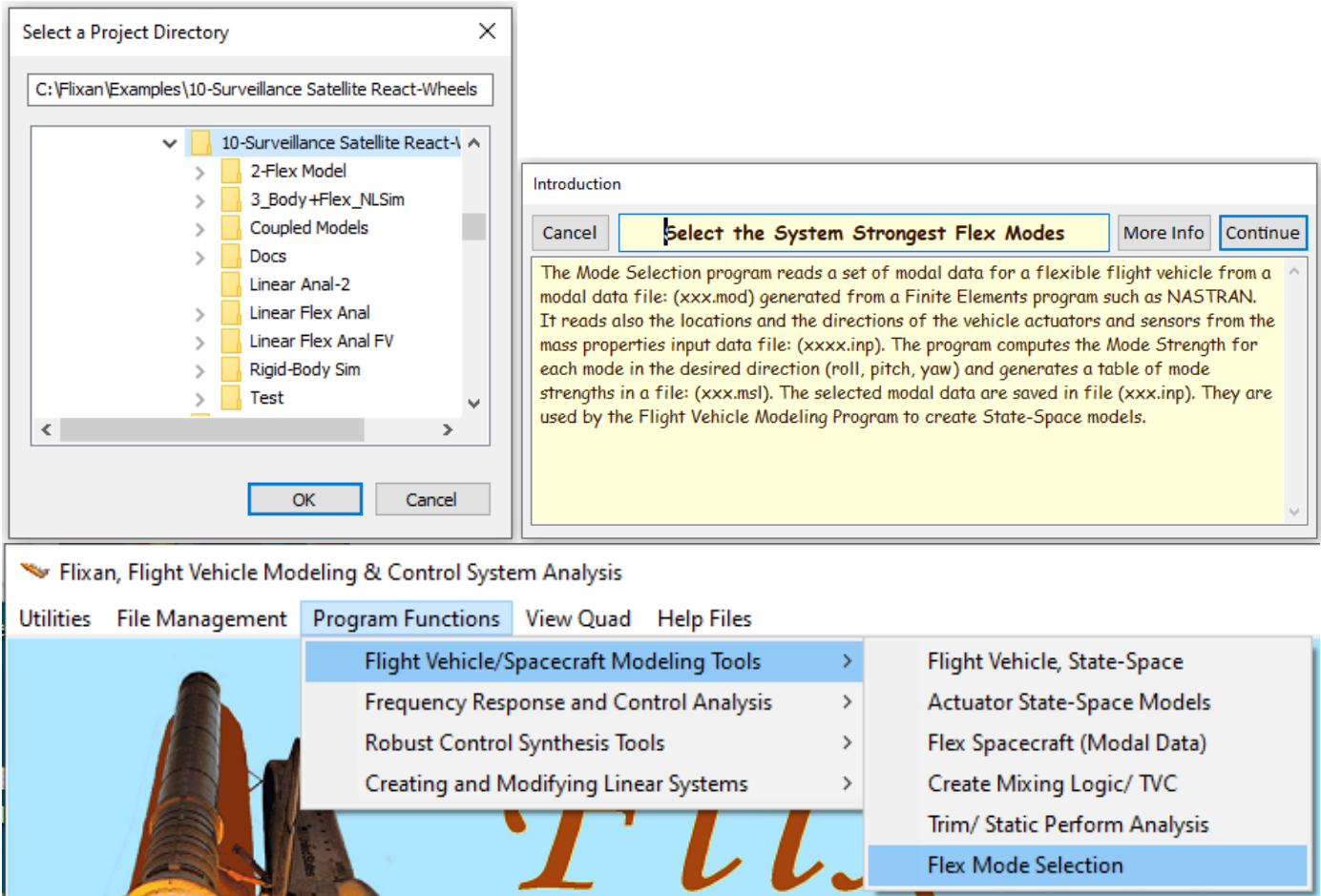
7.0 Further Analysis of the Surveillance Spacecraft Using the Flight Vehicle Modeling Program

In this section we will use a different approach to model and analyze the surveillance satellite. The spacecraft state-space system will be created using the Flixan Flight Vehicle Modeling Program (FVMP). This model consists of both: rigid-body and flex dynamics. It includes the momentum biased wheel, the two reaction wheels, the rotating telescope which is gimbaling in elevation and azimuth, the two solar arrays rotating in pitch, the RCS jet forces, Gravity-Gradient torques, and the LVLH vehicle attitude. The input data to the FVMP are in file: *“Surv_Sat_RB+Flx.Inp”* in folder *“\Examples\ 10-Surveillance Satellite React-Wheels”*. There are three sets of Flight Vehicle data in that file: (a) a rigid-body model, (b) a rigid-body model that includes rotating appendages, and (c) a flexible spacecraft model with the 4 gimbaling appendages. The analysis in this section focuses on the last system, whose title is *“Space Surveillance Satellite with RCS and Reaction Wheels (Gimbals & 60 Flex Modes)”*.

If you look in the input data file *“Surv_Sat_RB+Flx.Inp”*, below the title and the comment lines, the flag *“LVLH Attitude”* is included. This flag turns on the Gravity Gradient torques in the equations, and it calculates the LVLH attitude instead of Euler angles. The vehicle pitch rate is set to be equal to the orbital rate which is $\omega_o = -0.064744$ (deg/sec). There are 7 jets which are defined as *“Throttling”* because their thrust varies from zero to 0.05 (lbf). Actually, the RCS logic output is either zero or max thrust. There are 3 external disturbance torque inputs, about x, y, and z, which are used to apply the aerodynamic disturbances on the spacecraft. The spacecraft also includes 3 reaction wheels. The first one is actually a momentum wheel because it maintains a constant negative spin rate of -4774 (rpm) and its spin axis is in the y direction which provides pitch momentum biasing on the spacecraft. The other two are reaction wheels which are tilted in the y-z plane and can accelerate to provide pitch and yaw torques. None of the wheels has a roll component. They all have the same moment of inertia about their spin axes, 0.08 (slug-ft²). The spacecraft is also defined to have 13 rotational sensors, 3 rate-gyros, 10 attitude measurements for jitter analysis, and two accelerometers along the x and y axes. Near the bottom of the vehicle dataset there is a line that specifies the H-parameters filename *“Surveillance-Sat.Hpr”*. This file includes the inertial coupling coefficients that define the dynamic interaction between the spacecraft flexibility and the gimbaling bodies. It was also used to create the spacecraft models in Section 3. It contains the (100x4) H-parameters matrix, the gimbaling appendages moments of inertia matrix (slug-ft²), the masses (slugs), the hinge direction unit vectors in spacecraft body, the locations of the 4 hinges in (ft), and the CG locations of the 4 appendages in (ft) in spacecraft coordinates. Some of the data in the (Hpr) file were not used in Section 3 but they will be needed here. If the H-parameters filename line is missing from the input data file or if the program cannot locate the (Hpr) file, it will assume that there are no gimbaling bodies and the state variables associated with the gimbaling appendages will be excluded from the state-space model. The last two lines in the vehicle dataset specify the flexibility data. The spacecraft model will include 60 flex modes and the modes will be read from a previously created modal data set *“Space Surveillance Satellite with RCS and Reaction Wheels (60 Flex Pre-Selected Modes)”*. This is a separate dataset which includes preselected modes and is also included in file *“Surv_Sat_RB+Flx.Inp”*. There may be more than one set of selected modes in the same input file. They were extracted from the original modal data file *“Surveillance-Sat.Mod”* by means of a mode selection process that is described in Section 6.1. The modal data set consists of 60 modes. Each mode includes frequencies and shapes at key vehicle locations, such as: RCS jets, reaction wheels, disturbance locations, gyro and accelerometer sensors.

7.1 Mode Selection Process

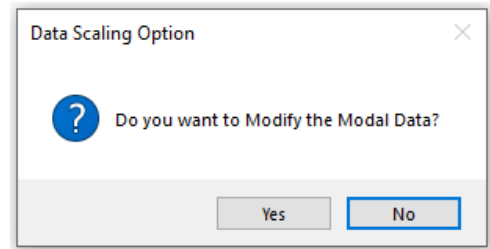
Before selecting the bending modes, we must make sure that the spacecraft dataset is already saved in file “*Surv_Sat_RB+Flx.Inp*” because the mode selection program needs to identify the effectors and sensors on the vehicle structure. The data files for this analysis are in directory “*Flixan\Examples\10-Surveillance Satellite React-Wheels*” and the Matlab analysis is performed in subdirectory “*\6-Linear Flex Anal FV*”. The with the satellite finite element structural modes is “*Surveillance-Sat.Mod*”. It contains the mode shapes and slopes for the first 100 modes, at 28 locations (also known as nodes). The modal data file is formatted to be recognizable by the mode selection program, and it contains frames of data for every mode frequency. Each frame consists of the mode frequency in (rad/sec), the modal damping coefficient (they are initially set to $\zeta=0.005$ but they can be modified as needed), the generalized masses are all set to 12, followed by the mode shapes and slopes at the 28 vehicle locations (translations along x, y, z, and rotations about x, y, z). The important locations for flight control analysis are the RCS jets, the RW locations, the external disturbance torque, and the sensors. The locations in the modal data file are listed in the map file “*Surveillance-Sat.Nod*”. This file contains a description for each node, the node numbers (in this case 1 to 28), a node identification number (which is a node number created in the FEM), and the node location in vehicle coordinates (this is only for reference and it is not used by the program). To run the mode selection program, start the Flixan program and select the folder “*\Examples\ 10-Surveillance Satellite React-Wheels*”. From the menu bar select “*Program Functions*”, then “*Flight Vehicle/ Spacecraft Modeling*”, and click on “*Flex Mode Selection*”, as shown below.



It begins with a filenames menu from where the user selects the modal data filename that has an extension (.Mod), the nodes file with extension (.Nod), the flight vehicle input data file (.Inp), and an output filename, default "Modsel.Msl", as shown below. This is where the program will save the relative mode strength at the completion of mode selection. The modal data and nodes map files are the same ones used in Section 3. After selecting the filenames, the next step is to locate the flight vehicle input dataset in file "Surv_Sat_RB+Flx.Inp". This dataset includes the information to create the vehicle state-space model, but it is also used by the mode selection program because the program needs to associate the FEM structural points with vehicle locations, such as, the RCS jets, reaction wheels, disturbance torques, gyros, accelerometers, etc. which are defined in the input data. From the "Flight Vehicle" selection menu below select the title "Space Surveillance Satellite with RCS and Reaction Wheels (Gimbals & 60 Flex Modes)" and click on the "Run Selected Input Set" button.

The next dialog is used to define the number of excitation and of sensor points to be used for mode selection. This is only for mode selection purposes, and it does not have to be equal to the number of actual vehicle effectors and sensors used in the model. We must also define the range of modes to be evaluated (1 to 100 modes in this case). But we will not select the first 6 modes which are rigid, we should include only structural modes in the flex mode set. Enter the number of forces excitations (1 force in this case), the number of torque excitations (1 torque locations in this case), and 3 rotational sensors for gyros. No translational sensors. These locations are only for mode strength comparison between effector and sensor nodes. We will also select the graphic mode selection option where the user selects the modes from a bar chart using the mouse. The number of modes to be selected does not apply in this case. We click "OK" to continue.

The program provides the capability for the user to change the units of the selected modal data or to reverse the directions of some coordinate axes of the finite elements model, if they are different, in order to match the units and directions of the rigid-body model. In this example, however, the units and directions are the same in both models and there is no need to scale the modal data. Answer “No” to the next question.



The next step is to identify the node for 1 force excitation and 1 torque excitation points. The nodes map, which is loaded from file “*Surveillance-Sat.Nod*” is used by the mode selection program to help the user identify the excitation and sensor nodes in the modal data file by using menus. The first RCS jet in node #21 is selected to apply the force excitation in the +y direction.

Definition of Vehicle Structural Nodes from FEM

In mode selection, you must define some node points in the Nastran model where the excitation forces and torques will be applied, and also their directions. It is used to calculate the mode strength and to compare the modes in specified directions

Similarly, you must define the sensor points, either translations or rotations and the sensing directions

Select a Location (Node) for Force Excitation : 1

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

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

Direction

- + (positive)
- (negative)

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

Definition of Vehicle Structural Nodes from FEM

In mode selection, you must define some node points in the Nastran model where the excitation forces and torques will be applied, and also their directions. It is used to calculate the mode strength and to compare the modes in specified directions

Similarly, you must define the sensor points, either translations or rotations and the sensing directions

OK
Cancel

Select a Location (Node) for Torque Excitation: 1

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

We also define 1 torque excitation point to be the cooler pump disturbance at node #8, in the +roll direction. Remember, that these locations are only for mode selection purposes. At this point they are arbitrarily chosen because we are planning to select the same mode numbers as those selected in Section 3.

Next, we select 3 locations to define the 3 rotational measurements. All 3 are in the same location, which is the Inertial Attitude Sensors, at node #6 (31001), selected 3 times in +roll, +pitch, and +yaw directions.

Definition of Vehicle Structural Nodes from FEM

In mode selection, you must define some node points in the Nastran model where the excitation forces and torques will be applied, and also their directions. It is used to calculate the mode strength and to compare the modes in specified directions

Similarly, you must define the sensor points, either translations or rotations and the sensing directions

Select a Location (Node) for Rotational Sensor: 1

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

OK
Cancel

Axis
Roll
Pitch
Yaw
Direction
+ (positive)
- (negative)

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

Definition of Vehicle Structural Nodes from FEM

In mode selection, you must define some node points in the Nastran model where the excitation forces and torques will be applied, and also their directions. It is used to calculate the mode strength and to compare the modes in specified directions

Similarly, you must define the sensor points, either translations or rotations and the sensing directions

Select a Location (Node) for Rotational Sensor: 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 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

OK
Cancel

Axis
Roll
Pitch
Yaw
Direction
+ (positive)
- (negative)

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

At this point the excitation and sensor points and directions for the mode selection process have been defined. The modal strength for each mode is determined by the values of the mode shapes at the nodes where the forces and torques are applied, the force directions, and also by the values of the mode shapes at the 3 rotational sensors along the measured directions. Large mode shape magnitudes at the excitation and sensor points, at a mode frequency, imply strong contributions from that mode. The mode selection program computes the mode strength at each mode frequency and saves the results in file "Modsel.Msl". The mode selection process, however, is not completed yet because the program needs additional info before allowing the user to select the modes. The program must identify structure node numbers that correspond to important vehicle locations, such as, effectors and sensor points. It will display similar tables of node menus (in light blue color) where the user can identify structural nodes at the required vehicle locations. From the following node selection menus the user must identify 7 nodes (#21 to #27) that correspond to the 7 RCS jets defined in the vehicle dataset in file "Surv_Sat_RB+Flx.Inp". The selection of the first and the 7th jets are shown below. The 3 reaction wheel locations, node numbers (#17, #18, and #19) are also selected.

Define Structure Nodes that Correspond to Vehicle Positions ✕

You must define some Points on the finite element model that correspond to important vehicle locations, as specified in the Vehicle Input Data. Such as points where Forces are Applied and Motion is Sensed, ex. TVC gimbals, CMG, RCS, Gyros, Accels, etc.

Select a Location (Node) for Thruster Engine : 1 OK

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

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

Define Structure Nodes that Correspond to Vehicle Positions



You must define some Points on the finite element model that correspond to important vehicle locations, as specified in the Vehicle Input Data. Such as points where Forces are Applied and Motion is Sensed, ex. TVC gimbals, CMG, RCS, Gyros, Accels, etc.

Select a Location (Node) for Thruster Engine : 7

OK

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

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

Define Structure Nodes that Correspond to Vehicle Positions



You must define some Points on the finite element model that correspond to important vehicle locations, as specified in the Vehicle Input Data. Such as points where Forces are Applied and Motion is Sensed, ex. TVC gimbals, CMG, RCS, Gyros, Accels, etc.

Select a Location (Node) for Reaction Wheel : 1

OK

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

Define Structure Nodes that Correspond to Vehicle Positions



You must define some Points on the finite element model that correspond to important vehicle locations, as specified in the Vehicle Input Data. Such as points where Forces are Applied and Motion is Sensed, ex. TVC gimbals, CMG, RCS, Gyros, Accels, etc.

Select a Location (Node) for Reaction Wheel : 3

OK

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

The next step is to define the location of the cryo-cooler disturbance torque, which is node #8 (40101). We select it three times in order to apply roll, pitch, and yaw torques, as defined in the vehicle data.

We must also select locations for the 13 rotational sensors. The first 6 are at the Inertial Attitude Sensors, node #6 (31001). It is measuring attitudes and rates in roll, pitch, and yaw.

Define Structure Nodes that Correspond to Vehicle Positions

You must define some Points on the finite element model that correspond to important vehicle locations, as specified in the Vehicle Input Data. Such as points where Forces are Applied and Motion is Sensed, ex. TVC gimbals, CMG, RCS, Gyros, Accels, etc.

Select a Location (Node) for External Torque : 1 OK

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

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

Define Structure Nodes that Correspond to Vehicle Positions

You must define some Points on the finite element model that correspond to important vehicle locations, as specified in the Vehicle Input Data. Such as points where Forces are Applied and Motion is Sensed, ex. TVC gimbals, CMG, RCS, Gyros, Accels, etc.

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

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			

OK

Define Structure Nodes that Correspond to Vehicle Positions

You must define some Points on the finite element model that correspond to important vehicle locations, as specified in the Vehicle Input Data. Such as points where Forces are Applied and Motion is Sensed, ex. TVC gimbals, CMG, RCS, Gyros, Accels, etc.

Select a Location (Node) for Gyro/Rate Sensor : 8

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			

OK

The next two rotational sensors (7 and 8) are in the Secondary Mirror at node #9 (40102). The next two rotational sensors (9 and 10) correspond to the Sensitive Instrument 2 at node #10 (40103). The last three rotational sensors (11, 12, and 13) are located in nodes (#11, #12, and #13).

We must also select locations for the two accelerometers to be used for sensitivity analysis. The accelerometers node #7 (31002) is selected twice along X and Y. We finally select node #8 (98008) for the disturbance torque location, which is not used in this analysis.

Define Structure Nodes that Correspond to Vehicle Positions

You must define some Points on the finite element model that correspond to important vehicle locations, as specified in the Vehicle Input Data. Such as points where Forces are Applied and Motion is Sensed, ex. TVC gimbals, CMG, RCS, Gyros, Accels, etc.

Select a Location (Node) for Gyro/Rate Sensor : 10

OK

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

Define Structure Nodes that Correspond to Vehicle Positions

You must define some Points on the finite element model that correspond to important vehicle locations, as specified in the Vehicle Input Data. Such as points where Forces are Applied and Motion is Sensed, ex. TVC gimbals, CMG, RCS, Gyros, Accels, etc.

Select a Location (Node) for Gyro/Rate Sensor : 11

OK

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

Define Structure Nodes that Correspond to Vehicle Positions

You must define some Points on the finite element model that correspond to important vehicle locations, as specified in the Vehicle Input Data. Such as points where Forces are Applied and Motion is Sensed, ex. TVC gimbals, CMG, RCS, Gyros, Accels, etc.

