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Whole Spacecraft Vibration Isolation

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AFIT/GSO/ENY/99M-05

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THESIS

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THESIS

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For Belly

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List of Acronyms

A	wetted area of LV
AFIT	Air Force Institute of Technology
AFRL	Air Force Research Laboratory
AFSPC	Air Force Space Command
AIAA	American Institute of Aeronautics and Astronautics
ρ	air density
ω	angular velocity of LV CM around earth center
C_D	Drag Coefficient
c_{ij}	inter-component damping coefficient
C_{ij}	inter-component damping force
CLA	Coupled-loads Analysis
CM	center of mass
D	Drag
DoF	Degree-of-Freedom
e	Earth Centered Inertial Reference Frame
g	gravitational acceleration ($g_O = 9.81$ m sec^{-1})
H	LV center of mass altitude
K_{ij}	inter-component stiffness force
k_{ij}	inter-component stiffness
LEO	Low Earth Orbit
LV	Launch Vehicle
M	Mach Number
m, M_G	Total Launch Vehicle Mass
M_1	Mass of Sub-component One Model Component
M_I	Mass of Inert Model Component
M_L	Mass of Lower Model Component

M_P	Mass of Payload Model Component
M_U	Mass of Upper Model Component
N_A	aeroacoustic vibration force
N_M	motor vibration force
P	pressure
Pa	Pascals (101,325 Pa = 1 atmosphere)
PAF	Payload Attach Fitting
PL	Payload
Psi	lb_f per in^2
r	radius from earth center to LV CM
$R_\oplus$	Radius of earth (6378.135 km)
SC	Sub-component
SRB (SRM)	Solid Rocket Booster/Motor
T	Thrust
T_{BO},T_{SL}, T_{VAC}	Burn-out, Sea-level, Vacuum thrust
t_{CO}	stage cut-off time
USAF	United States Air Force
V	Axial velocity
v	Launch Vehicle Reference Frame
WPAFB	Wright-Patterson Air Force Base
X	range, distance from launch site
$\ddot{X}_G$	Axial acceleration of LV CM

Abstract

The Department of Defense has identified launch vibration isolation as a major research interest. Reducing the loads a satellite experiences during launch will greatly enhance the reliability, lifetime, and payload to structure ratio. DoD satellite programs stand to benefit significantly from advances in vibration isolation technology.

This study explores potential hybrid vibration isolation control designs versus passive designs. A simple lumped mass dynamic model of a satellite and a representative launch vehicle was designed using Simulink. The analysis focuses on the various sources of transient launch accelerations such as aero-acoustic loads, separation events, wind gusts, and motor induced vibration. The passive vibration suppression design reduced axial "bounce" modes. Further reductions were made possible with an added active controller.

The results of modeling indicate that as much as a 90 percent improvement in loads on the satellite were recognized from the combination of active and passive vibration control techniques. The model also explored the response of a sub-component of the satellite payload. For passive isolation the sub-component remained near its low baseline level of response, but for hybrid isolation the sub-component is exposed to greater levels of loading as a function of passive isolation frequency.

Whole Spacecraft Vibration Isolation

1 Introduction

In almost all heavy industry endeavors, vibration suppression or isolation is a major concern. Preventing earthquake damage by mounting high rise buildings on massive springs and quieting the ride in a car with automotive suspensions are recognizable examples of vibration isolation or suppression. Vibration isolation and suppression allows for greater comfort, control or reduced risk depending on its application.

Recently, the Air Force supported the Navy GEOSAT Follow-on satellite launch on the Taurus launch vehicle. The Taurus is a solid-propelled, four-stage launch vehicle, which is capable of placing small satellites into low-earth orbits. The satellite, it was shown during testing, did not meet the required standards to survive the launch environment of the Taurus. The Air Force Research Laboratory (AFRL) was able to provide a satellite vibration isolation system that allowed GFO to be launched as is without a costly redesign [27].

This thesis seeks to extend the work currently being undertaken by AFRL. Using Simulink and Matlab [3] software packages several models were developed to explore passive and hybrid whole satellite vibration isolation. The models include a launch vehicle dynamic model and a flight model to re-create the loads a satellite may encounter during a launch. The research explored both lateral and axial vibration modes so that the dynamic coupling of the isolation system can be analyzed. Several types of active control systems were tried in the model to demonstrate the different benefits and shortcomings of the controllers. The final model used was designed with maximum flexibility so that the researcher could rapidly change system parameters and explore different launch environmental considerations.

1.1 Background

From the beginning of the space program it has been recognized that the launch vehicle vibration environment is a major source of failures of satellites. Over time NASA, the DoD and commercial launch providers have developed extensive test requirements for satellites in an effort to enhance satellite launch survivability from the beginning of the design phase. The testing program is costly in both time and currency, and frequently leads to the redesign of a satellite.

Personal experience has shown that a major consideration in the planning stages of a launch campaign is the satellite launch environment qualification test and verification process. This process includes lengthy discussions of the satellite's design, testing procedures, and coupled-loads analysis (CLA) results. Both launch provider and launch customer often require CLA. It is done on the satellite manufacturer's behalf for assurances that the design is sound when placed in the environment of a particular launch vehicle (LV). The process is repeated by the launch provider so that the dynamic response of the satellite to a LV induced loading can be estimated and the LV guidance computer programmed. The result is hundreds of hours of negotiation, testing, and modeling to confirm the safety of a launch.

Early references to satellite failure analysis show vibration to be a leading source of failure. Goddard Space Flight Center conducted a study of first day launch failures in 1971 [25]. This was followed-up three years later with an analysis of first month failures [24]. Both studies are of the same 57 spacecraft launch by NASA over the ten-year period of 1960 to 1970. The one LV environmental element singled out in the conclusion as the source of 30–60 percent of first day failures is the vibration/acoustic load. The paper goes on to note that it is not always possible to identify vibration as the source of a failure once the satellite is on orbit, but that ground testing, when done effectively, very often provides evidence that the source of a particular failure is vibration related.

The Jet Propulsion Laboratory has developed extensive testing procedures to verify the validity of a satellite or satellite sub-component design prior to launch. JPL also dedicates research efforts to optimizing future spacecraft testing. Being developed is a generic launch environment envelope that would allow for the pre-qualification of spacecraft hardware, thus minimizing testing requirements. This testing envelope attempts to encompass 95% of the environmental characteristics of nearly all current US launch vehicles as well as some foreign LVs [12]. The focus of recent experimentation at JPL and Los Alamos National Laboratory is improving the realism of hardware trials. Improving realism has involved creating special force limiting algorithms to notch certain frequency bands near resonant frequencies of the satellite to avoid damaging the test article, and also better matching the characteristics of the vibration loads anticipated during launch. The key difficulty of vibro-mechanical testing of satellites and components is that the shaker has infinite impedance and the satellite clearly does not.

Matching the impedance of the test bench to the test article improves the realism of a test program dramatically [12], [18], [22].

Joshi has numerically studied the effects of thrust-to-weight ratio versus transverse stiffness. The work looks to understand the relationship of trajectory and the fundamental modes of a launch vehicle structure. The key finding is that the modes of a LV are constantly changing as a function of the continuous mass change of the rocket. An overall reduction of the transverse modes results due to the increasing axial compression [7]. But of significance to this study is the constantly changing frequencies. This variability will complicate isolator designs, both passive and hybrid.

Another environmental factor that has received attention is wind gust buffet. Langley Research Center has conducted wind-tunnel tests to characterize the buffet response of hammerhead launch vehicles [2]. The research sought to create an aero-elastically scaled model of the upper portion of the Atlas LV. The results showed there is increased buffet due to the configuration of the payload fairing, but the ability to accurately characterize the buffet mechanism was limited by the wind-tunnel test facility. Prediction of environmental loads is a significant part of launch preparation. The launch vehicle manufacturer has to be able to represent the environment so that payload qualification can proceed accurately.

Coupled loads analysis seeks to computationally predict the response of a payload to the flight environment at various stages of an LVs flight. This is a costly, time consuming process. CLA is used as a design guide, and is used to direct testing programs [23]. CLA is costly because of the time required to create and verify a finite-element or statistical energy model of a spacecraft and the payload interface. The results may be inaccurate as well.

Efforts by Lee-Glauser, Ahmadi and Layton at Langley Research Center have focused on vibration isolation for the Space Transportation System (STS). They have developed passive and active vibration control strategies for shuttle payloads. Using a five DoF lump parameter model the satellite payload they have developed several isolator types. The models are used to simulate the isolation effectiveness of the first eight seconds of flight. For the STS, this is the period of greatest vibration energy as the solid rocket boosters and Space Shuttle Main Engines are ignited [13], [14], [15].

As mentioned previously, the US Air Force supported the launch of the GEOSat Follow-on Satellite (GFO) program by designing, testing and delivering a passive whole satellite launch vibration isolation system. The GFO satellite failed to qualify for launch in its pre-test configuration and as such was to incur a launch delay to improve the its response to test loads via a redesign. This delay was offset by the design of a simple passive isolator that added only a small change in forward location of the satellite. The Air Force contracted the design out to CSA Engineering. CSA rapidly prototyped the isolator design using the NASTRAN FEM software package. They then tested the design for flight qualification. The final design successfully flew with GFO on February 10, 1998 [27].

CSA is currently designing a larger payload isolation system for medium capability launch vehicles and 3000-kg class satellites. Their design constraints for a replacement payload attach fitting that would provide lateral vibration isolation are as follows. The isolator could not create structural modes below 6Hz because the low frequency modes would have an impact on the LV guidance, control and navigation system. The second constraint was to limit lateral oscillations to less than one inch total displacement or violate the dynamic fairing envelope. To do so would likely cause the failure of the launch if the satellite struck the payload fairing. Their work on the GFO isolation system and the effort described here is part of a broader USAF Air Force Research Lab effort in whole spacecraft vibration isolation [28].

Air Force Research Lab granted the Small Business Innovative Research contracts to CSA for their work on whole spacecraft vibration isolation. The Kirtland AFB efforts are initial experimental work on hybrid launch isolation. Their initial results show great gains over passive isolation systems for the reduction of vibration loads of a test article. Goals they have determined for a hybrid isolator are fail-safe design, limited weight increase, adaptive to changing environment, broadband and narrowband attenuation of the launch dynamic environment. Achievement of these goals will lead to decreased satellite mass (or conversely increased useful satellite payload mass), increased satellite reliability and survivability, and decreased life-cycle costs [19].

As a final note, the Department of Defense has indicated its top-level interest in vibration isolation studies in the 1998 Defense Technology Area Plan -- Space Platforms DTOs. The goals laid out by DoD are the reduction of launch vehicle structural mass by 40% and satellite launch loads 80% by FY01. These two are conflicting goals because reduced structural mass generally results in higher vibration loading on the satellite payload. Over the next five years approximately sixty million dollars are budgeted for these and similar efforts to be performed by the Air Force [1].

1.2 Research Objectives

Research into the nature of the dynamic loads on a satellite has been pursued since the beginning of the space program. Early failure analysis points to vibro-mechanical loads as the key failure mode. Characterization of the loads on a satellite is on-going. Passively isolating a satellite from the vibration loads created by the launch environment was recently achieved with the GFO satellite. Efforts to further control the environmental loads on a satellite are currently underway.

While CLA can explore the vibration modes of a satellite and payload interface it is time-invariant, focused on specific load cases and is limited in its application to dynamic control design. Though highly effective as a satellite qualification tool, CLA is too complex for the analysis of the dynamics that would drive a hybrid vibration isolation system design. Therefore, development of a time-varying model of a launch vehicle and associated environmental loads would assist the design process of a hybrid isolation system.

This study discusses the researcher's development of a time-variant launch vehicle and launch environment model upon which the study of passive and hybrid vibration isolation methods was based. The researcher discusses the results of analysis on passive and hybrid vibration isolation systems. The emphasis of the isolation research is the overall reduction of whole spacecraft loads and a payload sub-component. Finally, recommendations for future efforts in this area are summarized.

1.3 Organization of this Paper

This paper is divided into three sections. The first is background information exploring historical and current efforts in launch vibration isolation. The second section reviews the derivations necessary to build models of the launch vehicle to study its vibration characteristics, discusses the passive and active control theories pertinent to the design of passive and hybrid isolation systems, and then overviews the top-level design philosophy of the Simulink models created to implement the equations established earlier in the section. The third section provides the analysis of passive and hybrid simulation results. The appendices will provide detailed discussion of the model designs and source codes of the analysis tools developed for this research effort.

2 Model Development

In this chapter the equations used to describe the vibration loads and other forces that act on the launch vehicle and its payload as it flies to orbit are developed. The derivation begins with the fundamental gravity turn equations. The axial and lateral vibration equations are presented. These are followed by brief discussions of equations used to simulate environmental elements such as vibration loading. The last section of Chapter 2 details the integration of the parts into a Simulink model to test the benefits of passive and hybrid isolation. Detailed discussion of the simulation sub-systems is in Appendix A.

2.1 Derivation of the Equations of Motion

Fundamental to the generation of a flight environment is the LV trajectory and the quasi-static loads it creates. Quasi-static loads are the accelerations generated by the relatively slow changes of thrust, drag and gravity. The LV trajectory equations are derived in Section 2.1.1. The rapidly changing vibration dynamics of the LV's components create the axial and lateral vibration loads. The axial and lateral dynamics are derived in Section 2.1.2. Finally, having only referred to the environmental loads in general terms, they are fully described in detail in Section 2.2.

2.1.1 Gravity Turn Equations

The equations of the trajectory are derived in the form of a gravity turn [26]. The gravity turn equations are needed to create the quasi-static acceleration loads of the launch vehicle. The model uses a non-rotating, earth-centered system. For computational simplicity, the earth is assumed to be spherical. The equations for this study are derived for two-dimensional planar motion. The assumed symmetries of the launch vehicle and satellite allow this simplification.

Figure 1 is the free-body diagram of the rocket in flight. Ignoring lift, the forces acting on the LV are drag (D), thrust (T) and weight (Mg). In order to consider the LV in the familiar local horizon frame of reference, range (X) and altitude (H) are used in a non-rotating earth system. Each term is taken along one axis of an orthonormal set based at the earth's center. The range direction, X, is the $\mathbf{e_1}$ component. The altitude, H, is in the $\mathbf{e_2}$ direction and the $\mathbf{e_3}$ direction is the axis of rotation of the system or ω. Thus, the instantaneous position of the LV is always given by Equation 1. Likewise, the angular velocity, ω, is given in Equation 2.

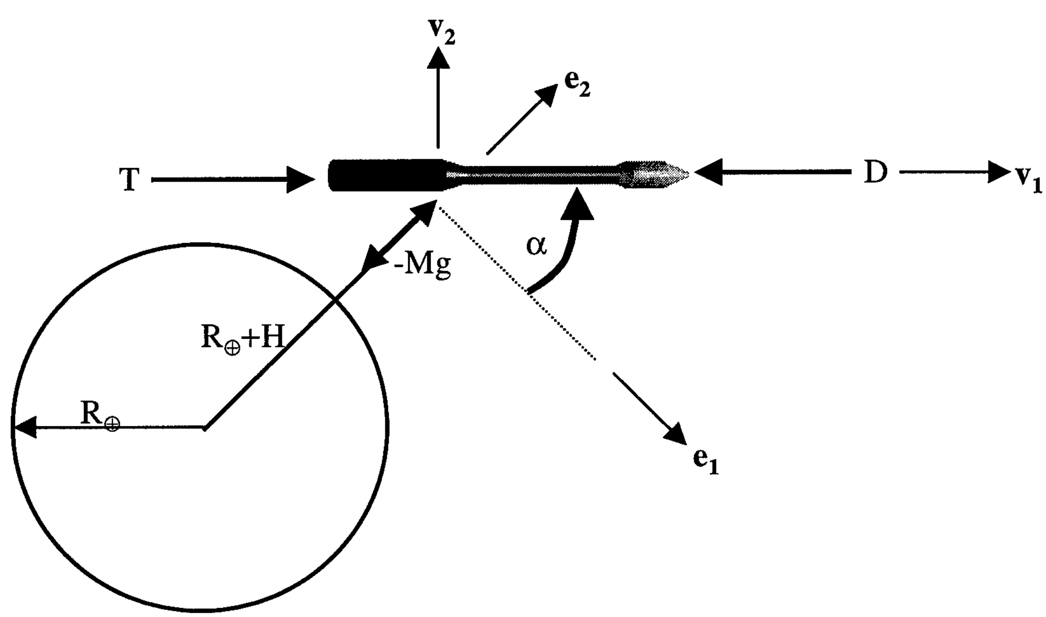

Figure 1 Free Body Diagram of Launch Vehicle in Flight

$$\vec{r} = R_{\oplus} + Hb\hat{e}_2 \tag{1}$$

$$\vec{\omega} = -\frac{\dot{X}}{R_{\oplus} + H}\hat{e}_3 \tag{2}$$

Taking two derivatives of the position vector results in Equation 3. This result captures the centripetal and Coriolis acceleration of the rocket as it flies into space. When combined with the thrust, drag and weight forces acting on the launch vehicle we can analyze the trajectory of the vehicle and also compute the accelerations on the payload.

$$\ddot{\vec{r}} = \left(\ddot{X} + \frac{\dot{X}\dot{H}}{R_{\oplus} + H}\right)\hat{e}_1 + \left(\ddot{H} - \frac{\dot{X}^2}{R_{\oplus} + H}\right)\hat{e}_2 \tag{3}$$

The flight path angle, given by α, indicates the direction of the velocity vector with respect to the local horizon. The thrust vector and drag also act along the velocity vector. Thus, we must resolve the forces acting on the LV, the **v** frame of reference, along the velocity vector to simplify the equations of motion. The result is Equation 4.

$$m(\ddot{X}\cos\alpha + \ddot{H}\sin\alpha) = -m\frac{\dot{X}\dot{H}}{R_{\oplus} + H}\cos\alpha - D + T - m\left\{g - \frac{\dot{X}^2}{R_{\oplus} + H}\right\}\sin\alpha\hat{v}_1 \tag{4a}$$

$$m(\ddot{H}\cos\alpha - \ddot{X}\sin\alpha) = m\frac{\dot{X}\dot{H}}{R_{\oplus} + H}\sin\alpha - m\left\{g - \frac{\dot{X}^2}{R_{\oplus} + H}\right\}\cos\alpha\hat{v}_2 \tag{4b}$$

Finally, one last simplification is possible. Noting that the acceleration can be given by $\ddot{\vec{r}} = V\hat{v}_1 + V\dot{\alpha}\hat{v}_2$ in the LV coordinate frame, the equations can be reduced from two second-order equations to four first-order state equations. This clearly simplifies integration of this highly non-linear system, and allows access to meaningful terms like the vehicle's speed and axial acceleration. Equation 5 is the final set of equations in body fixed coordinates (**v** frame), and includes the necessary integration of the vehicle's changing mass.

$$\dot{X} = V\cos\alpha \tag{5a}$$

$$\dot{H} = V\sin\alpha \tag{5b}$$

$$m\dot{V} = T - D + N_M - N_A - m\frac{\dot{X}\dot{H}}{R_\oplus + H}\cos\alpha - \left(mg - \frac{m\dot{X}^2}{R_\oplus + H}\right)\sin\alpha \tag{5c}$$

$$mV\dot{\alpha} = m\frac{\dot{X}\dot{H}}{R_\oplus + H}\sin\alpha - \left(mg - \frac{m\dot{X}^2}{R_\oplus + H}\right)\cos\alpha \tag{5d}$$

$$\frac{dm}{dt} = \dot{m} \tag{5e}$$

The equations above are of the center of mass of the LV. The forces acting on the CM are characterized below. Realism was a chief goal of the following equations.

Thrust force varies for two reasons. The first is that as the vehicle ascends into space the atmospheric back pressure gradually lessens. This has the effect of increasing thrust force at higher altitudes. The second effect is that solid rocket motors, near the end of stage operation, gradually burn out.

Modeling atmospheric pressure variability is accomplished using the following relationship. The ambient pressure is normalized into atmospheres by dividing by the constant 101,325 Pa.

$$\mathrm{T} = \mathrm{T_{SL}} + (1 - \mathrm{P}/101325)(\mathrm{T_{Vac}} - \mathrm{T_{SL}}) \tag{6}$$

The gradual tailing-off of thrust output is achieved by assuming an exponential decrease in thrust during the last seven seconds of motor operation. This models a smoother transition to a zero thrust condition at the end of the burn. Therefore, the source of shocks at staging events is the sudden loss of mass as an empty stage casing is jettisoned and not a step reduction of thrust. The tail-off is modeled as shown in Equation 7. T_{TO} is the reduced thrust (T being total thrust) which begins at time of motor cut-off, t_{co}, minus seven seconds.

$$T_{TO} = Te^{-[t-(t_{co}-7)]} \tag{7}$$

The Drag force is the well recognized relationship in Equation 8 [21].

$$D = C_D \frac{1}{2} \rho V^2 A \tag{8}$$

These losses in performance dramatically reduce the payload to orbit capability of this notional launch vehicle. The performance of the notional LV modeled here is representative of actual systems.

2.1.2 Axial and Lateral Vibration Models

The next step is to create a vibration model representative of some of the vibration modes of the launch vehicle as well as the some modes of the satellite. It would be easy to capture as many LV and satellite modes as possible, but computationally costly. Thus, very early on, it was decided to limit the model to two LV modes, one satellite mode and the isolator critical mode. The result is a four degree-of-freedom (DoF) system, when the rigid body mode is excluded. The lateral system will be similarly separated.

The notional launch vehicle model, however, is of a staged launch vehicle with the potential for each stage to have its own characteristics. For modeling simplicity a standard model was used and the characteristics of each stage are passed into the model as the vehicle changes configuration throughout its flight. The model that results is a fixed set of parameters for each of the flight configurations, thus allowing continuous integration as the vehicle states change. This has the nice effect of minimizing the number of simultaneously running integrators and reducing the number of blocks simulating the vehicle. This reduces program size and visual complexity, too.

The model is based on the idea that the operating motor or engine and aeroacoustic noise are the primary sources of vibration throughout the flight. Therefore, the LV is divided into three parts – the Lower (L) and Upper (U) components of the operating stage, and the Inert (I) component comprised of the remaining stages of the LV that have not been burned. These divisions allow for a DoF for the motor vibration source and the aeroacoustic noise source. What remains of the model is the satellite and the isolation system. The satellite is modeled as a mostly solid body with one axially moving part and one laterally rotating part of some specified mass. This allows the modeler to look at some satellite mode of interest. The isolation system (if there is one) is modeled as a spring or a spring and an active controller system separating the LV and the satellite. The satellite's degree of freedom within the model on top of the isolator is referred to as the Payload (P) component and the payload sub-components are designated as Sub-component 1 (1) in the axial direction, and Sub-component 2 (2) in the lateral direction. Figure 2 demonstrates the transition from a notional launch vehicle design to the standard model concept. The payload sub-components are not visible in this presentation because they are within the satellite component.

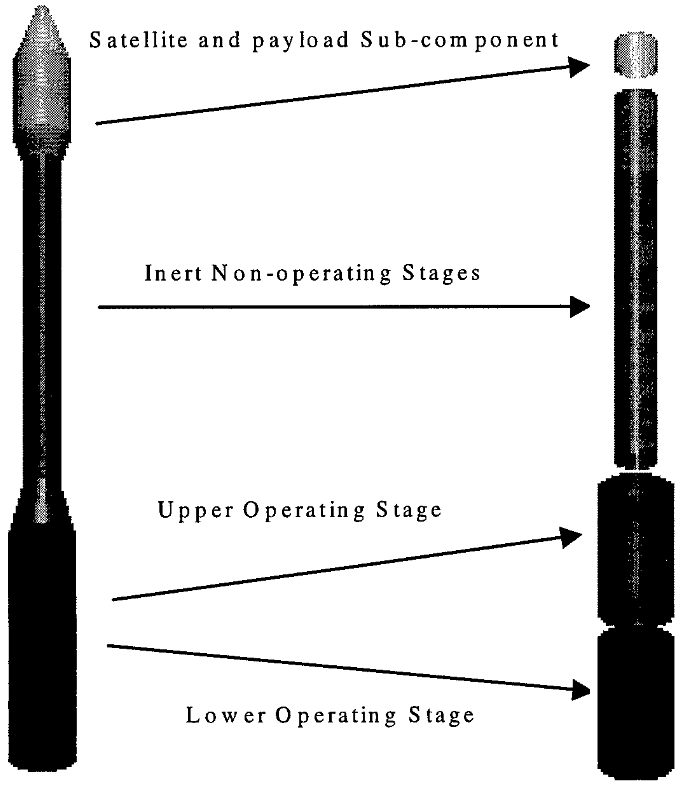

Figure 2 Notional Launch Vehicle to Vibration Model

2.1.2.1 The Axial Equations

Based on the conceptual model described above it is possible to derive a system of equations to describe the motion of the vehicle components.

