

**Space Shuttle Ascent Example**

The dynamic modeling section will be illustrated with a Space Shuttle ascent analysis example where the flight control system stability and performance will be analyzed. This is at 55 seconds after lift-off during first stage where the dynamic pressure is maximum. During stage-1 the Shuttle propulsion system consists of three Space Shuttle main engines, (SSME) and two solid rocket boosters, (SRB). The vehicle attitude and its flight direction are controlled by gimbaling the five engines in pitch and yaw. The vehicle attitude, rate, and acceleration are measured by an IMU, rate gyros, and accelerometer sensors which are located at the top section of the SRBs. Roll attitude and rate are measured by sensors which are located in the orbiter vehicle. Inside the orange external tank (ET) there are two large tanks containing the liquid propellants consisting of: liquid oxygen (LOX) tank located in the front section, and liquid hydrogen (LH2) tank in the aft section of the ET. During Max-Q the tanks are partially filled and fuel sloshing is a potential problem. If not properly taken care it may destabilize the vehicle by creating oscillatory disturbance forces that would cause the TVC engines to limit-cycle and throw the vehicle off-course. The control surfaces are not used during ascent but they are scheduled open-loop to minimize loading on the aero-surface actuators. Structural flexibility generated by the gimbaling of the TVC nozzles is significant and it is included in the analysis. Aero-elasticity, however, is not significant during ascent and it is not included. The tail-wags-dog dynamic coupling, however, between the engine nozzles and the supporting flex structure is significant and it will be included. The pitch and lateral axes will be analyzed separately. The detailed analysis, data and files for this example are not included in this book, but they can be downloaded from Flixan.com/ Shuttle Ascent Example.

**Pitch Axis Analysis**

The pitch axis analysis begins by developing rigid body dynamic models, the flight control system (which is continuous to begin with), and include simple actuator models for the 2 SRBs and the 3 SSMEs. Tail-wags-dog and actuator load-torques are not included at this point, because our main purpose is to make sure that the vehicle is stabilizable and it achieves a reasonable performance. The performance, however, is not expected to be great at max-Q because the load-relief feedback from the normal accelerometer degrades the response to guidance commands for the purpose of reducing the normal structural loads. The performance in this flight condition is measured by the vehicle capability to respond to wind-gusts by turning towards the airflow and reducing the aerodynamic angles, rather than how well it performs to commands. The guidance commands are typically zero or very small during high-Q. Our analysis at this point is limited to checking out the vehicle stability margins by performing classical frequency response analysis using Bode and Nichols plots. The open-loop block diagram system shown in Figure 1 is used for the frequency response calculation having the loop opened at the TVC output which is also the actuators input. A common SSME actuator transfer-function block is used for the 3 SSMEs and a common SRB actuator is used for the two SRBs. The TVC gains, which are normally in the flight control system output, are shown between the actuators and the vehicle dynamics.

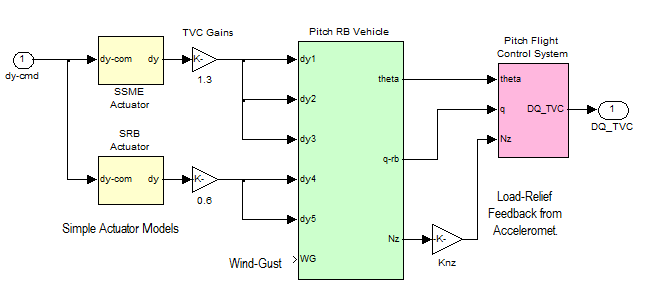
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Figure 1 Simple Block Diagram used for Open-Loop Frequency Response Analysis

**Pitch Flight Control System**

Figure 2 shows a simplified version of the Space Shuttle pitch flight control system during ascent. The inputs are: vehicle pitch attitude error () in (radians), pitch rate (q) in (rad/sec) coming from the SRB rate gyro, and normal acceleration (Nz) in (ft/sec2). The output DQ\_TVC is the command that drives the pitch actuators via the TVC. The gains are designed for this Max-Q flight condition and the load-relief gain is at its max level in order to enhance the load relief function. Flexibility filters are included which attenuate vibrations from the sensor signals. Notice that there is rate gyro cross-feed into the accelerometer feedback. This is because the accelerometer is not located at the vehicle CG and it is picking up rotational components instead of only normal acceleration. The compensated rate-gyro signal from the SRB takes out the rotational component from the accelerometer signal and helps the function of the load-relief.

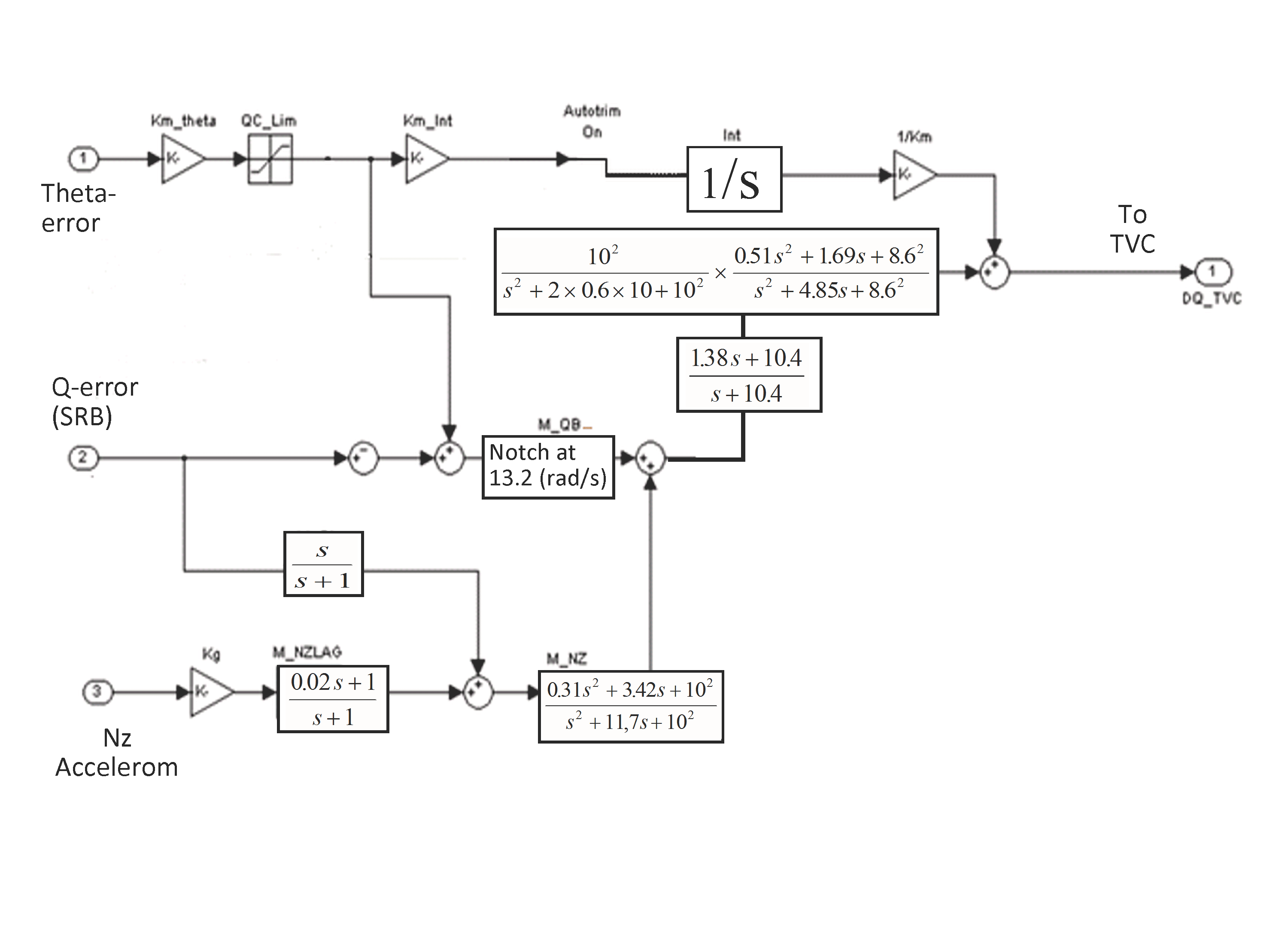


Figure 2 Flight Control System of the Space Shuttle during Max Dynamic Pressure

**Including the TWD Dynamics**

Having achieved an acceptable stability using the rigid-body model, our next step is to upgrade the vehicle and actuator models by including gimbal accelerations that will excite the TWD dynamics. We will also include the load-torque feedback that is a mechanical feedback loop from the gimbals to the actuator load-torque inputs. This is a gimbal torque generated by the swiveling of the nozzles that is reacting against the control torques provided by the actuators. The frequency response analysis is repeated using an upgraded open-loop Simulink model, shown in Figure 3. The new model uses upgraded actuator models to include load-torque inputs and gimbal acceleration outputs, as it is described in Chapter 4. The vehicle dynamics model is also upgraded to include gimbal acceleration inputs, in addition to gimbal positions, that connect to the actuator outputs. The vehicle block outputs now include load-torques at the 5 TVC gimbals that close the load-torque feedback loops with the actuators, as shown in Figure 3.