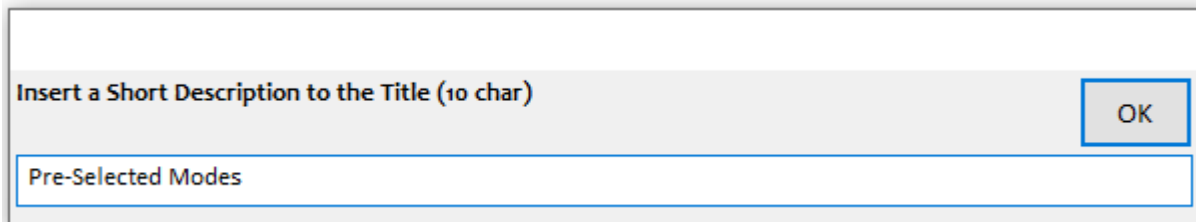
Select a Location (Node) for Accelerometer : 1

OK

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			

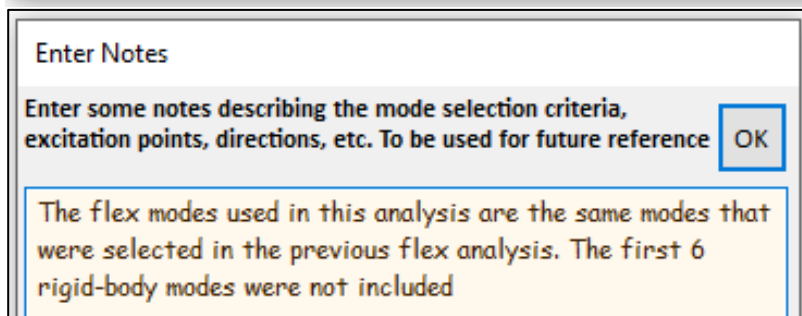
At this point the mode selection program displays the results of the mode strength comparison between the excitation points and the sensor points defined in earlier dialogs along specific directions. It saves the mode strength for each mode in file "Modsel.Dat" and displays the mode strength results in a bar chart (shown below) where the relative mode strength of each mode is plotted vertically versus the mode number. It will help the user to retain the strongest modes from the big modal data file. The height of each bar is logarithmically proportional to the relative mode strength. The strong modes appear tall and the weak modes are short. The modal strength is a relative number adjusted with respect to the minimum and maximum modal strengths. All bars are initially red before selection. The user selects some of the strongest modes from the chart by pointing the mouse cursor at the bar and clicking the mouse to select it. The modes change color from red to green when they are selected. Notice that the first six modes are not selected because they are rigid-body modes, and the rigid-body dynamics have already been included in the vehicle model. We select 60 flex modes, the same flex modes that were selected in Section 3 using the Flex Spacecraft Program and press the enter button to complete the mode selection. The program will create a smaller subset of the original modal data containing only the dominant modes and will include mode shapes only at the locations which are defined in the satellite model (RCS jets, RW locations, external disturbances, etc.). The selected modes dataset will be saved in the same input file.

The title of the modal data set will be similar to the vehicle dataset title "*Space Surveillance Satellite with RCS and Reaction Wheels (60 Flex Pre-Selected Modes)*". A short addition to the title can be inserted via a dialog that will make it easier to identify the modal data. The title of the selected modes should also be included at the bottom of the Satellite input dataset (below the number of flex modes) in order for the flight vehicle modeling program to associate the selected modes with the spacecraft input data. The user may also enter some comments that describe the modal data selection process. Describing for example what type of modes were selected and the conditions of mode selection, excitation points, measurement points, directions, etc. The comments will be included below the title of the modes set which is also saved in the input data file "*Surv_Sat_RB+Flx.Inp*".



Insert a Short Description to the Title (10 char) OK

Pre-Selected Modes

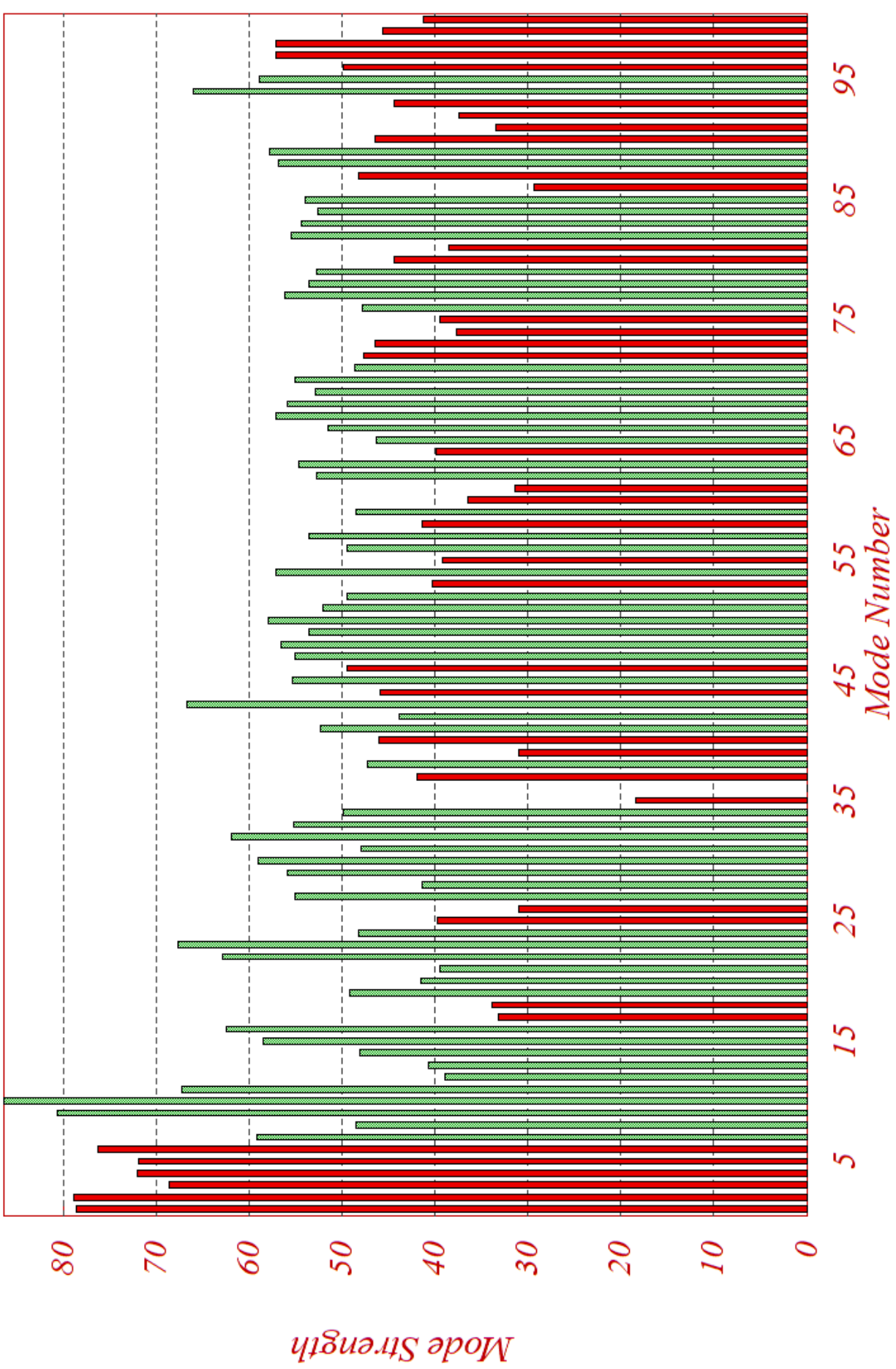


Enter Notes

Enter some notes describing the mode selection criteria, excitation points, directions, etc. To be used for future reference OK

The flex modes used in this analysis are the same modes that were selected in the previous flex analysis. The first 6 rigid-body modes were not included

*Mode Strength Comparison (use mouse to select the strongest modes)
Select Dominant Modes of: Surveillance Satellite with Reaction Wheels and Gimbalin*



Input File "Surv_Sat_RB+Flx.Inp"

BATCH MODE INSTRUCTIONS

Batch for the Surveillance Satellite with RCS Jets and Reaction Wheels
 ! This batch creates 3 Spacecraft models with Reaction Wheels, RCS, and Gimbaling Appendages
 ! from a Finite Elements Model with Inertial Coupling Coefficients using the
 ! Flight Vehicle Modeling Program and Flixan Utilities
 !

Flight Vehicle : Space Surveillance Satellite with RCS and Reaction Wheels (Rigid-Body)
 Flight Vehicle : Space Surveillance Satellite with RCS and Reaction Wheels (Gimbals, No Flex)
 Flight Vehicle : Space Surveillance Satellite with RCS and Reaction Wheels (Gimbals & 60 Flex Modes)
 !
 S-Z-Transform : Space Surveill Satellite with RCS and Reaction Wheels (Rigid-Body, Z-Transf)
 S-Z-Transform : Space Surveill Satellite with RCS and Reaction Wheels (Gimbals, No Flex, Z-Transf)
 S-Z-Transform : Space Surveill Satellite with RCS and Reaction Wheels (Gimbals, 60 Modes, Z-Transf)
 !
 To Matlab Format : Space Surveill Satellite with RCS and Reaction Wheels (Rigid-Body, Z-Transf)
 To Matlab Format : Space Surveill Satellite with RCS and Reaction Wheels (Gimbals, No Flex, Z-Transf)
 To Matlab Format : Space Surveill Satellite with RCS and Reaction Wheels (Gimbals, 60 Modes, Z-Transf)

FLIGHT VEHICLE INPUT DATA

Space Surveillance Satellite with RCS and Reaction Wheels (Gimbals & 60 Flex Modes)
 ! This Surveillance Satellite model is using the vehicle modeling program.
 ! It includes rigid-body LVLH dynamics with momentum bias and flexibility modes.
 ! The satellite has 7 RCS jets and 3 Reaction Wheels. One of the wheels has a
 ! momentum bias of -40 (ft-lb-sec). It has also four gimbaling appendages for
 ! an optical telescope that rotates in azimuth and elevation, and two solar arrays.
 ! The H-Parameters data are read from file Surveillance-Sat.Hpr. The are used to
 ! unlock the 2 telescope gimbals and the 2 Solar Arrays. The LVLH Attitude flag defines
 ! the spacecraft attitude in LVLH frame and activates the Gravity Gradient dynamics.
 !

Body Axes Output, LVLH Attitude

Vehicle Mass (lb-sec ² /ft), Gravity Accelerat. (g) (ft/sec ²), Earth Radius (Re) (ft)	: 50.0	0.0001	0.20896E+08		
Moments and products of Inertias Ixx, Iyy, Izz, Ixy, Ixz, Iyz, in (lb-sec ² -ft)	: 1045.3,	641.02,	505.05,	0.0,	-19.0,
CG location with respect to the Vehicle Reference Point, Xcg, Ycg, Zcg, in (feet)	: -0.05,	0.1,	22.625		
Vehicle Mach Number, Velocity Vo (ft/sec), Dynamic Pressure (psf), Altitude (feet)	: 0.0	29000.0	0.0001	800000.0	
Inertial Acceleration Vo_dot, Sensed Body Axes Accelerations Ax,Ay,Az (ft/sec ²)	: 0.0	0.0	0.0	0.0	0.0
Angles of Attack and Sideslip (deg), alpha, beta rates (deg/sec)	: 0.0	0.0	0.0	0.0	0.0
Vehicle Attitude Euler Angles, Phi_o, Thet_o, Psi_o (deg), Body Rates Po,Qo,Ro (deg/sec)	: 0.0000	0.000	0.0000	0.0000,	-0.064744,
W-Gust Azim & Elev angles (deg), or Torque/Force direction (x,y,z), Force Locat (x,y,z)	: Torque	0.0	1.0	0.0	
Surface Reference Area (feet ²), Mean Aerodynamic Chord (ft), Wing Span in (feet)	: 0.0	1.0	1.0		
Aero Moment Reference Center (Xmrc,Ymrc,Zmrc) Location in (ft), {Partial_rho/ Partial_H}	: 0.0	0.0	0.0	-0.0	
Aero Force Coef/Deriv (1/deg), Along -X, {Cao,Ca_alf,PCa/FV,PCa/Ph,Ca_alfdot,Ca_g,Ca_bet}	: 0.0	0.0	0.0	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	-0.0	0.0000	0.0000	0.0000
Aero Force Coeff/Deriv (1/deg), Along Z, {Czo,Cz_alf,Cz_g,Cz_bet,PCz/Ph,Cz_alfdot,PCz/FV}	: 0.0	-0.0	0.0000	0.0000	0.0000
Aero Moment Coeff/Derivat (1/deg), Roll: {Clo, Cl_beta, Cl_betdot, Cl_p, Cl_r, Cl_alfa}	: 0.0	-0.0	0.0000	0.0000	0.0000
Aero Moment Coeff/Deriv (1/deg), Pitch: {Cmo,Cm_alfa,Cm_alfdot,Cm_bet,Cm_g,PCm/FV,PCm/Ph}	: 0.0	-0.0	0.0000	0.0000	0.0000
Aero Moment Coeff/Derivat (1/deg), Yaw : {Cno, Cn_beta, Cn_betdot, Cn_p, Cn_r, Cn_alfa}	: 0.0	0.0	0.0000	0.0000	0.0000

Number of Thruster Engines, RCS Jets, No Engine Gimbaling : 7

RCS Jet No: 1	+X Back Top Center (0.05 lb jet)	: +X Top Jet	Throttling	Node 21
Engine Nominal Thrust, and Maximum Thrust in (lb) (for throttling)	: 0.0	0.05		
Mounting Angles wrt Vehicle (Dyn,Dzn), Maximum Deflections from Mount (Dymax,Dzmax) (deg):	: 0.0	0.0	0.0	0.0
Eng Mass (slug), Inertia about Gimbal (lb-sec ² -ft), Moment Arm, engine CG to gimbal (ft):	: 0.0	0.0	0.0	
Thruster location with respect to the Vehicle Reference Axes, Xjet, Yjet, Zjet, (ft)	: -2.3625	0.0,	18.075	
RCS Jet No: 2	+X Back Bottom center (0.05 lb jet)	: +X Bottom	Throttling	Node 22
Engine Nominal Thrust, and Maximum Thrust in (lb) (for throttling)	: 0.0	0.05		
Mounting Angles wrt Vehicle (Dyn,Dzn), Maximum Deflections from Mount (Dymax,Dzmax) (deg):	: 0.0	0.0	0.0	0.0
Eng Mass (slug), Inertia about Gimbal (lb-sec ² -ft), Moment Arm, engine CG to gimbal (ft):	: 0.0	0.0	0.0	
Thruster location with respect to the Vehicle Reference Axes, Xjet, Yjet, Zjet, (ft)	: -2.3625	0.0,	24.675	
RCS Jet No: 3	+Y Front-Left (0.05 lb jet)	: +Y Frnt Lft	Throttling	Node 23
Engine Nominal Thrust, and Maximum Thrust in (lb) (for throttling)	: 0.0	0.05		
Mounting Angles wrt Vehicle (Dyn,Dzn), Maximum Deflections from Mount (Dymax,Dzmax) (deg):	: 0.0	+90.0	0.0	0.0
Eng Mass (slug), Inertia about Gimbal (lb-sec ² -ft), Moment Arm, engine CG to gimbal (ft):	: 0.0	0.0	0.0	
Thruster location with respect to the Vehicle Reference Axes, Xjet, Yjet, Zjet, (ft)	: 1.270833,	-1.433333,	24.8025	
RCS Jet No: 4	-Y Front-Right (0.05 lb jet)	: -Y Frnt Rt	Throttling	Node 24
Engine Nominal Thrust, and Maximum Thrust in (lb) (for throttling)	: 0.0	0.05		
Mounting Angles wrt Vehicle (Dyn,Dzn), Maximum Deflections from Mount (Dymax,Dzmax) (deg):	: 0.0	-90.0	0.0	0.0
Eng Mass (slug), Inertia about Gimbal (lb-sec ² -ft), Moment Arm, engine CG to gimbal (ft):	: 0.0	0.0	0.0	
Thruster location with respect to the Vehicle Reference Axes, Xjet, Yjet, Zjet, (ft)	: 1.270833,	1.433333,	24.8025	
RCS Jet No: 5	-Y Back-Right (0.05 lb jet)	: -Y Back Rt	Throttling	Node 25
Engine Nominal Thrust, and Maximum Thrust in (lb) (for throttling)	: 0.0	0.05		
Mounting Angles wrt Vehicle (Dyn,Dzn), Maximum Deflections from Mount (Dymax,Dzmax) (deg):	: 0.0	-90.0	0.0	0.0
Eng Mass (slug), Inertia about Gimbal (lb-sec ² -ft), Moment Arm, engine CG to gimbal (ft):	: 0.0	0.0	0.0	
Thruster location with respect to the Vehicle Reference Axes, Xjet, Yjet, Zjet, (ft)	: -1.7875,	0.708333,	24.675	
RCS Jet No: 6	+Y Back-Left (0.05 lb jet)	: +Y Bck Lft	Throttling	Node 26
Engine Nominal Thrust, and Maximum Thrust in (lb) (for throttling)	: 0.0	0.05		
Mounting Angles wrt Vehicle (Dyn,Dzn), Maximum Deflections from Mount (Dymax,Dzmax) (deg):	: 0.0	+90.0	0.0	0.0
Eng Mass (slug), Inertia about Gimbal (lb-sec ² -ft), Moment Arm, engine CG to gimbal (ft):	: 0.0	0.0	0.0	
Thruster location with respect to the Vehicle Reference Axes, Xjet, Yjet, Zjet, (ft)	: -1.7875,	-0.708333,	24.675	
RCS Jet No: 7	+X Back Mid-Center (0.05 lb jet)	: +X Mid Cntr	Throttling	Node 27
Engine Nominal Thrust, and Maximum Thrust in (lb) (for throttling)	: 0.0	0.05		
Mounting Angles wrt Vehicle (Dyn,Dzn), Maximum Deflections from Mount (Dymax,Dzmax) (deg):	: 0.0	0.0	0.0	0.0
Eng Mass (slug), Inertia about Gimbal (lb-sec ² -ft), Moment Arm, engine CG to gimbal (ft):	: 0.0	0.0	0.0	
Thruster location with respect to the Vehicle Reference Axes, Xjet, Yjet, Zjet, (ft)	: -2.3625,	0.0,	21.45	

Number of External Torques on the Vehicle : 3
 Torque No 1 Direction (x, y, z) : 1.0 0.0 0.0
 Torque No 2 Direction (x, y, z) : 0.0 1.0 0.0
 Torque No 3 Direction (x, y, z) : 0.0 0.0 1.0

Double Gimbal Control Moment Gyro System (3-axes), Initial Momentum (x,y,z) (ft-lb-sec) : No

Number of Reaction Wheels : 3
 RW No: 1, Spin Direct. Unit Vect, Init Rot Speed (rpm), Rotor Mom of Inertia (slg-ft^2) : 0.0 1.0000 0.0000 -4774.6 0.08
 RW No: 2, Spin Direct. Unit Vect, Init Rot Speed (rpm), Rotor Mom of Inertia (slg-ft^2) : 0.0 0.93969262 -0.34202014 00.0 0.08
 RW No: 3, Spin Direct. Unit Vect, Init Rot Speed (rpm), Rotor Mom of Inertia (slg-ft^2) : 0.0 0.93969262 0.34202014 00.0 0.08

Number of Gyros, (Attitude and Rate) : 13
 Gyro No 1 Axis: (Pitch,Yaw,Roll), (Attitude, Rate, Accelerat), Sensor Locat, Node 6 : Roll Rate -0.747 0.114 25.572
 Gyro No 2 Axis: (Pitch,Yaw,Roll), (Attitude, Rate, Accelerat), Sensor Locat, Node 6 : Pitch Rate -0.747 0.114 25.572
 Gyro No 3 Axis: (Pitch,Yaw,Roll), (Attitude, Rate, Accelerat), Sensor Locat, Node 6 : Yaw Rate -0.747 0.114 25.572
 Gyro No 4 Axis: (Pitch,Yaw,Roll), (Attitude, Rate, Accelerat), Sensor Locat, Node 6 : Roll Attitude -0.747 0.114 25.572
 Gyro No 5 Axis: (Pitch,Yaw,Roll), (Attitude, Rate, Accelerat), Sensor Locat, Node 6 : Pitch Attitude -0.747 0.114 25.572
 Gyro No 6 Axis: (Pitch,Yaw,Roll), (Attitude, Rate, Accelerat), Sensor Locat, Node 6 : Yaw Attitude -0.747 0.114 25.572
 Gyro No 7 Axis: (Pitch,Yaw,Roll), (Attitude, Rate, Accelerat), Sensor Locat, Node 9 : Pitch Attitude 0.0 0.0 0.0
 Gyro No 8 Axis: (Pitch,Yaw,Roll), (Attitude, Rate, Accelerat), Sensor Locat, Node 9 : Yaw Attitude 0.0 0.0 0.0
 Gyro No 9 Axis: (Pitch,Yaw,Roll), (Attitude, Rate, Accelerat), Sensor Locat, Node 10 : Pitch Attitude 0.0 0.0 0.0
 Gyro No 10 Axis: (Pitch,Yaw,Roll), (Attitude, Rate, Accelerat), Sensor Locat, Node 10 : Yaw Attitude 0.0 0.0 0.0
 Gyro No 11 Axis: (Pitch,Yaw,Roll), (Attitude, Rate, Accelerat), Sensor Locat, Node 11 : Roll Attitude 0.0 0.0 0.0
 Gyro No 12 Axis: (Pitch,Yaw,Roll), (Attitude, Rate, Accelerat), Sensor Locat, Node 12 : Pitch Attitude 0.0 0.0 0.0
 Gyro No 13 Axis: (Pitch,Yaw,Roll), (Attitude, Rate, Accelerat), Sensor Locat, Node 13 : Yaw Attitude 0.0 0.0 0.0

Number of Accelerometers, Along Axes: (x,y,z) : 2
 Acceleromet No 1 Axis: (X,Y,Z), (Position, Velocity, Acceleration), Sensor Loc, Node 7 : X-axis Accelerat. 0.338 0.648 25.57
 Acceleromet No 2 Axis: (X,Y,Z), (Position, Velocity, Acceleration), Sensor Loc, Node 7 : Y-axis Accelerat. 0.338 0.648 25.57

Gimbaling Appendages (Requires Inertial Flex Coupling Coefficients), H-paramet. Filename : Surveillance-Sat.Hpr

Number of Bending Modes : 60
 Space Surveillance Satellite with RCS and Reaction Wheels (60 Flex Pre-Selected Modes)

 SELECTED MODAL DATA AND LOCATIONS FOR : Pre-Selected
 Space Surveillance Satellite with RCS and Reaction Wheels (60 Flex Pre-Selected Modes)
 ! The flex modes used in this analysis are the same modes that were selected in the previous flex
 ! surveillance spacecraft analysis. We start from Mode #7 because the first 6 rigid-body modes
 ! are not included in the modal data because the rigid-body dynamics are included in the vehicle.
 ! The Nodes correspond to vehicle locations defined in the vehicle data above.