The axial (**v_1**) equation of motion (Equation 5) describes the bulk motion of the launch vehicle. Summing forces in the **v_1** direction on each of the LV components results in the five equations of Equation 11. For brevity, terms such as K_{LU}, representing the stiffness force between the L and U components, are an abbreviation for the stiffness force equation $k_{LU}(X_L - X_U)$.

$$m_L(\ddot{X}_L+\ddot{X}_G)=T+N_M-m_L\left\{\left(g-\frac{\dot{X}_G^{\ 2}}{R_\oplus+H}\right)\sin\ +\frac{\dot{X}_G\dot{H}}{R_\oplus+H}\cos\ \right\}-K_{LU}-C_{LU} \tag{9a}$$

$$m_U(\ddot{X}_U+\ddot{X}_G)=-m_U\left\{\left(g-\frac{\dot{X}_G^{\ 2}}{R_\oplus+H}\right)\sin\ +\frac{\dot{X}_G\dot{H}}{R_\oplus+H}\cos\ \right\}-K_{UI}-C_{UI}+K_{LU}+C_{LU} \tag{9b}$$

$$m_I(\ddot{X}_I+\ddot{X}_G)=-m_I\left\{\left(g-\frac{\dot{X}_G^{\ 2}}{R_\oplus+H}\right)\sin\ +\frac{\dot{X}_G\dot{H}}{R_\oplus+H}\cos\ \right\}-K_{IP}-C_{IP}+K_{UI}+C_{UI}-D+N_A-I_L-I_R \tag{9c}$$

$$m_P(\ddot{X}_P+\ddot{X}_G)=-m_P\left\{\left(g-\frac{\dot{X}_G^{\ 2}}{R_\oplus+H}\right)\sin\ +\frac{\dot{X}_G\dot{H}}{R_\oplus+H}\cos\ \right\}-K_{P1}-C_{P1}+K_{IP}+C_{IP}+I_L+I_R \tag{9d}$$

$$m_1(\ddot{X}_1+\ddot{X}_G)=-m_1\left\{\left(g-\frac{\dot{X}_G^{\ 2}}{R_\oplus+H}\right)\sin\ +\frac{\dot{X}_G\dot{H}}{R_\oplus+H}\cos\ \right\}+K_{P1}+C_{P1} \tag{9e}$$

Manipulating the equations to solve for the component accelerations, and substituting from Equation 4 for the acceleration of the vehicle center of mass yields the following.

$$m_L\ddot{X}_L=\left(1-\frac{m_L}{m_G}\right)(T+N_M)-\frac{m_L}{m_G}(-D+N_A)-K_{LU}-C_{LU} \tag{10a}$$

$$m_U\ddot{X}_U=-\frac{m_U}{m_G}(T+N_M-D+N_A)-K_{UI}-C_{UI}+K_{LU}+C_{LU} \tag{10b}$$

$$m_I\ddot{X}_I=\left(1-\frac{m_I}{m_G}\right)(-D+N_A)-\frac{m_I}{m_G}(T+N_M)-K_{IP}-C_{IP}+K_{UI}+C_{UI}-D+N_A-I_L-I_R \tag{10c}$$

$$m_P\ddot{X}_P=-\frac{m_P}{m_G}(T+N_M-D+N_A)-K_{P1}-C_{P1}+K_{IP}+C_{IP}+I_L+I_R \tag{10d}$$

$$m_1\ddot{X}_1=-\frac{m_1}{m_G}(T+N_M-D+N_A)+K_{P1}+C_{P1} \tag{10e}$$

Dividing each equation of Equation 10 by the mass of each component solves for the accelerations. This system of equations will be easily programmed into Simulink. Next, the lateral equations of motion are derived.

2.1.2.2 The Lateral Equations

Following a similar line of reasoning, the lateral equations of motion are derived. The equations developed here will allow analysis of the rocking motion of the satellite caused by vibration and transient events like wind gusts.

Referring again to Equation 2, we take one derivative of the angular velocity and get the result in Equation 11. Figure 3is the free body diagram of the moments acting on the launch vehicle. Multiplying this by the total moment of inertia of the notional launch vehicle and adding moments caused by vibration and gust forces to the moment equation yields the result in Equation 12.

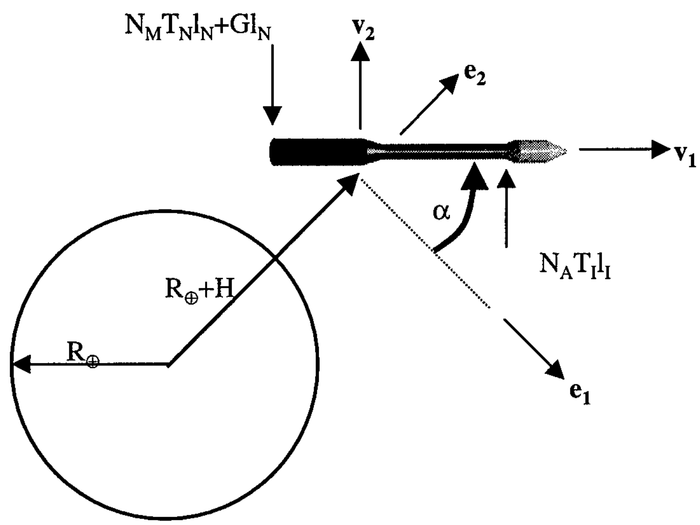

Figure 3 Free Body Diagram of Moments Acting on the LV

$$\dot{\vec{\omega}} = -\frac{\ddot{X}}{R_{\oplus} + H} + \frac{\dot{X}\dot{H}}{(R_{\oplus} + H)^2}\hat{v}_3 \tag{11}$$

$$I_V\left\{-\frac{\ddot{X}}{R_{\oplus} + H} + \frac{\dot{X}\dot{H}}{(R_{\oplus} + H)^2}\right\} = N_M T_N l_N + N_A T_I l_I + Bl_N \tag{12}$$

Analyzing the internal moments of the LV is similar to the axial force analysis. Each of the rocket body components is considered with respect to the vehicle's center of mass. This simplifies the final equations of motions, but adds the requirement for tracking the motion of the center of mass within the LV. This constraint is constantly changing position during motor operation. Thus, a necessity to the final model will be a full description of the rocket components. Equation 13 lists the lateral equations.

$$I_L\ddot{\Theta}_L + C_{MLU}(\dot{\Theta}_L - \dot{\Theta}_u) + K_{MLU}(\Theta_L - \Theta_U) = M_L \tag{13a}$$

$$I_U\ddot{\Theta}_U + C_{MUI}(\dot{\Theta}_U - \dot{\Theta}_I) + K_{MUI}(\Theta_U - \Theta_I) = C_{MLU}(\dot{\Theta}_L - \dot{\Theta}_U) + K_{MLU}(\Theta_L - \Theta_U) + M_U \tag{13b}$$

$$I_I\ddot{\Theta}_I + \frac{d}{4}C_{IP}(\dot{\Theta}_I - \dot{\Theta}_P) + \frac{d}{4}K_{IP}(\Theta_I - \Theta_P) = C_{MUI}(\dot{\Theta}_U - \dot{\Theta}_I) + K_{MUI}(\Theta_U - \Theta_I) + M_I \tag{13c}$$

$$I_P\ddot{\Theta}_P + C_{MP2}(\dot{\Theta}_P - \dot{\Theta}_2) + K_{MP2}(\Theta_P - \Theta_2) = \frac{d}{4}C_{IP}(\dot{\Theta}_I - \dot{\Theta}_P) + \frac{d}{4}K_{IP}(\Theta_I - \Theta_P) + M_P \tag{13d}$$

$$I_2\ddot{\Theta}_2 - C_{P2}(\dot{\Theta}_P - \dot{\Theta}_2) - K_{P2}(\Theta_P - \Theta_2) = M_2 \tag{13e}$$

The M_i terms are the internal torques and are expanded in equation 14.

$$M_L = -\frac{I_L}{I_V}\{N_M T_N l_N + N_A T_I l_I + Bl_N\} + N_M T_N l_N + Bl_N - m_L g l_L \cos\alpha \tag{14a}$$

$$M_U = -\frac{I_U}{I_V}\{N_M T_N l_N + N_A T_I l_I + Bl_N\} - m_U g l_U \cos\alpha \tag{14b}$$

$$M_I = -\frac{I_I}{I_V}\{N_M T_N l_N + N_A T_I l_I + Bl_N\} + N_A T_I l_I - m_I g l_I \cos\alpha + \frac{d}{4}(I_R - I_L) \tag{14c}$$

$$M_P = -\frac{I_P}{I_V}\{N_M T_N l_N + N_A T_I l_I + Bl_N\} - m_P g l_P \cos\alpha - \frac{d}{4}(I_R - I_L) \tag{14d}$$

$$M_2 = -\frac{I_2}{I_V}\{N_M T_N l_N + N_A T_I l_I + Bl_N\} - m_2 g l_2 \cos\alpha \tag{14e}$$

Except for I_L and I_R the I_i terms are the mass moments of inertia relative to the LV center of mass (c.m.). The I_V term is the LV total mass moment of inertia. IL and IR are the left and right lateral control force inputs. N_M is the vibration noise generated by the operating motor, and N_A is the aeroacoustic vibration. The motor noise is observed at the nozzle of the operating stage and is at a distance l_N from the c.m. of the LV. The lateral vibration is assumed to be a fractional value of the axially generated vibration and is multiplied by the lateral transmission factor, T_N. Similarly, the aeroacoustic noise is observed at the payload interface, a distance l_I from the LV c.m., and is multiplied by the interface lateral transmission factor, T_I.

In several places in Equations 13 and 14 terms with *d/4* appear. These terms relate to the interface, where *d* is the diameter of the PAF. The model must represent a circular distribution of the interface stiffness, such as when a satellite is mounted on a ring of passive isolators at the payload interface. The derivation for this is rather simple. Figure 4below is a diagram of the parts of the interface.

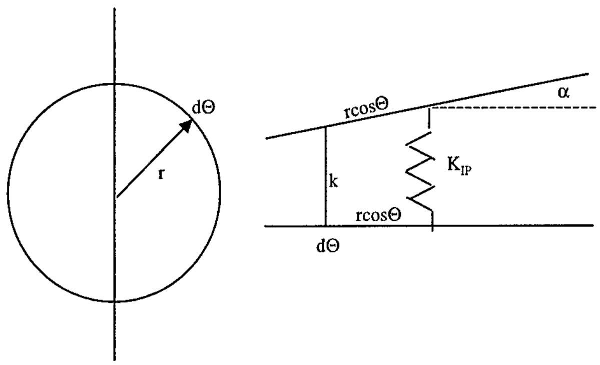

Figure 4 Diagram for the derivation of the lateral stiffness

The derivation is as follows. Assuming that the relative deflection angle, α, of the payload to the interface is small, then the following linearized relationship is derived.

$$\frac{dM}{d\Theta} = k(r\cos\Theta)^2\alpha \tag{15}$$

Equation 15 states that the rate of change of the moment at the interface with respect to the incremental angular coordinate on the payload interface ring is equal to the incremental circumferential stiffness, k, at a distance $r\cos\Theta$ from the center of rotation times the deflection of k by the arc of $\alpha r\cos\Theta$. Integrating this result around the payload interface ring and simplifying yields the following relationship between the axial stiffness, K_{IP}, and the equivalent stiffness moment.

$$M = r\frac{K_{IP}}{2}\alpha \tag{16}$$

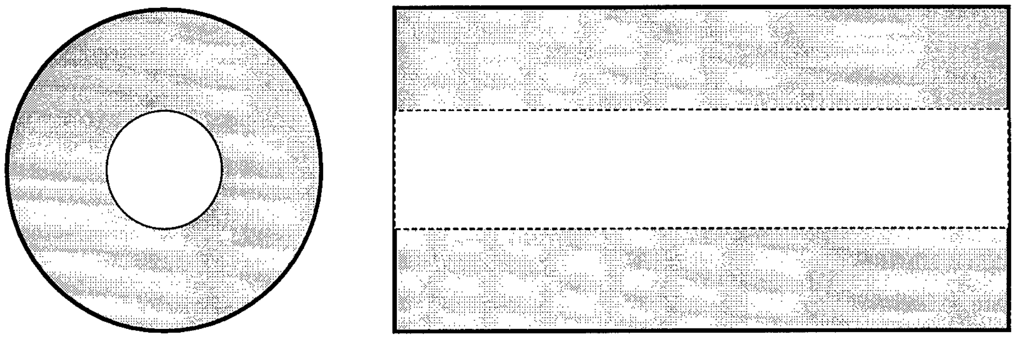

Figure 5 Notional solid rocket motor and case

It is also necessary to develop a method for computing the moments of inertia of the components of the LV. For the solid rocket motor the most common design is a progressive burn design similar to Figure 5. This calls for special consideration as the motor burns and the mass moment of inertia is changing at a rate proportional to the mass flow rate of the operating motor. Also there are mass distribution considerations with the inclusion of a nozzle. The model derived also combines several stages into one degree of freedom.

Equation 17 was used to develop a method for solving the instantaneous mass moment of inertia about the c.m. of the component [10]. The equation is for a cylindrical solid. Thus a shell for the motor case has to be calculated and then a solid for the propellant added back. Likewise, a portion of the propellant has to be removed incrementally as the motor burns. Finally, adding the mass of the nozzle contributes to the total moment of inertia. Equation 15 is the method of calculation.

$$I = \frac{\rho V}{12}\left[3r^2 + l^2\right] \tag{17}$$

$$I_{Compnent} = I_{CaseVolume} - I_{CaseVoid} + I_{\Pr opellantVolume} - I_{\Pr opellantVoid} + I_{Nozzle} \tag{18}$$

For each component the volume of the case, the volume of propellant and wall thickness, and nozzle mass must be specified to fully define the component. Also, the center of mass of each component must be instantaneously computed to properly calculate the contribution of the nozzle.

It is important to note at this point that Equation 16 allows the decoupling of the axial and lateral systems of equations. They are merely linked by the axial stiffness of the interface. This is only true for the simplified lumped mass model developed here. If the system were modeled as beams in bending and compression then there would be a direct coupling of lateral stiffness to axial compression due to the acceleration of the LV [7]. The use of linear springs in the model eliminates this effect.

2.2 Environmental Loads

Three types of loads, other than the quasi-static loads of gravity, thrust and drag are considered. They are motor generated vibration, aeroacoustically generated vibration and gust loads. Each of these is empirically defined so that a representative amount of vibration and load is passed to the satellite at the PAF. The vibration loads presented here are filtered for frequency content in Simulink. A fourth-order Butterworth high-pass filter is used to shape the frequency output of a band-limited white noise source. The purpose is to more closely match the two-sigma spectral density proposed by Larson and Newell for a range of launch vehicles [12]. Also, the frequencies of interest are limited to the 0-100 hertz range [11]. This limitation helps to reduce the stiffness of the equations to be integrated.

2.2.1 Motor Generated Vibration

The motor generated vibration source is defined to originate at the nozzle of the operating stage. It includes a random, band-limited white noise component and a resonant burn component. The resonant burn component is assigned a frequency and amplitude that is representative of the motor being considered. The band-limited white noise component is also assigned a magnitude that results in an appropriate level of vibration at the payload attach fitting (PAF). The random component is also weighted by a ratio of the current thrust to the maximum thrust of the first stage motor. Thus, later stages produce less noise than the first and largest stage. This is true in actual operation [11].

Resonant burn is a condition arising in solid rocket motors when the combustion cavity and the mass flow rate create a resonance. Resonant burn is a problem for large solid rocket motors. The vibrations cause an oscillation of the propellant remaining in the motor [11].

2.2.2 Aeroacoustically Generated Vibration

For the purpose of this model the atmosphere is defined to be isothermal. The temperature is based on the 1976 Standard Atmosphere. An altitude averaged temperature was computed to be 249K. The result is a smooth pressure and density contour into space. Neither value will actually go to zero but this is true for the LEO orbits considered by this model. Thus, the Mach Number of the LV can be expressed by M=v/c. Where the speed of sound, c, is constant for all altitudes. This reduces computational demands and fits well with the simplified drag model also in use. As a result of drag the model demonstrates the orbital instability caused by drag when allowed to run for long times.

Several sources site the transonic flight regime as being the most intense period of aeroacoustic loading [9], [11]. Another period of intense loading is maximum dynamic pressure, or max-q. To that end the vibration load acting on the upper most part of the LV structure is assigned magnitude according to a profile of the Mach number and dynamic pressure. This relationship is given as inversely proportional to Mach number and proportional to the dynamic pressure and density. Empirical tests of the model to create appropriate accelerations at the payload interface dictated the constants used. Thus, the aeroacoustic vibration scale factor is given as Equation 19.

$$S = \rho \left[\frac{1}{\frac{1}{2} + \left|1 - M^2\right|^{0.5}} + 12 \frac{P}{101325} \right] \tag{19}$$

This equation is plotted for first stage flight in Figure 6. Note the peak at approximately 27 seconds. It corresponds to passage through Mach 1.

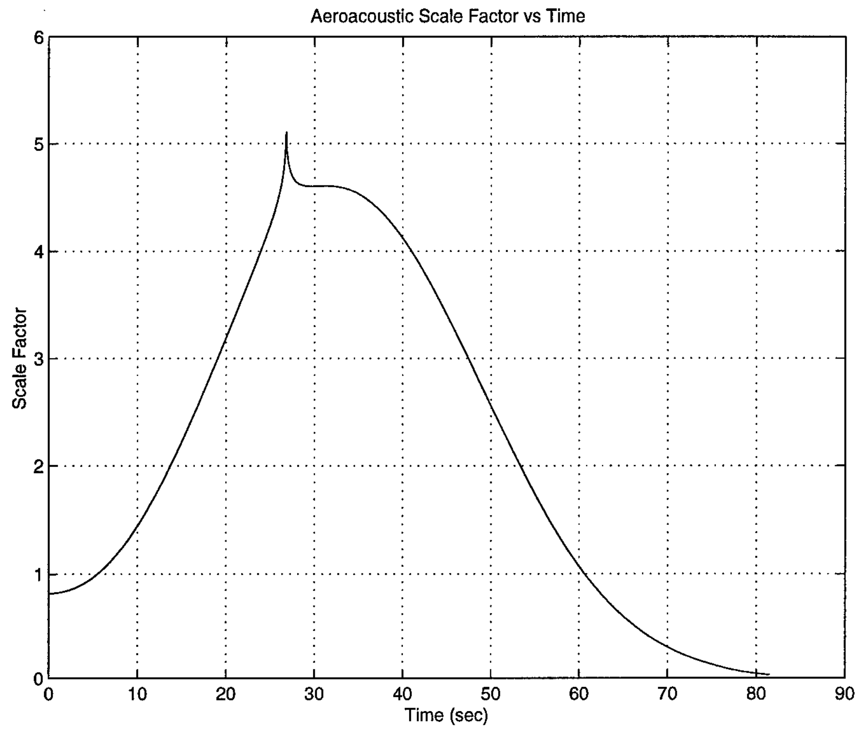

Figure 6 Aeroacoustic Vibration Scale Factor vs Time

2.2.3 Gust Loads

The gust load for the lateral case is modeled as a step input with duration and magnitude tuned to create a resonance with a specified frequency. This is a typical coupled loads analysis approach to creating a gust load [11]. In this model the gust load is input at the base of the Lower component.

2.2.4 Model Mission Profile

The discussion of the model environment would be incomplete without characterizing the mission profile. The profile developed for this study is similar to small solid-propellant launch vehicles. Figure 7 shows the event timing of the LV ascent. The trajectory modeled is an eastern equatorial launch so that planar motion can be assumed.

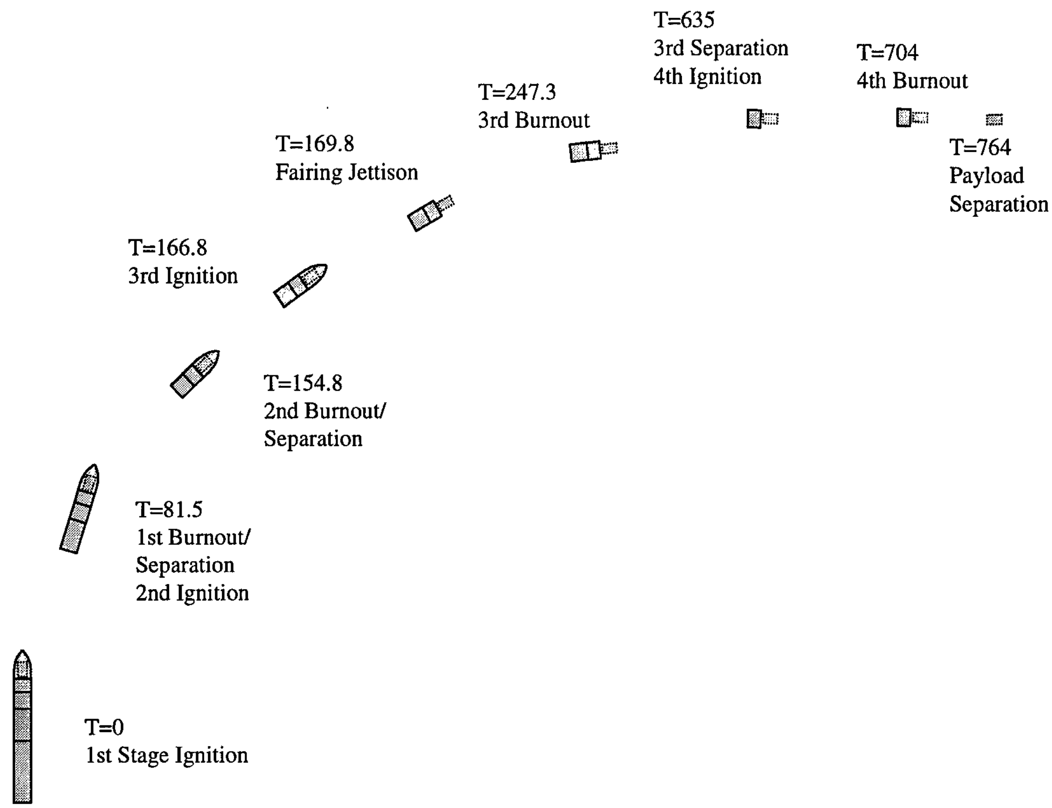

Figure 7 LV mission profile

Further, the basic vehicle parameters are listed in Table 1. These characteristics were required to accurately model the LV.

Combining all of the elements discussed in this chapter results in the total mission acceleration profile that appears in Figure 8. This acceleration profile was generated by the model developed for this research.