This model is used to calculate the TWD frequency, shown in Figure 5. The TWD frequency is defined to be the frequency at which the normal thrust components of force at the gimbal are cancelled by the inertial reaction components. When the engine oscillates at that frequency the magnitude of the engine inertia reaction force is equal and opposite to the magnitude of the lateral component of thrust and the engine inertia force at the hinge cancels the lateral component of thrust. This TWD phenomenon introduces a complex pair of zeros in the transfer function “θ(s)/δ(s)”, which also causes a 180° phase reversal occurring at frequencies greater than the TWD frequency.

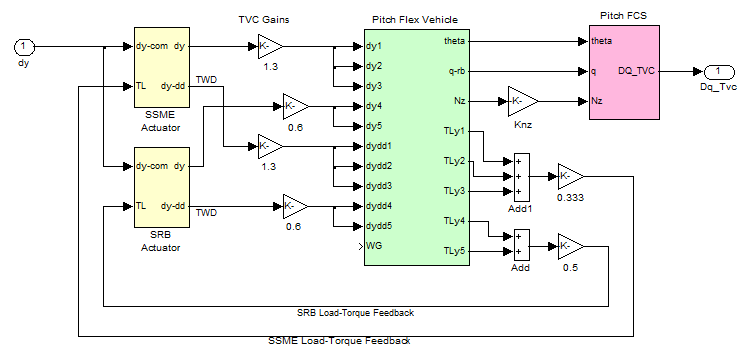
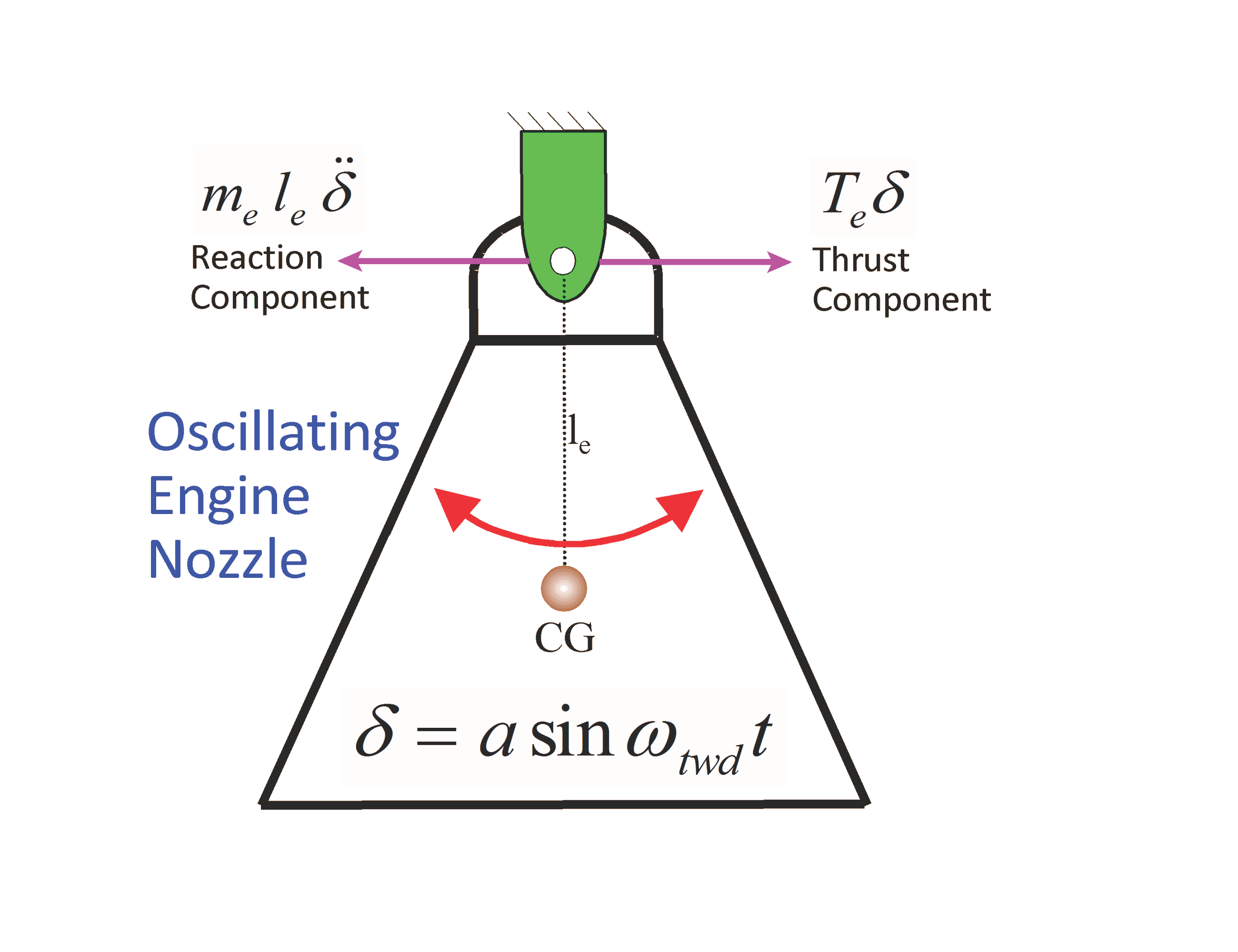


Figure 3 Analysis Model that includes Tail-Wags-Dog and Load-Torque Feedback, used to calculate the Pitch System Frequency Response

****Below this so called "tail-wags-dog" (TWD) frequency, the resultant lateral force at the gimbal is predominantly due to thrust being in-phase with the gimbal angle. That is, an increase in gimbal angle results in an increase in lateral force. Above this frequency, the engine inertia forces produce the dominant lateral force which is in-phase with the gimbaling acceleration, or 180° out of phase with the gimbal angle. A system designed without the TWD consideration may perform unsatisfactorily above the TWD frequency.

In particular, some of the higher frequency flex modes may be driven into divergent oscillations by this phase reversal if adequate structural damping or filter attenuation is not present. The TWD frequency should, therefore, be higher than the control system bandwidth. Fortunately, the TWD phenomenon provides significant amount of attenuation at around the TWD frequency which helps attenuating the flex modes. For a typical launch vehicle it is calculated from Equation 1. In this example, using a combined engine thrust (Te =66 lb), a total engine mass (me=2200 slugs), and an average distance (le=3.1 feet) between the engine CG and its pivot point, which is assumed positive when the pivot is ahead of the engine center of mass, we obtain a TWD frequency equal to 29.6 (rad/sec).