MODE#	1/ 7, Frequency (rad/sec), Damping (zeta), Generalized Mass=	3.0998	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 ID# Modal Data at the 7 Engines, (x,y,z)...							
RCS Jet #1 (+X)	98001	-0.43556D+00	-0.25842D-02	0.14383D+00	-0.11015D-02	0.64939D-01	-0.10968D-02
RCS Jet #2 (+X)	98002	-0.69445D-02	0.46878D-02	0.14383D+00	-0.11019D-02	0.64943D-01	-0.10976D-02
RCS Jet #3 (+Y)	98003	-0.25866D-03	0.84179D-03	-0.90543D-01	-0.11015D-02	0.64943D-01	-0.10969D-02
RCS Jet #4 (-Y)	98004	0.28867D-02	0.84191D-03	-0.93702D-01	-0.11023D-02	0.64944D-01	-0.10973D-02
RCS Jet #5 (-Y)	98005	-0.61695D-02	0.40557D-02	0.10571D+00	-0.11017D-02	0.64943D-01	-0.10902D-02
RCS Jet #6 (+Y)	98006	-0.77244D-02	0.40575D-02	0.10727D+00	-0.11019D-02	0.64943D-01	-0.11047D-02
RCS Jet #7 (+X)	98007	-0.21638D+00	0.11339D-02	0.14383D+00	-0.11013D-02	0.64937D-01	-0.10964D-02
Node ID# Modal Data at the 3 Reaction Wheels...							
Reaction Wheel #1 CG	58041	-0.20700D+00	-0.43105D-03	0.41763D-01	-0.11013D-02	0.64943D-01	-0.10960D-02
Reaction Wheel #2 CG	58042	-0.20783D+00	-0.16859D-02	-0.31758D-01	-0.11002D-02	0.64942D-01	-0.11005D-02
Reaction Wheel #3 CG	58043	-0.20632D+00	-0.17810D-02	-0.38780D-01	-0.11033D-02	0.64942D-01	-0.10951D-02
Node ID# Modal Data at the 3 External Torque Points...							
Cryo Cooler Pump	40101	0.10119D+00	0.39271D-02	-0.98352D-02	-0.11022D-02	0.64950D-01	-0.10992D-02
Cryo Cooler Pump	40101	0.10119D+00	0.39271D-02	-0.98352D-02	-0.11022D-02	0.64950D-01	-0.10992D-02
Cryo Cooler Pump	40101	0.10119D+00	0.39271D-02	-0.98352D-02	-0.11022D-02	0.64950D-01	-0.10992D-02
Node ID# Modal Data at the 13 Gyros ...							
Inertial Attitude Sensors	31001	0.51466D-01	0.39036D-02	0.38773D-01	-0.11017D-02	0.64943D-01	-0.10969D-02
Inertial Attitude Sensors	31001	0.51466D-01	0.39036D-02	0.38773D-01	-0.11017D-02	0.64943D-01	-0.10969D-02
Inertial Attitude Sensors	31001	0.51466D-01	0.39036D-02	0.38773D-01	-0.11017D-02	0.64943D-01	-0.10969D-02
Inertial Attitude Sensors	31001	0.51466D-01	0.39036D-02	0.38773D-01	-0.11017D-02	0.64943D-01	-0.10969D-02
Inertial Attitude Sensors	31001	0.51466D-01	0.39036D-02	0.38773D-01	-0.11017D-02	0.64943D-01	-0.10969D-02
Inertial Attitude Sensors	31001	0.51466D-01	0.39036D-02	0.38773D-01	-0.11017D-02	0.64943D-01	-0.10969D-02
Second Mirror	40102	0.17864D+00	0.52413D-02	-0.98558D-02	-0.11024D-02	0.64950D-01	-0.10994D-02
Second Mirror	40102	0.17864D+00	0.52413D-02	-0.98558D-02	-0.11024D-02	0.64950D-01	-0.10994D-02
Sensitive Instrument 2	40103	0.99605D-01	0.41431D-02	0.46061D-02	-0.11016D-02	0.64944D-01	-0.10966D-02
Sensitive Instrument 2	40103	0.99605D-01	0.41431D-02	0.46061D-02	-0.11016D-02	0.64944D-01	-0.10966D-02
Sensitive Instrument 3	40104	0.10548D+00	0.36774D-02	-0.28874D-01	-0.11017D-02	0.64943D-01	-0.10968D-02
Sensitive Instrument 4	40105	0.10576D+00	0.35477D-02	-0.36834D-01	-0.11017D-02	0.64943D-01	-0.10968D-02
Sensitive Instrument 5	40106	0.96563D-01	0.34621D-02	-0.32667D-01	-0.11017D-02	0.64943D-01	-0.10968D-02
Node ID# Modal Data at the 2 Accelerometers, along (x,y,z)...							
Accelerometers	31002	0.51889D-01	0.27108D-02	-0.32279D-01			
Accelerometers	31002	0.51889D-01	0.27108D-02	-0.32279D-01			
Node ID# Modal Data at the Disturbance Point							
RCS Jet #8 (+X)	98008	-0.19474D+00	0.14764D-02	0.14237D+00	-0.11013D-02	0.64937D-01	-0.10964D-02

```

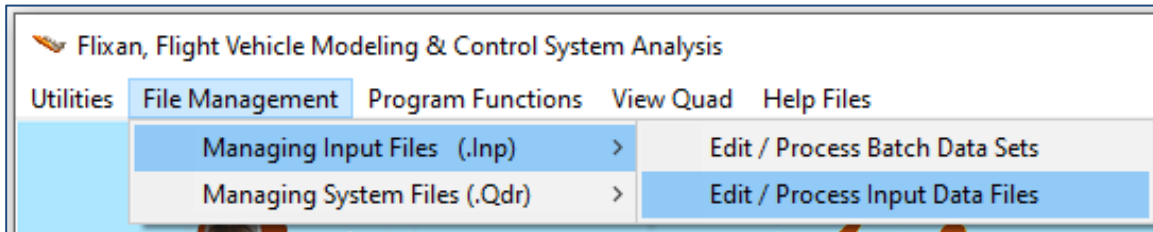
-----
S to Z TRANSFORMATIONS
-----
TRANSFORM A SYSTEM (S-Z-W) ..... (New z-system title, Comments, Old s-system title, Transform)
Space Surveill Satellite with RCS and Reaction Wheels (Rigid-Body, Z-Transf)
! Transform the Rigid vehicle model to Discrete using the
! S to Z Transformation method and 0.01 sec Sampling Period
!
Space Surveillance Satellite with RCS and Reaction Wheels (Rigid-Body)
From S-plane to Z-plane using the Z-Transform, dT= 0.01
-----
TRANSFORM A SYSTEM (S-Z-W) ..... (New z-system title, Comments, Old s-system title, Transform)
Space Surveill Satellite with RCS and Reaction Wheels (Gimbals, No Flex, Z-Transf)
! Transform the Rigid vehicle model with Gimbals to Discrete using the
! S to Z Transformation method and 0.01 sec Sampling Period
!
Space Surveillance Satellite with RCS and Reaction Wheels (Gimbals, No Flex)
From S-plane to Z-plane using the Z-Transform, dT= 0.01
-----
TRANSFORM A SYSTEM (S-Z-W) ..... (New z-system title, Comments, Old s-system title, Transform)
Space Surveill Satellite with RCS and Reaction Wheels (Gimbals, 60 Modes, Z-Transf)
! Transform the Flex vehicle model with Gimbals to Discrete using the
! S to Z Transformation method and 0.01 sec Sampling Period
!
Space Surveillance Satellite with RCS and Reaction Wheels (Gimbals & 60 Flex Modes)
From S-plane to Z-plane using the Z-Transform, dT= 0.01
-----
MATLAB CONVERSIONS
-----
CONVERT TO MATLAB FORMAT ..... (TITLE, SYSTEM/MATRIX, M-FILENAME)
Space Surveill Satellite with RCS and Reaction Wheels (Rigid-Body, Z-Transf)
System
fv_rb.m
-----
CONVERT TO MATLAB FORMAT ..... (TITLE, SYSTEM/MATRIX, M-FILENAME)
Space Surveill Satellite with RCS and Reaction Wheels (Gimbals, No Flex, Z-Transf)
System
fv_grb.m
-----
CONVERT TO MATLAB FORMAT ..... (TITLE, SYSTEM/MATRIX, M-FILENAME)
Space Surveill Satellite with RCS and Reaction Wheels (Gimbals, 60 Modes, Z-Transf)
System
fv_60.m
-----

```

7.2 Creating the Spacecraft Systems in Batch Mode

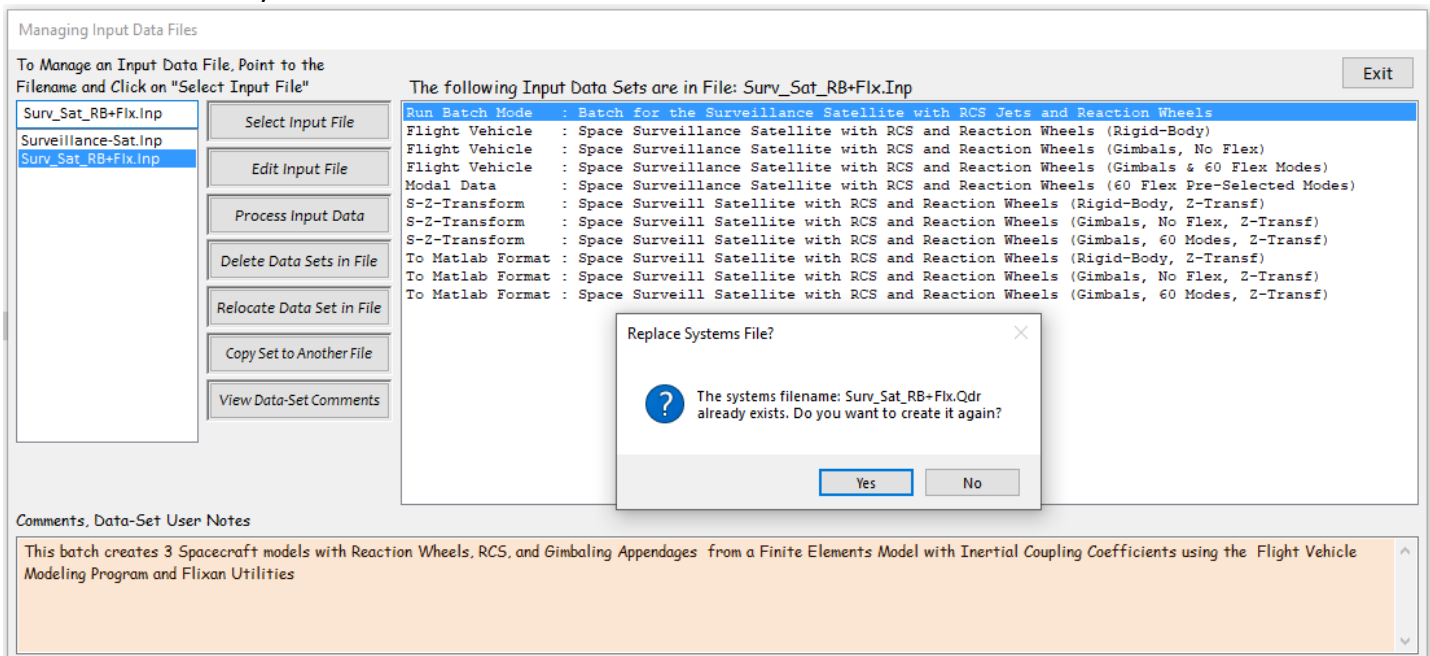
At the top of the input data file: *“Surv_Sat_RB+Flx.Inp”* there is a dataset of batch instructions that can be used to speed up the execution of the spacecraft systems by processing the input file in batch mode, instead of running them separately, discretizing them, and transforming them to Matlab. Its title is *“Batch for the Surveillance Satellite with RCS Jets and Reaction Wheels”*. It creates 3 spacecraft systems, *“Space Surveillance Satellite with RCS and Reaction Wheels (Rigid-Body)”* for the rigid-body model without gimbaling appendages, *“Space Surveillance Satellite with RCS and Reaction Wheels (Gimbals, No Flex)”* for the rigid-body model with the four gimbaling appendages, and *“Space Surveillance Satellite with RCS and Reaction Wheels (Gimbals & 60 Flex Modes)”* for the 60-mode flex spacecraft with the four gimbaling appendages. The systems are saved in systems file *“Surv_Sat_RB+Flx.Qdr”*. The batch then calls the S to Z transformation program to discretize the 3 systems at 10 msec sampling rate and it saves them in the same systems file. The discrete system titles are: *“Space Surveill Satellite with RCS and Reaction Wheels (Rigid-Body, Z-Transf)”*, *“Space Surveill Satellite with RCS and Reaction Wheels (Gimbals, No Flex, Z-Transf)”*, and *“Space Surveill Satellite with RCS and Reaction Wheels (Gimbals, 60 Modes, Z-Transf)”* respectively.

The batch finally converts the 3 discrete systems to Matlab format for further analysis. The m-function filenames for the 3 discrete systems are “fv_rb.m”, “fv_grb.m”, and “fv_60.m” respectively. They are saved in subdirectory: “Examples\10-Surveillance Satellite React-Wheels\6-Linear Flex Anal FV”. Start the Flixan program and go to directory: “Examples\10-Surveillance Satellite React-Wheels”. From the top menu select “File Management”, “Managing Input Files”, and select “Edit/Process Input Data Files”.



The input file management dialog comes up. From the menu on the left side select the filename “Surv_Sat_RB+Flx.Inp” and click on the “Select Input File” button. The right menu shows the datasets which are in the input file. Select the top title “Batch for the Surveillance Satellite with RCS Jets and Reaction Wheels” and then click on “Process Input Data”.The program will execute the top batch dataset in file “Surv_Sat_RB+Flx.Inp”. It will ask if it is acceptable to recreate the state-space systems file “Surv_Sat_RB+Flx.Qdr”. Answer “Yes”, and the program will process the vehicle datasets to generate the 3 discretized spacecraft systems.

The 3 systems “fv_rb.m”, “fv_grb.m”, and “fv_60.m” will be saved in the root directory and from there they can be moved to subdirectory “\Examples\10-Surveillance Satellite React-Wheels\6-Linear Flex Anal FV” for further Matlab analysis.



7.3 The Simulation Model

The flexible spacecraft simulation model is shown in Figure 7.1. The spacecraft dynamic system is the green block that includes the discretized system “*Space Surveill Satellite with RCS and Reaction Wheels (Gimbals, 60 Modes, Z-Transf)*” from the systems file “*Surv_Sat_RB+Flx.Qdr*” and is loaded from file “*fv_60.m*”. The simulation parameters are initialized from file “*start.m*” which also loads the state-space matrices. The m-file “*pl.m*” plots the simulation results.

Linear Simulation of Spacecraft with Reaction Wheels, RCS Jets and Pitch Momentum Bias

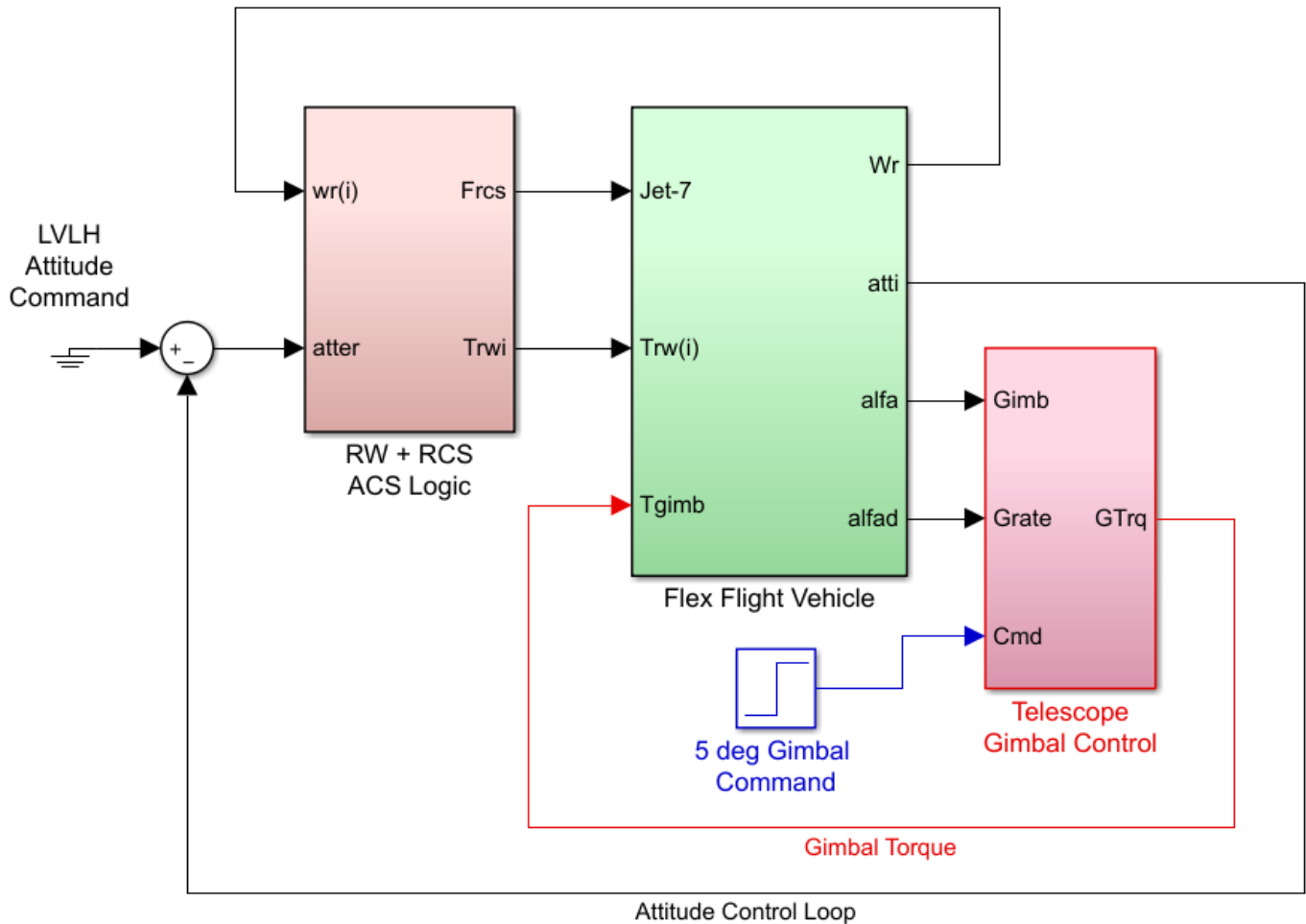


Figure 7.1 Flexible Spacecraft Linear Simulation Model “Flex_Sim.Slx”

The two telescope gimbals loops for elevation and azimuth are closed via PD controllers which are designed to provide a 2 (rad/sec) bandwidth. The telescope position control loop also includes low-pass filters. Figure 7.3 shows the combined RCS/ RW Attitude Control logic which includes a state-flow mode-switching logic that decides which controller remains active and which one is turned off based on the magnitude of the RW momentum. The RW steering logic converts the pitch and yaw torque commands to RW#2 and RW#3 torque commands.