	First	Second	Third	Fourth	Payload	PLF
Length (m)	9	8.9	2.7	1.23	2	6
Diameter (m)	2.4	1.3	1.3	1.3	1.3	1.3
Total Mass (kg)	53020	14020	3370	985	1780	205
Propellant Mass (kg)	48809	12152	3025	782		
Case Mass (kg)	3415.7	1631.9	226.3	150.2		
Nozzle Mass (kg)	795.3	235.4	118.7	52.8		
Mass Flow Rate (kg sec^{-1})	-598.883	-166.011	-37.485	-11.333		
Burn Time (sec)	81.5	73.2	80.7	69		
Initial Grain Dia. (m)	0.4	0.3	0.15	0.1		
Propellant Density (kg m^{-3})	1354.013	1277.124	960.723	614.027		
Case Density (kg m^{-3})	8010.822	7911.227	8001.177	7996.407		
Case Wall Thickness (m)	0.0063	0.0057	0.00257	0.00375		

Table 1 LV Physical Properties

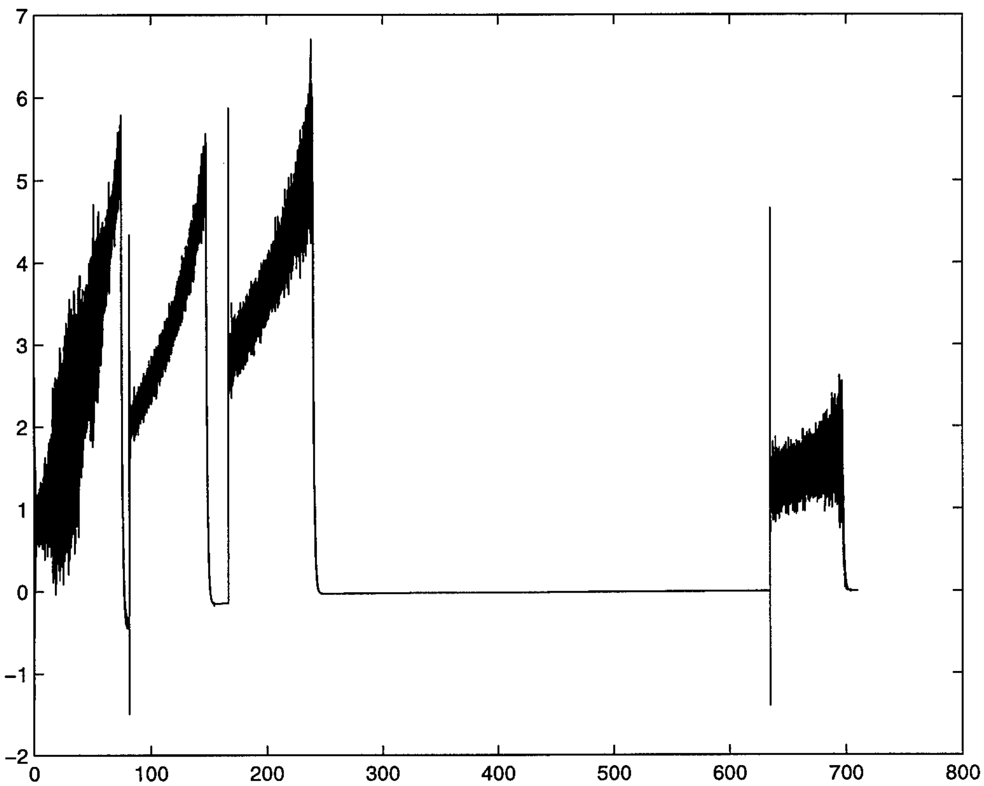

Figure 8 Full mission acceleration profile

2.3 Controller Theories

The controller theories studied for this thesis are briefly discussed. Proportional (P), proportional plus derivative (PD), proportional plus integral (PI), and proportional plus integral plus derivative (PID) are the classic control methods explored as alternatives for hybrid isolation. Positive position feedback (PPF was also studied.

2.3.1 PI, PD, and PID

PI, PD ad PID are the standards of discussion for most classical control approaches. These controllers are developed for negative closed-loop feedback. Many of the controller design methods are prescribed for this controller family. Tools like root-locus and Bode diagrams have detailed design methodologies to support PID control.

The fundamental PID controller feedback equation is shown below in Equation 20. Proportional control retains only the gain K. The $K_I s^{-1}$ is the integral term, and the term $K_D s$ is the derivative control term.

$$G(s) = K + \frac{K_I}{s} + K_D s \tag{20}$$

For a more detailed discussion of PI, PD, and PID control and other classical control methods, please refer to Reference [5].

2.3.2 Positive Position Feedback

The positive position feedback (PPF) control law is shown in Equation 21. The first equation listed is the equation of motion of the system. The disturbance force is d, and control force is $\gamma\omega_n^2 Z$. The active feedback equation specifies the frequency to be isolated, ω_c, and takes its input from the position, X, of the payload component. The appearance of the PPF equations is similar to a 2DoF system, however Equation 21b is of a virtual mass.

$$\ddot{X} + 2\zeta\omega_n\dot{X} + \omega_n^2 X = \gamma\omega_n^2 Z + d \tag{21a}$$

$$\ddot{Z} + 2\zeta_c\omega_c\dot{Z} + \omega_n^2 Z = \omega_c^2 X \tag{21b}$$

For a more detailed discussion of PPF control, please refer to Goh and Caughey (1985) [6].

2.4 Model Layout

The top-level Simulink model is briefly addressed in this section. The model is discussed in nauseating detail in Appendix A. Appendix B provides the source code listing of the various models implemented for the analysis presented in Section 3.

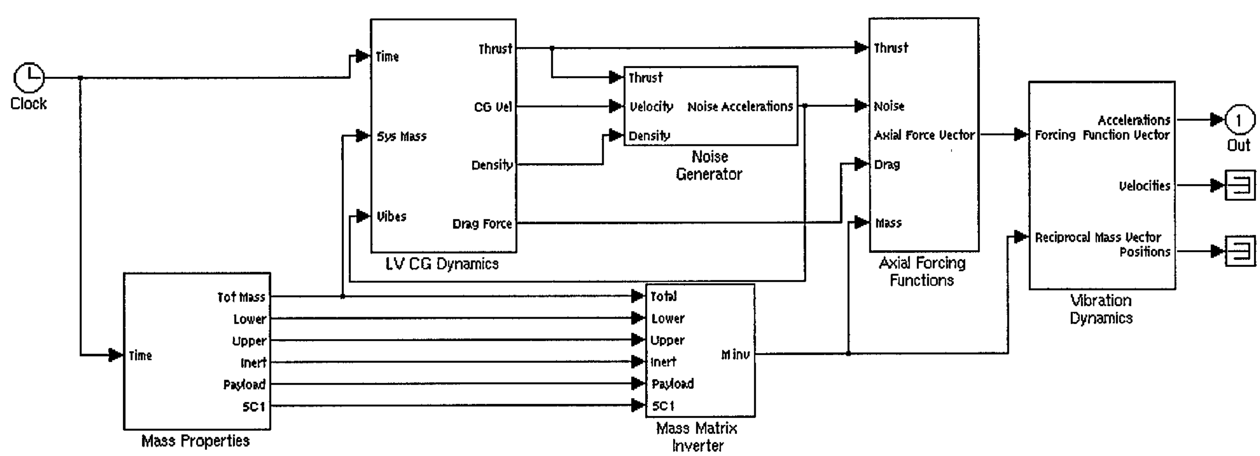

Figure 9 The top-level diagram of the passive isolation model

Figure 9 is of the top-level model. Without exception, the blocks at this level are sub-systems or masked blocks. This top-level view emphasizes that the clock drives the model. The clock drives many events of the model. Staging, gusts and other flight events are triggered by the clock. The model divides roughly into two parts – environment generation and dynamic output. The *Noise Generator*, *LV CG Dynamics*, and *Mass Properties* blocks generate the environment that excites the model vibration dynamics. The *Axial Forcing Functions* and the *Axial Vibration Dynamics* calculate the dynamic output of the model. The end results are the positions, velocities and accelerations of the LV components. The model demonstrates this flow from clock to dynamic output. The blocks of the model can be combined to create new models.

Environment generation in any simulation is the same. The three blocks, *LV CG Dynamics*, *Mass Properties* and the *Noise Generator*, are used universally. These blocks represent the characteristics of the launch vehicle and its mission profile. These are the only three time dependent blocks and are the source of the full simulation's non-linearity. These will be discussed later in Appendix A. The *LV CG Dynamics* block is based on the gravity-turn equations derived in Section 2.1.1.

The most basic model is the five-DoF simulation in Figure 9. Adding active controls results in models similar to Figure 10. This model uses model reference adaptive control. The LV model can be radically simplified to use a state-space linear time invariant representation for rapid controller prototyping as in Figure 11. Note that in the state-space model the dynamic output does not rely on the different component masses due to time-invariance. This model approximates the vehicle's state at 27 seconds after launch. The state-space block calls on workspace variables defined in sscont3ppf.m

(Appendix B) executed prior to the simulation that establish the time invariant model components.

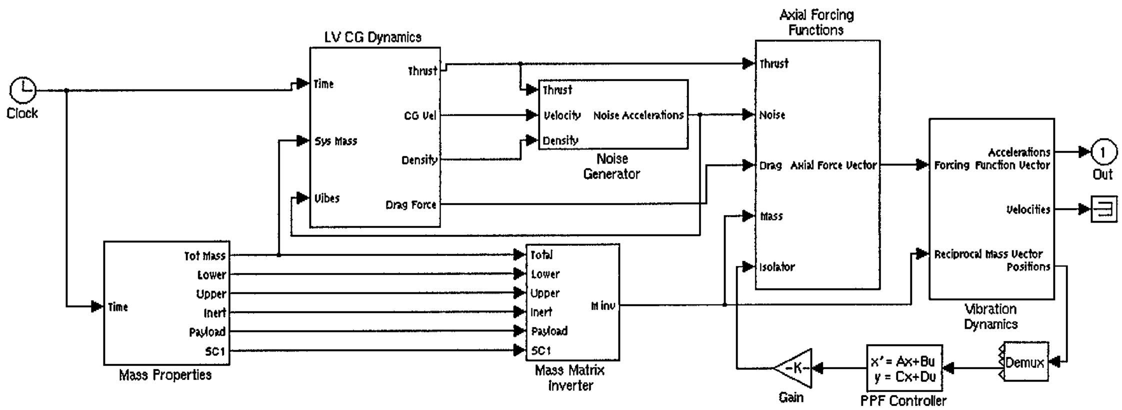

Figure 10 Model of hybrid isolation system using PPF

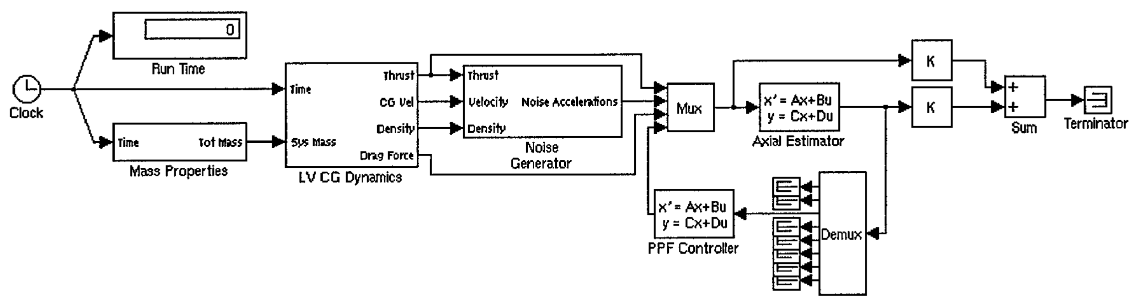

Figure 11 Estimator model of hybrid isolation system using PPF control

2.5 Summary of Axial and Lateral Equations

The equations of lateral and axial motion compared side-by-side. The reader will note that the only dependence the lateral equations have on the axial equations is the stiffness of the payload interface. This fact is substantiated by the assumption of a linear spring separating the Payload and Inert model components.

$$m_L \ddot{X}_L = -K_{LU} - C_{LU} + \left(1 - \frac{m_L}{m_G}\right)(T + N_M) - \frac{m_L}{m_G}(-D + N_A) \tag{10a}$$

$$m_U \ddot{X}_U = -K_{UI} - C_{UI} + K_{LU} + C_{LU} - \frac{m_U}{m_G}(T + N_M - D + N_A) \tag{10b}$$

$$m_I \ddot{X}_I = -K_{IP} - C_{IP} + K_{UI} + C_{UI} - D + N_A - I_L - I_R + \left(1 - \frac{m_I}{m_G}\right)(-D + N_A) - \frac{m_I}{m_G}(T + N_M) \tag{10c}$$

$$m_P \ddot{X}_P = -K_{P1} - C_{P1} + K_{IP} + C_{IP} + I_L + I_R - \frac{m_P}{m_G}(T + N_M - D + N_A) \tag{10d}$$

$$m_1 \ddot{X}_1 = K_{P1} + C_{P1} - \frac{m_1}{m_G}(T + N_M - D + N_A) \tag{10e}$$

Equation 10 above is the axial equations and Equation 13 below is the lateral equations of motion.

$$I_L \ddot{\Theta}_L = -C_{MLU}(\dot{\Theta}_L - \dot{\Theta}_u) - K_{MLU}(\Theta_L - \Theta_U) + M_L \tag{13a}$$

$$I_U \ddot{\Theta}_U = -C_{MUI}(\dot{\Theta}_U - \dot{\Theta}_I) - K_{MUI}(\Theta_U - \Theta_I) + C_{MLU}(\dot{\Theta}_L - \dot{\Theta}_U) + K_{MLU}(\Theta_L - \Theta_U) + M_U \tag{13b}$$

$$I_I \ddot{\Theta}_I = -\frac{d}{4}C_{IP}(\dot{\Theta}_I - \dot{\Theta}_P) - \frac{d}{4}K_{IP}(\Theta_I - \Theta_P) + C_{MUI}(\dot{\Theta}_U - \dot{\Theta}_I) + K_{MUI}(\Theta_U - \Theta_I) + M_I \tag{13c}$$

$$I_P \ddot{\Theta}_P = -C_{MP2}(\dot{\Theta}_P - \dot{\Theta}_2) - K_{MP2}(\Theta_P - \Theta_2) + \frac{d}{4}C_{IP}(\dot{\Theta}_I - \dot{\Theta}_P) + \frac{d}{4}K_{IP}(\Theta_I - \Theta_P) + M_P \tag{13d}$$

$$I_2 \ddot{\Theta}_2 = C_{P2}(\dot{\Theta}_P - \dot{\Theta}_2) + K_{P2}(\Theta_P - \Theta_2) + M_2 \tag{13e}$$

3 Isolation Results

The results and analysis of data collected using the models described in the previous section is presented. The aim of the research was to show that passive and hybrid isolation of whole spacecraft from the LV induced vibration environment substantially reduce the loads felt by the spacecraft and a payload sub-component. While equations of the axial and lateral case were derived, it was shown that the axial and lateral cases de-couple. Thus, the focus of this paper will be on the axial case alone.

This section is organized in the following fashion. After developing the baseline response of the model (Section 3.1), the passive isolation results will be analyzed (Section 3.2). The hybrid results will then be presented in Section 3.3. The isolation system effectiveness is compared to the baseline system repeatedly. In each case the analysis will focus on the first 90 seconds of flight. This time period captures ignition, transonic flight, max-q, and staging/ignition of stage two. In addition, the chief variable in the performance analysis is the passive isolator critical frequency. The analysis of the model will focus on passive isolator frequencies between 25 and 40 Hz. This band brackets the second mode range during the transonic and max-q flight periods.

Several methods of comparison will be used to analyze the effectiveness of a particular isolation combination. Power spectral density (PSD) comparisons of the acceleration of the Baseline, Passive and Hybrid systems for the Payload and Sub-component are used. Supplementing the PSD is the spectrogram. The spectrogram is a time history of the PSD of the model. It takes small time slices of the output signal and performs a fast Fourier transform of those slices to create a plot mapping the intensity of a given frequency band with respect to time. Finally, the root-mean-sum-square (RMS) of the acceleration of a given component is computed for each run. Comparison of the RMS boils the performance of an isolator combination down to a single number.

3.1 Baseline Characterization

Of the five degrees of freedom of the model, the spacecraft comprises two. The satellite modeled has a mass of 1780 kg. The Sub-component of the payload is 1 kg. The Sub-component has as its critical vibration frequency, 50 Hz. This was chosen to match the resonant burn frequency (also 50 Hz) of the first stage.

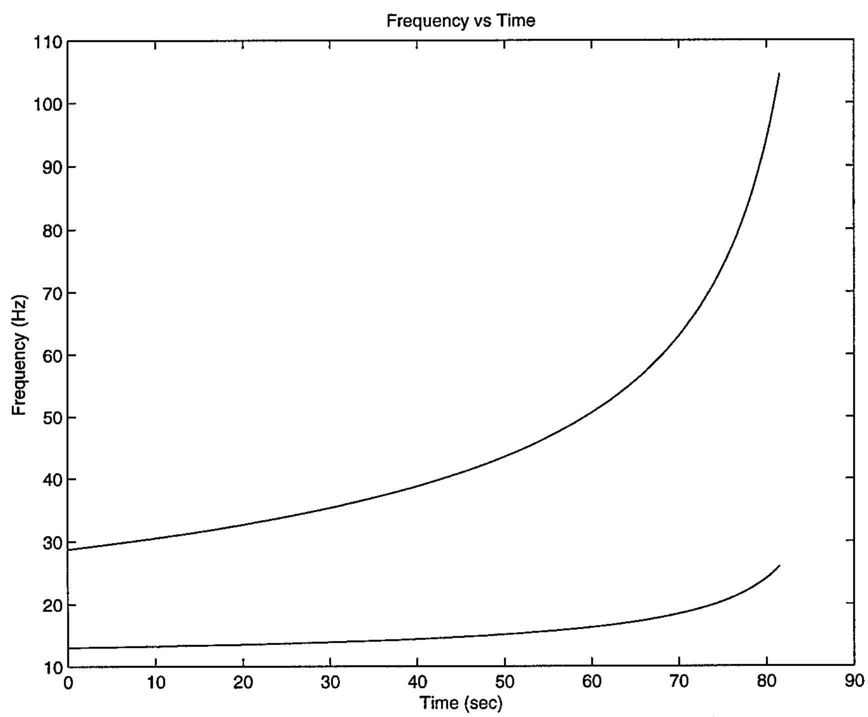

Figure 12 First Stage LV structural modes

Given the non-linearity and time-variance of the model, some expectation of the behavior of the model is needed. The mass of the LV changes constantly as the motor operates. This causes the mass of the Lower and Upper component of the model to lessen. This lessening of mass combined with constant structural stiffness of the LV will cause the LV modes to constantly vary throughout stage operation. It will be necessary to consider this variation and the multiple modes of the LV structure to select a successful isolation design. Figure 12 plots the time-varying modes of the LV. It supports the previous conclusion and the results of past analysis of launch vehicle structural modes [7].

The inter-component stiffness were $k_{LU} = 4x10^8$ N/m and $k_{UI} = 1x10^8$ N/m. As the diagram above shows this creates a low frequency first mode that varies only slightly, and a rapidly changing higher frequency mode. This second mode has the important feature of transitioning through the critical frequency of the model Sub-component. This combined with resonant burn of the first stage motor creates several resonance situations.

The baseline LV/Payload system is taken from the five DoF model. The baseline is intended to represent a spacecraft that is hard-mounted to the payload attach fitting (PAF). The PAF is generally a ring to which the spacecraft separation system is attached. The payload isolation system mounts between the PAF and the spacecraft separation system.

In the model, the hard-mounted case is considered to be an extremely stiff linear spring between the Inert and Payload components. The critical frequency of the hard-mount is 200 Hz. The first figure presented is the spectrogram of the baseline system (See Figure 13). Clearly visible in the spectrogram are the first and second modes of the LV, and the resonant burn condition, which exists throughout first stage operation. At 80-82 seconds after launch the second stage event is obvious as a broadband shock.

Intensification at approximately 60 seconds after launch is visible along the 50 Hz line as the resonant burn and second LV mode cross. The black band along the right edge of the graph is an artifact of scaling and FFT windowing.

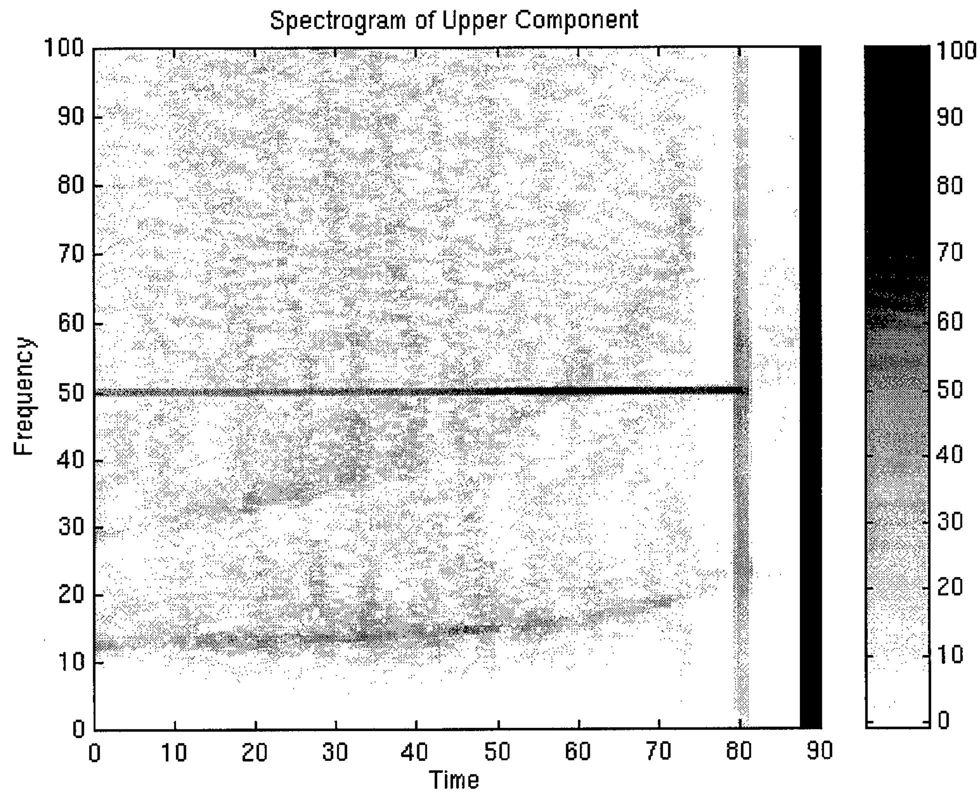

Figure 13 Baseline Spectrogram of Upper Component

The next three diagrams are power spectral density (PSD) plots of the frequency response of the Inert component, Payload component and Sub-component. The PSDs are time averaged frequency response plots. It is easy to locate the LV modes and in the case of (Fig SC) the critical frequency of the Sub-component is the prominent feature of the diagram.