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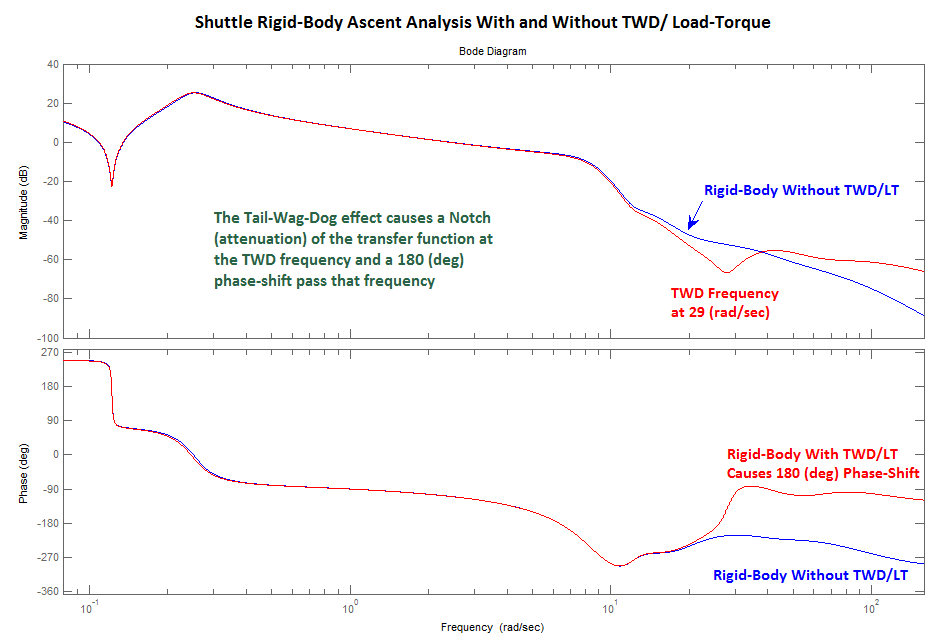


Figure 5 Frequency Response Analysis of the Open-Loop System with and without TWD and Load-Torque Feedback

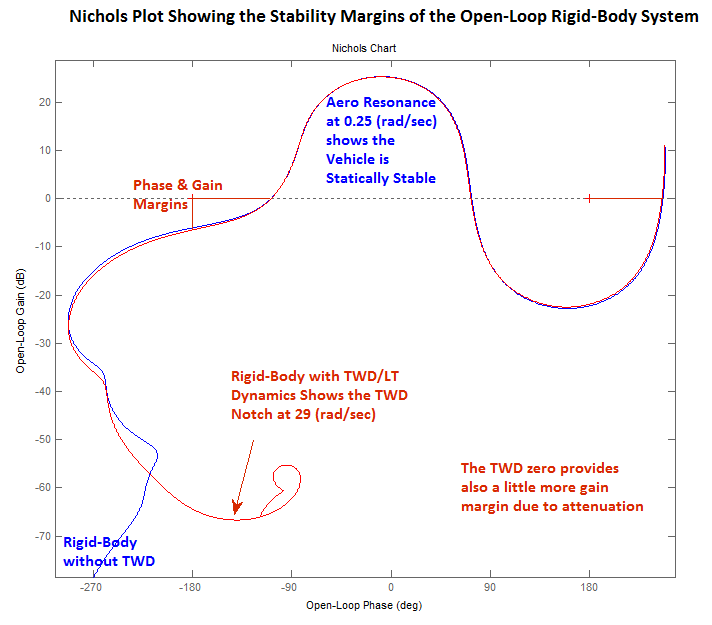
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Figure 6 Nichols Plot Showing the Phase and Gain Margins of the Rigid-Body Space Shuttle System with and without TWD and Load-Torque Feedback

**Adding Propellant Sloshing in the Analysis Model**

The next step is to include propellant sloshing for the liquid oxygen and the liquid hydrogen propellant tanks, as it was described in Section 2.6. Figure 7 shows a simplified diagram of the Space Shuttle vehicle with the SSME and SRB thrust vectoring engines and the two sloshing tanks. The oscillating slosh masses represent the sloshing portion of the propellant. Notice that the slosh mass deflections and the liquid surfaces are not exactly perpendicular to the tank centerline. This is because the acceleration vector AT is not exactly aligned with the vehicle x axis. Figure 8 is the open-loop frequency response of the new system against the previous case that did not include slosh. It shows the TWD zero and the two slosh resonances. Notice that the LH2 resonance is smaller because the slosh mass is also smaller, plus the overall response is attenuated because of the additional slosh weight. Figure 9 is a Nichols plot that shows the phase and gain margins and the 3 resonances of the pitch axis open-loop system.

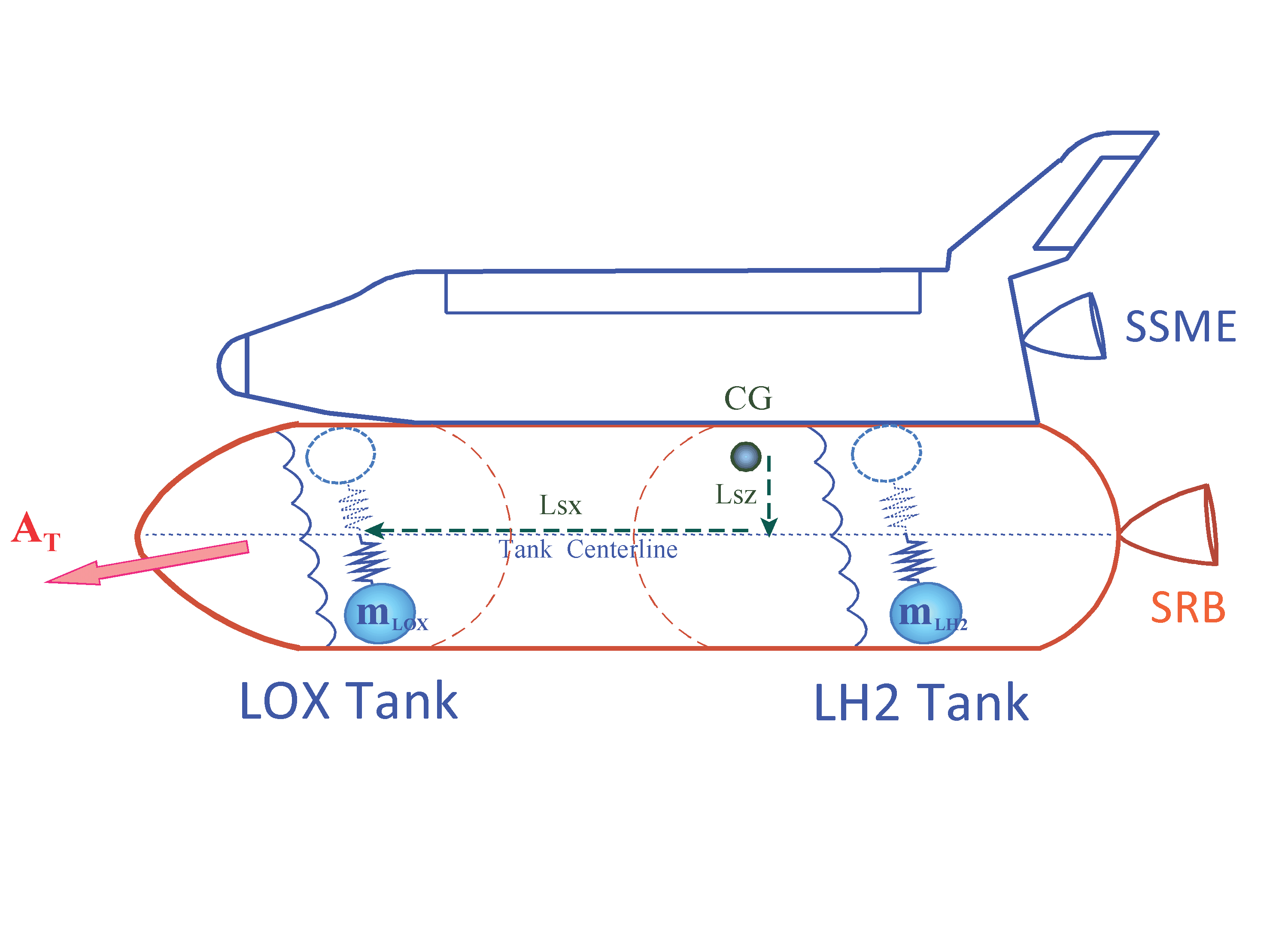


Figure 7 Simple Diagram of the Space Shuttle during First Stage showing the TVC Engines and Sloshing Tanks

**Adding Structural Flexibility**

The pitch axis stability analysis concludes by adding structural flexibility in the previous vehicle model and calculating the open-loop frequency response, as before. Several dominant pitch modes were selected from a finite-elements model that contains hundreds of flex modes, using a mode-selection process. Figure 10 shows the open-loop frequency response of the flex system against the previous case that did not include flexibility. The continuous flight control system was also replaced with a discrete FCS sampled at 40 msec. Figure 11 is a Nichols plot showing the resonances and the phase and gain margins. Notice that all flex modes are gain stabilized, that is, their peaks are below the 0 dB horizontal line. However, the LOX slosh resonance is only phase-stable.