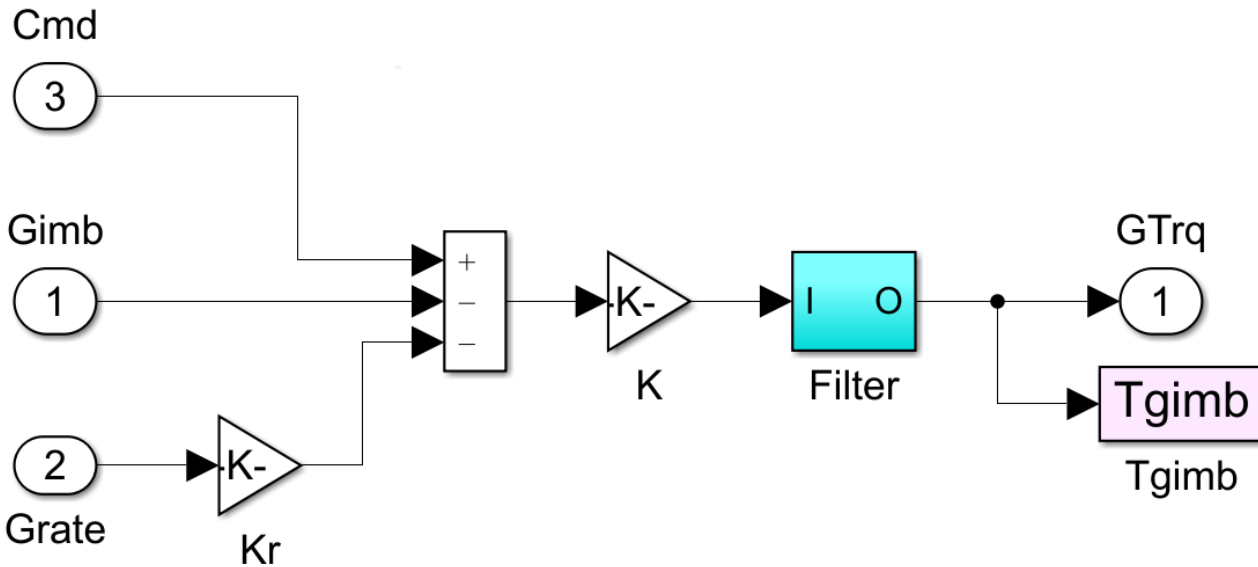


Figure 7.2 Telescope Gimbal Control System

RCS and RW Attitude Control System RW Steering and Mode Switching Logic

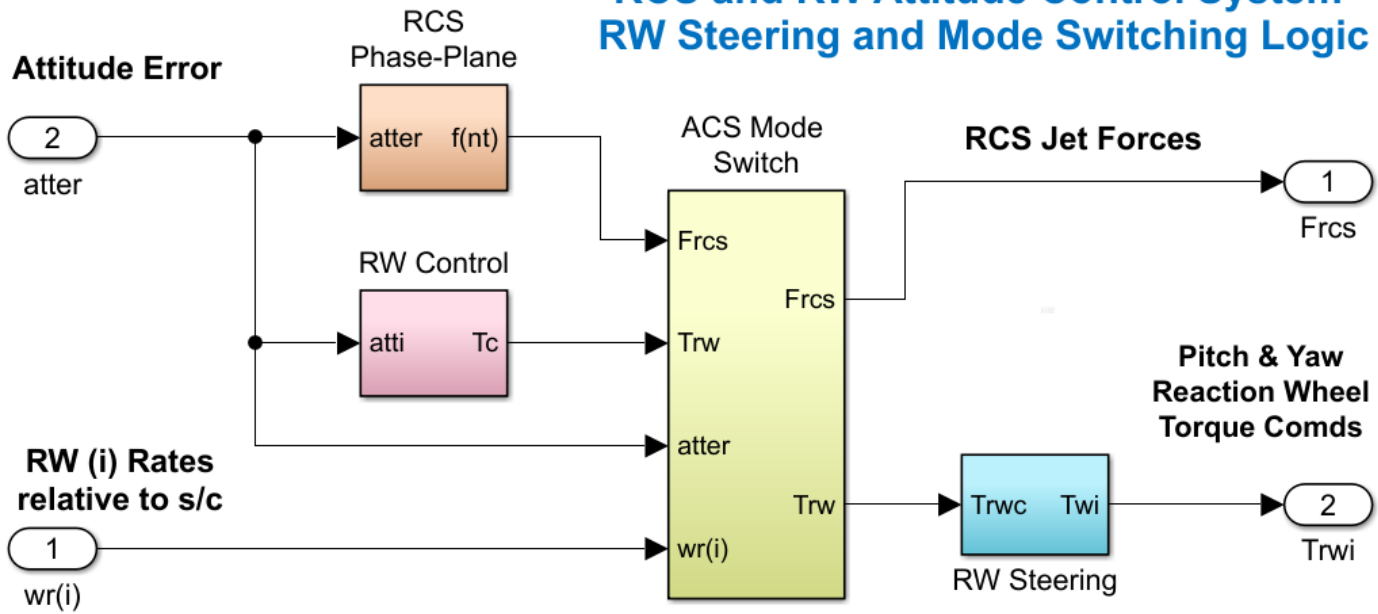


Figure 7.3 RW/ RCS Combined Attitude Control System with Switching Logic

It starts in the reaction wheel mode and when the wheel momentum magnitude exceeds the RW momentum capability H_{max} it switches to RCS1 mode. In RCS1 mode the jets control the vehicle attitude while the wheels are torqued in the direction to reduce the momentum in unison. It remains in RCS mode as long as the RW momentum is greater than $H_{max}/10$ or the spacecraft rate is greater than R_{lim} . When the RW momentum drops below $H_{max}/10$ and the spacecraft rate is below R_{lim} it switches back to the RW mode. Otherwise, if the momentum reaches below $H_{max}/10$ but the rate is still higher than R_{lim} it switches to the RCS2 mode where the jets still control attitude but the RW torque is set to zero. It remains in RCS2 mode until the rate magnitude drops below R_{lim} and then it switches back to the RW control mode.

Mode Switching Logic

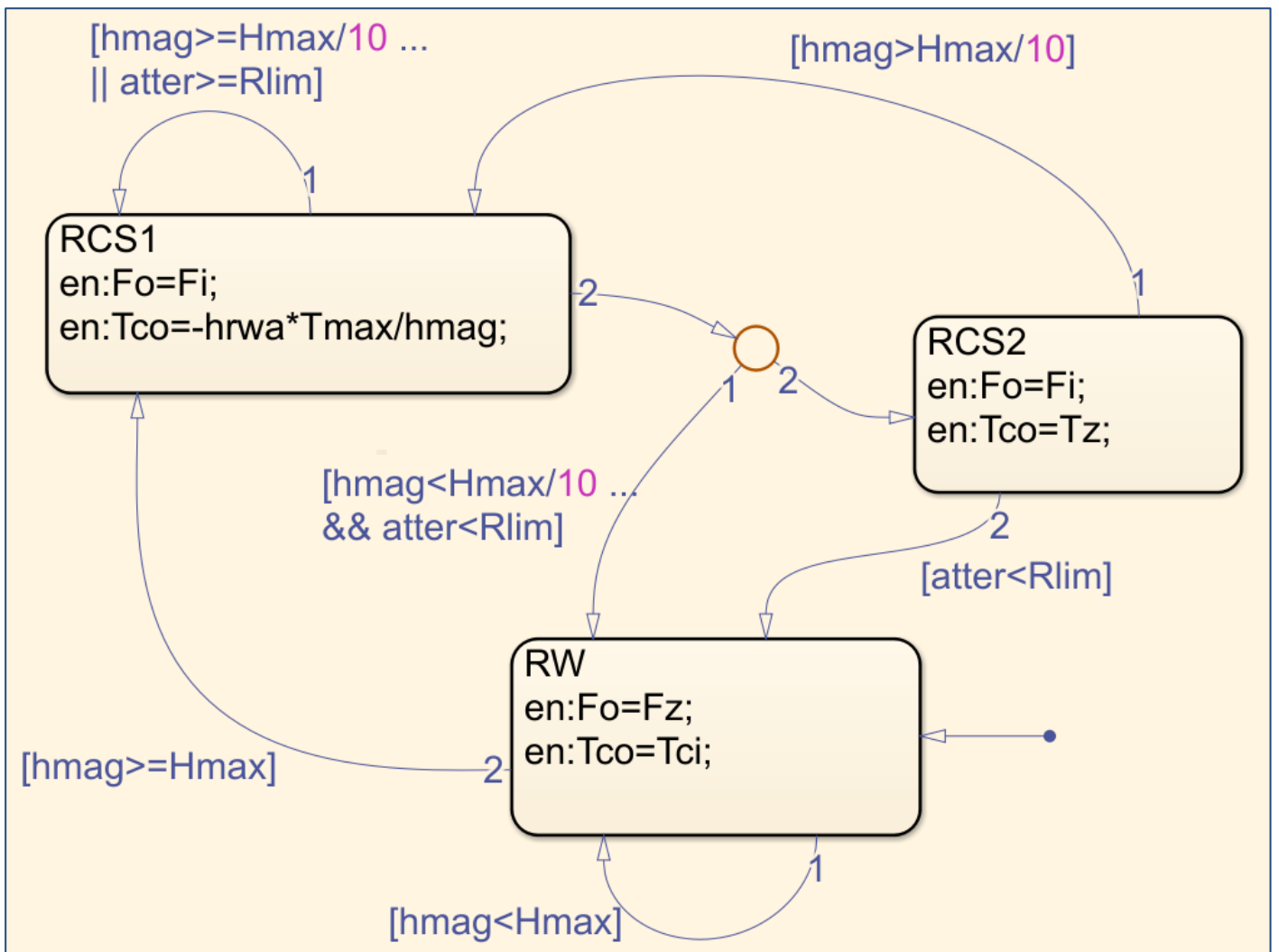
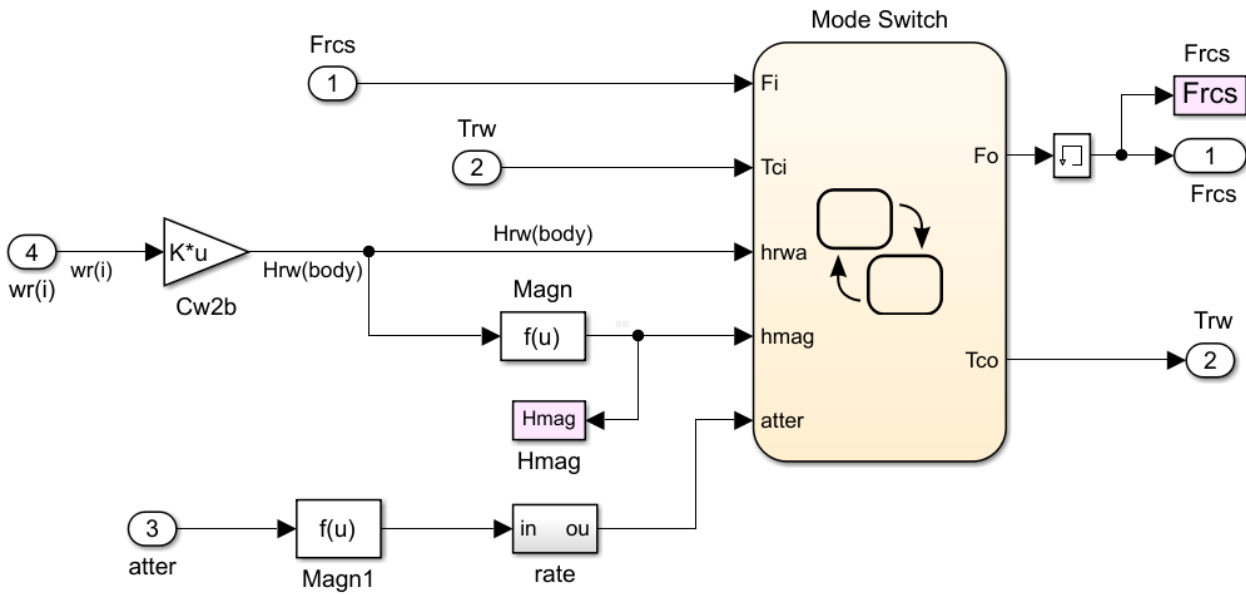


Figure 7.4 Attitude Control Mode State-Flow Switching Logic

**Discretized Flight Vehicle Flex Model from File: fv_60.m
Space Surveill Satellite with RCS and Reaction Wheels
(Gimbals, 60 Modes, Z-Transf)**

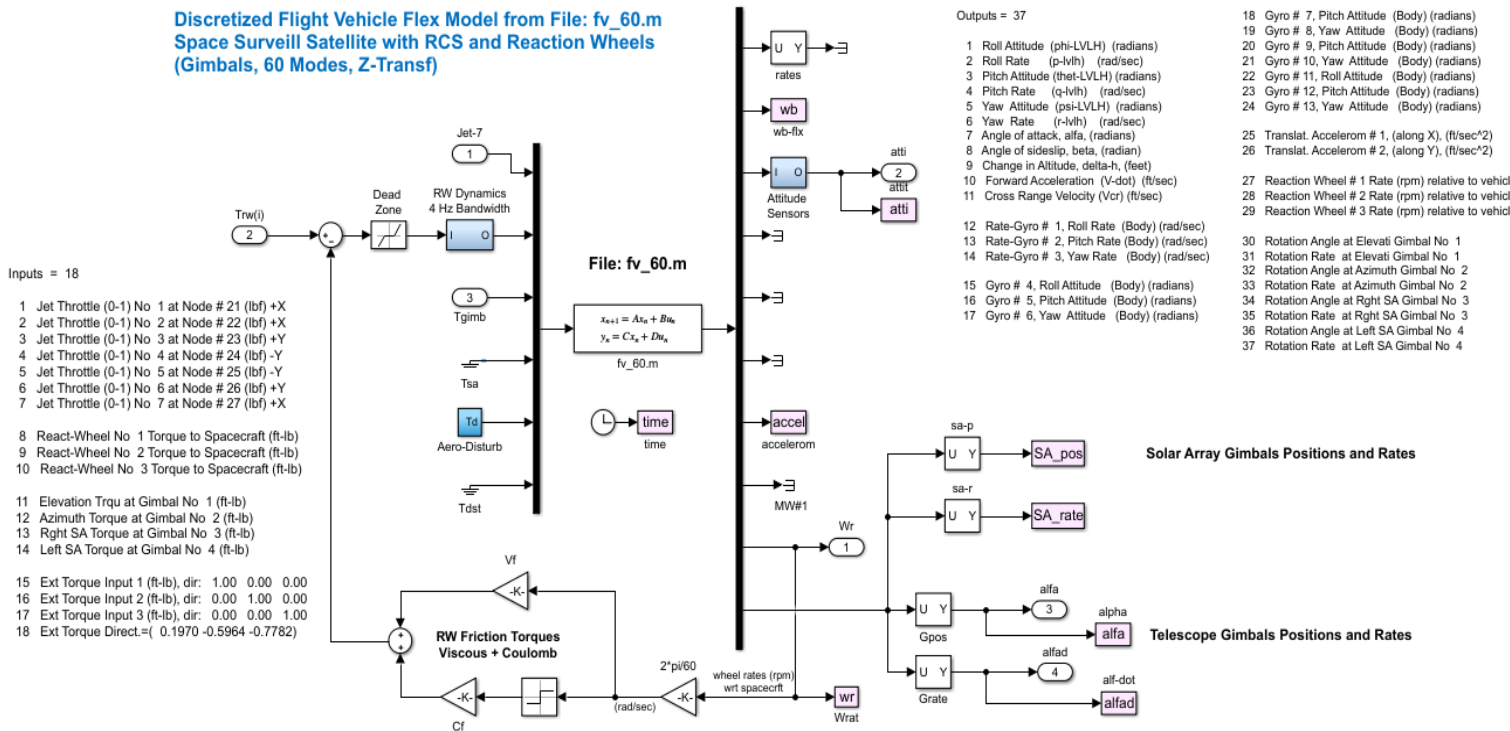


Figure 7.5 Discrete Spacecraft State-Space Model from file "fv_60.m"

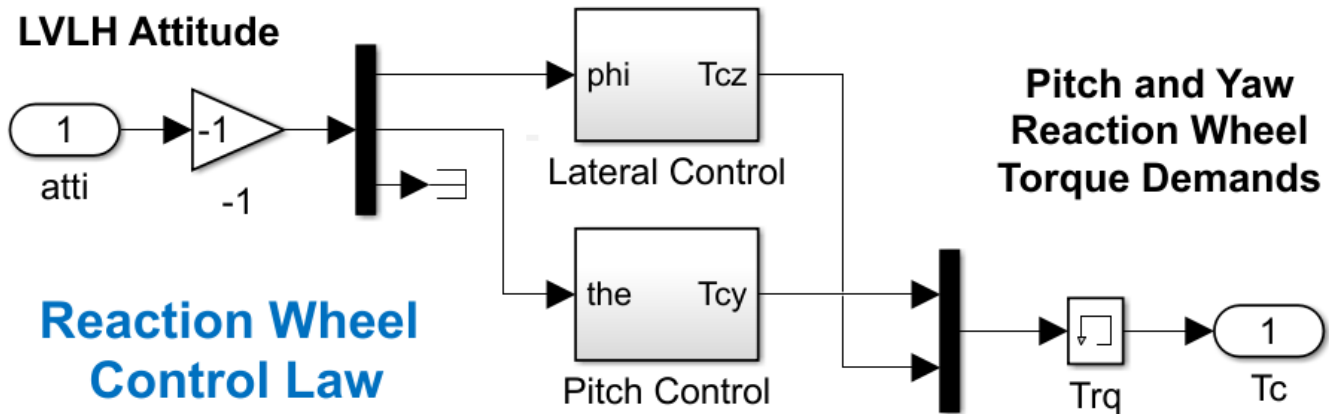


Figure 7.6 Reaction Wheel Control System

The vehicle block is shown in detail in Figure 7.5. The RW control law is already described and shown in Figure 7.6. Figures 7.7 to 7.9 show the simulation results. The spacecraft is not maneuvering but it is commanded to stay at zero LVLH attitude. Only the telescope is commanded to rotate 5° in both azimuth and elevation, beginning to rotate at 20 sec. The spacecraft responds to the cyclic aerodynamic and gravity gradient disturbances which are slightly biased and they are driving the wheels to saturation.