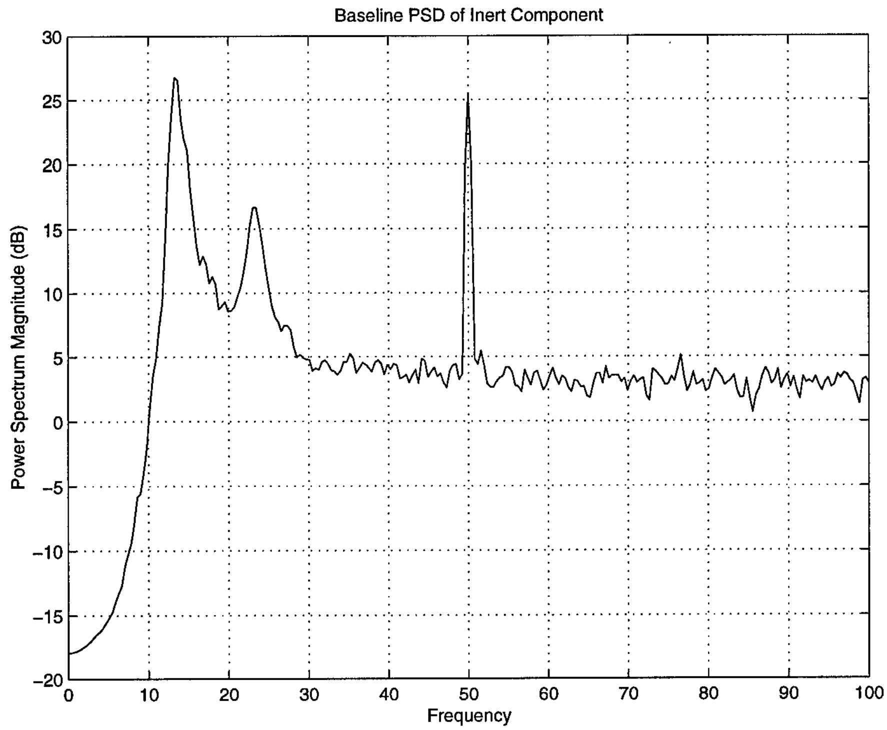

Figure 14 Baseline PSD of Inert Component

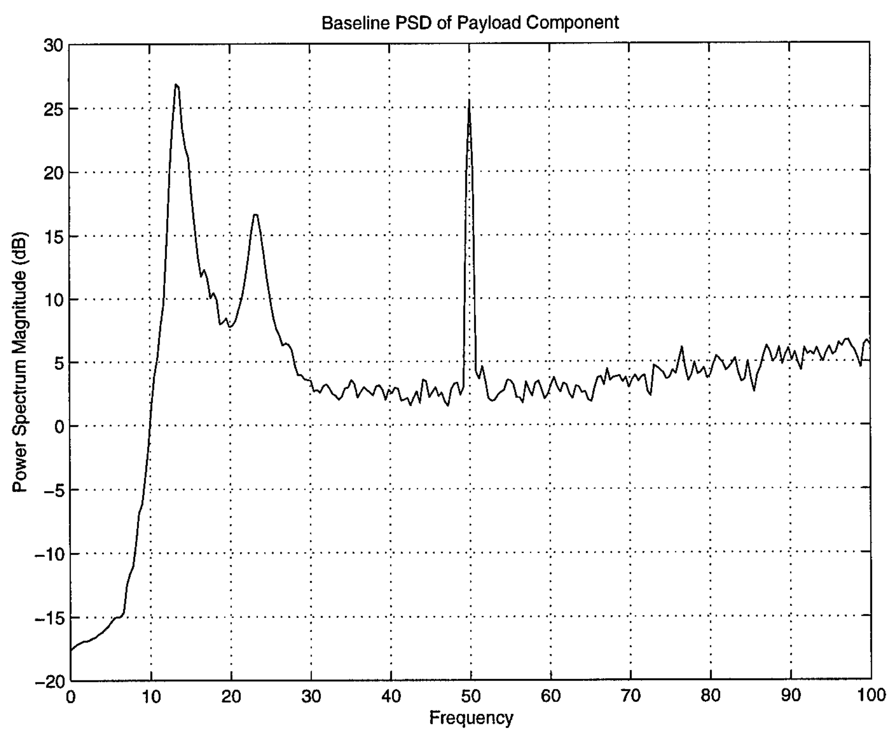

Figure 15 Baseline PSD of Payload Component

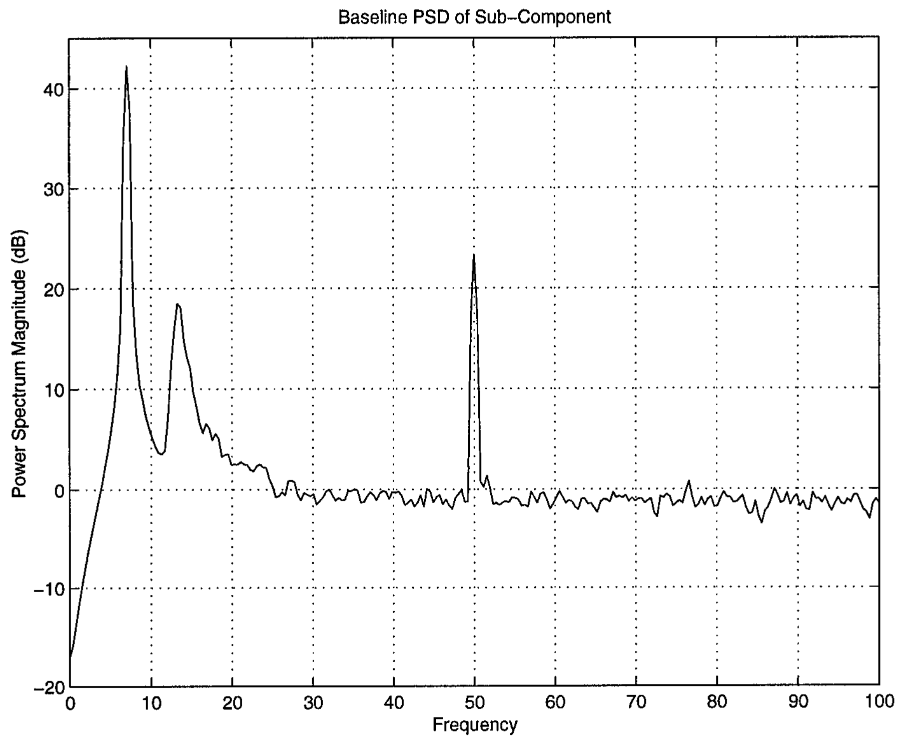

Figure 16 Baseline PSD of Sub-component

The RMS acceleration in *g* of the Payload and Sub-component of the baseline case are listed in Table 2.

	Baseline-PL	Baseline-SC
Acceleration (g)	13.35	0.7716

Table 2 Baseline RMS – g acceleration of the Payload and Sub-component

Spectrograms of the Payload and Sub-component indicate the environmental factors that most influence the system dynamics. Figure 17 is the spectrogram of the baseline system for the Payload component. The most prominent features of this figure are the trace of the first LV mode, the intensification of the 50 Hz excitation at approximately 50 seconds, and the broadband impact of the staging event at 81.5 seconds.

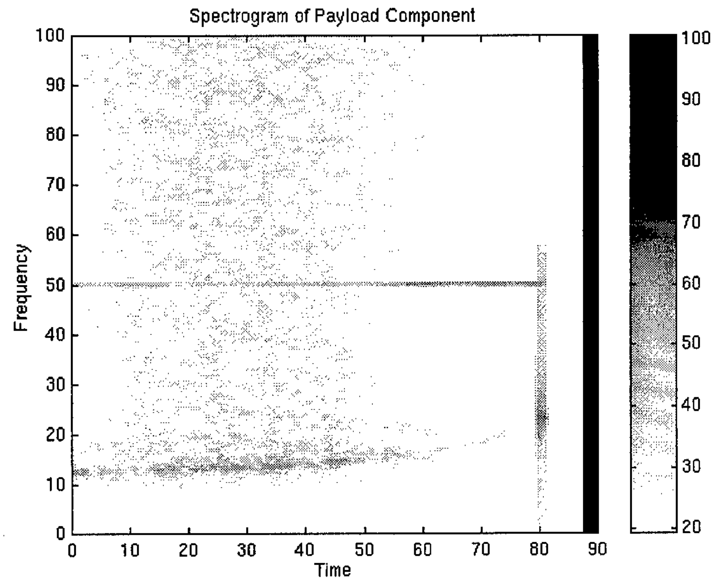

Figure 17 Baseline Spectrogram of Payload Component

The baseline spectrogram of the Sub-component is included in Figure 18.

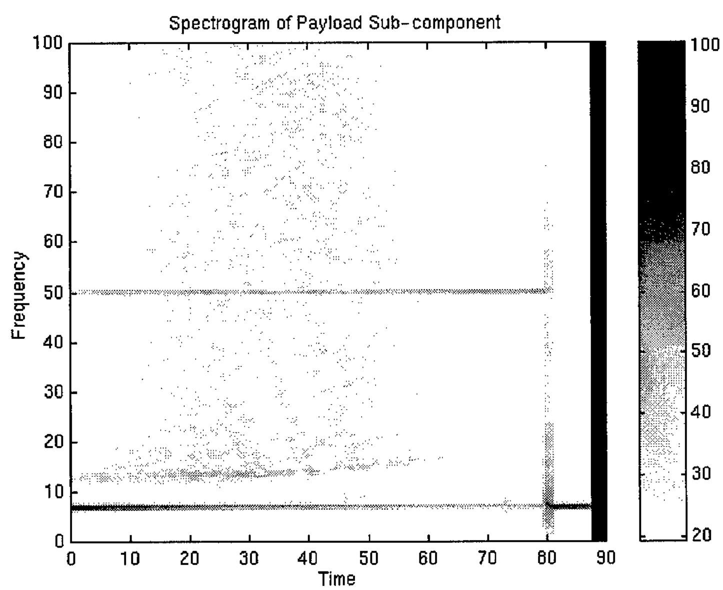

Figure 18 Baseline Spectrogram of the Sub-component

The most significant feature of the spectrogram of the Sub-component is the appearance of a mode at 7 Hz. This mode was not predicted by analysis of the system.

3.2 Passive Isolation Results

Use of passive isolation in the full model is marked by significant load reduction for the whole spacecraft. The Sub-component experiences a minor increase in loading, but for the most part remains near the un-isolated response level.

3.2.1 Overall System Response

The passive isolator was studied for first stage flight, from zero to 90 seconds. A range of passive isolator frequencies (Critical Frequencies: 25-40 Hz) was studied so that a broader understanding of the effects of passive isolation was possible. Figure 19 shows the RMS – g acceleration of the payload and Sub-component. The Payload (or whole spacecraft) greatly benefits from the passive isolator at all frequencies observed. However, the Sub-component experiences increasing loading as the isolator frequency is increased. This is expected, because harmonic excitation from the resonant burn effect is enhanced by the resonance of the passive isolator.

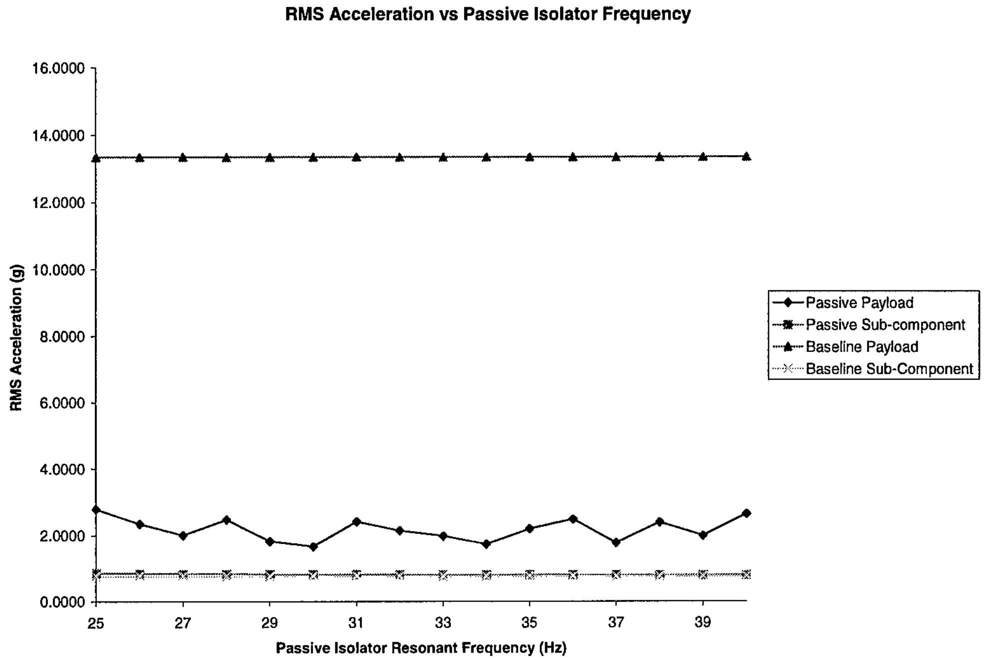

Figure 19 Passive isolator effectiveness vs passive isolator frequency

Data was not taken in the vicinity of the first LV mode (13.2 Hz at lift-off), because the lateral mode of the Payload component with a low frequency passive isolator might be low enough to interact with the guidance, navigation and control of a real LV. Thus, 25 Hz was chosen as a reasonable lower limit. The data show that the passive isolator significantly reduces payload vibration for the entire range of passive isolator critical frequencies. In addition, there is a marginal increase for the Sub-component. Figure 20 compares the passive isolated Sub-component to the baseline case. The gradually reduced loading continues beyond 40 Hz. At 70 Hz the Sub-component acceleration is less than that of the baseline case. Figure 21 explains this result. The crossover of the Payload baseline and passive isolated case occurs at approximately 60Hz. Thus, in the case of this model, satellite components with resonance above 60 Hz will be further isolated, but below 60 Hz satellite sub-components will experience increased loading.

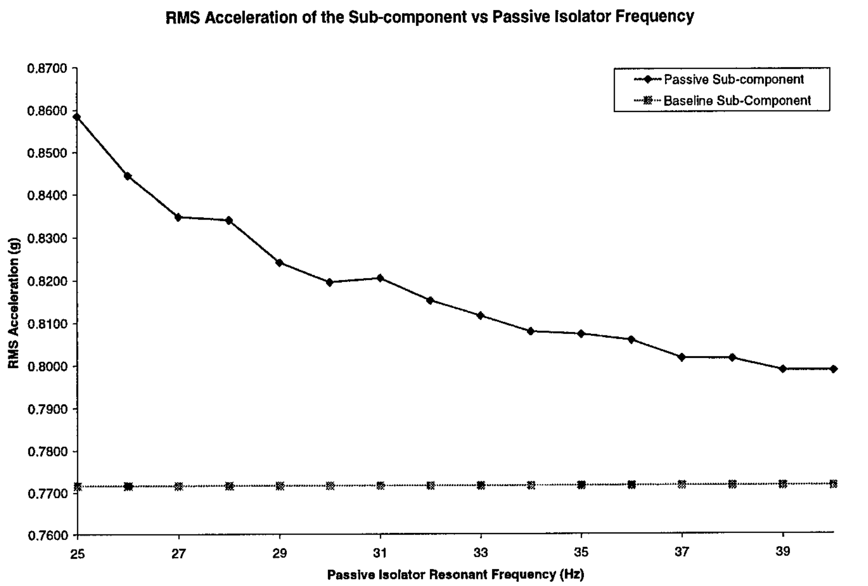

Figure 20 Passive Isolator Effect on the Sub-Component

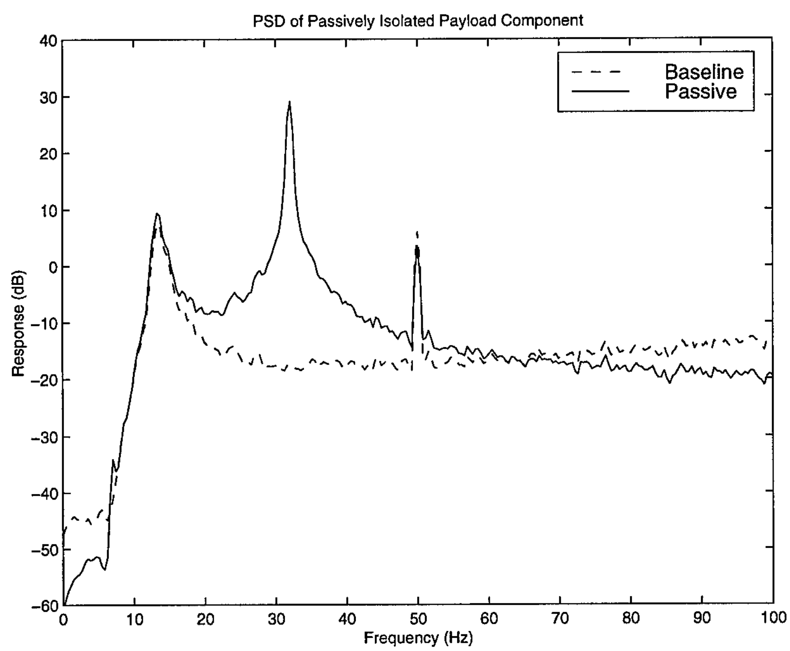

Figure 21 PSD indicating 60 Hz crossover frequency on the Payload Component

3.2.2 Best Case Response: 30 Hz Passive Isolator Critical Frequency

The best result is obtained at a passive isolator critical frequency of 30 Hz. At this frequency the passive isolator reduces the vibration load on the payload 87.5 percent from the baseline case. This isolation frequency is discussed in more detail.

Figure 22 is the PSD of the Payload component. The plot compares the baseline and passive isolation case at an isolator resonant frequency of 30 Hz. The passive isolator effectively attenuates all frequencies above 30 Hz. The isolator notably reduces the response to the resonant burn excitation at 50 Hz. Figure 23 of the Sub-component further confirms the earlier discussion that the passive isolation does little to change the response of the Sub-component.

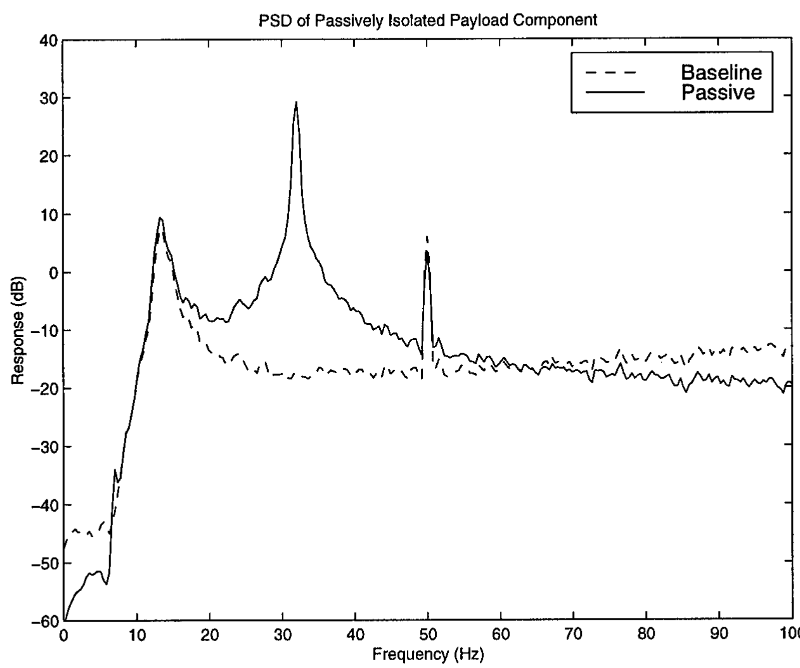

Figure 22 PSD of Passive Isolated Payload Component

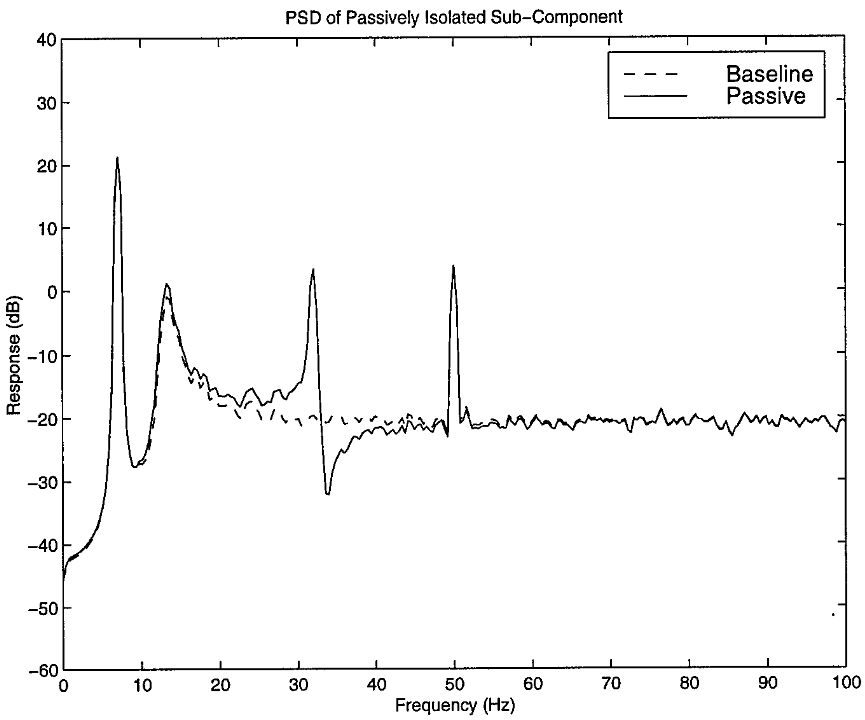

Figure 23 PSD of Passive Isolated Sub-Component

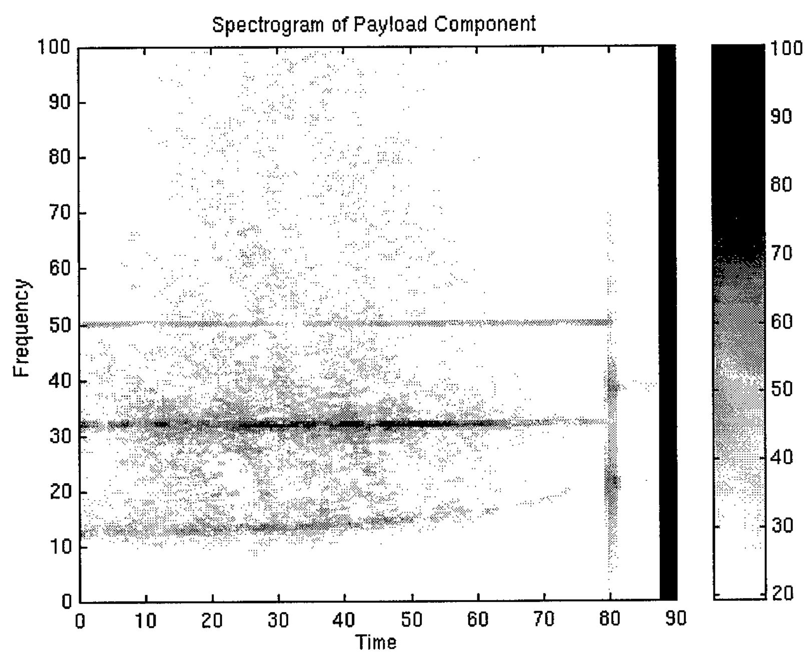

Figure 24 Spectrogram of the Passive Isolated Payload Component

The spectrogram of the Payload component in Figure 24 clearly shows the passive isolator critical frequency at 30 Hz. Comparisons of this to the baseline spectrogram may seem to indicate overall intensified loading the isolator significantly attenuates high frequency vibration loading. This reduces loading by 87.5% from the baseline case for the Payload component. Figure 25 is the spectrogram of the Sub-component. The passive isolator's effect is apparent by the overall leveling of the loads on the Sub-component.

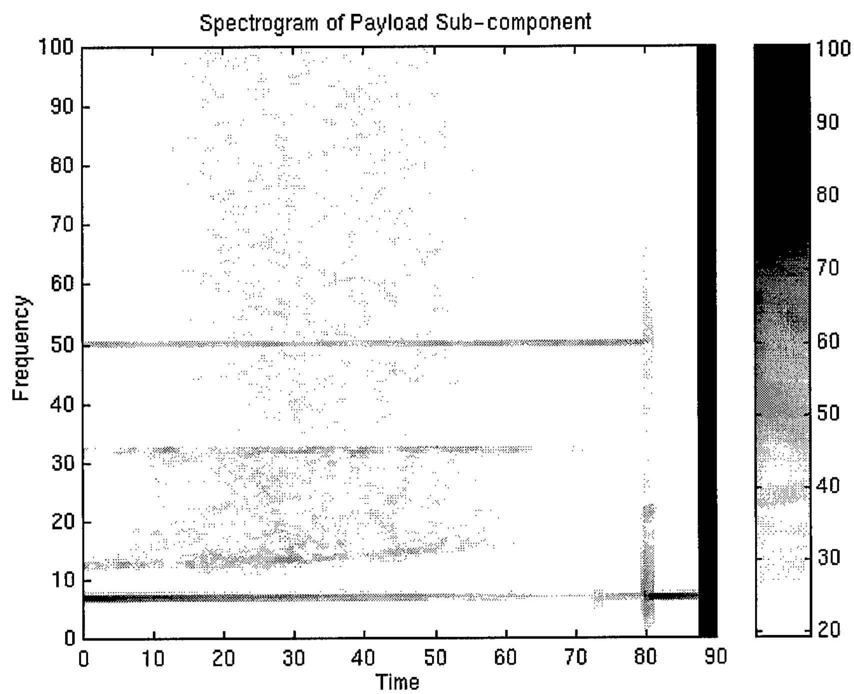

Figure 25 Spectrogram of the Passive isolated Sub-component

3.2.3 Damping Ratio Effects on the Passive Isolator

The effect of damping ratio was also explored. The damping ratio was allowed to vary between 0.25% and 4%. The range reflects the use of visco-elastic damping applications to the passive isolation system. At each passive isolator critical frequency the damping ratio was doubled. 0 shows that over the available range the damping ratio made little difference to the response of the payload.