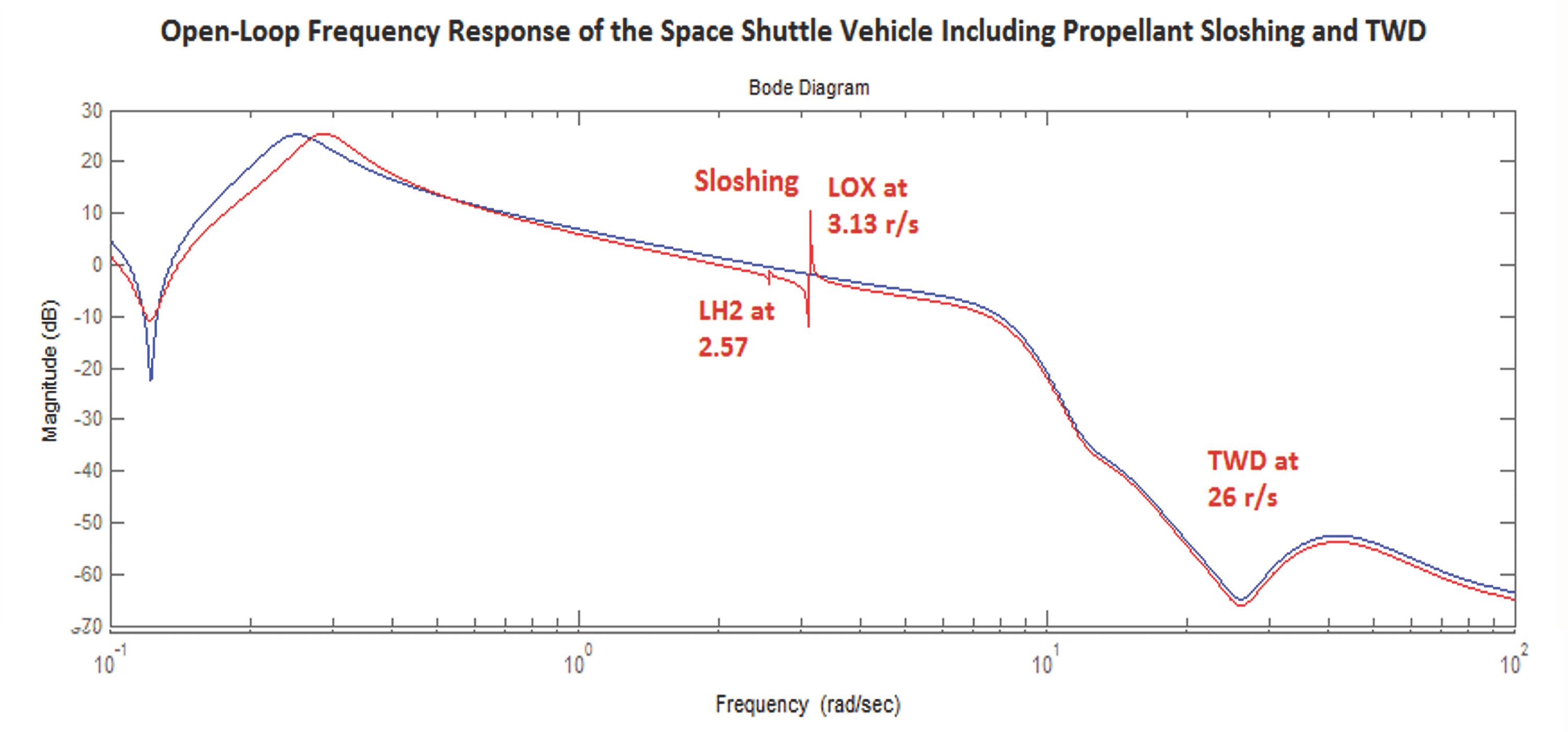


Figure 8 Frequency Response of the Pitch System including Propellant Sloshing and TWD Dynamics

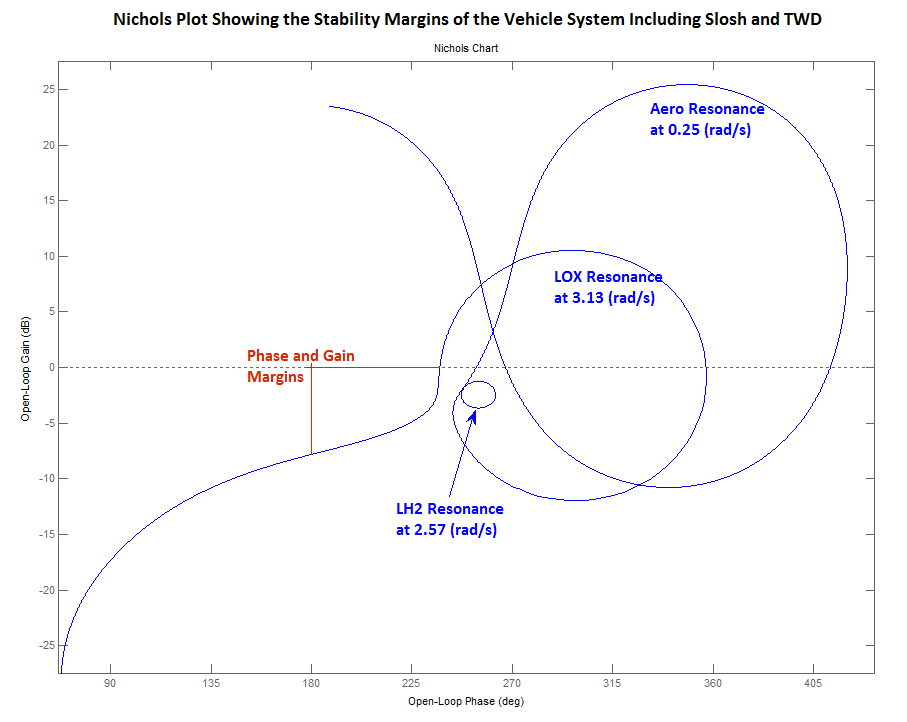


Figure 9 Nichols Plot Showing the Phase and Gain Margins of the Pitch Axis Space Shuttle System including Propellant Sloshing, TWD and Load-Torque Feedback