Figure 7.7 shows the switching from RW to RCS control when the RW momentum exceeds 10 (ft-lb-sec). During RCS control mode, the wheels are torqued in the direction to reduce the wheel momentum. The telescope gimbals are also torqued to maintain constant gimbal angles. Figure 7.9 shows the telescope gimbal response to 5 (deg) gimbal commands in both: Elevation and Azimuth directions which occurs at 20 seconds.

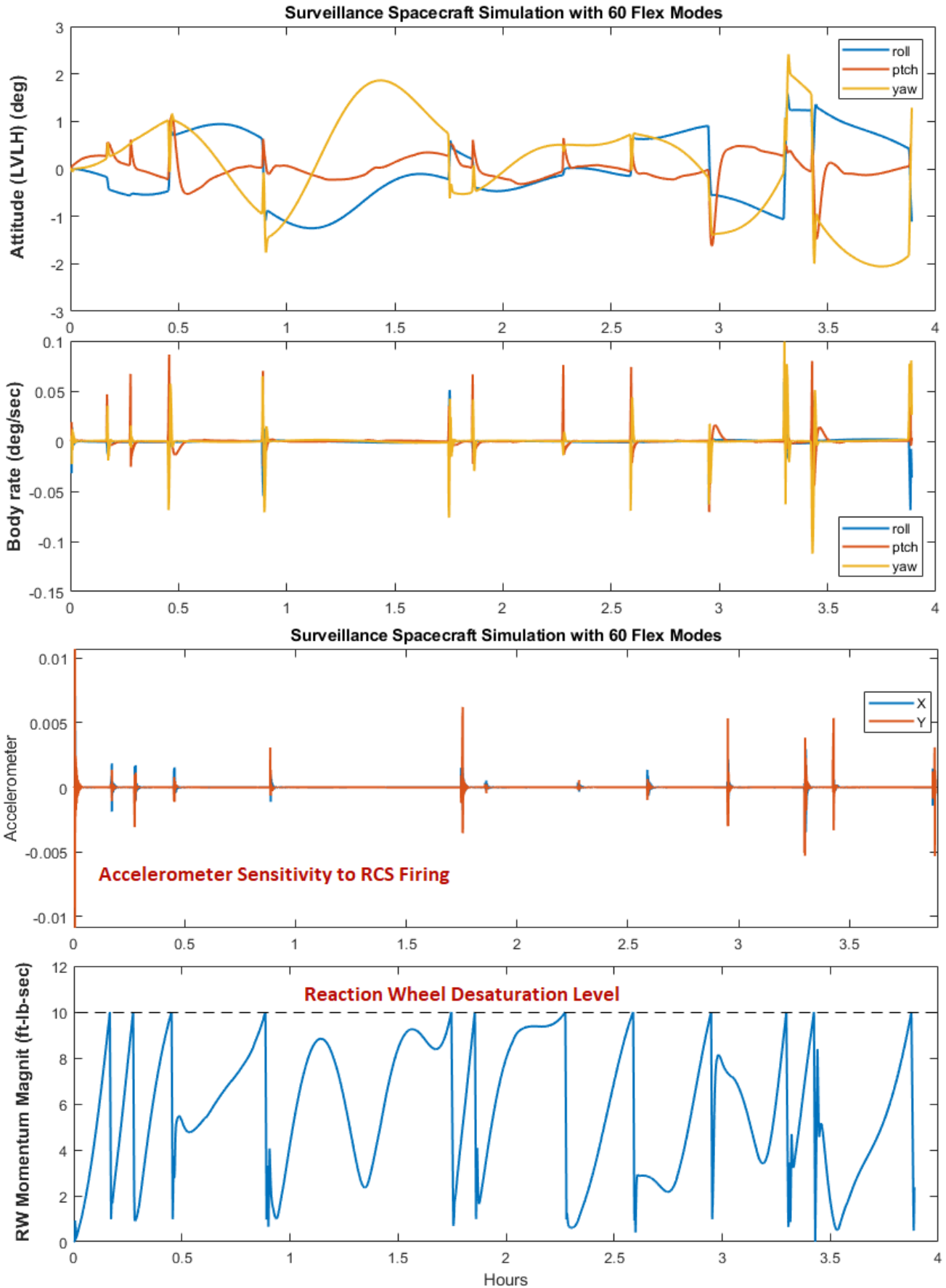


Figure 7.7 Spacecraft Control Switches Between the RW and RCS Modes to Desaturate the Wheel Momentum

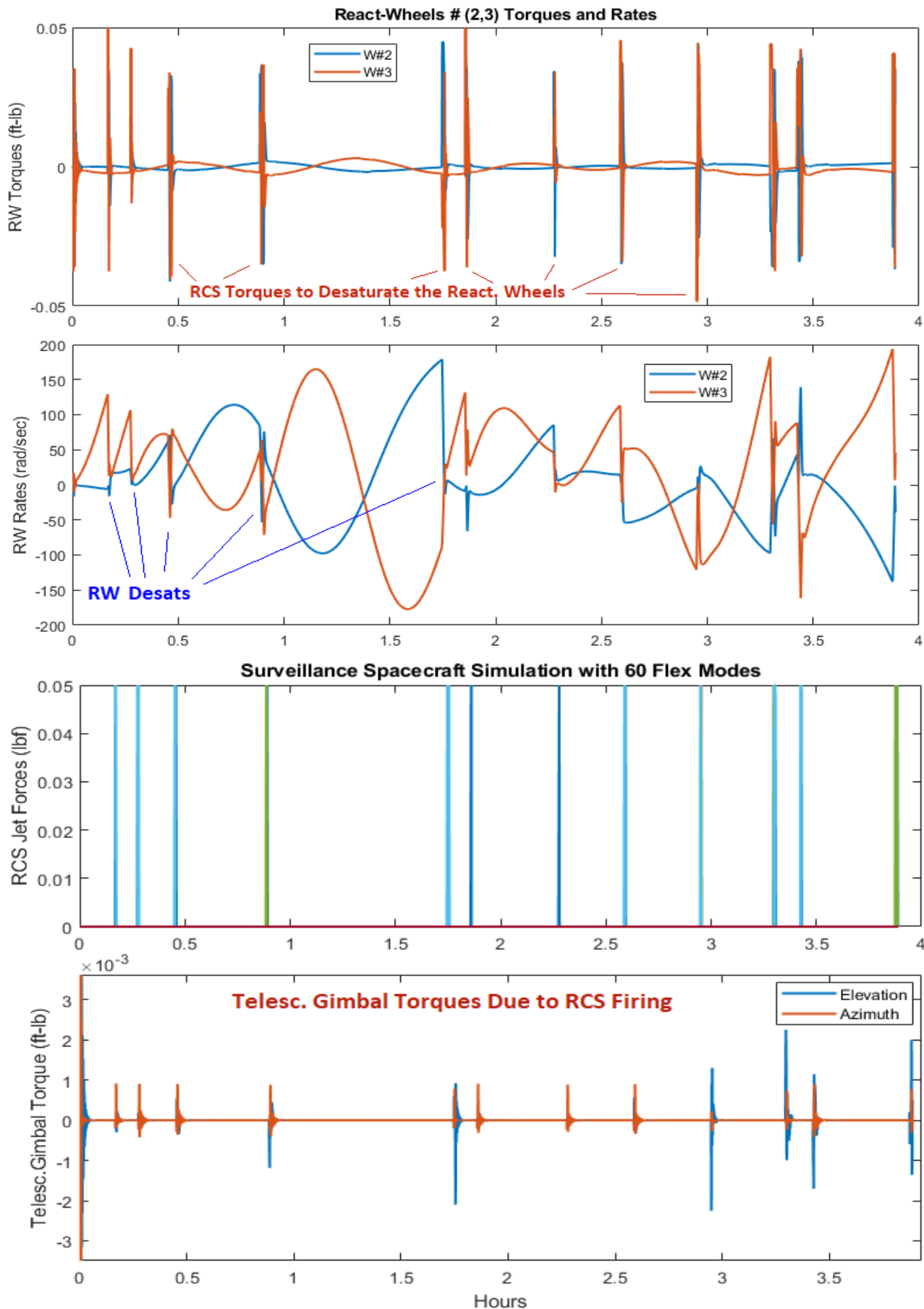


Figure 7.8 During RCS Attitude Control, Max RW Torque is Applied in the Direction to Minimize RW Momentum

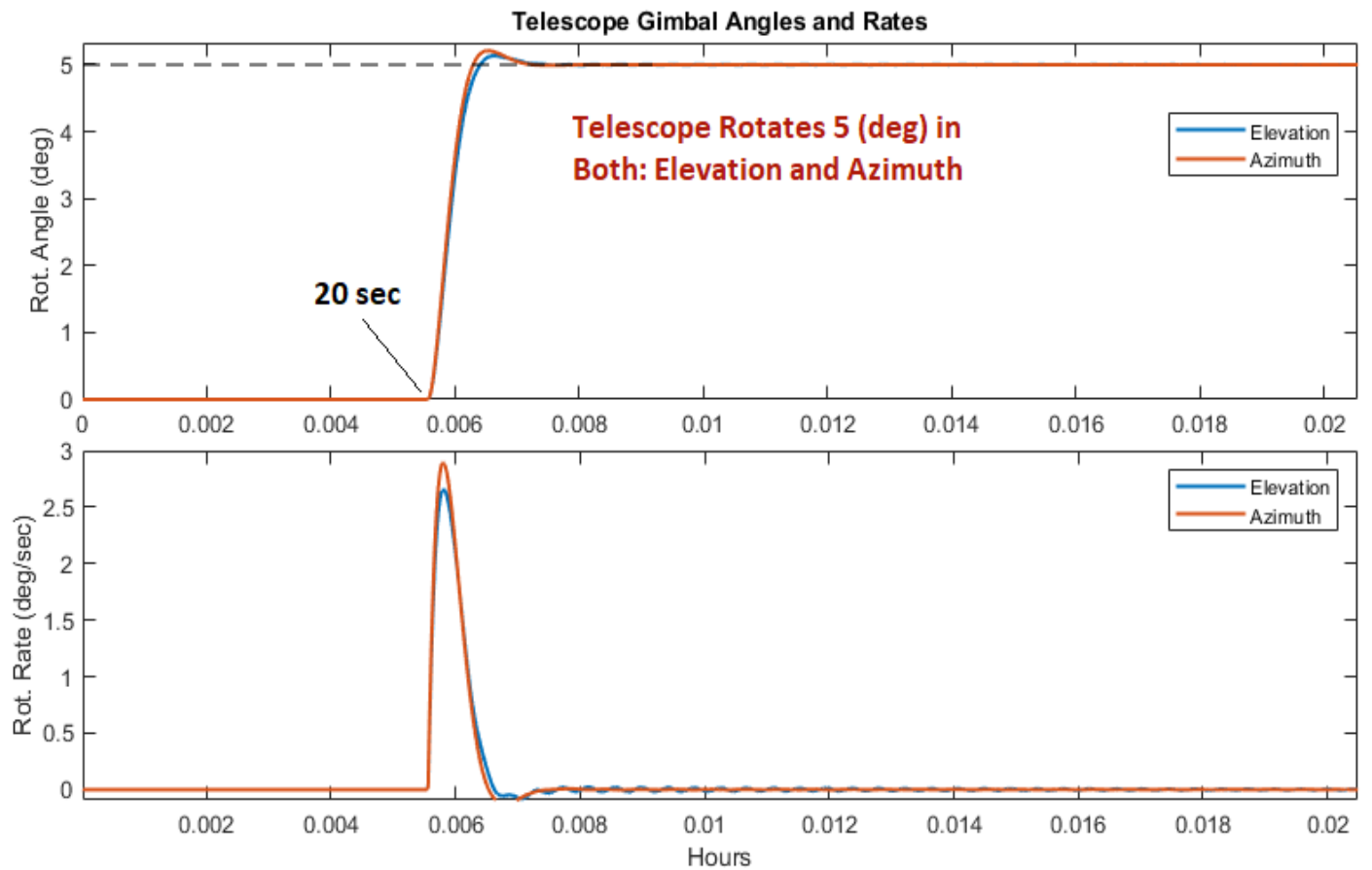
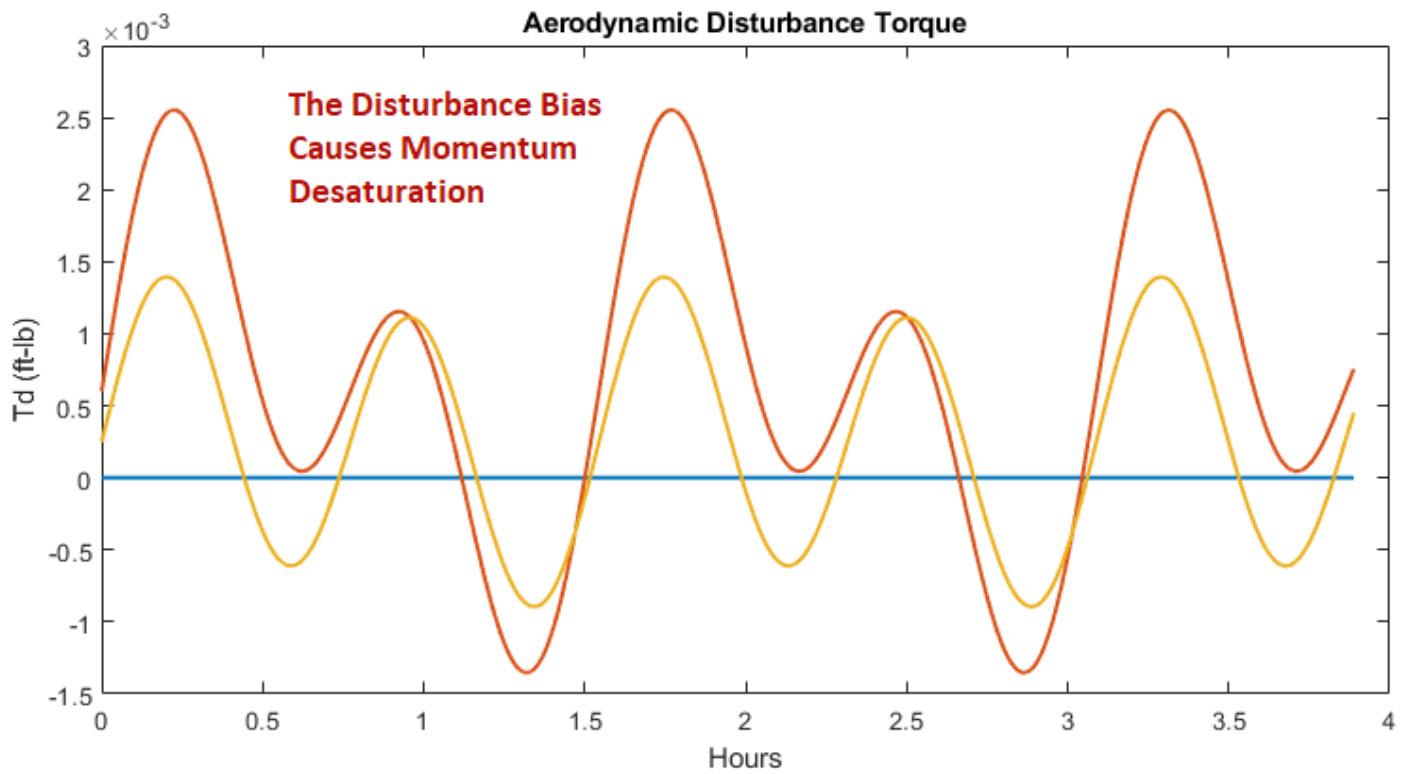


Figure 7.9 Telescope Gimbal Responses to a Simultaneous 5 (deg) Command in both Elevation and Azimuth.

7.4 Stability Analysis

The Simulink model “*Open_Anal_Flx.Slx*” is used for RW attitude control stability analysis in the frequency domain, shown in Figure 7.10. The RCS control loop is not included. Only the RW control system stability will be analyzed in the in-plane, and out-of-plane directions. The vehicle model is the same as the one used in Figure 7.5. The telescope pointing loop is closed. In the configuration shown below is for out-of-plane stability analysis, the lateral loop is opened and the pitch loop is closed. For in-plane analysis the model should be modified by closing the lateral loop and opening the pitch loop. The frequency responses are calculated by running the Matlab file “*Lin_Ana_Flx.m*”. There is also a similar model “*Open_Anal_GRB.Slx*” used for rigid-body stability analysis. It uses the rigid-body system in file “*fv_rb.m*” and a similar file “*Lin_Ana_GRB.m*” for calculating the rigid-body frequency response plots.

Open-Loop React. Wheel Linear Analysis with Flex

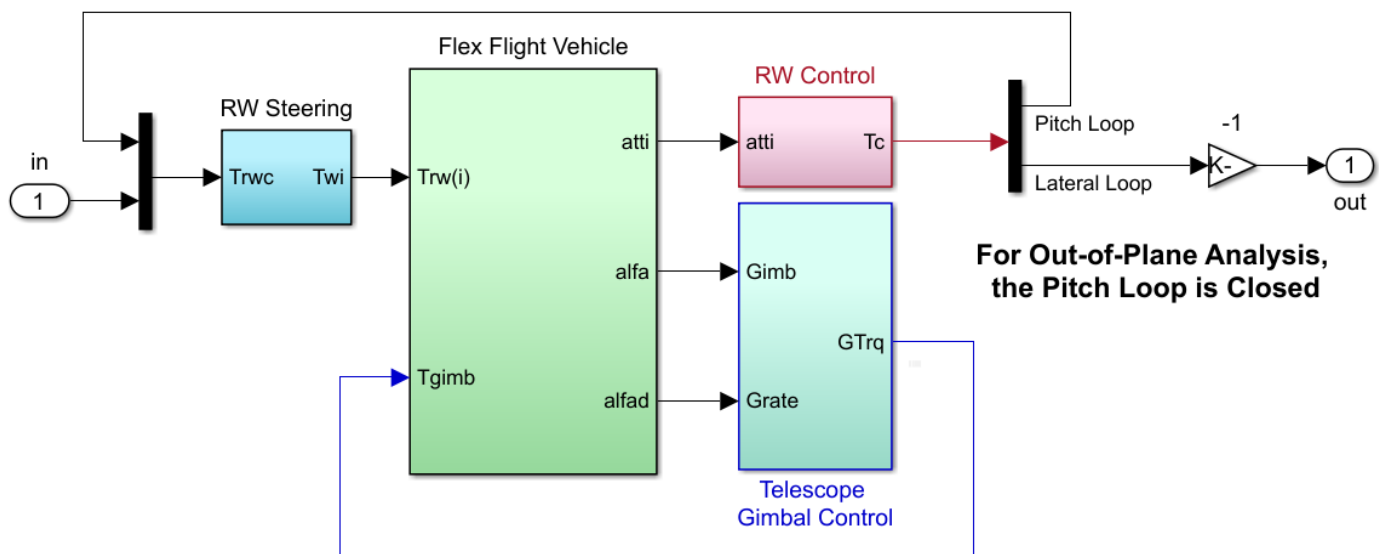


Figure 7.10 Simulink Model “*Open_Anal_Flx.Slx*” for Linear ACS Stability Analysis with Flexibility

Figure 7.11 shows the open-loop frequency response and Nichols plot for the pitch axis. It looks very similar to previous results shown in figures (4.11 and 5.9). There is more phase lag at high frequencies because of an additional (z^{-1}) sample delay included in the loop. All modes are gain stable and there is a big mode at orbital rate because the dynamics are with respect to the LVLH frame. Similarly, Figure 7.12 shows the open-loop frequency response and Nichols plot for the lateral axis and it is similar to previous results in figures (4.13 and 5.8).