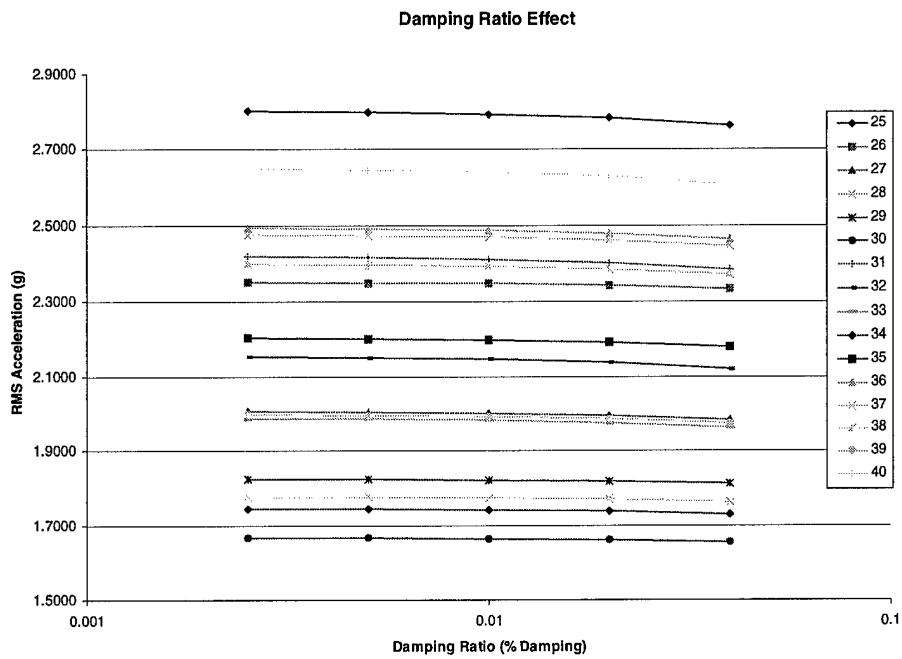

Figure 26 Effect of Damping Ratio Variations on the Payload Component

3.3 Hybrid Isolation Results

Extending on the passive isolation concept is hybrid isolation. Hybrid isolation is the combination of passive and active vibration control. Most hybrid concepts collocate the passive and active controllers. One suggested design is the placement of piezo-ceramic actuator stacks in the high strain areas of the passive isolator [19]. In this way, the hybrid design seeks to maintain the fail-safe capability of passive isolation, should the active component fail.

Implementing an active control design involves taking acceleration data with accelerometers or position data from strain calculations based on output from the piezo-ceramic stacks. This data is in turn used as input to the controller scheme. The output of the controller is then used to drive the active component of the isolation system

Again, data on various hybrid designs was taken across a range of critical frequencies for the passive isolator (25-40 Hz). This variability was needed to explore the synergy of passive and active control. At each passive isolator frequency, the active component was tuned to maximize effectiveness. Among time-invariant control designs, proportional-plus-integral-plus-derivative (PID) and positive position feedback (PPF) were attempted.

3.3.1 Overall System Response

An interesting result of the hybrid control is an apparent dependence on the passive isolator critical frequency for the amount of load attenuation that is gained by hybrid isolation. At some frequencies there is increased loading compared to the passive isolation case. The same effect was observed for the passive case. Figure 27 compares the passive isolated and hybrid isolated Payload component. Notably the passive isolator outperforms the hybrid isolator and conversely the hybrid creates gains over the passive case

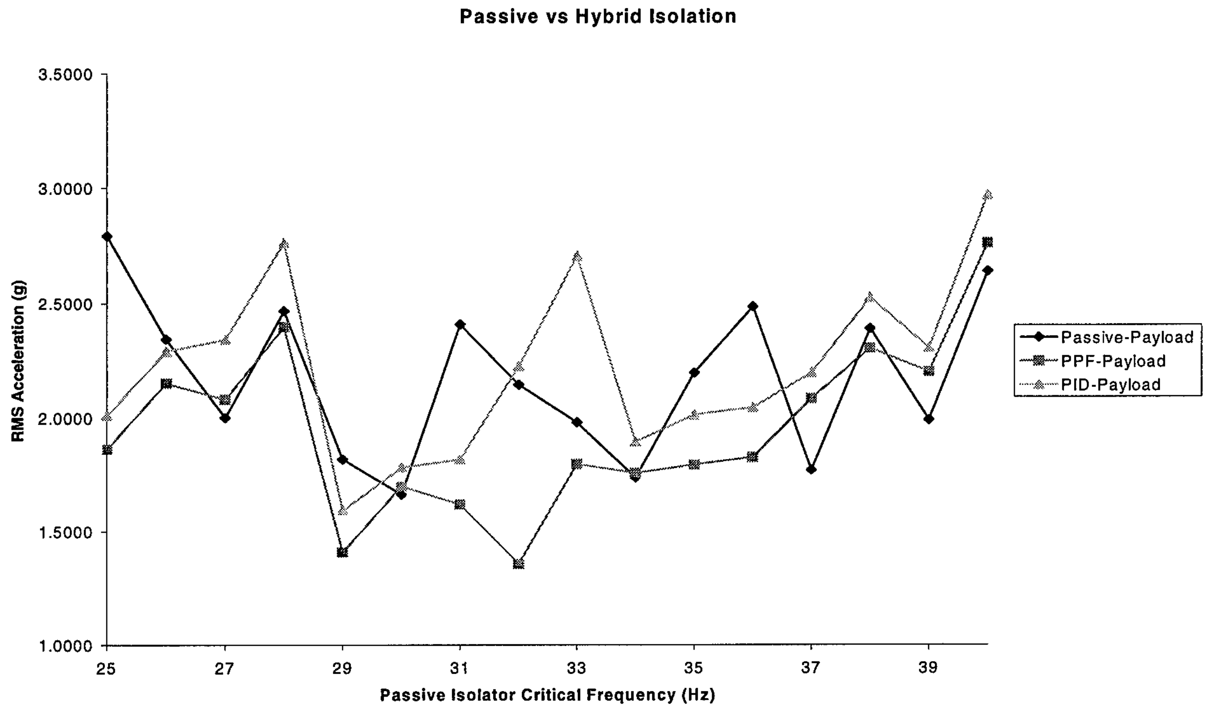

Figure 27 .Passive vs Hybrid Isolation at the Payload Component

Over the range of passive isolator critical frequencies studied, the average improvement was an 83.7% reduction in g-loading on the whole satellite. Hybrid isolation improves on passive another 9.8%.As was mentioned previously, PID and PPF were studied as potential active control laws. Figure 28 demonstrates there is little difference in the effectiveness of either control design. Other factors outside of the scope of this thesis that may realistically influence control law choice are control power required to effectively deploy the design, and ease of implementation. By ease of implementation, recognize that PID requires accelerometers installed on the satellite, while PPF will require the use of strain measurements to estimate the relative position of the Payload to the interface.

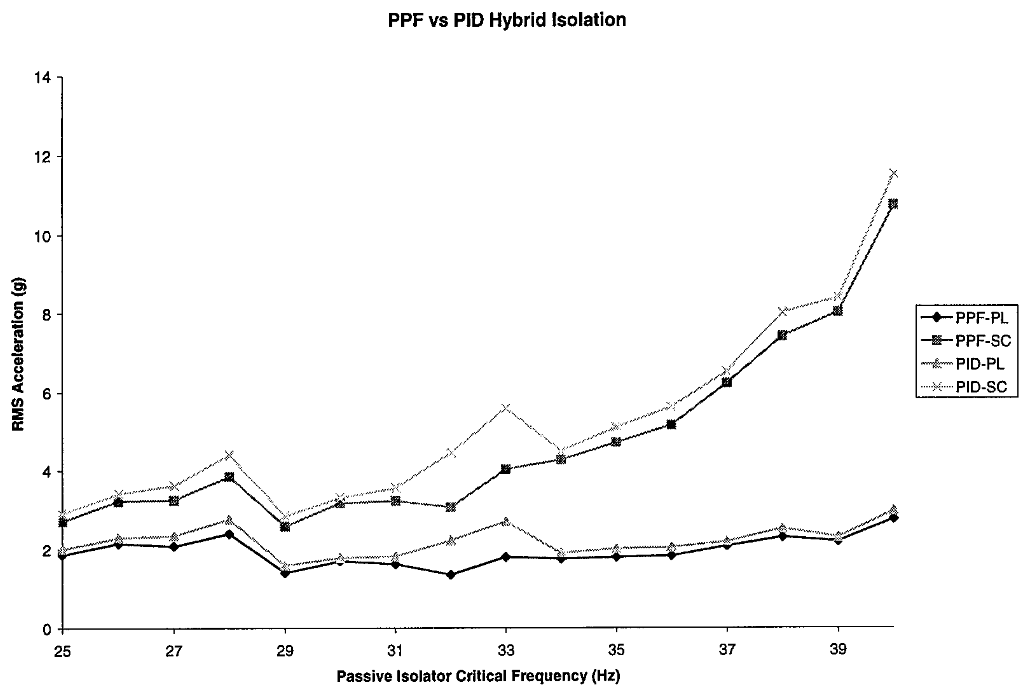

Figure 28 PPF vs PID Hybrid Isolation

Figure 28 also indicates a potential risk of using hybrid isolation. While tremendous improvements are recognized by the use of passive isolation, and on average hybrid isolation increases attenuation on the Payload, the Sub-component is exposed to a greater level of loading. This effect is difficult to explain. A potential explanation may be that the active component creates harmonic excitation at a frequency that is a multiple of the critical frequency of the Sub-component. Another cause may be that the active controller creates a steady-state error that is transmitted to the Sub-component.

3.3.2 Best Case Response: 32 Hz Passive Isolator Critical Frequency

For PPF control, the next two plots bear this last concept out. Figure 29 compares the ratio of the PSD of the passively isolated and the hybrid (PPF) isolated Payload component to the baseline un-isolated Payload component. The diagram shows the steady-state error introduced by the hybrid isolator, and it also shows where the PPF controller has eliminated the response of the first LV mode and has reduced the response at the passive isolator critical frequency. The passive isolator critical frequency in this plot is 32 Hz.

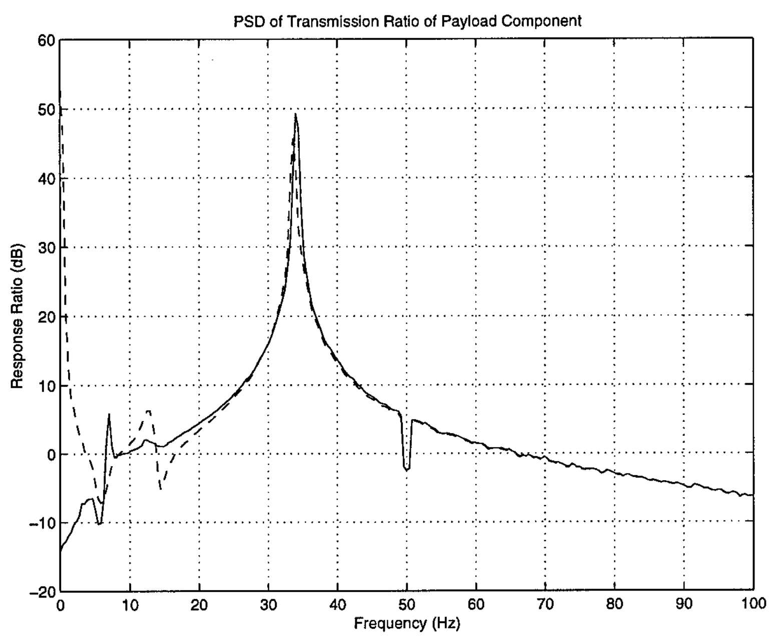

Figure 29 Transmission ratio comparison: Passive and Hybrid (PPF) Systems

A further comparison of the hybrid and passive case is possible by examining the ratio of the PSDs of the hybrid and passive. This is plotted in Figure. The PPF controller is tuned at three frequencies – the first LV mode (~13.2 Hz), the passive isolator critical frequency (~31.5 Hz) and the resonant frequency of the Sub-component (~49.5 Hz). The plot shows that the active controller affects the frequency response in the vicinity of the frequencies addressed by the PPF control law.

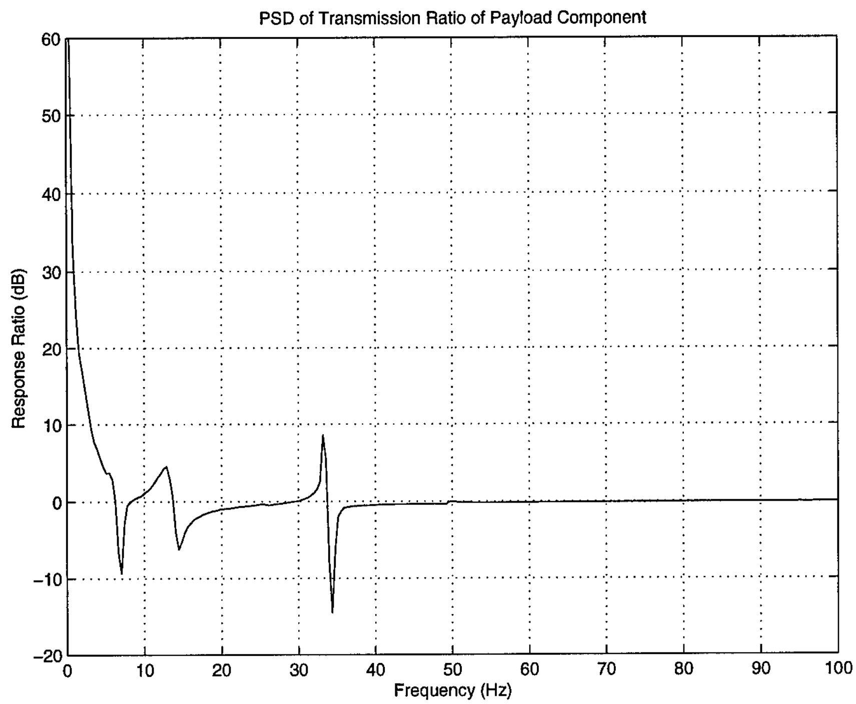

Figure 30 Ratio of the Passive and Hybrid (PPF) PSDs

While the PPF controller introduces substantial steady-state error, the following plots of the PSDs of a hybrid system using PID control indicate that PID control adds no steady-state error into the system. Continuing the comparison at a passive isolator critical frequency of 32 Hz, Figure 31 plots the transmission ratios of the passive and hybrid systems. Unlike Figure 29, there is no steady-state error in the system, yet PID eliminates the first LV mode, like the PPF controller. Thus, steady-state error introduced by the controller cannot be the culprit for the increased loading on the Sub-component.

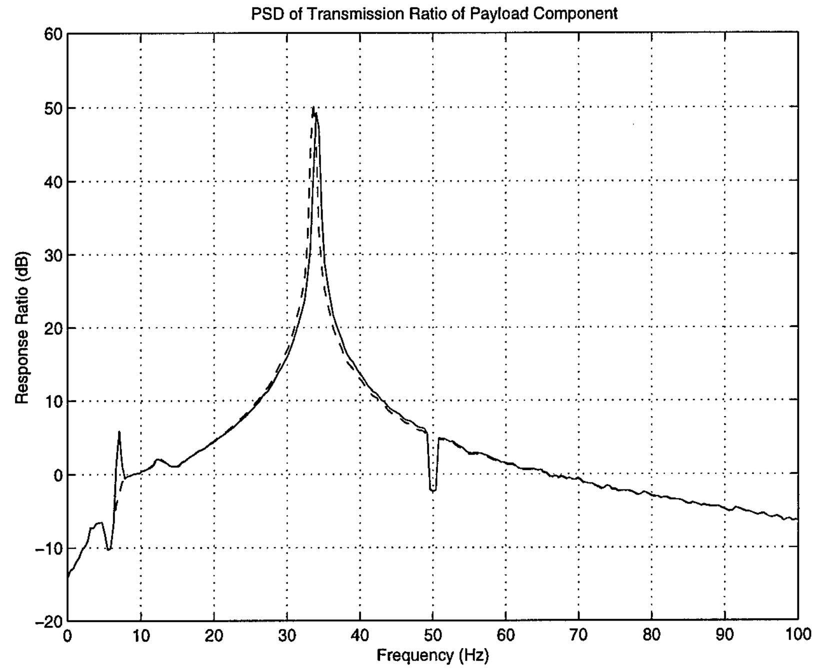

Figure 31 Transmission ratio comparison: Passive and Hybrid (PID)

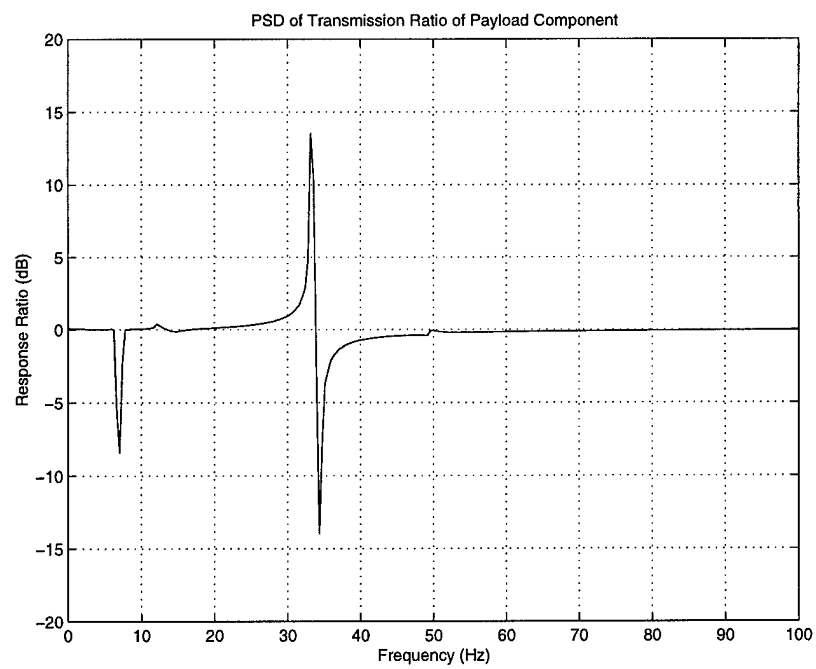

Figure 32 Ratio of the Passive and Hybrid (PID) PSD

Figure 32 clearly shows how the PID controller notches the first LV mode (13.2 Hz) and by lowering the effective frequency of the passive isolator creates a symmetrical amplification then attenuation around the passive isolator. The gains to be gotten from PID will be from how aggressively the controller attenuates the first LV mode.

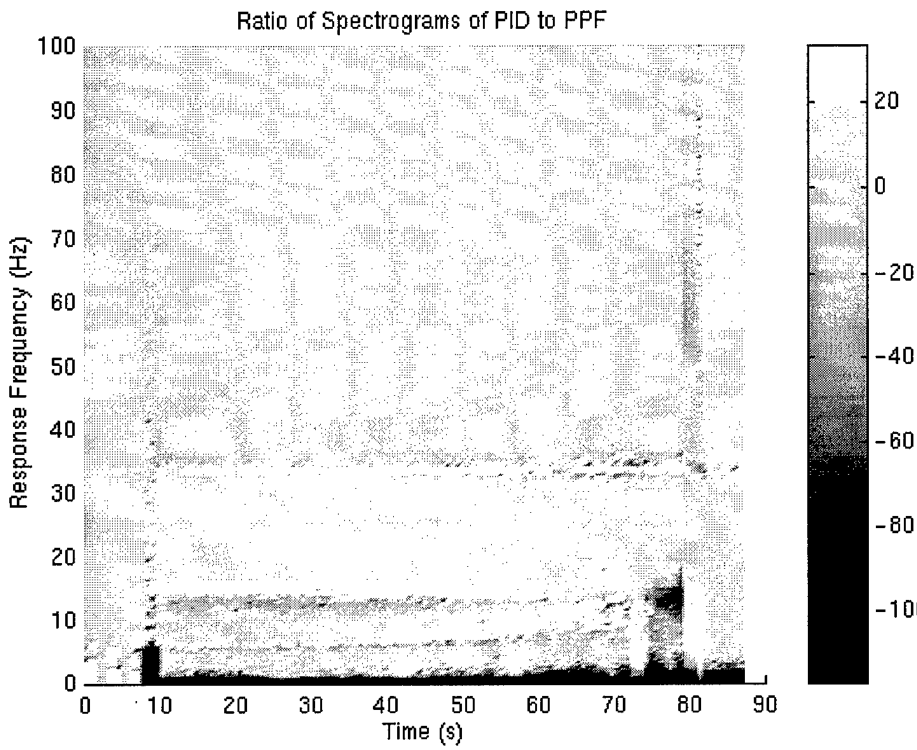

Figure 33 Ratio of the Spectrograms of PID to PPF at 32 Hz

The ratio of the spectrograms of the PID controlled isolator to the PPF controlled isolator indicates the differences of the two control methods. Interpreting the spectrogram ratio is easy. Areas of brightening on the plot indicate that the PPF controller is outperforming PID. Conversely, darkening indicates the PID method is outperforming PPF. The steady-state error induced by PPF is highlighted along the bottom edge of the plot.

3.4 Isolation Summary

Passive isolation is characterized by a significant reduction in loading on the Payload. The Sub-component experiences a marginal increase in acceleration loads, but these loads decrease with the critical frequency of the Sub-component. Above approximately 60 Hz, the Sub-component RMS acceleration drops below the baseline acceleration of the Sub-component. This might encourage designers to produce components that have initial modes above the crossover frequency of the satellite system in question. This is impractical especially in light of one of the fundamental goals of isolation research -- the creation a launch environment that encourages standard off the shelf components for use on any satellite system.

Hybrid isolation promises great things for whole satellite isolation by further improvement beyond passive isolation. This is tempered by the increased response of the Sub-component above the baseline and the passive cases. Further exploration of the modal response of the Sub-component is necessary to understand this phenomena.

4 Conclusions and Recommendations

4.1 Conclusion

This study follows in the steps of the recent successful demonstration of passive vibration isolation during launch of a satellite payload. Isolating components of a satellite payload and reinforcing the design of a satellite and its sub-components has long been common practice in the satellite manufacturing community. As a result, much study has gone into improving satellite component testing and satellite construction techniques. However, as satellite payloads become smaller in order to take advantage of cheap, light capability launch vehicles, the susceptibility of these small satellites to launch vibration loads increases. This has sparked a research shift in the vibration isolation community to whole spacecraft isolation.

The research of the past several years in launch vibration isolation falls roughly into two classes of modeling. They are Coupled Loads Analysis and lumped mass systems. The CLA approach sacrifices speed and simplicity for accuracy. While the lumped mass approach sacrifices the full fidelity of CLA for broader applicability to general design considerations. For this research the author has constructed a lumped mass parameter model of a launch vehicle and satellite using Simulink. The use of which is to construct various passive and hybrid vibration isolation systems and study their effectiveness.

The chief difference in the researcher's simulations and other parallel efforts is that the model constructed is of a full LV mission profile. CLA and other lumped mass parameter research efforts focus on very short simulations of less than 20 seconds of simulated flight around very specific flight environmental conditions or in many cases much simpler loads, such as impulse, step or sine sweeps. Using the researcher's full flight model that simulates vibration loads encountered during launch provides insight to the demanding environmental transitions for which a hybrid control design will have to account.

Further, the model constructed for this study also captures the non-linear, time-variant nature of the dynamics of a LV flight to orbit. A full set of gravity turn equations is the basis for simulating the motion of a LV to orbit around a spherical non-rotating earth. The changing mass properties of a LV are represented giving rise to structural frequency shifts that greatly complicate passive and hybrid vibration isolation design. The researcher has demonstrated the controllability of the vibration loads on a satellite and its payload component for axial load cases.

Model analysis began by characterizing a baseline case against which the effectiveness of passive and hybrid vibration isolator designs could be compared. Subsequent runs of passive isolators showed tremendous gains over the un-isolated baseline case. The improvement was on average an 80 percent or more reduction on the whole satellite. Other researchers have confirmed this level of improvement [13], [20], [27], [28]. On the other hand, this simulation also included the dynamics of a sub-component within the satellite. The surprising result was the dynamic amplification of the loading on the Sub-component. Hybrid isolation designs analyzed by the researcher PID and PPF control. The research indicate that PID may be an appropriate control technique for whole spacecraft isolation.

4.2 Recommendations for future research

The relative simplicity of the five DoF model designed for this research was sufficient for these initial results, however the researcher feels that future work with this simulation system should begin by increasing the model's degrees of freedom. Doing so will allow the identification of more LV modes and satellite modes. The first stage Inert component of this model is very large and should be broken up in to smaller degrees of freedom. In addition, the inclusion of additional, and/or off-centerline axial components in a lateral model will create interesting coupling effects that should be studied.

While this study explored the effect of varying the passive isolator critical frequency it does not analyze the conditions that arise as the Payload mass or Sub-component mass and/or stiffness change. Collecting this information will characterize the envelope of controllability for a particular design. This has direct ramifications on actual isolation system design for use on LVs. Furthermore, it has been shown that the interface stiffness of the LV has a direct impact on the control force that can be generated to reduce vibration loads.