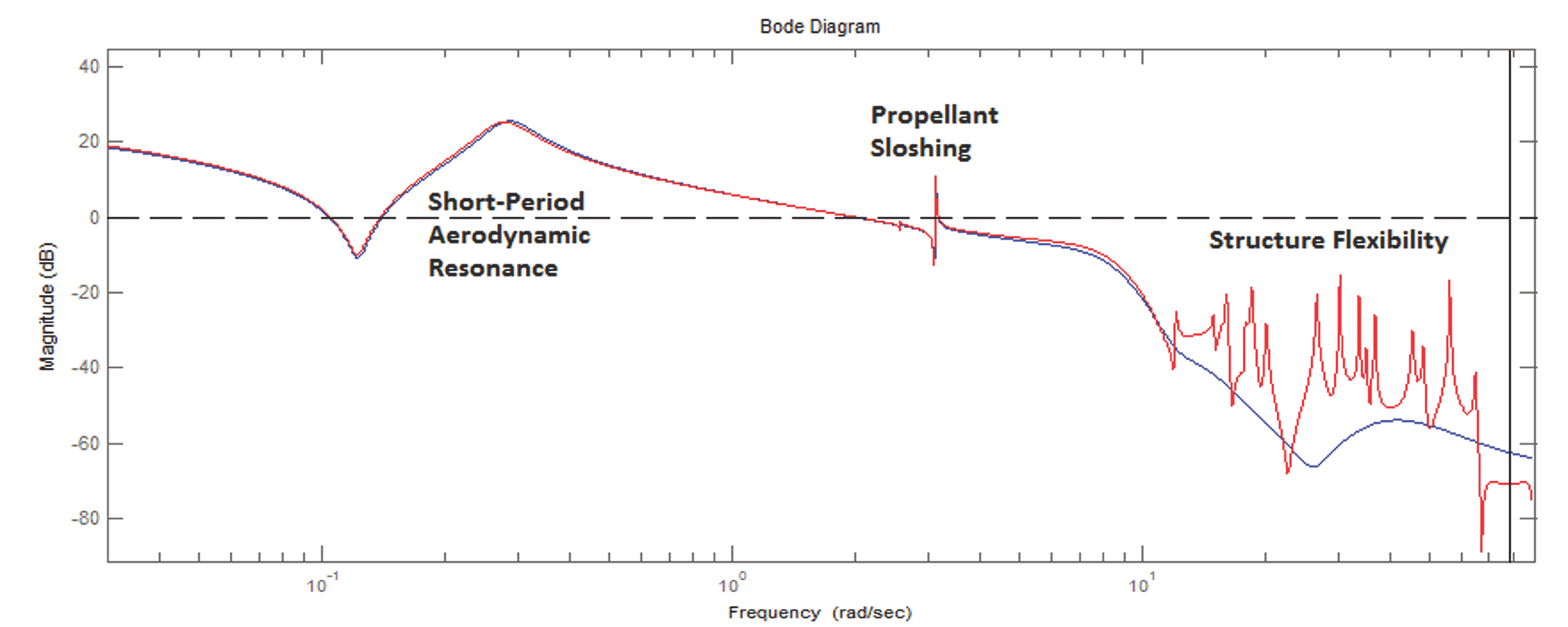


Figure 10 Frequency Response of the Pitch System including Flexibility, Propellant Sloshing and TWD

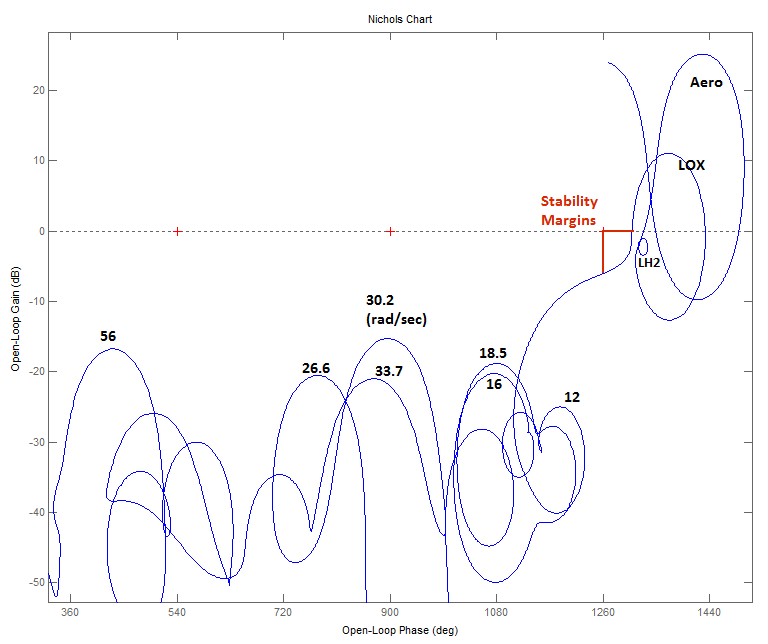


Figure 11 Nichols Plot of the Space Shuttle Pitch Axis System including Structural Flexibility and a Discrete Flight Control System

**Lateral Axes Flight Control System**

The lateral flight control system controls the roll and yaw axes which are coupled due to the aerodynamics generated by the vertical stabilizer and the cross-product of inertia Ixz. The control system, therefore, has a cross-feed from the yaw TVC command to the roll-rate command, as shown in Figure 12. The inputs to the flight control system are: yaw attitude error (e) in (radians), roll attitude error (e) in (radians), yaw rate (r), roll rate (p), in (rad/sec), and lateral acceleration (Ny) in (ft/sec2). The outputs are roll and yaw flight control demands (DP\_TVC and DR\_TVC) that drive the thrust vector control matrix. The roll and yaw flight control systems are shown in Figure 14. Figure 13 shows a block diagram system used for yaw stability analysis. It calculates the frequency response of the system with the yaw loop opened at DR\_TVC. Roll stability is calculated similarly by closing the yaw loop and opening the roll loop at the DP\_TVC output.

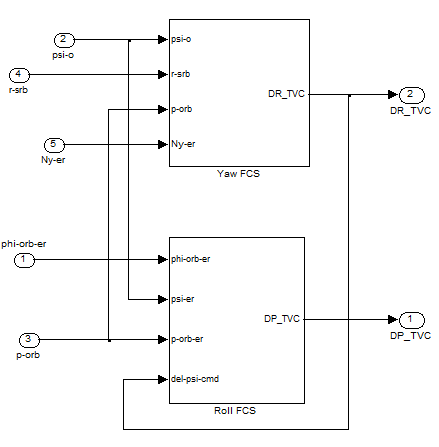
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Figure 12 Shuttle Ascent Flight Control System Showing the Roll and Yaw Cross-Coupling

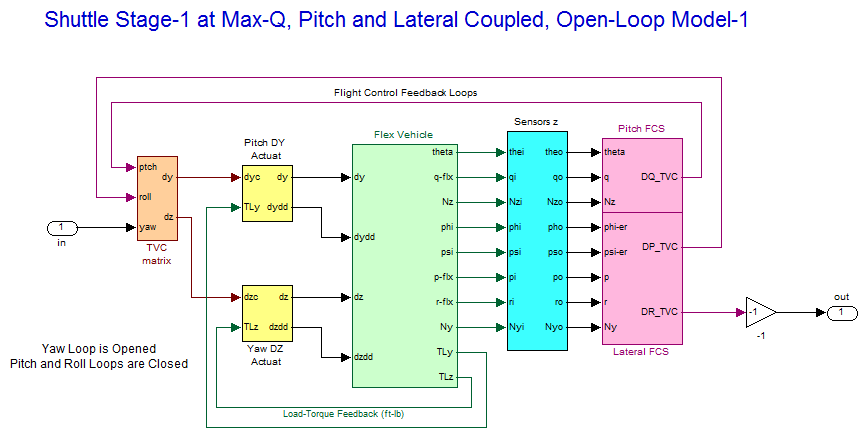
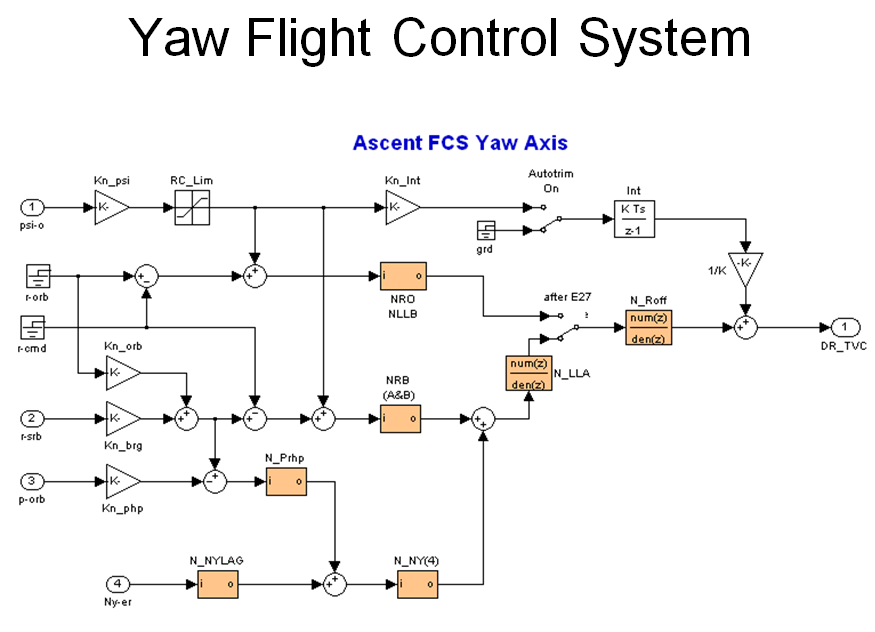