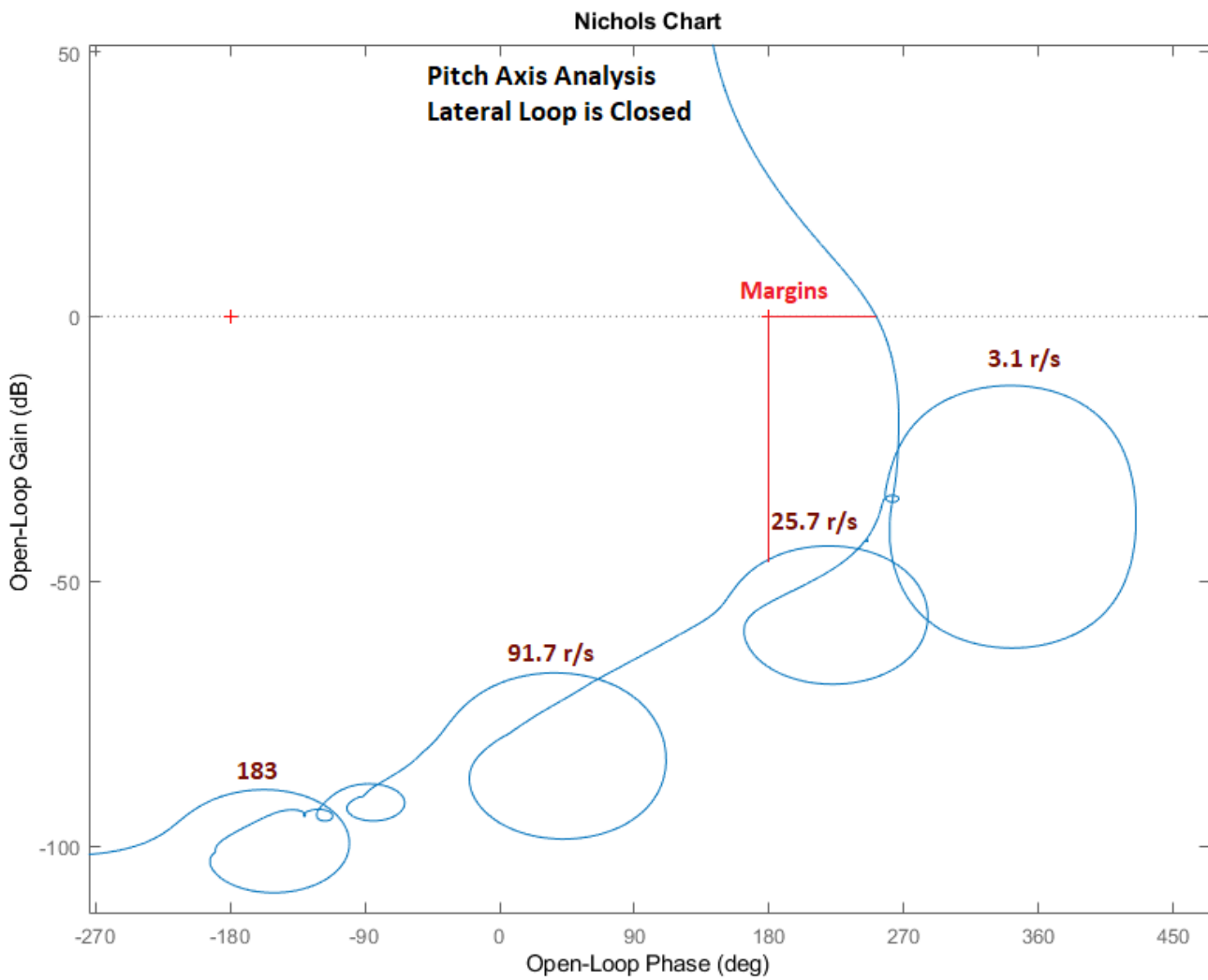
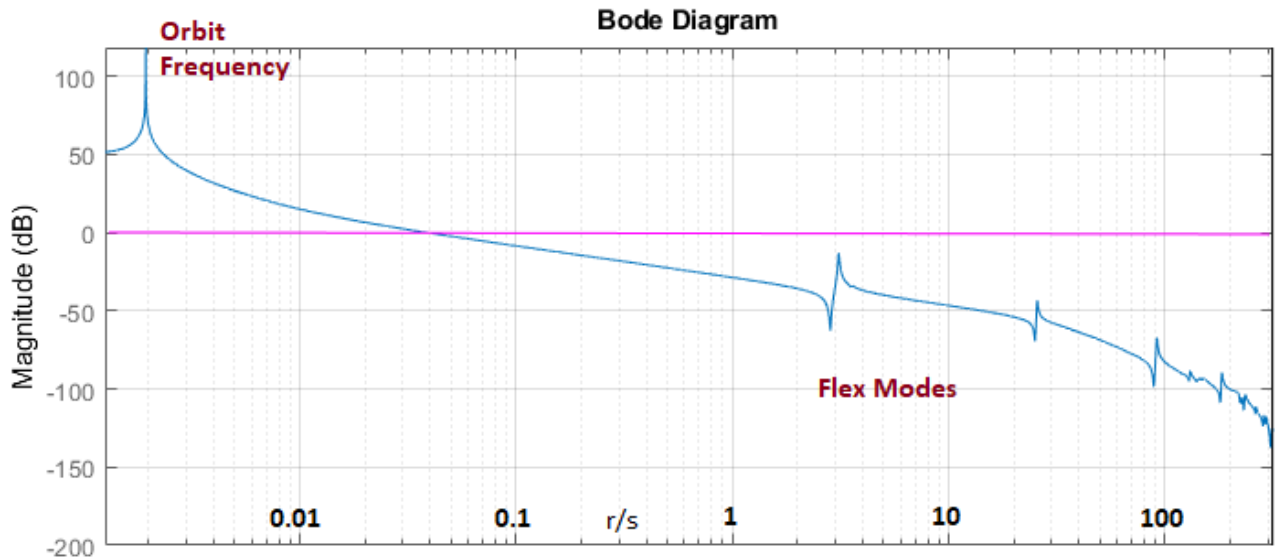


Figure 7.11 Stability Analysis of the Pitch loop with the Lateral Loop Closed

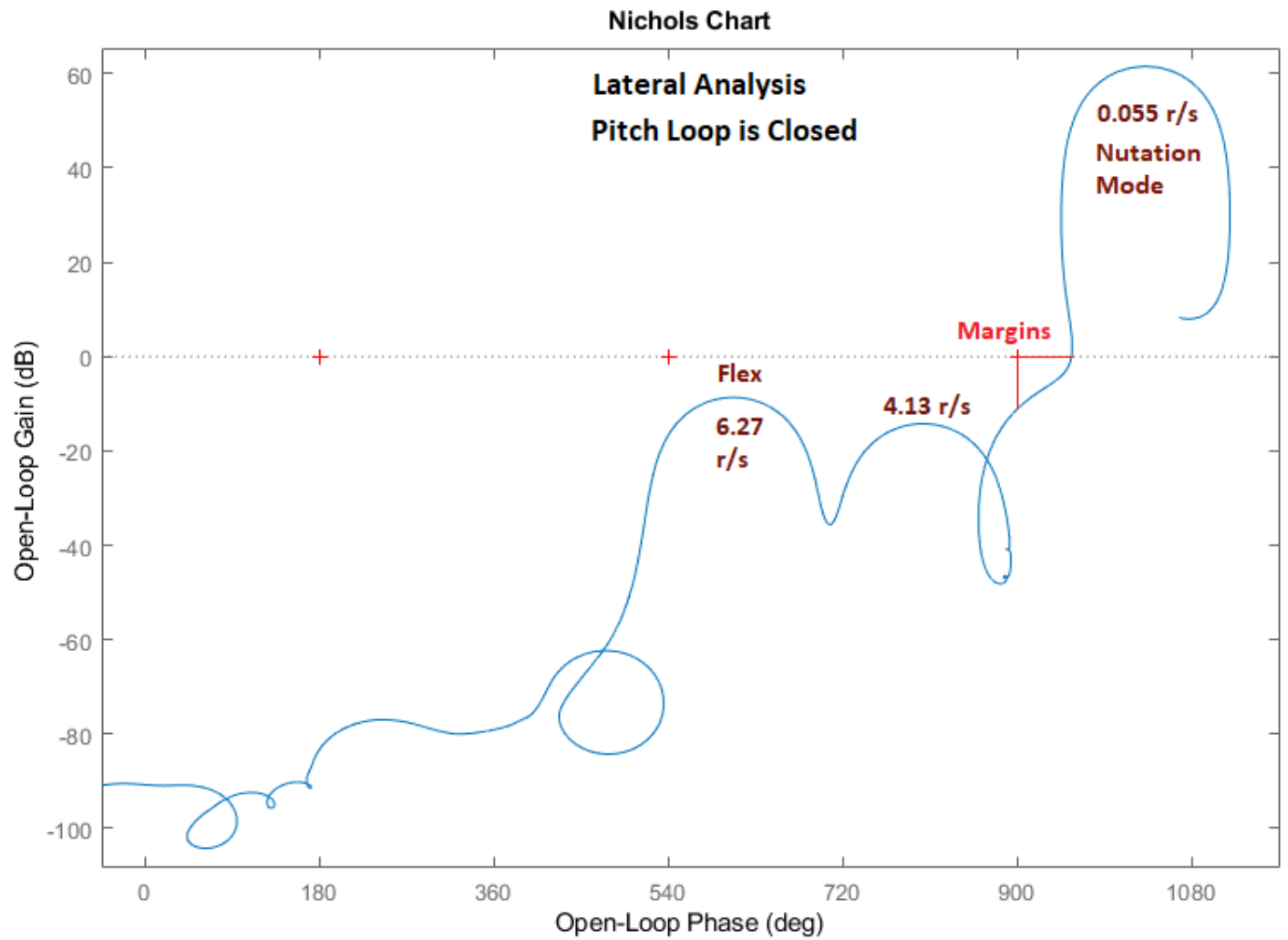
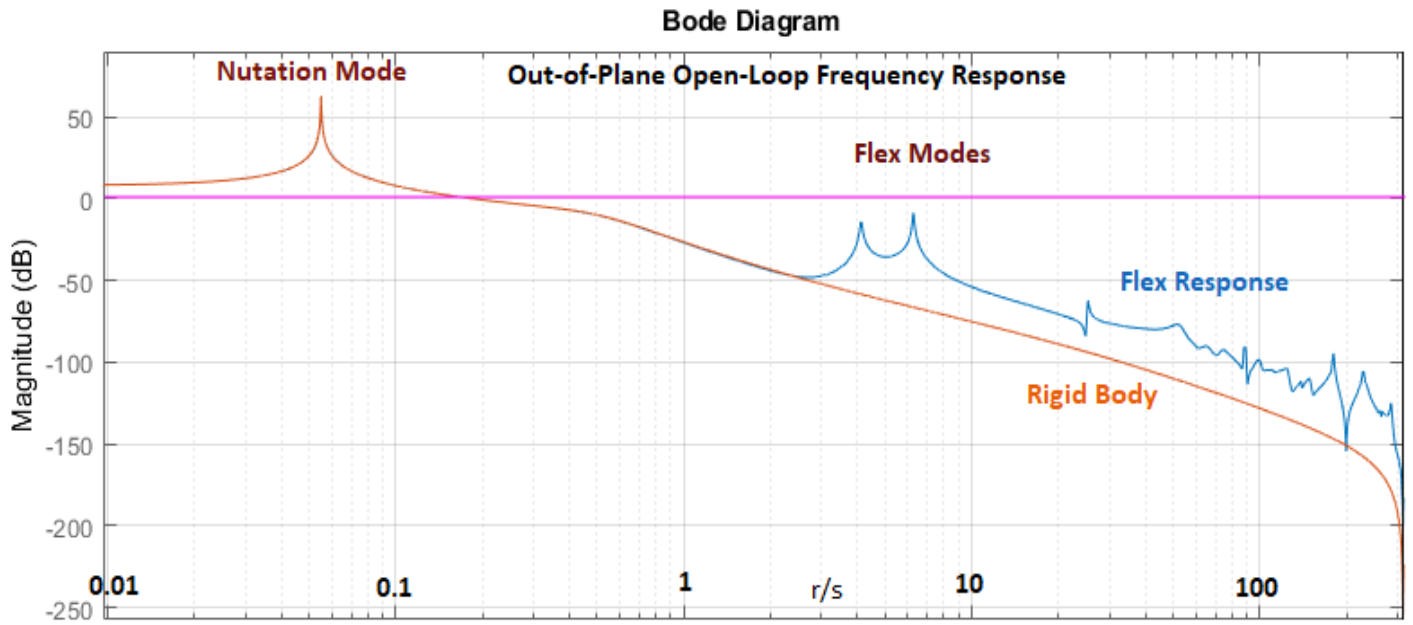


Figure 7.12 Stability Analysis of the Lateral Loop with the Pitch Loop Closed

Open-Loop React. Wheel Linear Analysis with Flex

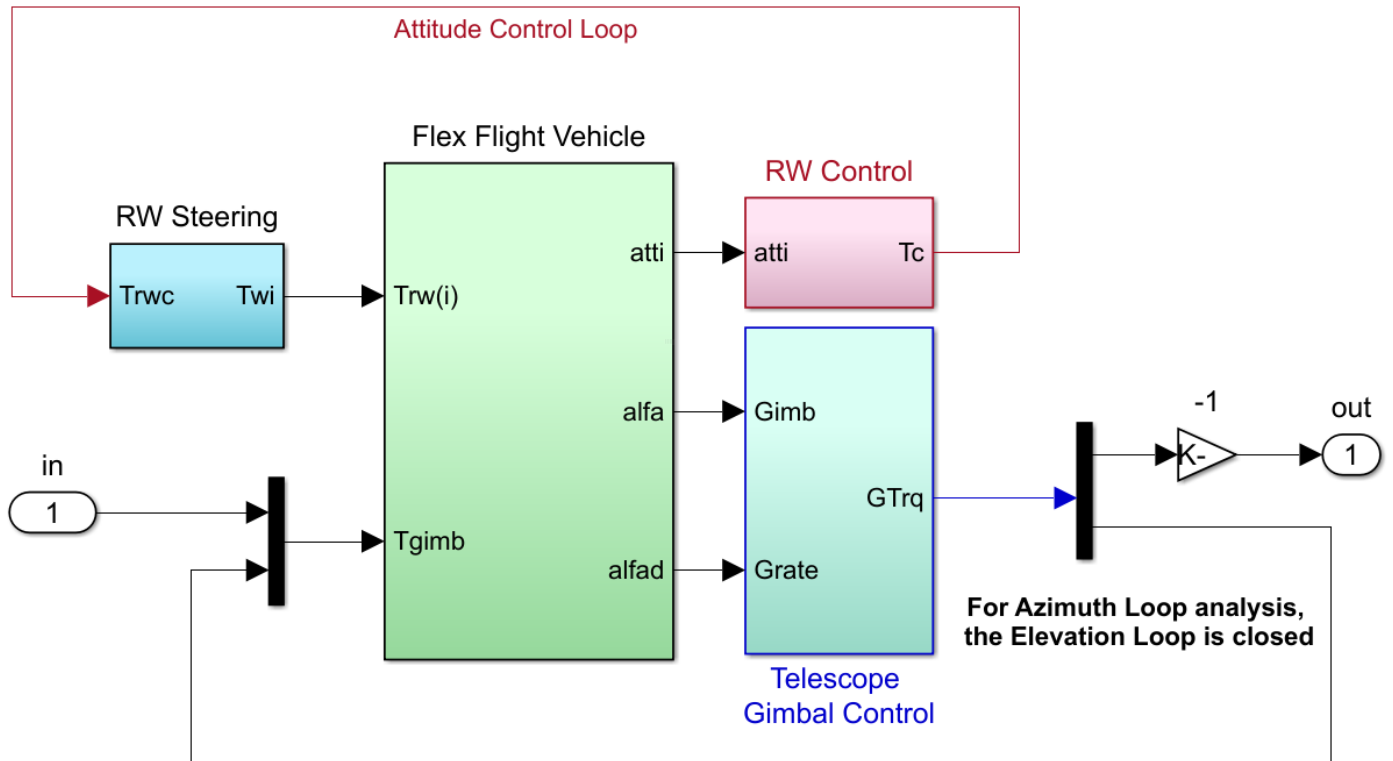
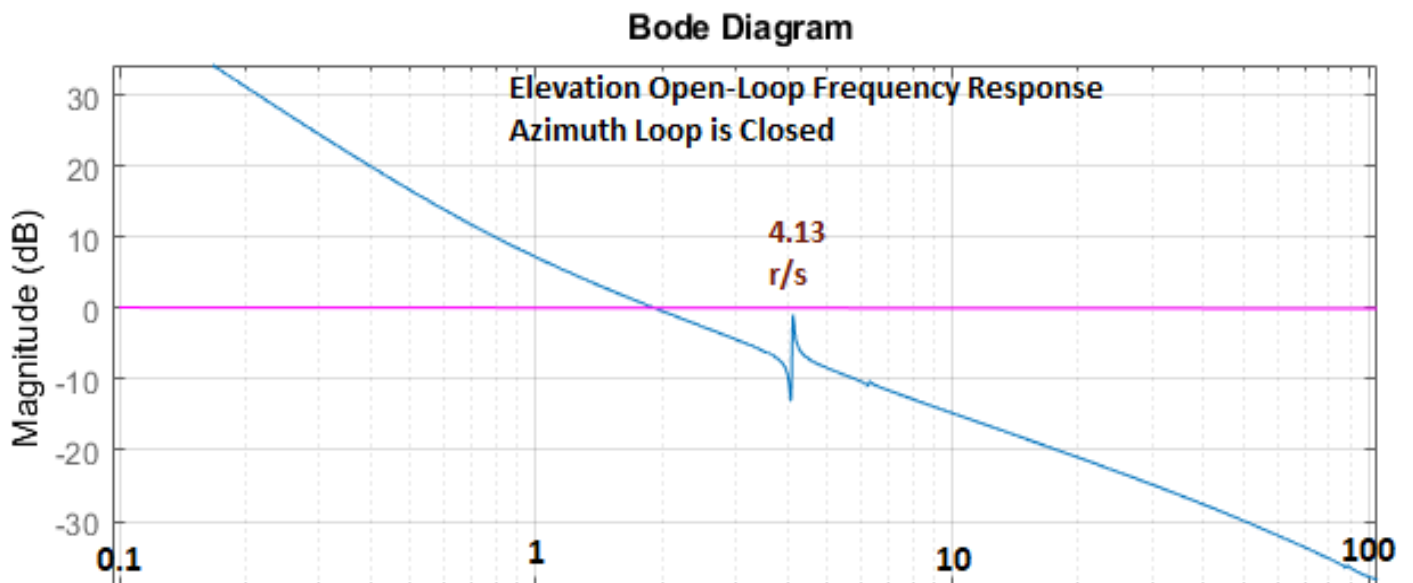


Figure 7.13 Simulink Model "Open_Anal_Gimb.Slx" for Telescope Gimbal Stability Analysis

The stability of telescope gimbals is obtained by closing the attitude control loop and opening the gimbal loop, one axis at a time, as shown in the Simulink model "Open-Anal-Gimb.Slx". When analyzing azimuth stability, the azimuth loop is opened and the elevation loop is closed, as shown in Figure 7.13. The stability margins of the azimuth and elevation loops are shown in Figures 7.14. Both gimbal loops have a bandwidth of approximately 2 (rad/sec).