Adaptive control methods should be explored. Several other self-tuning control methods exist. The simulation model created for this study is fully modular and can easily accept new control designs. The only limitation to what can be tried is the future researcher's creativity.

The lateral equations of motion were presented in this study as part of the derivation. This model focused on axial vibration isolation once it was shown that, for the assumption of linear spring rates between the LV and satellite components, the axial and lateral vibration cases de-couple. The GFO launch, while successfully demonstrating passive axial vibration isolation, showed that lateral loads increase as axial stiffness decreases due to the passive isolator. Laterally stiffening the satellite on the isolation system, but axially softening the ride will limit this increased rocking mode. Too much lateral motion can result in the catastrophic loss of the satellite if it were to strike the payload fairing.

Identifying the source of the dynamic amplification of loads on the Sub-component caused by the hybrid isolator is a priority. Once lateral vibration is explored, the author suggests that the correct use of active control will be to only control the lateral rocking modes caused by the softening of the payload interface.

Appendix A: Model Block Design Documentation

Appendix A documents the design of the various Simulink model blocks. The emphasis here is on the design for compatibility throughout the various models that were built. The author is quite pleased that the final block designs are fully compatible across the several models that were ultimately built. The concept used was to assure compatibility so that the researcher could quickly assemble a new model focused on some aspect of LV vibration and produce results that are comparable to previous results.

Focused model construction allows for simulation speed. A great deal of effort went into model optimization. Certainly, there are many places where the models could be simplified and further enhance processing speed. Potential areas for future speed enhancements are converting the models to State Flow, and/or Real Time Workshop. Real Time Workshop will probably have the greatest impact on speed because it converts the Simulink model into executable code. Another area of improvement may be to create a more detailed model of only first stage flight. Much of the vibration loading on a satellite occurs during first stage flight, and the benefits of higher fidelity could be realized in future controller work.

Simulink Primer

Three key Simulink features were utilized for model construction. They are 1) sub-systems and masks, 2) vectors, and 3) the workspace. The sub-systems and masks greatly simplify model appearance. Masks take the sub-system to a greater level of independence because they allow the creation of dialog boxes from which it is possible to enter variable values. This feature allows the user to quickly change a value of interest and re-run a simulation with minimum fuss.

The second feature of note is vectors. Use of vectors requires dedicated documentation of signal lines or outputs/inputs. Vectors allow for greater use of matrix functions and function blocks. The function block reduces overall block and signal line count by combining several functions simultaneously. Figure 34 emphasizes this concept. Output 1 and 2 will result in the same value, but Output 1 required only two blocks to produce. The 'Mux' block vectorizes several signal lines. If the Wide Vector Lines formatting feature is selected, vectorized signal lines will appear as wider lines (see Figure 34). A 'Demux' block will de-vectorize a signal line.

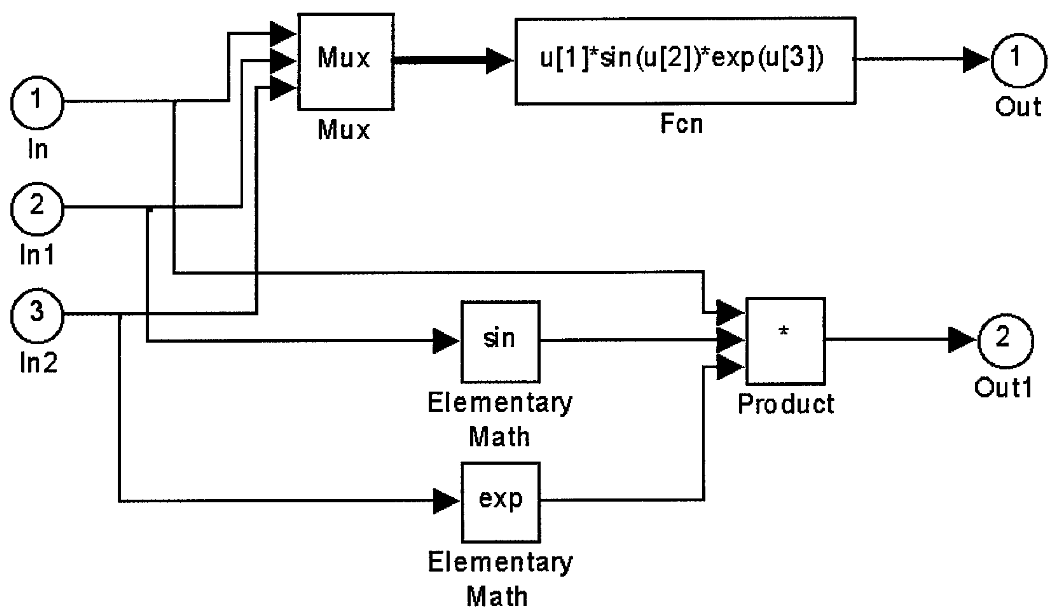

Figure 34 Example vector and function model

Finally, the workspace allows the user to specify the results of complex calculations as variables to be used by the Simulink model. This is achieved by writing and executing a Matlab '.m-file' or defining a variable at the Matlab prompt. Subsequently calling that variable from the Simulink model will use its value in the model. This greatly simplifies block definitions. A good example is the use of a filter in the noise model. Figure 35 is a sample model of a noise filter. The filter shapes the frequency content of the band-limited white noise block. The filter numerator (bp) and denominator (ap) are defined by running a short .m-file prior to executing the simulation. In this example, the filter values are passed from the workspace through a masked sub-system. Therefore, the variable names are called in the mask dialog box.

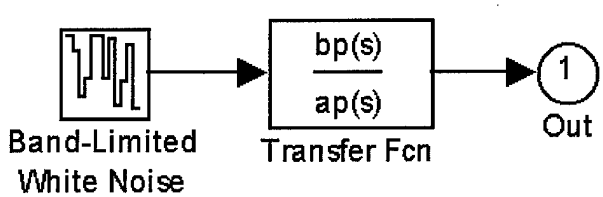

Figure 35 Exploded masked sub-system demonstrating use of workspace variables

Excellent on-line documentation is available on the AFIT Alpha computers at file:/local/matlab5/help/helpdesk.html. The Helpdesk has detailed summaries and examples of Matlab and Simulink functions or blocks. It also contains Portable Document Format versions of the entire Simulink Users Guide and other Matlab users guides. Having a web browser hot-linked to this page was essential.

In this discussion of the simulations and model systems the block names will be *italicized.*

Top-Level Model

is of the top-level model. With little exception, the blocks at this level are sub-systems or masked blocks. This top-level view emphasizes that the clock drives the model. The clock drives many events of the model. Staging, gusts and other flight events are triggered by the clock. The model divides roughly into two parts – environment generation and dynamic output. The *Noise Generator*, *LV CG Dynamics*, and *Mass Properties* blocks generate the environment that excites the model vibration dynamics. The *Axial* or *Lateral Forcing Functions* and the *Axial* or *Lateral Vibration Dynamics* calculate the dynamic output of the model. The end results are the positions, velocities and accelerations of the LV components. The model demonstrates this flow from clock to dynamic output. The blocks of the model can be combined to create new models.

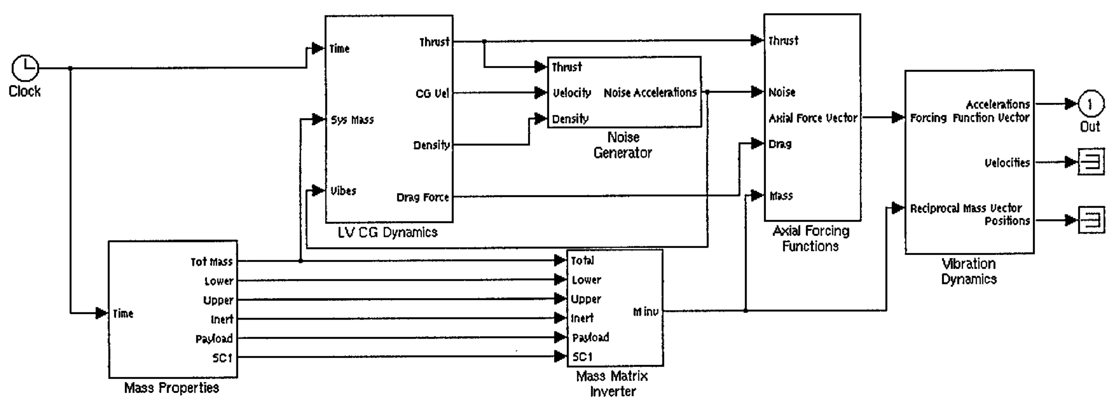

Figure 36 Top level of the Five DoF passive isolation model

Environment generation in any simulation is the same. The three blocks, *LV CG Dynamics*, *Mass Properties* and the *Noise Generator*, are used universally. The blocks represent the characteristics of the launch vehicle and its mission profile. These are the only three time dependent blocks and are the source of the full simulation's non-linearity.

These will be discussed later in this Appendix. The *LV CG Dynamics* block is based on the gravity-turn equations derived in Section 2.1.1.

The most basic model is the five-DoF simulation in Figure 36. Adding active controls results in Figure 37. The LV model can be radically simplified to use a state-space linear time invariant representation for rapid controller prototyping as in Figure 11. Note that in the state-space model the dynamic output does not rely on the different component masses due to time-invariance. This model is only accurate at 27 seconds after launch. The state-space block calls on workspace variables defined in sscont3ppf.m (see Appendix B) executed prior to the simulation.

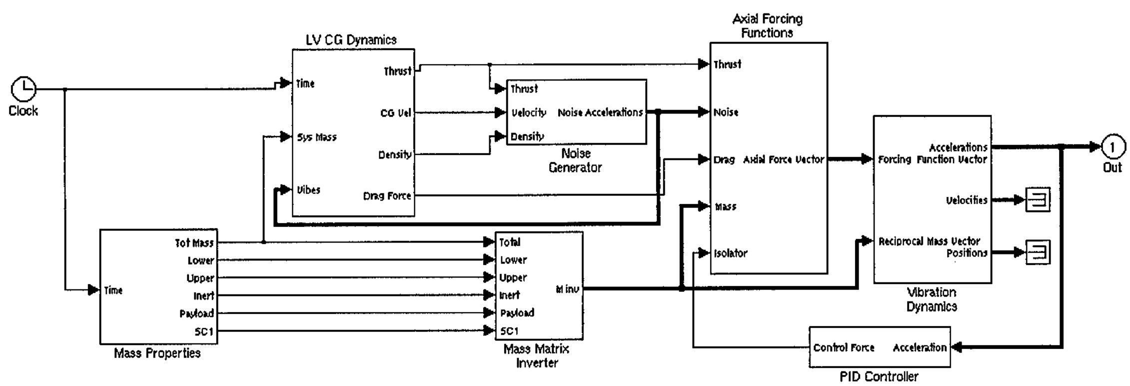

Figure 37 Top level of five DoF PID model

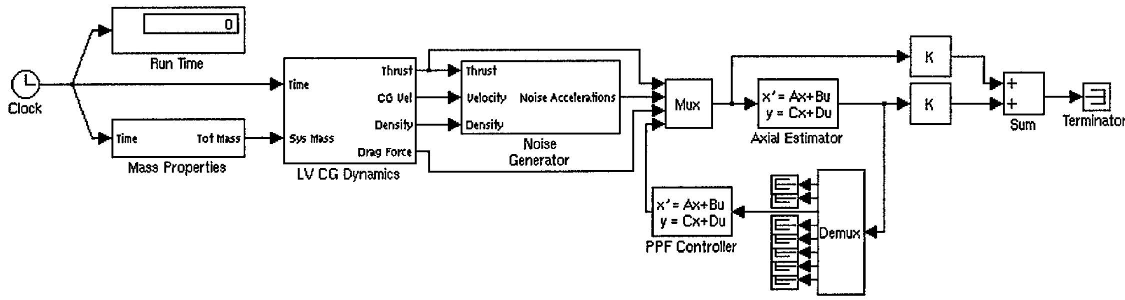

Figure 38 Top level of the state space estimate of the full model

Mass Properties

The very defining characteristics of a LV are its masses and dimensions. The *Mass Properties* sub-system mask defines these characteristics. This block is marked by extensive use of timing switches or step functions. A diagram is presented in Figure 39.

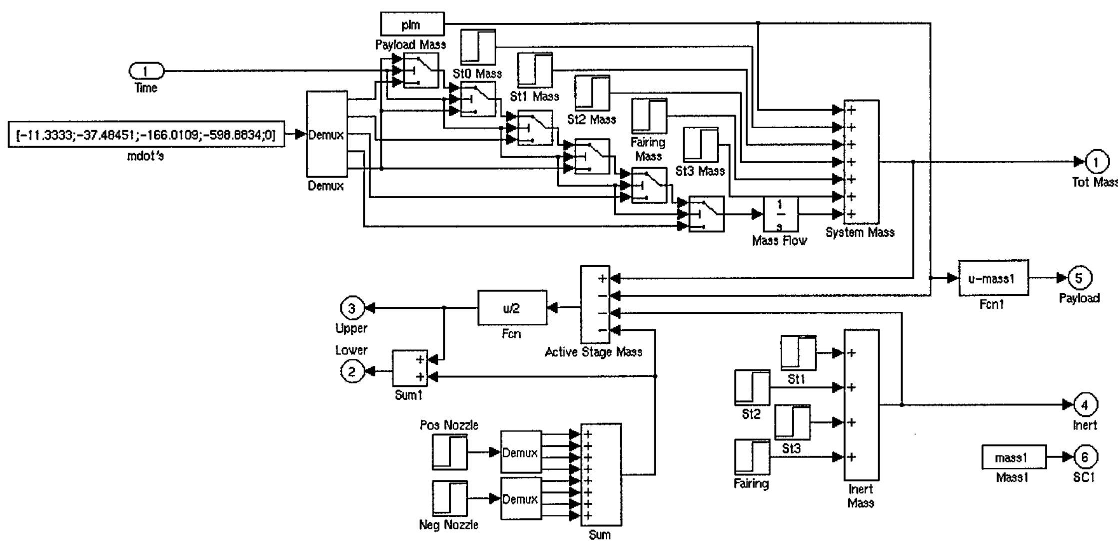

Figure 39 Axial mass properties sub-system diagram

The only input to this block is the simulation time. The time is connected the cascade of timing switches at the top of the system figure. This cascade switches the mass flow rate constants (*mdot's*) at the staging events. The cascade is essentially an extended if-then block that determines the appropriate mass flow rate of the solid motor at the indicated simulation time. Table 3 is a listing of the constant mass properties used to define the model. It should be noted that these values could be defined by an .m-file run prior to executing the simulation. A new set of these values would define a new LV.

Characteristic/Stage	First	Second	Third	Third/PFJ	Fourth
Inert CM (m)	15.6100	10.8831	3.9105	3.2820	1.2312
Payload CM (m)	22.8300	13.8300	4.9300	4.9300	2.2300
Const Inert Inertia (kg m^2)	7892606.6	280826.4	38742.2	34039.5	10.6
Operating Stage Length (m)	9	8.9	2.7	2.7	1.23
Nozzle Mass (kg)	795.3	235.4	118.7	118.7	52.8
Propellant Density (kg m^{-3})	1354.0	1277.1	960.7	960.7	614.0

Table 3 The *Const Mass Props* stored values

The use of step inputs was mentioned previously. These are used in lieu of timing switches to specify certain mass change events more explicitly. The Simulink step input function refers internally to the simulation time. This creates some flexibility in defining timed events. A switch is used to define a system state change. While the step input functions refer to mass change events. System state changes involve values that are integrated and mass changes are instantaneous mass losses.

Utilizing the previous definitions, the cascade timing switches at the top of the diagram is more clearly understood. The empty stage masses and fairing mass appear as a cascade of step inputs. These will drop off at the appropriate moment. At the same time the switches determine which of the vector of *mdot's* is to be integrated by the *Mass Flow* integrator. These values summed with the Payload Mass is the total mass of the LV sent to output 1 – *Tot Mass*. The total mass is used to calculate the mass values of the Lower and Upper model components using the other known system values. The known values are held within the various step functions. These include *Pos Nozzle*, the *Inert Mass* of stage one, two, three and the fairing. The payload mass, *plm*, is defined externally by the user in a dialog box that is accessed by double clicking on the *Mass Properties* block at the top level of the model. The mass of the Sub-component, *mass1*, is also updated in the same dialog box. It should be obvious by inspection of the model that the Lower and Upper component mass are half of the total stage mass minus the nozzle mass.

LV CG Dynamics

The *LV CG Dynamics* block creates the basis of the acceleration environment. The block calculates Thrust, Drag, local air density, pressure, gravitational acceleration and the fundamental states of the LV's center of mass. The equations being modeled are presented in Section 2.1.1. Figure is the block diagram of *LV CG Dynamics*.

The diagram looks somewhat complex, but it is actually straightforward. The four integrators are the basis of the block. These integrate the velocity (*CG Velocity*), altitude (*CG Altitude*), range (*CG Range*) and flight path angle (*CG Alpha*). *CG Vel Dot* and *Alpha Dot* are function blocks. You'll recall that the equations of velocity and flight path angle are somewhat lengthy. This complexity is handled in the function block. The equations in the function blocks are equivalent to Equations (5c) and (5d). The rest of the sub-system brings together the various environmental factors that make the gravity turn equations very non-linear.

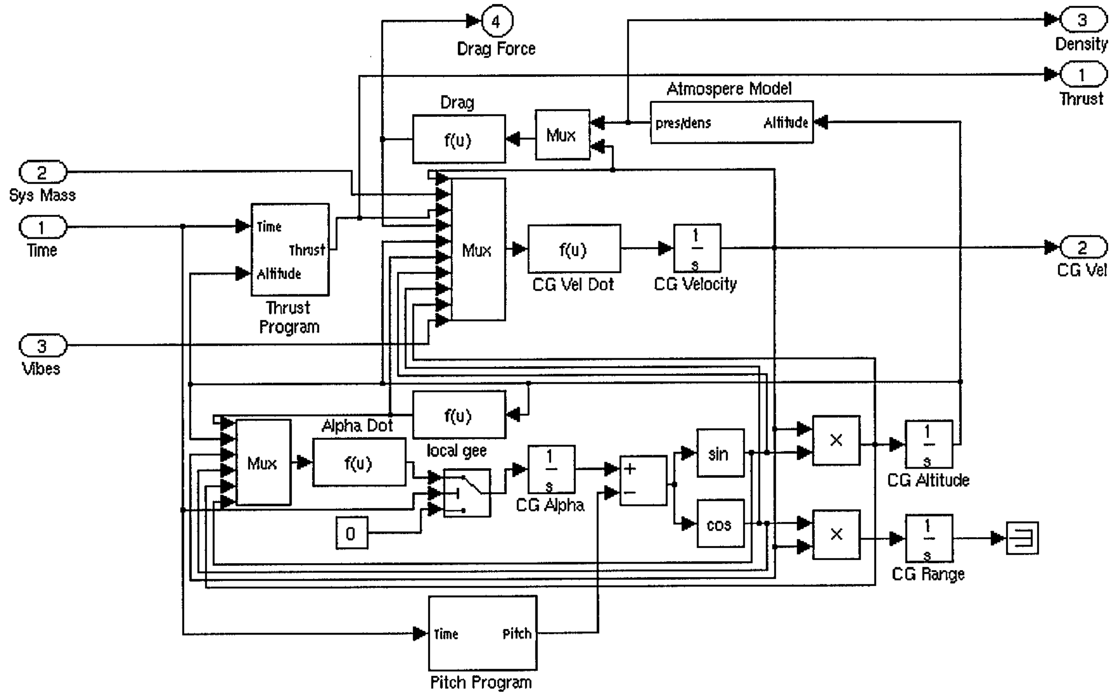

Figure 40 LV CG Dynamics Block Diagram

The *Thrust Program* block serves two purposes. First, it dictates by means of switches the level of thrust that the flight conditions dictate. This varies near sea-level because of atmospheric pressure. Second, it calculates an exponential thrust tail-off beginning seven seconds before burn-out. Figure 41 is of the *Thrust Program.* There are five thrust states. Four of these states are the stages and the fifth is motor off or the coast state.

Stage one (*St0 Thrust* in the diagram) and two (*St1 Thrust*) thrust sub-systems are enabled. This means that the blocks are only on when they are operating. Otherwise they are turned off to reduce computational overhead. (Note: Simulink calculates the state of all blocks in a model unless they are triggered, or enabled.)

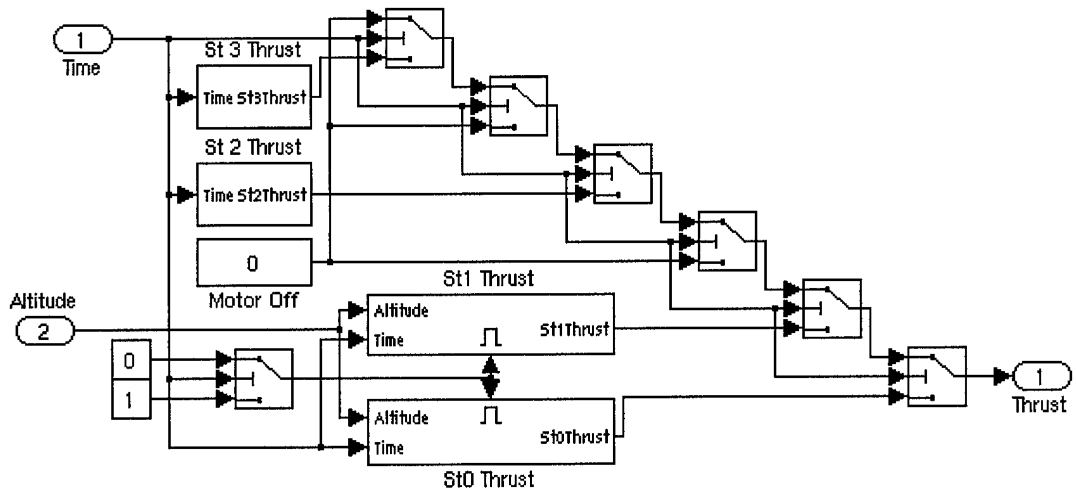

Figure 41 The *Thrust Program* Block Diagram

The thrust tail-off before burn-out is models an effect all solid rocket motors produce. The math model is in Section 2.1.1, Equation 6.

Pitch Program is a simple sub-system that indicates the time and pitch angle for the flight path angle computation. This is similar to commanding thrust vector maneuvers just after lift-off to begin the gravity turn maneuver. You'll note the zero constant block just below the *Alpha Dot* block. This is the initial nozzle deflection angle. This is fed to a switch. The switch makes it possible to keep Simulink from integrating the full flight path angle equation until two seconds after lift-off, because this value is undefined for zero velocity (See Equation 5d). At which point the notional rocket has cleared the tower and can begin the gravity turn. The *Pitch Program* then commands a three second ramp up then a three second ramp down to zero. The pitch program gain can be set in the *LV CG Dynamics* dialog box.

The *Atmosphere Model* computes atmospheric data for an isothermal atmosphere. The 249K temperature of the model atmosphere was determined by integrating the layers of the 1976 Standard Atmosphere and averaging the temperatures. Pressure and Density are computed as appropriate.

The user can specify the ignition times of Third and Fourth stage as well as the pitch program gain and initial conditions for the integrators in the dialog box for the *LV CG Dynamics* block. Specifying *correct* initial conditions allows the user to examine a different part of the mission profile without having to start at zero. Use the lvcgdyn.mdl model to determine correct initial conditions for a given start time.

Inputs to the *LV CG Dynamics* are *Time, Sys Mass,* and *Vibes*. *Vibes* originates at the *Noise Generator* block. *Sys Mass* originates at the *Mass Properties* block. *Time* originates at the *Clock*. Outputs are *Thrust, CG Vel, Density and Drag Force.*

Noise Generator

The user can specify the aeroacoustic and motor noise power, magnitude of resonant burn, and frequency of resonant burn in the dialog box of the *Noise Generator.* This block creates the vibration forces that are the focus of this thesis. Figure 42 is the block diagram of the noise generator.