Figure 13 Block Diagram used to calculate the Open-Loop Frequency Response in Yaw, Yaw Loop is Opened at the TVC input, Pitch and Roll Loops are Closed



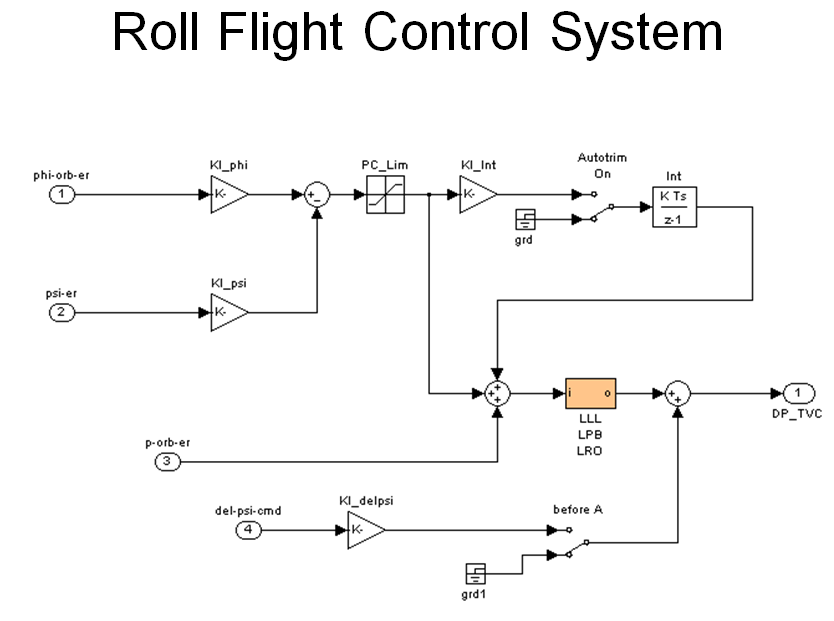
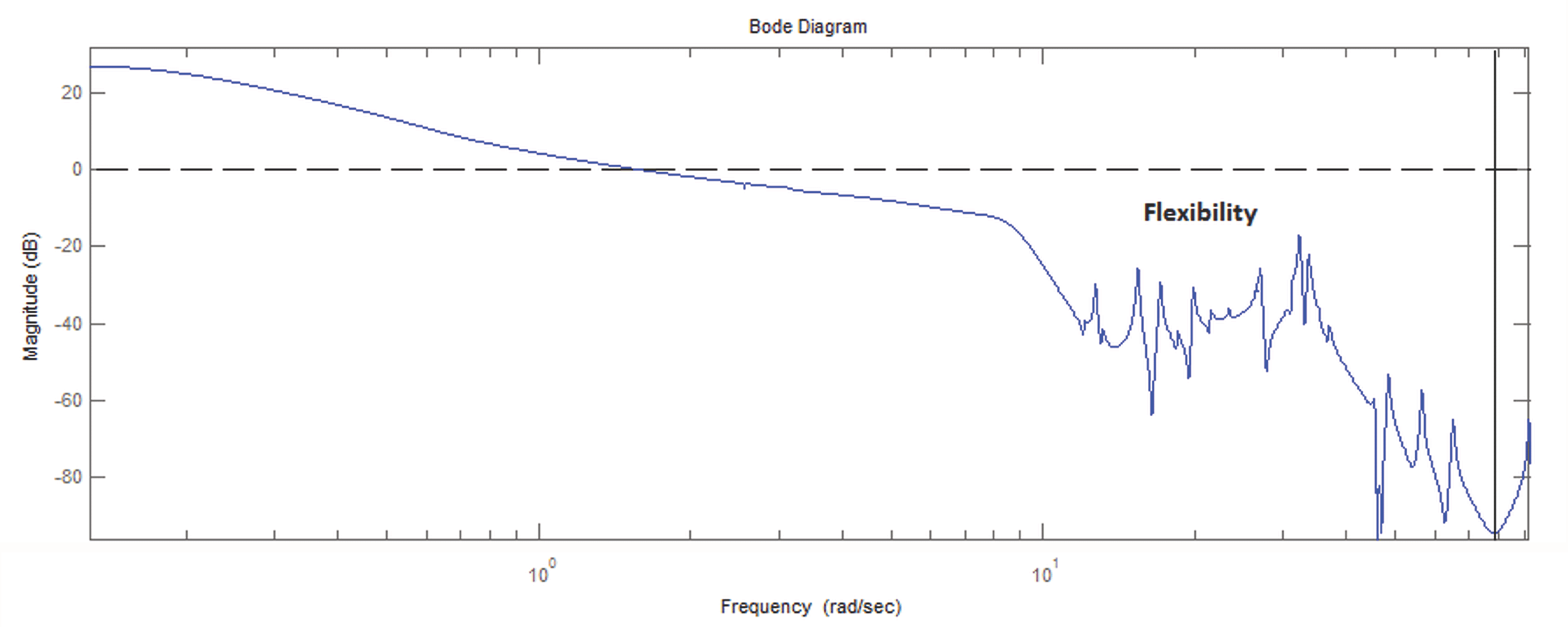