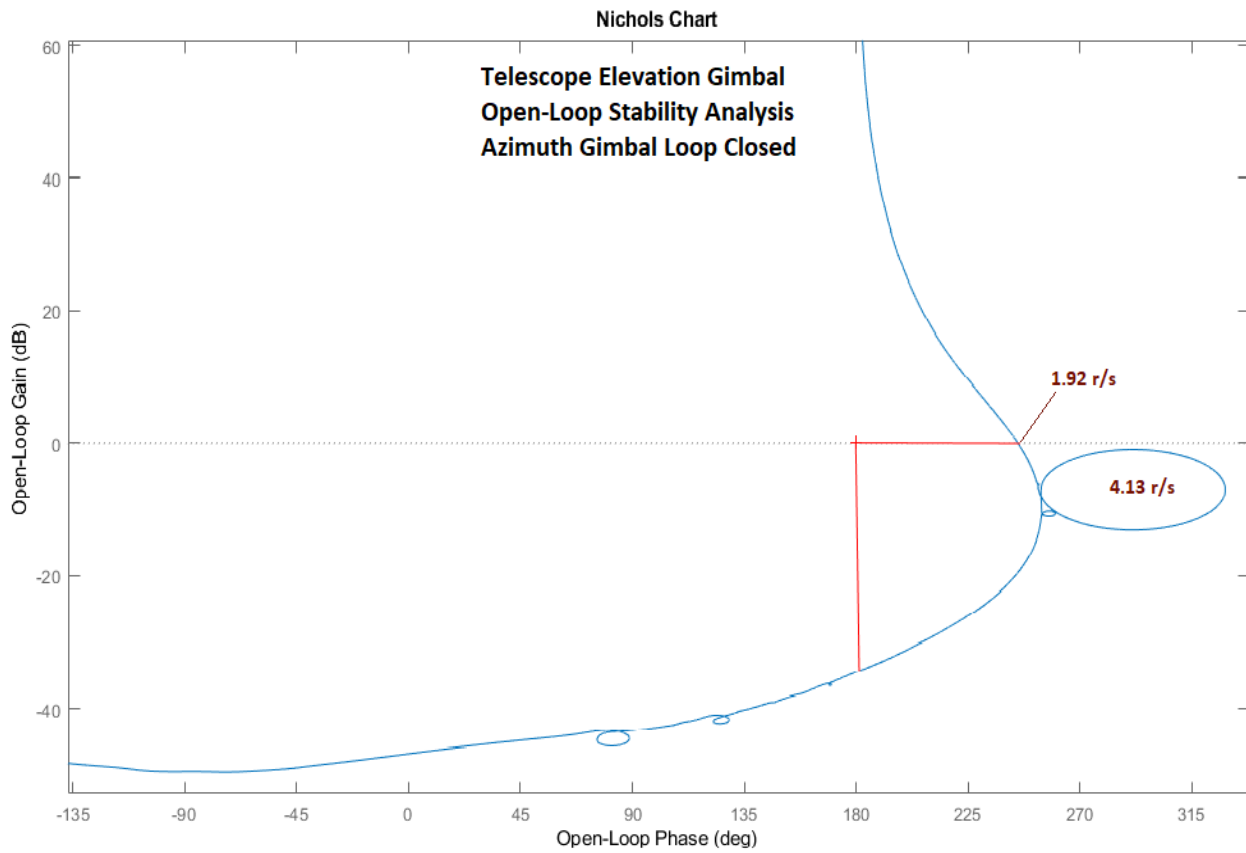
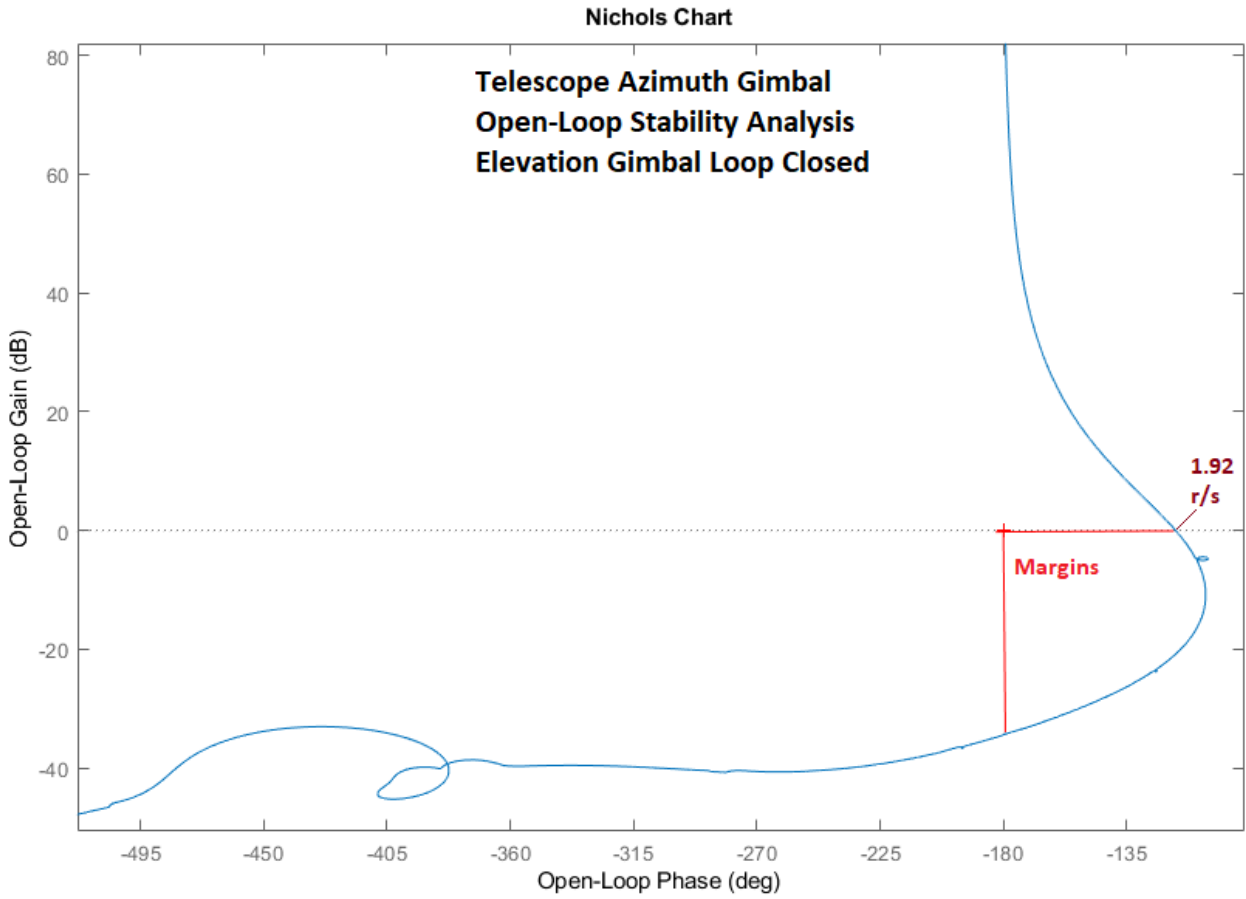


Figure 7.14 Telescope Gimbal Azimuth and Elevation Loops Stability Margins

7.5 Sensitivity to Solar Array and Cryo-Cooler Motor Disturbances

The two solar arrays rotate about the spacecraft y axis and they perform a full 360° rotation relative to the spacecraft for every orbit. The rate of rotation is 0.00113 (rad/sec). The rotation is controlled by stepper-motors at each solar array joint which generate a train of torque pulses that rotate the arrays at this average rate. The frequency of the pulses is 2 Hz and they consist of a 0.08 (ft-lb) positive pulse followed by an opposite negative pulse. These pulses generate disturbances on the spacecraft that produce jitter on the telescope Line-of-Sight (LOS). The following analysis uses a simulation to model the stepper motor torque pulses, apply them differentially at the joints of the two solar arrays, and observe the LOS jitter sensitivity effects at the telescope azimuth and elevation gimbals. The sensitivity analysis Simulation model in this case is “*Sensitivity-Sim.Slx*”, shown in figure 7.15. It has both attitude control and gimbal control loops closed. It is excited by the Solar Array stepper motor pulses and also by the cryo-cooler pump disturbance.

Jitter Sensitivity Analysis Model

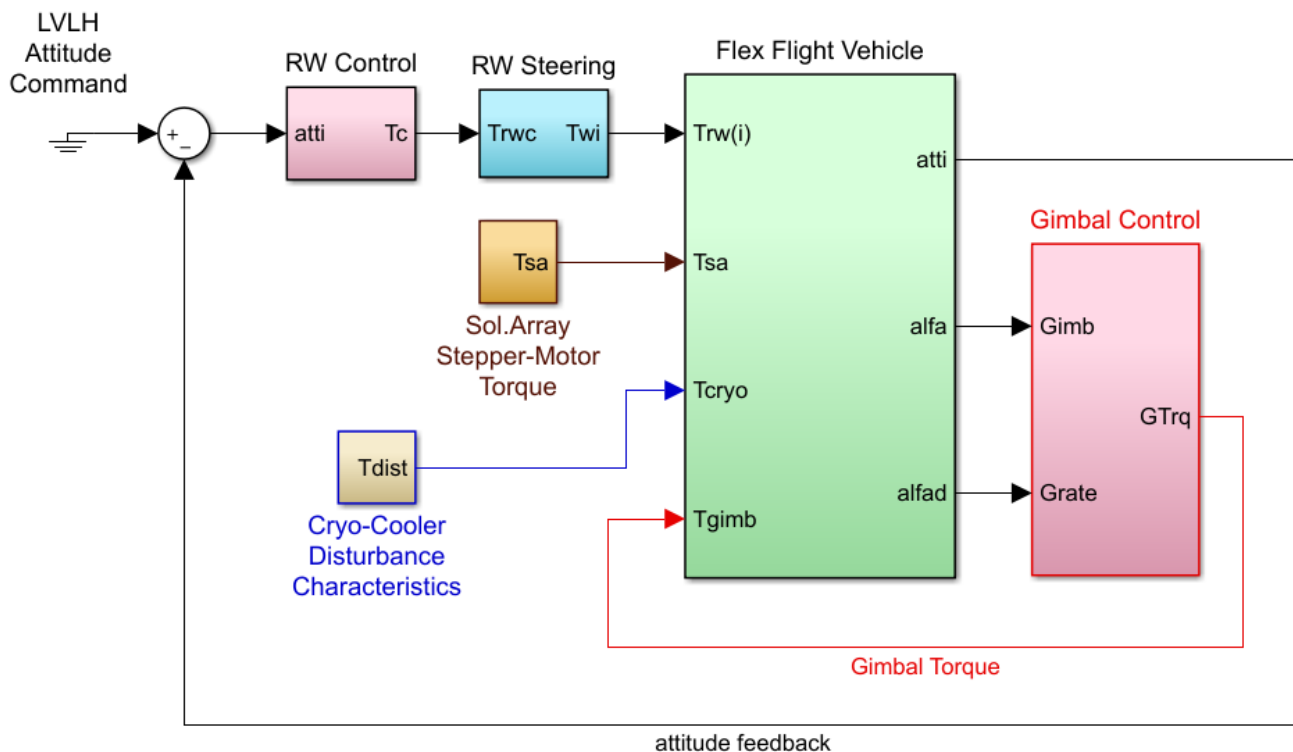


Figure 7.15 Jitter Sensitivity Analysis Model “*Sensitivity_Sim.Slx*”

In the first analysis we will apply only the stepper motor disturbance torque and disconnect the cryo-cooler. Figure 7.16 shows the disturbance effect on the telescope jitter. It plots the gimbal rates versus angle in both: elevation (blue) and azimuth (orange). The azimuth rotation is affected more than the elevation. Figure 7.17 shows the solar array rotation and rate. The average rate is equal to the orbital rate, 0.00113 (rad/sec) but it oscillates because of the stepper motor pulses. Figure 7.18 shows the stepper motor effect on the spacecraft rate which is zero average because the ACS is closed. Figure 7.19 shows the SA effect on the reaction wheels (2 & 3) which converge to a negative rate since the SA rate is positive. Figure 7.20 shows the SA stepper-motor torque pulses and the telescope gimbal torques. The elevation torque is bigger because it carries a bigger load. The script file “*p1d.m*” plots the data.

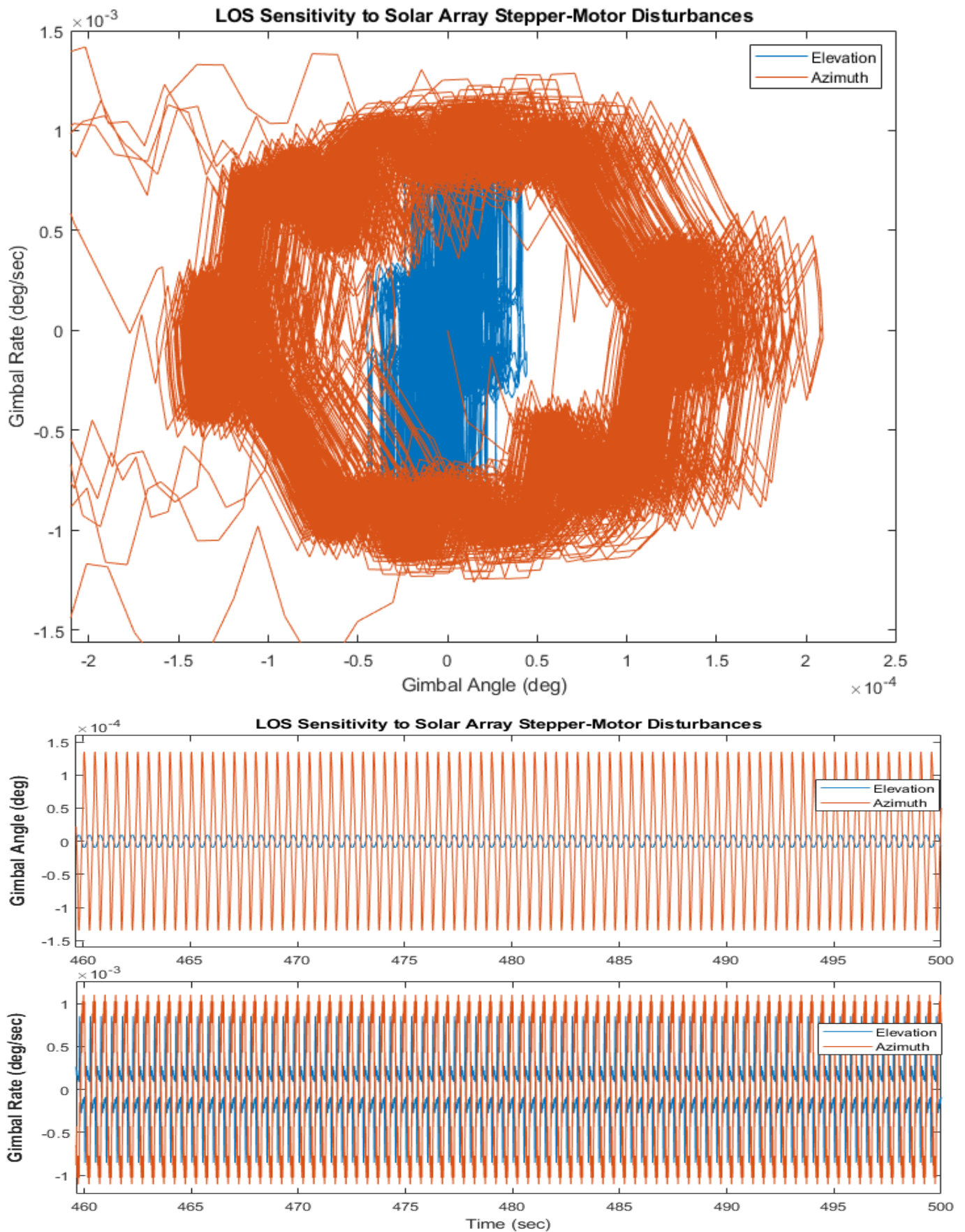


Figure 7.16 LOS Jitter on the Telescope Azimuth and Elevation Gimbals

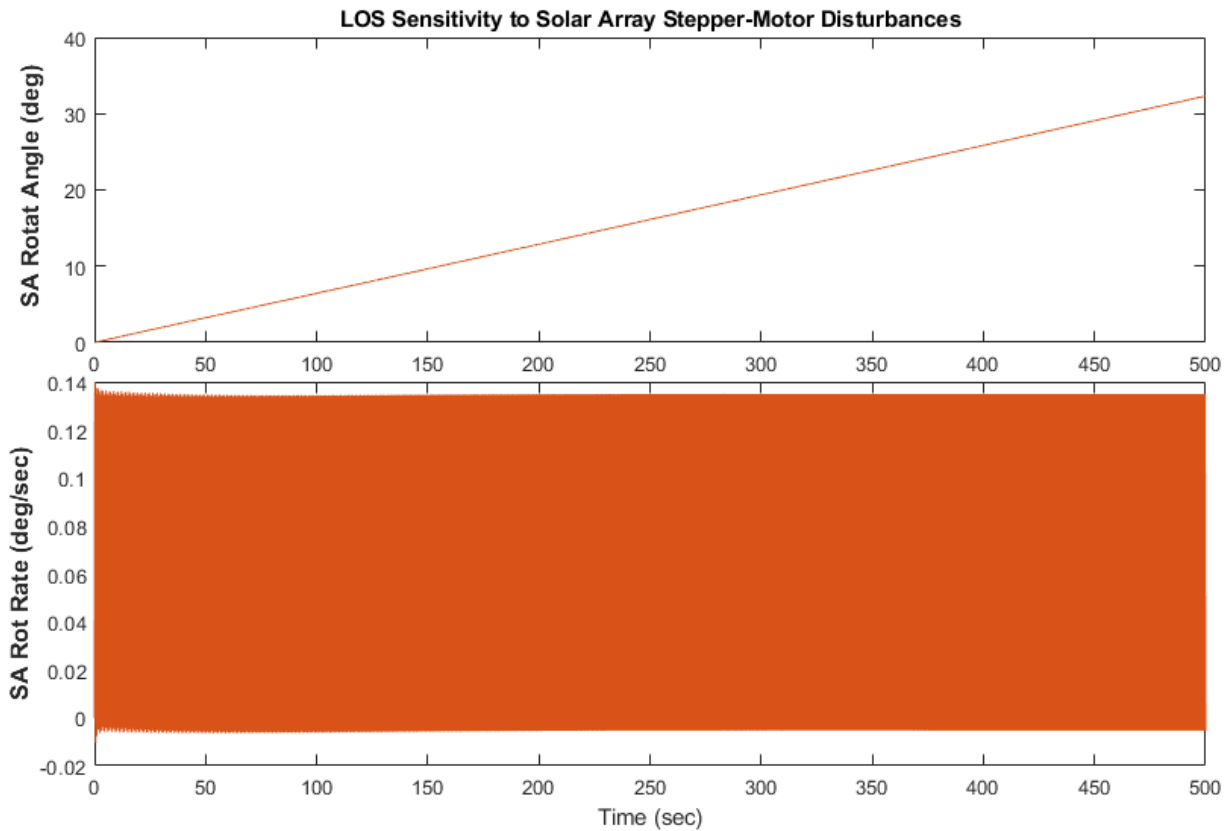


Figure 7.17 Solar Array rotation angle and rate which has an average rate equal to the orbital rate 0.064 (deg/sec)