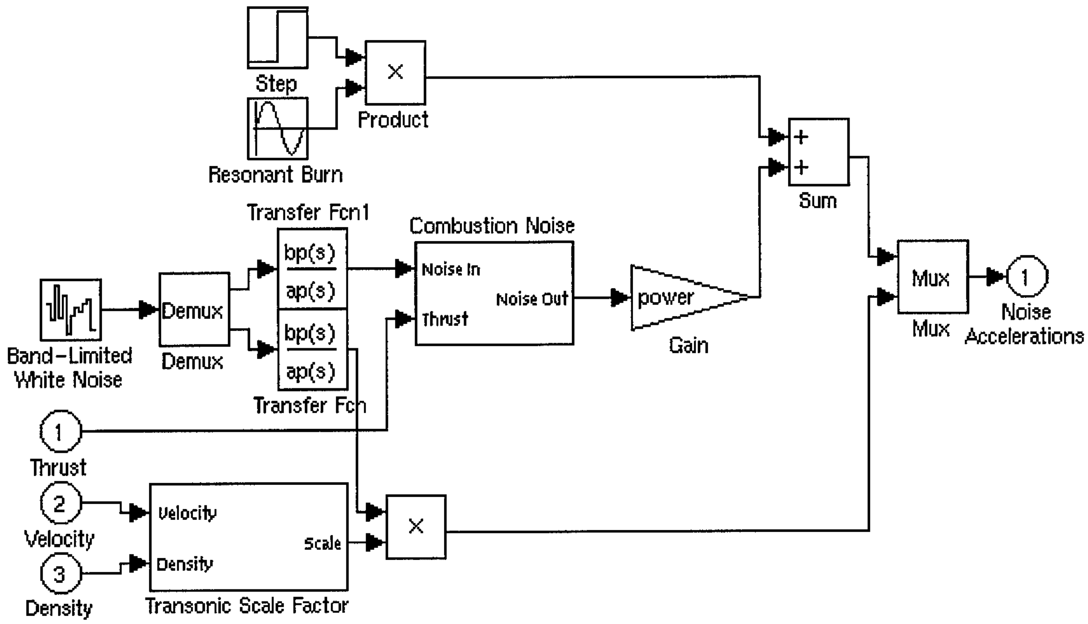

Figure 42 The Noise Generator Block

Resonant burn is the harmonic oscillation of the burning gases inside the combustion chamber of a solid rocket motor (SRM). This problem is typical for large SRMs. The on or off state of the resonant burn condition is modeled as a step function. The step function multiplies the sine function to generate the oscillating force. The resonant burn condition only exists for first stage.

A band-limited white noise block creates the random noise that is the basis of the vibration signal. The block simultaneously computes two values, one for motor noise the other for aeroacoustic noise. The values are filtered to correct the frequency content according to the noisefilt.m program. noisefilt.m must be run at least once prior to a simulation session so that the filter transfer function will be in the Matlab workspace. These vibration signals are then passed to the *Combustion Noise* block or multiplied by the *Transonic Scale Factor*.

The *Combustion Noise* block amplifies the inputted vibration signal by the ratio of the current thrust value to the maximum thrust of the first stage motor. In this way the thrust level tailors the vibration magnitude. The *noise out* is multiplied by the motor noise power gain specified in the dialog box for the *Noise Generator* block.

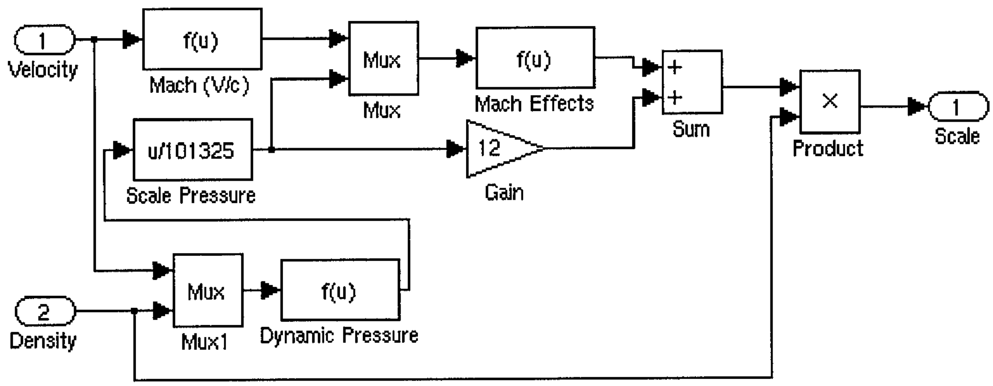

Figure 43 The Transonic Scale Factor Block

Referring to Section 2.2.2, Equation 19 we can understand Figure 43. This block creates the profile of the aeroacoustic vibration experienced during transonic and max-q flight. From the velocity input the Mach number is calculated, and the dynamic pressure is calculated from the air density input. The dynamic pressure is normalized to atmospheres. A Mach effect value is computed, as well as a scaled dynamic pressure effect. The sum of these effects is multiplied by the atmospheric density. The density is the final scale factor because the effects of atmosphere should lessen as the air thins. The resulting *scale* is used as a gain on the aeroacoustic vibration force. The vibration forces are combined into a single signal and passed to the *LV CG Dynamics* block and the *Axial Forcing Functions* block.

Axial Forcing Functions

This relatively simple block creates the "right-hand-sides" of the equations of motion. All of the relevant forces are multiplexed and fed into one of four force function blocks. Only four are needed because upon inspection of Equations (10b) (Upper component) and (10e) (Sub-component) you'll agree that the right hand sides of these equations are the same. The forces input here are *Thrust, Noise*, and *Drag*. The inverse mass matrix is also input to this block. The output is formed into a single multiplex line with all five *Axial Forces*. Figure 44 is the block diagram.

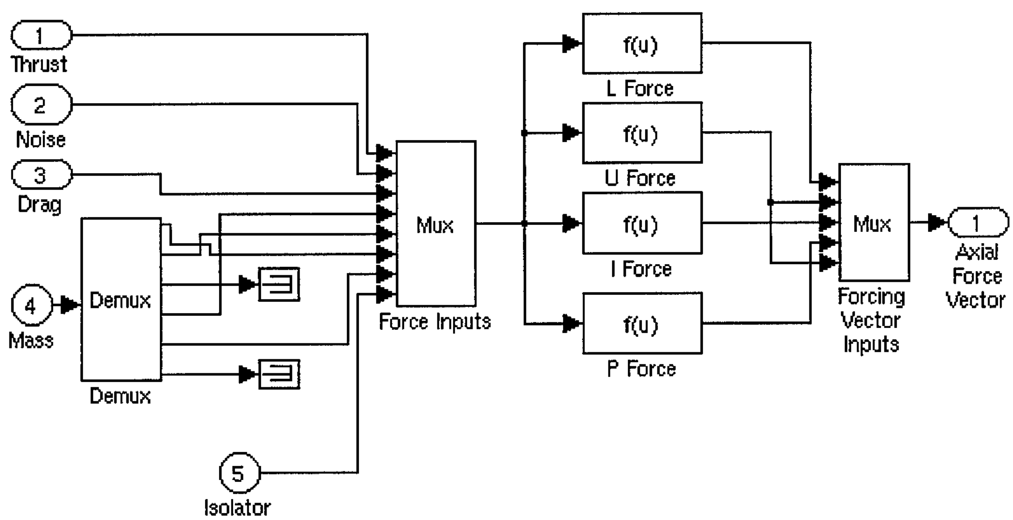

Figure 44 The Axial Forcing Functions Block

Vibration Dynamics

This block is ostensibly the heart of the simulation. The general appearance of this block is the classic state-space wiring diagram (Figure 45). The general layout should need no explanation, but the *Damping* and *Stiffness* blocks may require discussion.

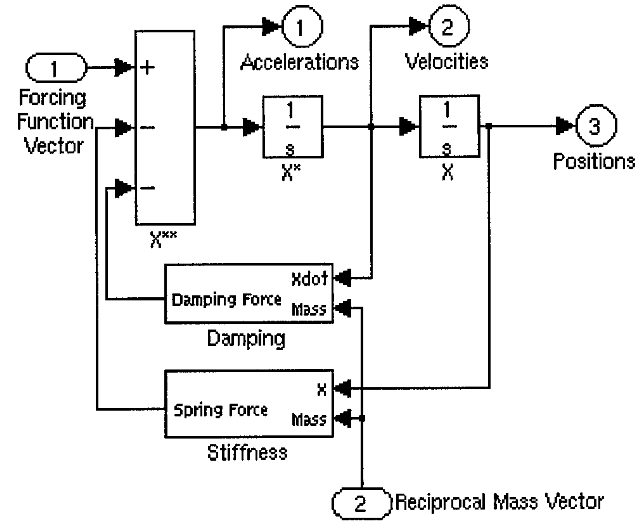

Figure 45　The Vibration Dynamics Block

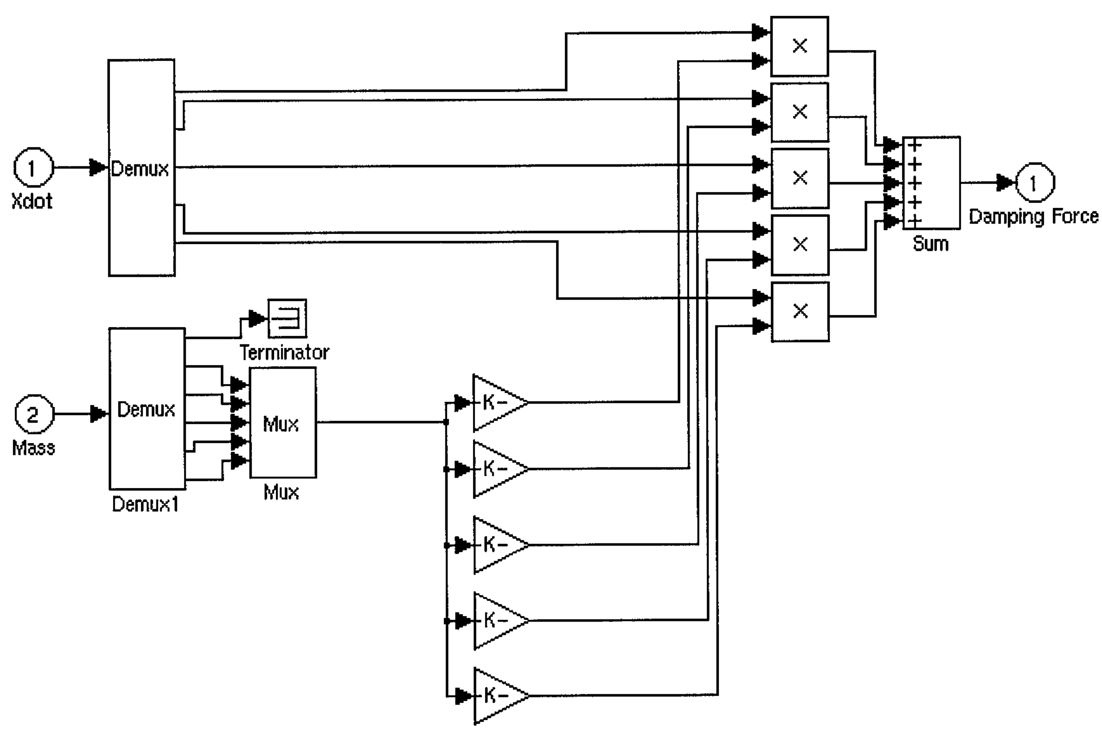

Figure 46　The Damping Forces Block

Figure 46 is the block diagram of *Damping*. *Damping* and *Stiffness* are structured identically because they are an elaboration of the matrix form of the equation of motion. Simulink cannot pass matrices, only vectors. This results in some difficulties in implementing a time varying mass matrix. The inverse of the mass values are inputted. The total mass of the rocket is separated from the inverse mass vector. The mass inverses are then multiplied by a damping or stiffness vector appropriate to the row of the equations of motion the mass inverse belongs. These squares of the modal frequencies or damping ratios are then multiplied by the position or velocity state as appropriate. These are summed and passed on as a vector of damping or stiffness forces.

PID Controller

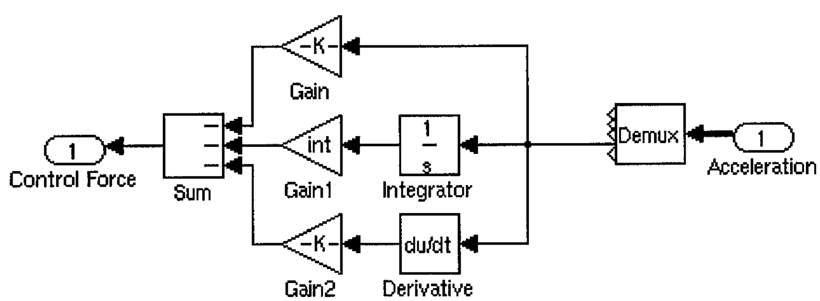

Figure 47 The PID Controller Block

The block diagram above is intuitively obvious when one considers Equation 20. The block is presented for completeness. The PPF controller is implemented using a state-space block, provided by Simulink.

Appendix B: .m-file Analysis Source Code

The Matlab source code of the various .m-files developed for this thesis are presented. The programs listed are sscont3ppf.m, freqflux2.m, rmsg.m, and noisefilt.m. These programs are fundamental to the analysis or production of data by the Simulink models used for this study.

sscont3ppf.m

```
% sscont3ppf creates a state-space model, sys, of the launch vehicle
satellite
% combination at 27 seconds.  This time is chosen to corespond to
transonic
% flight. The .m-file then builds a state-space PPF controller, cntrl.
% sys and cntrl are combined in closed loop form to create sysfeed
%
% Specify frequency of passive isolator, f, and controller gain ,G,
% controller damping, zc, and controller frequency, fc.
%

% Declare PPF controller frequencies
%
fc=49.5;
zc=0.05;
fc2=13.1;
zc2=0.08;
fc3=29.0;
zc3=0.05;
G=0.002;
% System at 27 sec
M=[19120 0 0 0 0;0 18330 0 0 0;0 0 18580 0 0;0 0 0 1779 0;0 0 0 0 1];
k=1e8;
ki=(2*pi*f)^2*1779;
K=[4*k -4*k 0 0 0;-4*k 5*k -k 0 0;0 -k k+ki -ki 0;0 0 -ki ki+98696 -
98696;0 0 0 -98696 98696];
C=[9e4 -9e4 0 0 0;-9e4 9e4*1.5 -45e3 0 0;0 -45e3 54839 -9838.7 0;0 0 -
9838.7 9844.9 -6.2832;0 0 0 -6.2832 6.2832];
F=[(1-M(1,1)/57810) (1-M(1,1)/57810)   -M(1,1)/57810      M(1,1)/57810
0;
   -M(2,2)/57810    -M(2,2)/57810      -M(2,2)/57810      M(2,2)/57810
0;
   -M(3,3)/57810    -M(3,3)/57810     -(1-M(3,3)/57810) (1-
M(3,3)/57810) -G*(2*pi*f)^2;
```

```
   -1779/57810        -1779/57810         -1779/57810         1779/57810
G*(2*pi*f)^2;
   -1/57810           -1/57810            -1/57810              1/57810
0];
% Reduce System
T=[1 0 0 0;-19120/18330 -18580/18330 -1779/18330 -1/18330;0 1 0 0;0 0 1
0;0 0 0 1];
Mr=T'*M*T;
Kr=T'*K*T;
Cr=T'*C*T;
Br=T'*F;
%create state model
A=zeros(8,8);
O1=zeros(4,8);
A(1:4,5:8)=eye(4);
A(5:8,1:4)=-inv(Mr)*Kr;
O1(:,1:4)=-inv(Mr)*Kr;
A(5:8,5:8)=-inv(Mr)*Cr;
O1(:,5:8)=-inv(Mr)*Cr;
B=zeros(8,5);
B(5:8,:)=Br;
C=eye(8,8);
D=zeros(8,5);
sys=ss(A,B,C,D);
%Create Controler Model
Ac=[0 0 0 1 0 0;
    0 0 0 0 1 0;
    0 0 0 0 0 1;
    -(2*pi*fc)^2 0             0              -2*zc*(2*pi*fc) 0
0;
    0            -(2*pi*fc2)^2 0              0               -
2*zc2*(2*pi*fc2) 0;
    0            0             -(2*pi*fc3)^2 0               0
-2*zc3*(2*pi*fc3)];
Bc=[0 0 0 -(fc*2*pi)^2 -(fc2*2*pi)^2 -(fc3*2*pi)^2]';
Cc=[1 1 1 0 0 0];
Dc=0;
cntrl=ss(Ac,Bc,Cc,Dc);
sysfeed=feedback(sys,cntrl,[5],[3],+1);
```

freqflux2.m

```
% freqflux2 calculates the time varying modes of the LV and satellite
system
% for a five degree of freedom model
%
% Declarations
%
l=[816;733;808;691]; % length of event counts
mdot=[-598.8834;-166.0109;-37.48451;-11.3333]; % mass flow rates
MLi=[26907.7;7127.35;1744.35;518.9]; % Lower component masses
```

```
MUi=[26112.35;6891.95;1625.65;466.1]; % Upper component masses
MIi=[18580;4560;1190;985]; % Inert component masses
MPi=1779;
M1i=1;
k1=4*1e8; % inter-component stiffness KLU
k2=1e8;   % inter-component stiffness KUI
k3=(29*2*pi)^2*MPi; % inter-component stiffness KIP in form
(frequency^2)*mass
k4=(50*2*pi)^2*M1i; % inter-component stiffness KP1 in form
(frequency^2)*mass
%
for x=1:1 % 1 to number of stages
n=1;  % event counts
t=0:0.1:(l(x)/10-.1);  % time vector
lam=zeros(l(x),4);      % initialize eigenvalues
while n <= l(x)
  M=[MLi(x)+t(n)*mdot(x)/2;MUi(x)+t(n)*mdot(x)/2];  %  calculate
current masses
  ML=M(1); MU=M(2); MI=MIi(x); MP=MPi; M1=M1i;
  %  create transpostion matrix
  T=[1 0 0 0;-ML/MU -MI/MU -MP/MU -M1/MU;0 1 0 0;0 0 1 0;0 0 0 1];
  m=[ML 0 0 0 0;0 MU 0 0 0;0 0 MI 0 0;0 0 0 MP 0;0 0 0 0 M1];  % mass
matrix
  % stiffness matrix
  K=[k1 -k1 0 0 0;-k1 k1+k2 -k2 0 0;0 -k2 k2+k3 -k3 0;0 0 -k3 k3+k4 -
k4;0 0 0 -k4 k4];
  [vec,val]=eig(inv(T'*m*T)*T'*K*T); % instantaneous
eigenvalues/vectors
  lam(n,:)=(((val)^0.5)*[1;1;1;1])'; % compute frequencies
  n=n+1;  % increment event counter
end; % while
%
% Plot output
figure;plot(t,lam(:,1:4)/(2*pi));
title('Frequency vs Time');
xlabel('Time (sec)');
ylabel('Frequency (Hz)');
end; % for
```

rmsg.m

```
function boo=rmsg(n,c);
%computes rms in g's of channel, c, of matrix, n.
boo=norm(n(:,c))/sqrt(size(n,1));
%end rmsg
```

noisefilt.m

```
% noisefilt is to be run prior to any simulation
% This file shapes the frequency content of the input
% band limited white noise in the Noise Generator block
[z,p,k]=buttap(4);  % Build fourth order Butterworth Prototype Filter
[b,a]=zp2tf(z,p,k);  % Convert to transfer function format
[bp,ap]=lp2hp(b,a,20*pi);  % Convert filter from lowpass to high pass
form
clear a; clear b; clear k; clear z; clear p; % clear extraneous
variables
```