Figure 14 Shuttle Ascent Yaw and Roll Flight Control Systems



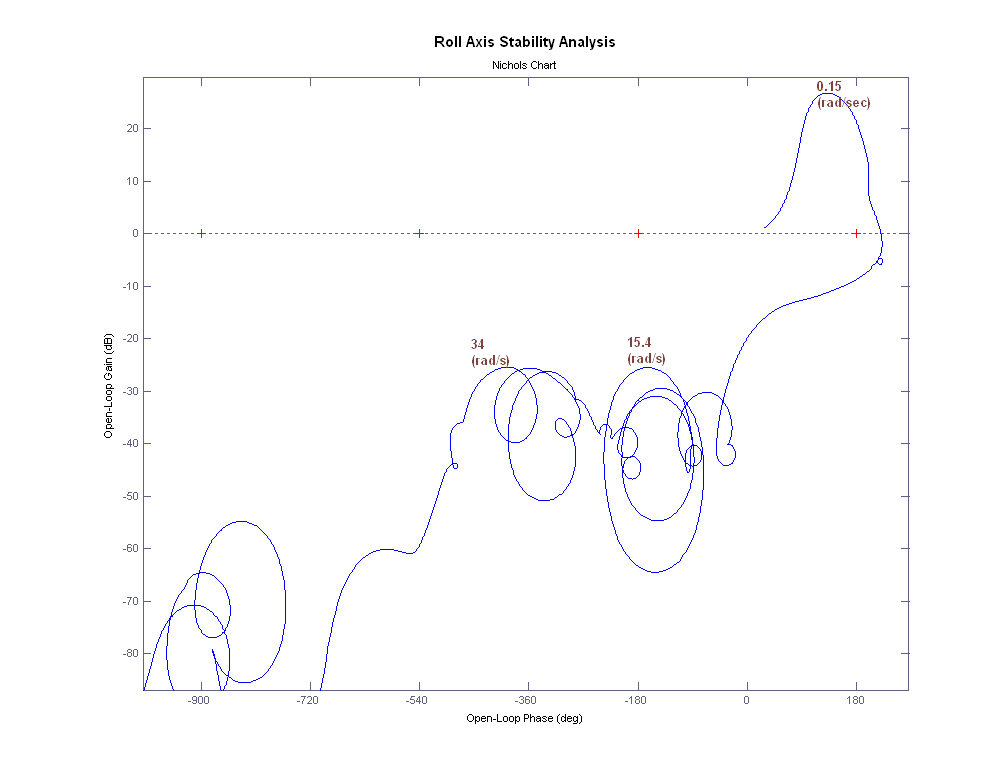
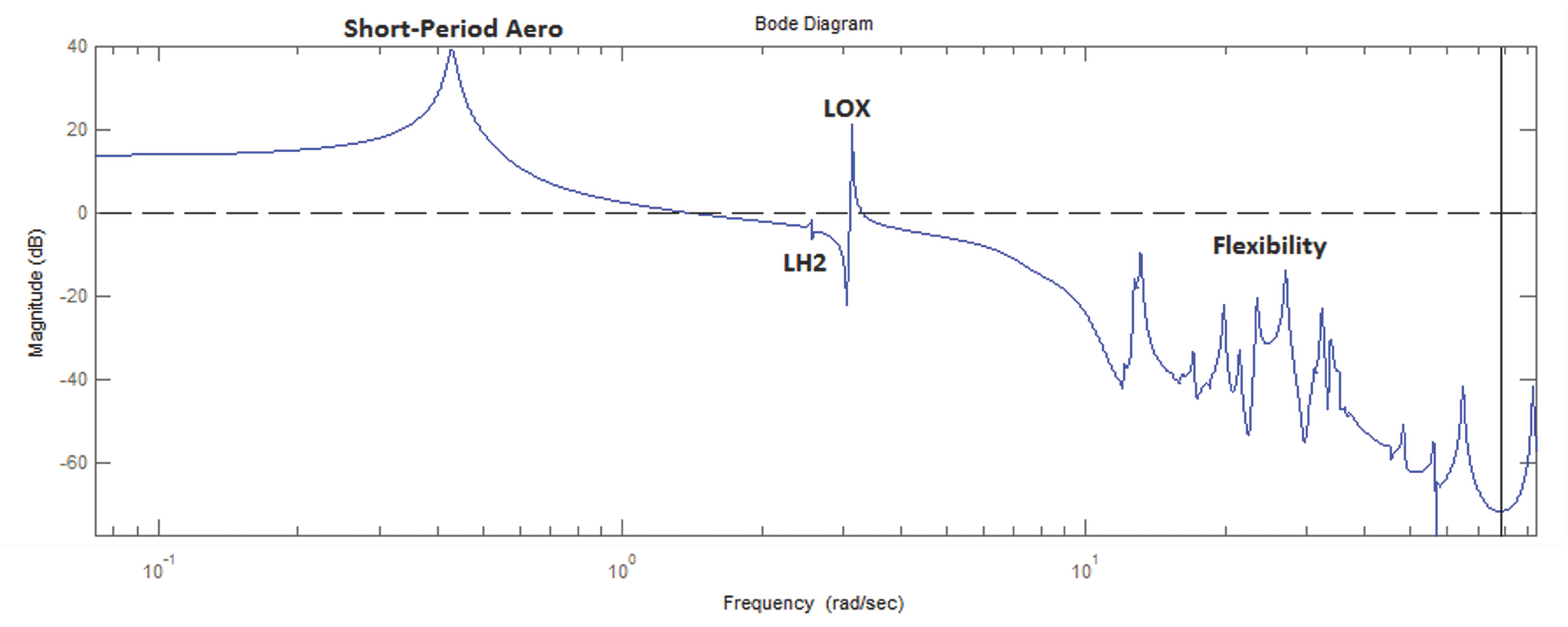
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Figure 15 Roll Axis Body and Nichols Plots including Slosh, Flexibility and TWD, Showing Stability Margins



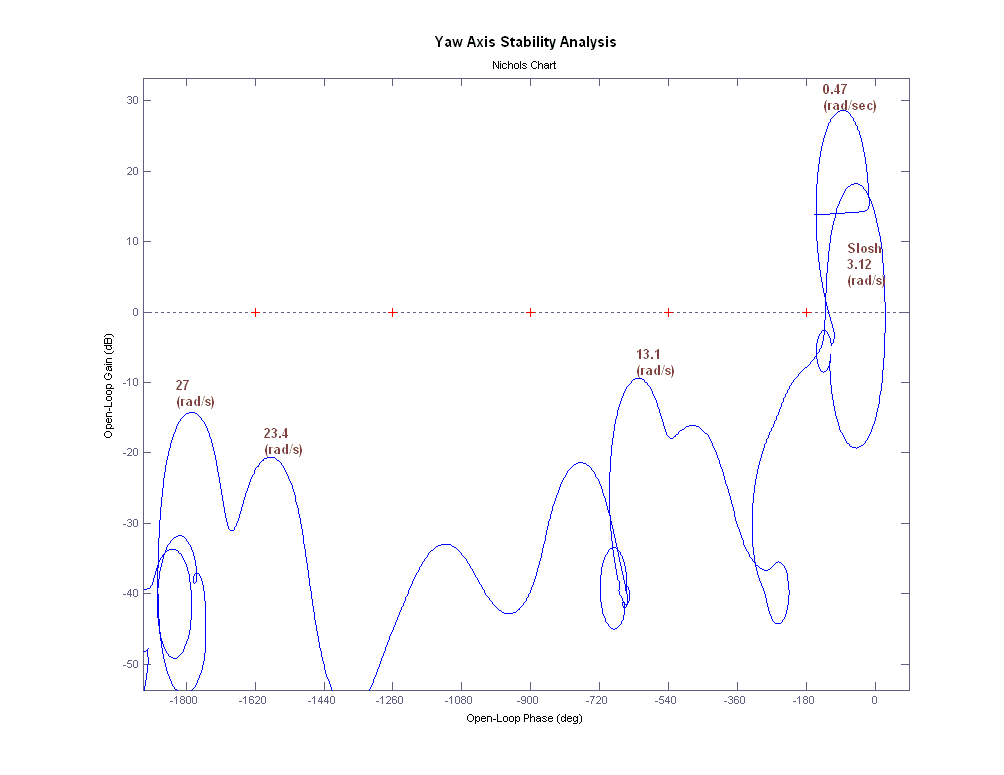
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Figure 16 Yaw Axis Body and Nichols Plots including Slosh, Flexibility and TWD, Showing Stability Margins

**Closed-Loop Simulation Analysis**

The following closed-loop model in Figure 17 is used for analyzing the Space Shuttle system response to attitude commands and to wind-gust disturbances. The vehicle dynamic model includes both: pitch and lateral dynamics, with TWD, load-torques, flexibility, and propellant sloshing. In the simulation case below, a wind-gust pulse is applied perpendicular to the vehicle x axis, and skewed at 45º between the +Y and the +Z axes to excite both pitch and lateral directions. The wind-gust disturbance causes transients in the angles of attack and sideslip which oscillate but the oscillations are eventually taken out by the flight control system. It also causes transients in the vehicle attitude, rates, and accelerometer responses. The engines respond by gimbaling in pitch and yaw. Notice that the wind disturbance causes a significant amount of roll oscillations.