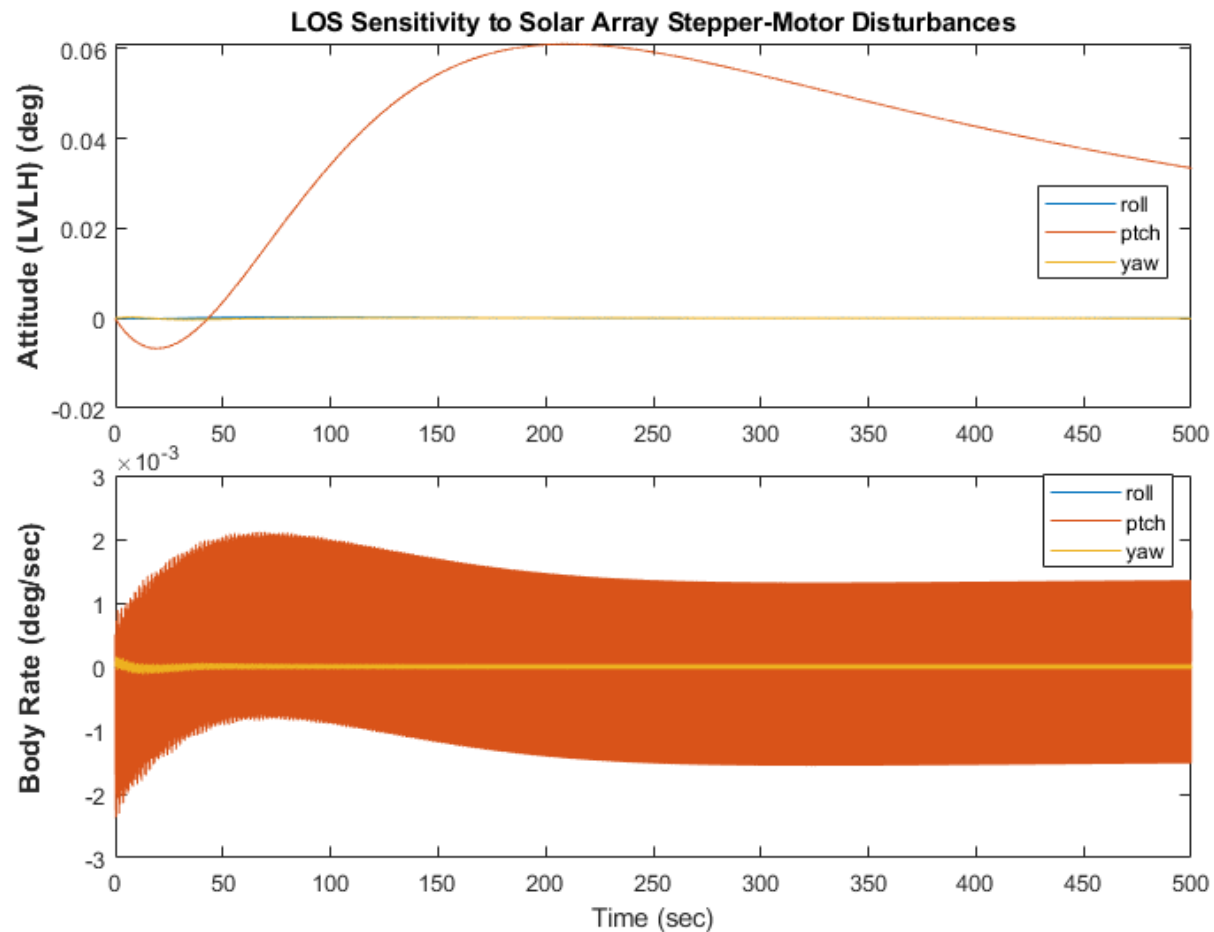


Figure 7.18 Spacecraft Attitude and Rate, shows the effect of the stepper motor on the spacecraft rate

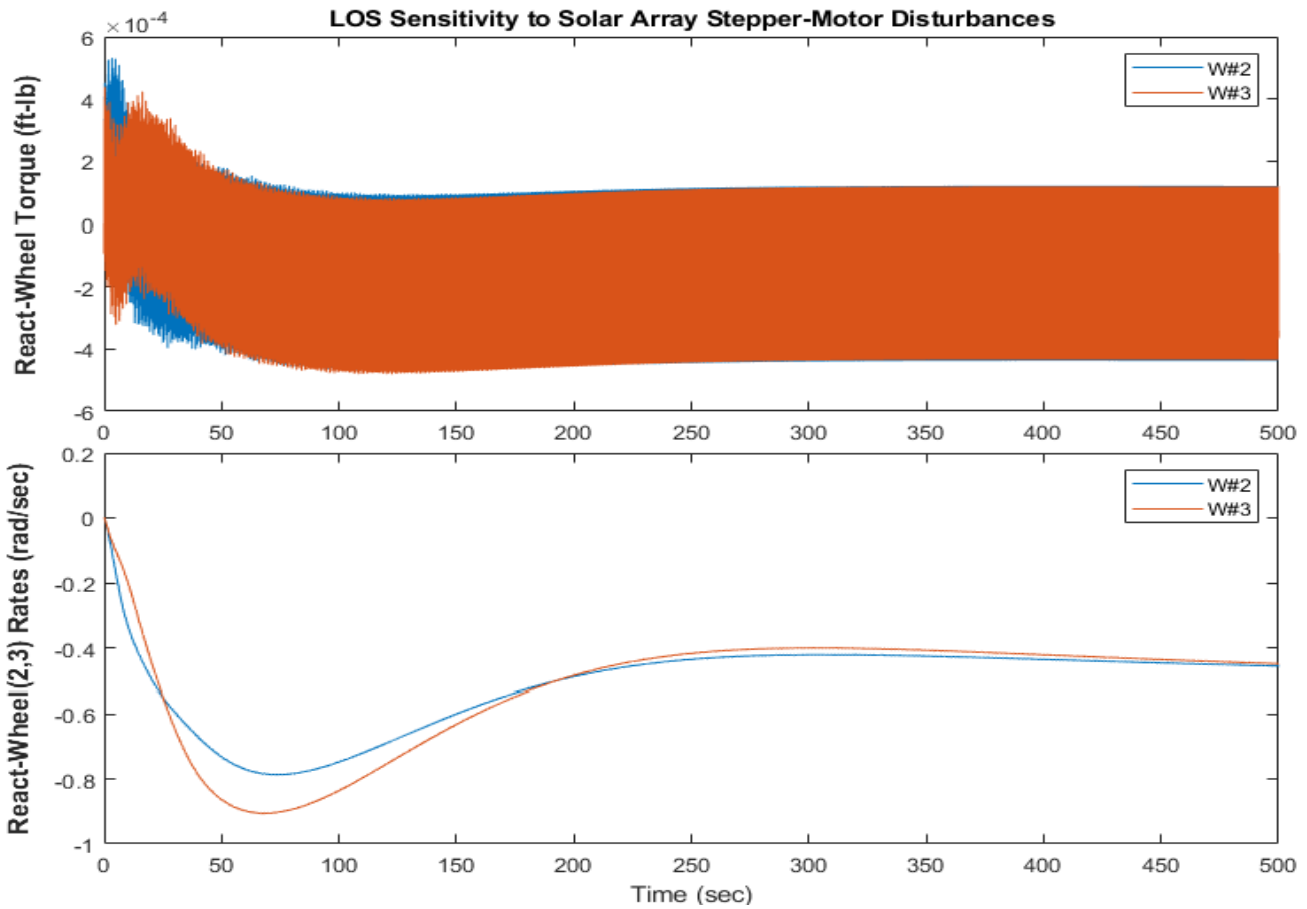


Figure 7.19 Reaction Wheel (2 & 3) Torques and Rates

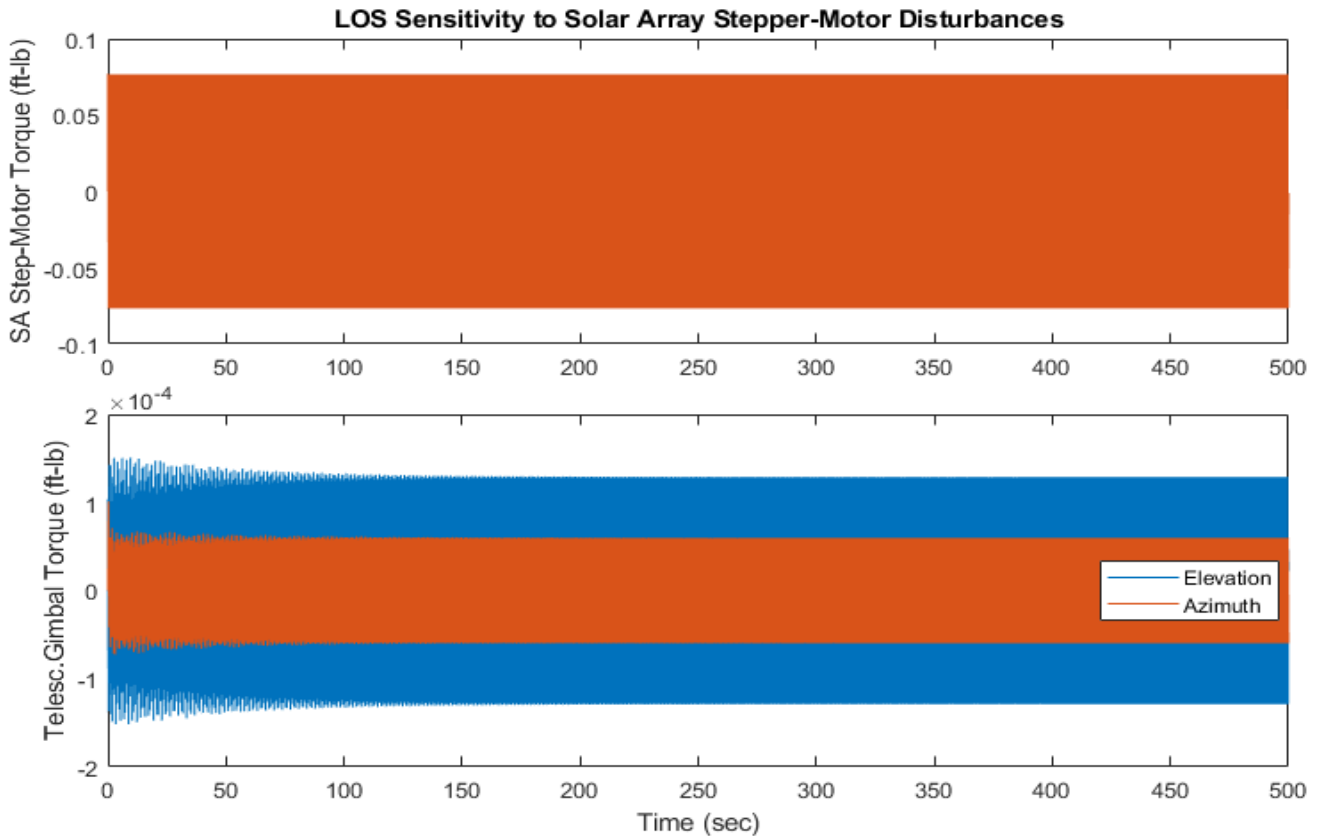


Figure 7.20 Open-Loop Stepper-Motor Torque at the Solar Arrays and Torques at the Telescope Gimbals

7.6 LOS Sensitivity to the Cryo-Cooler Disturbances

The cryo-cooler is a mechanical pump that circulates fluid around the spacecraft for heat exchanging purposes. It is another disturbance source that causes jitter on the telescope image and we must analyze its effect on the azimuth and elevation gimbals. The Simulink model “*Sensitivity_Sim.Slx*” in folder “*Examples\10-Surveillance Satellite React-Wheels\6-Linear Flex Anal FV*” in Figure 7.15 will be used again, this time we disconnect the Solar Array stepper-motor disturbance and connect the cryo-cooler source which is a white noise generator shaped by the frequency characteristics of the pump disturbance. This disturbance torque excites the spacecraft bus in all 3 directions by the same amount. Figure 7.21 shows the telescope gimbal rates versus LOS jitter angle, in elevation (blue) and azimuth (brown).

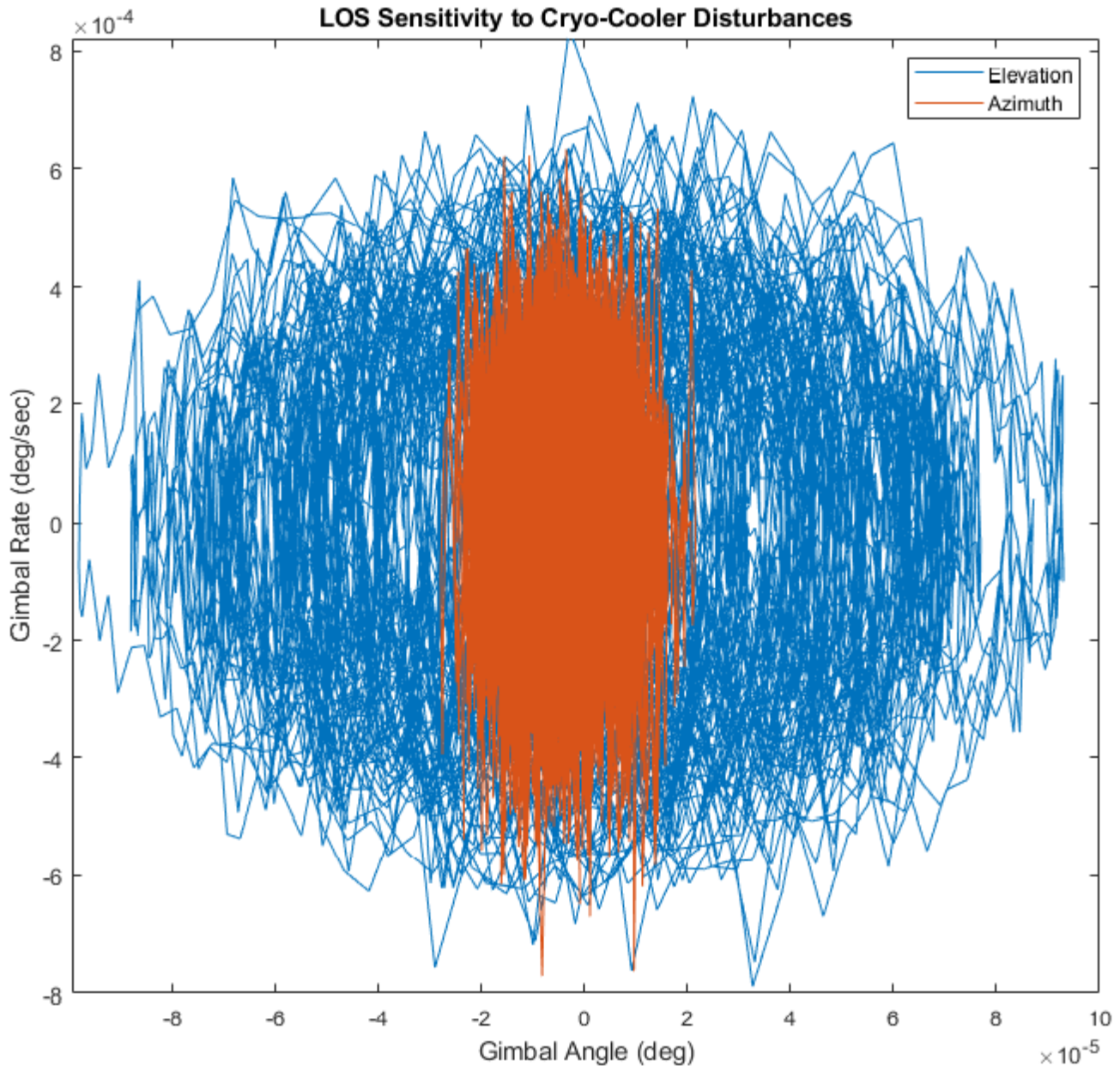


Figure 7.21 LOS Jitter on the Telescope Azimuth and Elevation Gimbals due to the Cryo-Cooler

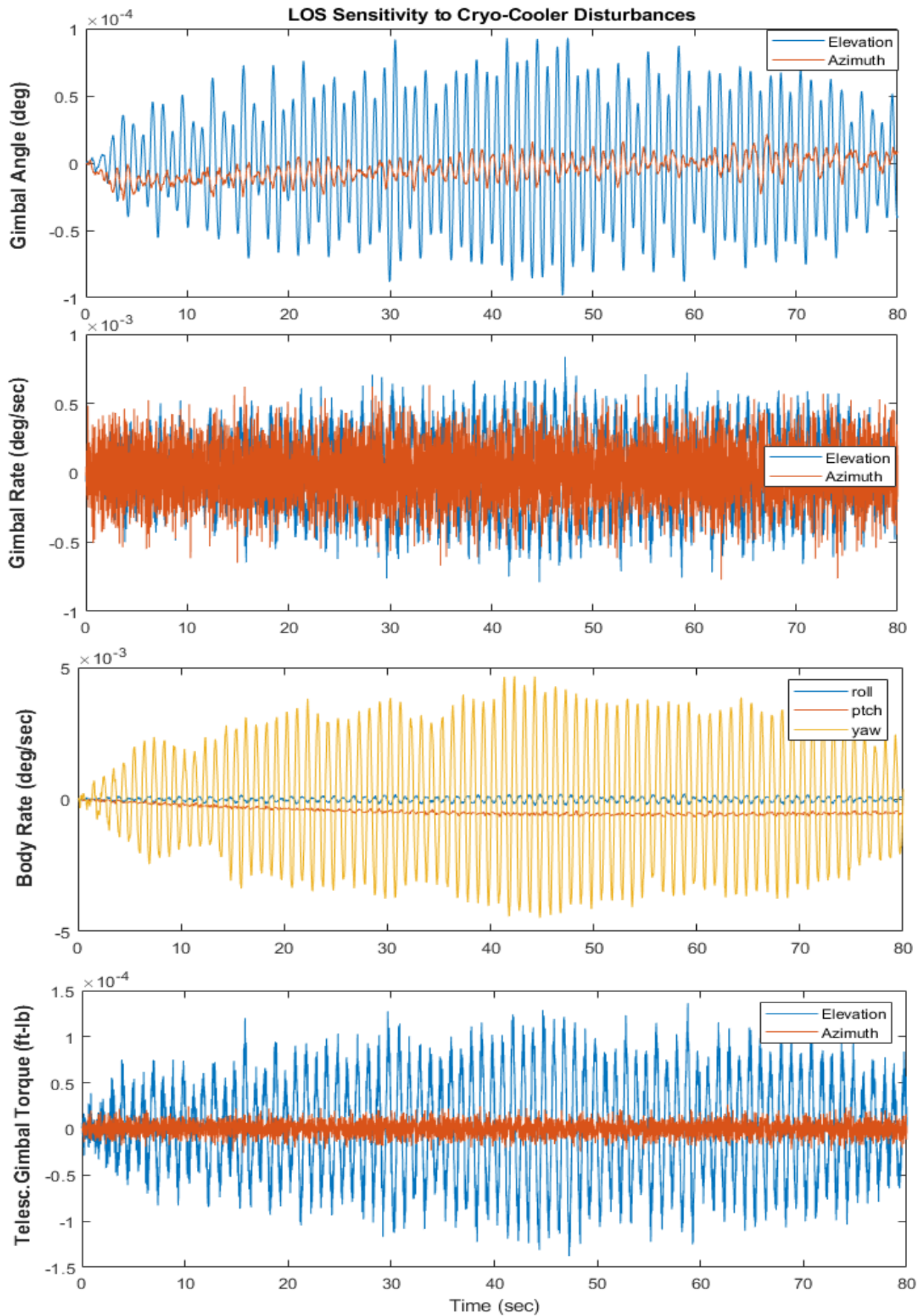


Figure 7.21 Effect of the Cryo-Cooler Disturbance on Spacecraft Rates and Gimbal Torques