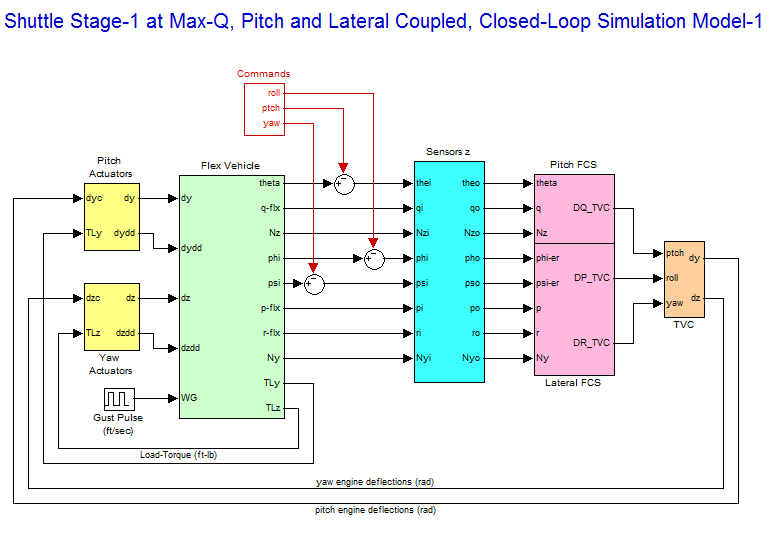


Figure 17 Block Diagram of the Combined Pitch and Lateral Closed-Loop System

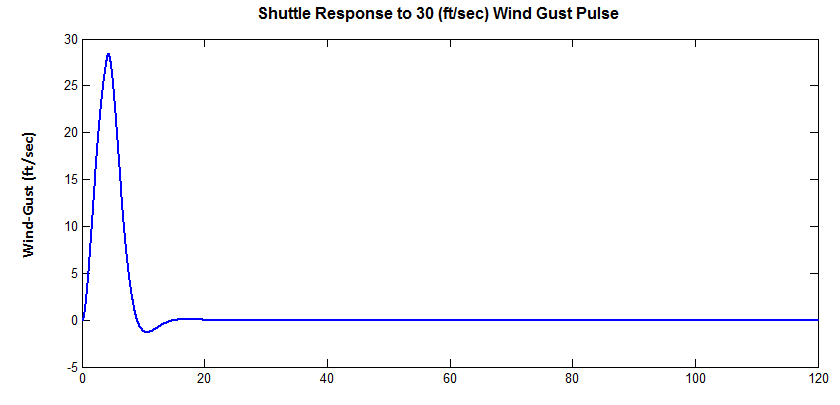


Figure 18 Wind-Gust Velocity Excitation

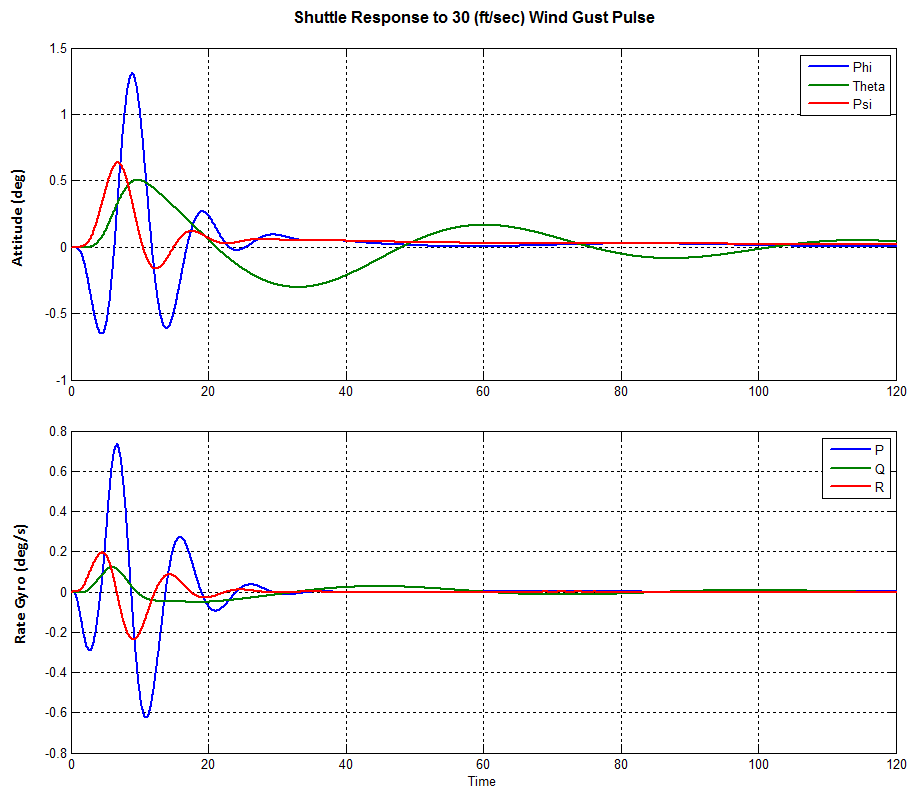


Figure 19 Roll, Pitch and Yaw Vehicle Attitude and Body Rates

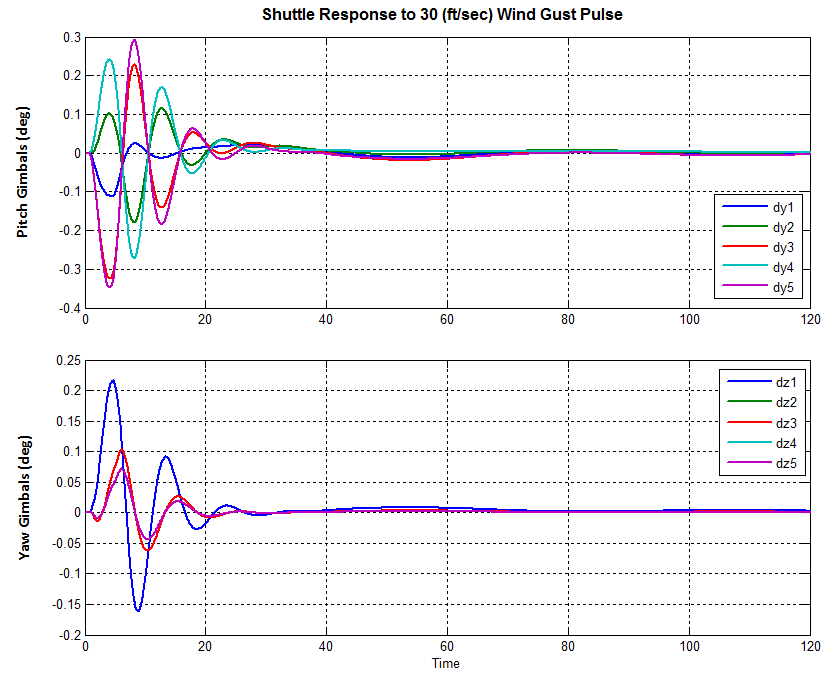


Figure 20 Pitch and Yaw Gimbal Responses of the 5 TVC Engines

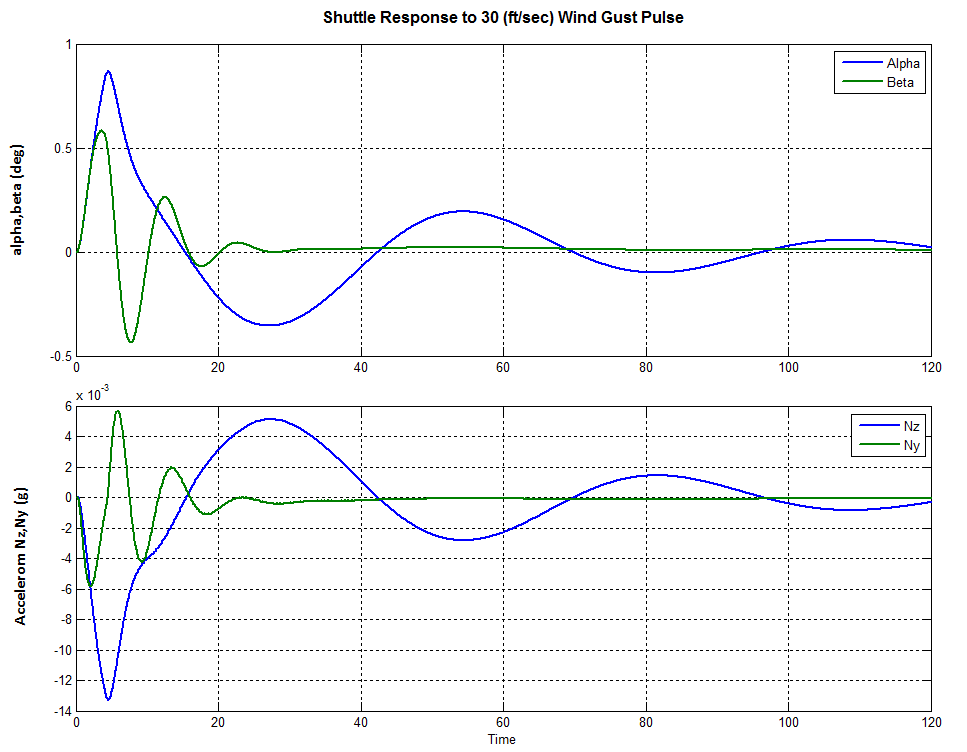


Figure 21 Aerodynamic Angles and Accelerometer Responses