Appendix C: Model Source Code

The Simulink source code of the PID hybrid model is provided.

```
Model {
  Name                    "fivedofhybridPIDFL"
  Version                 2.09
  SimParamPage            Diagnostics
  SampleTimeColors        off
  InvariantConstants      off
  WideVectorLines         on
  ShowLineWidths          off
  PaperOrientation        landscape
  PaperType               usletter
  PaperUnits              inches
  StartTime               "0.0"
  StopTime                "90"
  Solver                  ode45
  RelTol                  "1e-3"
  AbsTol                  "1e-6"
  Refine                  "1"
  MaxStep                 "auto"
  InitialStep             "auto"
  FixedStep               "1/800"
  MaxOrder                5
  OutputOption            RefineOutputTimes
  OutputTimes             "[]"
  LoadExternalInput       off
  ExternalInput           "[t, u]"
  SaveTime                off
  TimeSaveName            "tout"
  SaveState               off
  StateSaveName           "xout"
  SaveOutput              off
  OutputSaveName          "yout"
  LoadInitialState        off
  InitialState            "xInitial"
  SaveFinalState          off
  FinalStateName          "xFinal"
  LimitMaxRows            off
  MaxRows                 "1000"
  Decimation              "1"
  AlgebraicLoopMsg        warning
  MinStepSizeMsg          warning
  UnconnectedInputMsg     none
  UnconnectedOutputMsg    none
  UnconnectedLineMsg      warning
  ConsistencyChecking     off
  ZeroCross               on
  SimulationMode          normal
  RTWSystemTargetFile     "grt.tlc"
  RTWInlineParameters     off
  RTWRetainRTWFile        off
  RTWTemplateMakefile     "grt_unix.tmf"
  RTWMakeCommand          "make_rtw"
  RTWGenerateCodeOnly     off
  ExtModeMexFile          "ext_comm"
  ExtModeBatchMode        off
```

```
BlockDefaults {
  Orientation                     right
  ForegroundColor         black
  BackgroundColor         white
  DropShadow                      off
  NamePlacement           normal
  FontName                        "Helvetica"
  FontSize                        10
  FontWeight                      normal
  FontAngle                       normal
  ShowName                        on
}
AnnotationDefaults {
  HorizontalAlignment             center
  VerticalAlignment       middle
  ForegroundColor         black
  BackgroundColor         white
  DropShadow                      off
  FontName                        "Helvetica"
  FontSize                        10
  FontWeight                      normal
  FontAngle                       normal
}
LineDefaults {
  FontName                        "Helvetica"
  FontSize                        9
  FontWeight                      normal
  FontAngle                       normal
}
System {
  Name                    "fivedofhybridPIDFL"
  Location                        [227, 588, 1257, 935]
  Open                    on
  ScreenColor                     white
  Block {
    BlockType                       SubSystem
    Name                    "Axial Forcing\nFunctions"
    Ports                   [5, 1, 0, 0, 0]
    Position                        [615, 27, 715, 223]
    NamePlacement           alternate
    ShowPortLabels          on
    System {
          Name                            "Axial Forcing\nFunctions"
          Location                [141, 34, 707, 317]
          Open                            off
          ScreenColor                     white
          Block {
            BlockType                       Inport
            Name                            "Thrust"
            Position              [15, 18, 45, 32]
            Port                            "1"
            PortWidth                       "-1"
            SampleTime                      "-1"
          }
          Block {
            BlockType                       Inport
            Name                            "Noise"
            Position              [15, 50, 45, 70]
            Port                            "2"
            PortWidth                       "-1"
            SampleTime                      "-1"
          }
          Block {
            BlockType                       Inport
            Name                            "Drag"
            Position              [15, 88, 45, 102]
            Port                            "3"
            PortWidth                       "-1"
```

```
  SampleTime              "-1"
}
Block {
  BlockType               Inport
  Name                    "Mass"
  Position        [15, 150, 35, 170]
  Port                    "4"
  PortWidth               "-1"
  SampleTime              "-1"
}
Block {
  BlockType               Inport
  Name                    "Isolator"
  Position        [120, 235, 140, 255]
  Port                    "5"
  PortWidth               "-1"
  SampleTime              "-1"
}
Block {
  BlockType               Demux
  Name                    "Demux"
  Ports                   [1, 6, 0, 0, 0]
  Position        [50, 117, 90, 198]
  Outputs         "6"
}
Block {
  BlockType               Mux
  Name                    "Force Inputs"
  Ports                   [8, 1, 0, 0, 0]
  Position        [210, 79, 250, 161]
  Inputs          "8"
}
Block {
  BlockType               Mux
  Name                    "Forcing\nVector\nInputs"
  Ports                   [5, 1, 0, 0, 0]
  Position        [435, 91, 470, 149]
  Inputs          "5"
}
Block {
  BlockType               Fcn
  Name                    "I Force"
  Position        [305, 105, 365, 135]
  Expr                    "-u[7]*(u[1]+u[2])+(u[7]-u[5])*(u[4]+u[3])-u["
                          "9]/u[5]"
}
Block {
  BlockType               Fcn
  Name                    "L Force"
  Position        [305, 15, 365, 45]
  Expr                    "(u[6]-u[7])*(u[1]+u[2])+u[7]*(u[4]+u[3])"
}
Block {
  BlockType               Fcn
  Name                    "P Force"
  Position        [305, 155, 365, 185]
  Expr                    "-u[7]*(u[1]+u[2]-u[3]-u[4])+u[9]/u[8]"
}
Block {
  BlockType               Terminator
  Name                    "Terminator23"
  Position        [140, 142, 160, 158]
  ShowName                off
}
Block {
  BlockType               Terminator
  Name                    "Terminator25"
  Position        [140, 188, 160, 202]
```

```
    ShowName                         off
  }
  Block {
    BlockType                        Fcn
    Name                             "U Force"
    Position               [305, 60, 365, 90]
    Expr                             "-u[7]*(u[1]+u[2]-u[4]-u[3])"
  }
  Block {
    BlockType                        Outport
    Name                             "Axial\nForce\nVector"
    Position               [490, 113, 520, 127]
    Port                             "1"
    OutputWhenDisabled               held
    InitialOutput                    "0"
  }
  Line {
    SrcBlock               "P Force"
    SrcPort                1
    Points                 [50, 0]
    DstBlock               "Forcing\nVector\nInputs"
    DstPort                4
  }
  Line {
    SrcBlock               "Demux"
    SrcPort                5
    Points                 [90, 0; 0, -35]
    DstBlock               "Force Inputs"
    DstPort                7
  }
  Line {
    SrcBlock               "Isolator"
    SrcPort                1
    Points                 [45, 0; 0, -90]
    DstBlock               "Force Inputs"
    DstPort                8
  }
  Line {
    SrcBlock               "Forcing\nVector\nInputs"
    SrcPort                1
    DstBlock               "Axial\nForce\nVector"
    DstPort                1
  }
  Line {
    Labels                 [1, 0]
    SrcBlock               "L Force"
    SrcPort                1
    Points                 [50, 0]
    DstBlock               "Forcing\nVector\nInputs"
    DstPort                1
  }
  Line {
    SrcBlock               "I Force"
    SrcPort                1
    DstBlock               "Forcing\nVector\nInputs"
    DstPort                3
  }
  Line {
    SrcBlock               "U Force"
    SrcPort                1
    Points                 [30, 0; 0, 35]
    Branch {
      Points                [0, 30]
      DstBlock                        "Forcing\nVector\nInputs"
      DstPort               5
    }
    Branch {
      DstBlock                        "Forcing\nVector\nInputs"
```

```
      DstPort              2
    }
  }
  Line {
    SrcBlock           "Demux"
    SrcPort            6
    DstBlock           "Terminator25"
    DstPort            1
  }
  Line {
    SrcBlock           "Demux"
    SrcPort            3
    DstBlock           "Terminator23"
    DstPort            1
  }
  Line {
    SrcBlock           "Demux"
    SrcPort            2
    Points             [15, 0; 0, -10]
    DstBlock           "Force Inputs"
    DstPort            5
  }
  Line {
    SrcBlock           "Demux"
    SrcPort            4
    Points             [25, 0; 0, -50]
    DstBlock           "Force Inputs"
    DstPort            4
  }
  Line {
    SrcBlock           "Demux"
    SrcPort            1
    Points             [0, 10; 20, 0; 0, 5]
    DstBlock           "Force Inputs"
    DstPort            6
  }
  Line {
    SrcBlock           "Mass"
    SrcPort            1
    DstBlock           "Demux"
    DstPort            1
  }
  Line {
    SrcBlock           "Force Inputs"
    SrcPort            1
    Points             [20, 0]
    Branch {
      Points             [0, 50]
      DstBlock                   "P Force"
      DstPort            1
    }
    Branch {
      DstBlock                   "I Force"
      DstPort            1
    }
    Branch {
      Points             [0, -45]
      Branch {
        Points             [0, -45]
        DstBlock                   "L Force"
        DstPort                    1
      }
      Branch {
        DstBlock                   "U Force"
        DstPort                    1
      }
    }
  }
```

```
        Line {
          SrcBlock              "Thrust"
          SrcPort               1
          Points                [145, 0]
          DstBlock              "Force Inputs"
          DstPort               1
        }
        Line {
          Labels                [2, 0]
          SrcBlock              "Noise"
          SrcPort               1
          Points                [140, 0; 0, 35]
          DstBlock              "Force Inputs"
          DstPort               2
        }
        Line {
          SrcBlock              "Drag"
          SrcPort               1
          Points                [40, 0; 0, 10]
          DstBlock              "Force Inputs"
          DstPort               3
        }
  }
}
Block {
  BlockType               Clock
  Name          "Clock"
  Position                [15, 55, 35, 75]
  Location                [21, 63, 128, 108]
}
Block {
  BlockType               Demux
  Name          "Demux"
  Ports         [1, 5, 0, 0, 0]
  Position                [910, 27, 945, 63]
  Outputs                 "5"
}
Block {
  BlockType               SubSystem
  Name          "LV CG Dynamics"
  Ports         [3, 4, 0, 0, 0]
  Position                [255, 32, 360, 173]
  NamePlacement alternate
  ShowPortLabels          on
  MaskType                "LV CG Dynamics"
  MaskDescription         "Computes flight path of launch vehicle CG. "
                "Vary flnal orbit altitude by adjusting Payload "
                "Mass, Pitch Program Gain and Fourth Stage "
                "Ignition Time.\n\nNote: 4th Stage ignition "
                "time must be at least 80.7 sec after 3rd "
                "Stage Ignition."
  MaskHelp                "Circular Orbits are possible with the following "
                "combinations:\n3d Ig=166.8      \n4th Ig=635   "
                "     \nPitch Gain =0.133127"
  MaskPromptString        "2nd Stage Ignition Time|3rd Stage ignition "
                "Time|Pitch Gain|Range Initial Conditions|Altitud"
                "e Initial Condition|Velocity Initial Condition "
                "|Flight Path Angle Initial Condition"
  MaskStyleString         "edit,edit,edit,edit,edit,edit,edit"
  MaskVariables           "st2ig=@1;st3ig=@2;pitch=@3;rnought=@4;hnought=@5"
                ";vnought=@6;anought=@7;"
  MaskIconFrame           on
  MaskIconOpaque          on
  MaskIconRotate          none
  MaskIconUnits           autoscale
  MaskValueString         "166.8|635|0.133127|0|0|0|pi/2"
  System {
        Name                    "LV CG Dynamics"
```

```
Location		[157, 141, 928, 651]
Open			off
ScreenColor		white
Block {
 BlockType		Inport
 Name			"Time"
 Position		[20, 148, 50, 162]
 Port			"1"
 PortWidth		"-1"
 SampleTime		"-1"
}
Block {
 BlockType		Inport
 Name			"Sys Mass"
 Position		[20, 113, 50, 127]
 Port			"2"
 PortWidth		"-1"
 SampleTime		"-1"
}
Block {
 BlockType		Inport
 Name			"Vibes"
 Position		[20, 223, 50, 237]
 Port			"3"
 PortWidth		"-1"
 SampleTime		"-1"
}
Block {
 BlockType		Fcn
 Name			"Alpha Dot"
 Position		[210, 320, 270, 350]
 NamePlacement		alternate
 Expr			"-(u[1]*u[4]-(u[5]*u[3]*u(6)+u[4]*u[3]^2)/(63"
			"78135+u[2]))/u[3]"
}
Block {
 BlockType		SubSystem
 Name			"Atmospere Model"
 Ports			[1, 1, 0, 0, 0]
 Position		[430, 77, 535, 103]
 Orientation		left
 NamePlacement		alternate
 ShowPortLabels		on
 MaskType		"Atmosphere Model"
 MaskDescription	"Calculates exponential pressure and density "
			"based on isothermal atmosphere. T=249K.\n\nu"
			"(1)=pressure\nu(2)=density"
 MaskIconFrame		on
 MaskIconOpaque		on
 MaskIconRotate		none
 MaskIconUnits		autoscale
 System {
  Name			"Atmospere Model"
  Location		[647, 715, 982, 847]
  Open			off
  ScreenColor		white
  Block {
   BlockType		Inport
   Name			"Altitude"
   Position		[25, 58, 55, 72]
   Port			"1"
   PortWidth		"-1"
   SampleTime		"-1"
  }
  Block {
   BlockType		Fcn
   Name			"Density"
   Position		[120, 50, 180, 80]
```

```
      Expr                  "1.2250 * exp(-(1.3728e-4) * u)"
    }
    Block {
      BlockType                 Outport
      Name                  "pres/dens"
      Position                  [260, 58, 290, 72]
      Port                  "1"
      OutputWhenDisabled    held
      InitialOutput         "0"
    }
    Line {
      SrcBlock                  "Density"
      SrcPort                   1
      DstBlock                  "pres/dens"
      DstPort                   1
    }
    Line {
      Labels                [1, 0]
      SrcBlock                  "Altitude"
      SrcPort                   1
      DstBlock                  "Density"
      DstPort                   1
    }
  }
}
Block {
  BlockType                 Integrator
  Name                      "CG Alpha"
  Ports                     [1, 1, 0, 0, 0]
  Position              [350, 325, 380, 355]
  ExternalReset             none
  InitialConditionSource  internal
  InitialCondition      "anought"
  LimitOutput               off
  UpperSaturationLimit      "inf"
  LowerSaturationLimit      "-inf"
  ShowSaturationPort   off
  ShowStatePort             off
  AbsoluteTolerance     "auto"
}
Block {
  BlockType                 Integrator
  Name                      "CG Altitude"
  Ports                     [1, 1, 0, 0, 0]
  Position              [595, 310, 625, 340]
  ExternalReset             none
  InitialConditionSource  internal
  InitialCondition      "hnought"
  LimitOutput               off
  UpperSaturationLimit      "inf"
  LowerSaturationLimit      "-inf"
  ShowSaturationPort   off
  ShowStatePort             off
  AbsoluteTolerance     "auto"
}
Block {
  BlockType                 Integrator
  Name                      "CG Range"
  Ports                     [1, 1, 0, 0, 0]
  Position              [595, 370, 625, 400]
  ExternalReset             none
  InitialConditionSource  internal
  InitialCondition      "rnought"
  LimitOutput               off
  UpperSaturationLimit      "inf"
  LowerSaturationLimit      "-inf"
  ShowSaturationPort   off
  ShowStatePort             off
```

```
    AbsoluteTolerance     "auto"
  }
  Block {
    BlockType             Fcn
    Name                  "CG Vel Dot"
    Position              [350, 155, 410, 185]
    Expr                  "(u[3]+u[10]-u[11]-u[4]-(u[2]*u[6]*u[7]+(u[1]"
                          "*u[9]*u[8]-u[2]*u[7]*u[1]^2)/(6378135+u[5]))"
                          ")/u[2]"
  }
  Block {
    BlockType             Integrator
    Name                  "CG Velocity"
    Ports                 [1, 1, 0, 0, 0]
    Position              [445, 155, 475, 185]
    ExternalReset         none
    InitialConditionSource internal
    InitialCondition      "vnought"
    LimitOutput           off
    UpperSaturationLimit  "inf"
    LowerSaturationLimit  "-inf"
    ShowSaturationPort    off
    ShowStatePort         off
    AbsoluteTolerance     "auto"
  }
  Block {
    BlockType             Constant
    Name                  "Constant"
    Position              [225, 370, 245, 390]
    ShowName              off
    Value                 "0"
  }
  Block {
    BlockType             Fcn
    Name                  "Drag"
    Position              [275, 85, 335, 115]
    Orientation           left
    NamePlacement         alternate
    Expr                  "0.08*u[1]*u[2]^2"
  }
  Block {
    BlockType             Mux
    Name                  "Mux"
    Ports                 [6, 1, 0, 0, 0]
    Position              [160, 308, 195, 362]
    ShowName              off
    Inputs                "6"
  }
  Block {
    BlockType             Mux
    Name                  "Mux1"
    Ports                 [10, 1, 0, 0, 0]
    Position              [300, 125, 335, 215]
    ShowName              off
    Inputs                "10"
  }
  Block {
    BlockType             Mux
    Name                  "Mux2"
    Ports                 [2, 1, 0, 0, 0]
    Position              [355, 82, 390, 113]
    Orientation           left
    ShowName              off
    Inputs                "2"
  }
  Block {
    BlockType             SubSystem
    Name                  "Pitch Program"
```

```
Ports                [1, 1, 0, 0, 0]
Position             [285, 421, 355, 469]
ShowPortLabels       on
System {
 Name                "Pitch Program"
 Location            [253, 605, 558, 793]
 Open                off
 ScreenColor         white
 Block {
  BlockType          Inport
  Name               "Time"
  Position           [25, 53, 55, 67]
  Port               "1"
  PortWidth          "-1"
  SampleTime         "-1"
 }
 Block {
  BlockType          Constant
  Name               "Constant"
  Position           [30, 90, 50, 110]
  ShowName           off
  Value              "1"
 }
 Block {
  BlockType          Constant
  Name               "Constant1"
  Position           [50, 25, 70, 45]
  ShowName           off
  Value              "0"
 }
 Block {
  BlockType          SubSystem
  Name               "Pitch Program"
  Ports              [0, 1, 1, 0, 0]
  Position           [185, 119, 225, 161]
  ShowPortLabels     on
  System {
        Name                 "Pitch Program"
        Location             [664, 675, 1030, 882]
        Open                 off
        ScreenColor          white
        Block {
         BlockType           EnablePort
         Name                "Enable"
         Ports               [0, 0, 0, 0, 0]
         Position            [30, 20, 50, 40]
         StatesWhenEnabling  held
         ShowOutputPort      off
        }
        Block {
         BlockType           Sum
         Name                "Event2\nTvector1"
         Ports               [3, 1, 0, 0, 0]
         Position            [160, 102, 195, 138]
         ShowName            off
         Inputs              "+++"
        }
        Block {
         BlockType           Gain
         Name                "Gain"
         Position            [215, 105, 275, 135]
         Gain                "pitch"
        }
        Block {
         BlockType           Reference
         Name                "Ramp1"
         Ports               [0, 1, 0, 0, 0]
         Position            [90, 75, 120, 105]
```

```
  ShowName              off
  SourceBlock           "simulink/Sources/Ramp"
  SourceType            "Ramp"
  slope                 "1/3"
  start                 "2.0"
  X0                    "-1"
}
Block {
  BlockType             Reference
  Name                  "Ramp2"
  Ports                 [0, 1, 0, 0, 0]
  Position          [50, 105, 80, 135]
  ShowName              off
  SourceBlock           "simulink/Sources/Ramp"
  SourceType            "Ramp"
  slope                 "-2/3"
  start                 "5"
  X0                    "1"
}
Block {
  BlockType             Reference
  Name                  "Ramp3"
  Ports                 [0, 1, 0, 0, 0]
  Position          [90, 135, 120, 165]
  ShowName              off
  SourceBlock           "simulink/Sources/Ramp"
  SourceType            "Ramp"
  slope                 "1/3"
  start                 "8"
  X0                    "0"
}
Block {
  BlockType             Outport
  Name                  "Pitch"
  Position          [315, 110, 335, 130]
  Port                  "1"
  OutputWhenDisabled    held
  InitialOutput         "0"
}
Line {
  SrcBlock          "Gain"
  SrcPort           1
  DstBlock          "Pitch"
  DstPort           1
}
Line {
  SrcBlock          "Event2\nTvector1"
  SrcPort           1
  DstBlock          "Gain"
  DstPort           1
}
Line {
  SrcBlock          "Ramp1"
  SrcPort           1
  Points            [0, 20]
  DstBlock          "Event2\nTvector1"
  DstPort           1
}
Line {
  SrcBlock          "Ramp2"
  SrcPort           1
  DstBlock          "Event2\nTvector1"
  DstPort           2
}
Line {
  SrcBlock          "Ramp3"
  SrcPort           1
  Points            [0, -20]
```

```
        DstBlock              "Event2\nTvector1"
        DstPort               3
      }
    }
  }
  Block {
    BlockType                 Switch
    Name              "Switch"
    Position                  [90, 45, 120, 75]
    ShowName                  off
    Threshold                 "8"
  }
  Block {
    BlockType                 Switch
    Name              "Switch1"
    Position                  [150, 80, 180, 110]
    ShowName                  off
    Threshold                 "2"
  }
  Block {
    BlockType                 Outport
    Name              "Pitch"
    Position                  [250, 133, 280, 147]
    Port              "1"
    OutputWhenDisabled    held
    InitialOutput     "0"
  }
  Line {
    SrcBlock                  "Pitch Program"
    SrcPort                   1
    DstBlock                  "Pitch"
    DstPort                   1
  }
  Line {
    SrcBlock                  "Switch1"
    SrcPort                   1
    Points            [20, 0]
    DstBlock                  "Pitch Program"
    DstPort                   enable
  }
  Line {
    SrcBlock                  "Time"
    SrcPort                   1
    Points            [15, 0]
    Branch {
          Points                  [0, 35]
          DstBlock            "Switch1"
          DstPort                 2
    }
    Branch {
          DstBlock            "Switch"
          DstPort                 2
    }
  }
  Line {
    SrcBlock                  "Constant1"
    SrcPort                   1
    Points            [0, 0]
    Branch {
          Points                  [50, 0; 0, 70]
          DstBlock            "Switch1"
          DstPort                 3
    }
    Branch {
          DstBlock            "Switch"
          DstPort                 1
    }
  }
```

```
      Line {
        SrcBlock                    "Constant"
        SrcPort                     1
        Points             [10, 0; 0, -30]
        DstBlock                    "Switch"
        DstPort                     3
      }
      Line {
        SrcBlock                    "Switch"
        SrcPort                     1
        Points             [10, 0]
        DstBlock                    "Switch1"
        DstPort                     1
      }
    }
  }
  Block {
    BlockType                 Product
    Name                      "Product"
    Ports                     [2, 1, 0, 0, 0]
    Position          [535, 307, 565, 338]
    ShowName                  off
    Inputs            "2"
  }
  Block {
    BlockType                 Product
    Name                      "Product1"
    Ports                     [2, 1, 0, 0, 0]
    Position          [535, 367, 565, 398]
    ShowName                  off
    Inputs            "2"
  }
  Block {
    BlockType                 Sum
    Name                      "Sum"
    Ports                     [2, 1, 0, 0, 0]
    Position          [410, 332, 440, 363]
    ShowName                  off
    Inputs            "+-"
  }
  Block {
    BlockType                 Switch
    Name                      "Switch"
    Position          [295, 340, 325, 370]
    ShowName                  off
    Threshold                 "2.0"
  }
  Block {
    BlockType                 Terminator
    Name                      "Terminator26"
    Position          [660, 375, 680, 395]
    ShowName                  off
  }
  Block {
    BlockType                 SubSystem
    Name                      "Thrust\nProgram"
    Ports                     [2, 1, 0, 0, 0]
    Position          [170, 141, 220, 199]
    ShowPortLabels    on
    System {
      Name             "Thrust\nProgram"
      Location                  [144, 599, 746, 891]
      Open             off
      ScreenColor               white
      Block {
        BlockType                 Inport
        Name             "Time"
        Position                  [45, 33, 75, 47]
```

```
      Port                "1"
      PortWidth                "-1"
      SampleTime          "-1"
    }
    Block {
      BlockType                Inport
      Name                "Altitude"
      Position                 [25, 183, 55, 197]
      NamePlacement       alternate
      Port                "2"
      PortWidth                "-1"
      SampleTime          "-1"
    }
    Block {
      BlockType                Constant
      Name                "Constant"
      Position                 [75, 215, 95, 235]
      ShowName                 off
      Value               "1"
    }
    Block {
      BlockType                Constant
      Name                "Constant1"
      Position                 [75, 195, 95, 215]
      ShowName                 off
      Value               "0"
    }
    Block {
      BlockType                Constant
      Name                "Motor Off"
      Position                 [120, 143, 180, 167]
      Value               "0"
    }
    Block {
      BlockType                SubSystem
      Name                "St 2 Thrust"
      Ports               [1, 1, 0, 0, 0]
      Position                 [120, 104, 180, 136]
      NamePlacement       alternate
      ShowPortLabels      on
      System {
        Name                      "St 2 Thrust"
        Location             [221, 351, 758, 518]
        Open                      off
        ScreenColor               white
        Block {
          BlockType                 Inport
          Name                      "Time"
          Position            [85, 15, 105, 35]
          Port                      "1"
          PortWidth                 "-1"
          SampleTime                "-1"
        }
        Block {
          BlockType                 Mux
          Name                      "Mux"
          Ports                     [2, 1, 0, 0, 0]
          Position            [190, 17, 225, 53]
          Inputs              "2"
        }
        Block {
          BlockType                 Product
          Name                      "Product"
          Ports                     [2, 1, 0, 0, 0]
          Position            [355, 27, 385, 58]
          Inputs              "2"
        }
        Block {
```

```
 BlockType              Constant
 Name                   "St2 Thrust"
 Position           [245, 108, 305, 132]
 Value                  "180000"
}
Block {
 BlockType              Step
 Name                   "Step"
 Position           [140, 30, 170, 60]
 Time                   "[st2ig+73 st2ig+80]"
 Before             "[0 1]"
 After                  "[1 0]"
}
Block {
 BlockType              Switch
 Name                   "Switch"
 Position           [410, 65, 440, 95]
 Threshold              "st2ig+73"
}
Block {
 BlockType              Fcn
 Name                   "Thrust Tail off"
 Position           [250, 20, 310, 50]
 Expr                   "u[2]*exp(-(u[1]-(st2ig+73)))"
}
Block {
 BlockType              Outport
 Name                   "St2Thrust"
 Position           [485, 70, 505, 90]
 Port                   "1"
 OutputWhenDisabled     held
 InitialOutput          "0"
}
Line {
 SrcBlock           "St2 Thrust"
 SrcPort            1
 Points             [30, 0]
 Branch {
  DstBlock              "Product"
  DstPort            2
 }
 Branch {
  Points             [55, 0]
  DstBlock              "Switch"
  DstPort            3
 }
}
Line {
 SrcBlock           "Switch"
 SrcPort            1
 DstBlock           "St2Thrust"
 DstPort            1
}
Line {
 SrcBlock           "Mux"
 SrcPort            1
 DstBlock           "Thrust Tail off"
 DstPort            1
}
Line {
 SrcBlock           "Step"
 SrcPort            1
 DstBlock           "Mux"
 DstPort            2
}
Line {
 SrcBlock           "Thrust Tail off"
 SrcPort            1
```

```
          DstBlock              "Product"
          DstPort               1
        }
        Line {
          SrcBlock              "Product"
          SrcPort               1
          Points                [5, 0]
          DstBlock              "Switch"
          DstPort               1
        }
        Line {
          SrcBlock              "Time"
          SrcPort               1
          Points                [15, 0]
          Branch {
            DstBlock                    "Mux"
            DstPort             1
          }
          Branch {
            Points              [0, 55]
            DstBlock                    "Switch"
            DstPort             2
          }
        }
  }
}
Block {
  BlockType                 SubSystem
  Name                "St 3 Thrust"
  Ports               [1, 1, 0, 0, 0]
  Position                  [120, 54, 180, 86]
  NamePlacement       alternate
  ShowPortLabels      on
  System {
        Name                    "St 3 Thrust"
        Location            [239, 438, 776, 605]
        Open                    off
        ScreenColor             white
        Block {
          BlockType                     Inport
          Name                          "Time"
          Position          [85, 15, 105, 35]
          Port                          "1"
          PortWidth                     "-1"
          SampleTime                    "-1"
        }
        Block {
          BlockType                     Mux
          Name                          "Mux"
          Ports                         [2, 1, 0, 0, 0]
          Position          [190, 17, 225, 53]
          Inputs            "2"
        }
        Block {
          BlockType                     Product
          Name                          "Product"
          Ports                         [2, 1, 0, 0, 0]
          Position          [355, 27, 385, 58]
          Inputs            "2"
        }
        Block {
          BlockType                     Constant
          Name                          "St3 Thrust"
          Position          [250, 108, 310, 132]
          Value                         "35000"
        }
        Block {
          BlockType                     Step
```

```
    Name                      "Step"
    Position          [140, 30, 170, 60]
    Time                      "[st3ig+62 st3ig+69]"
    Before            "[0 1]"
    After                     "[1 0]"
  }
  Block {
    BlockType                 Switch
    Name                      "Switch"
    Position          [410, 65, 440, 95]
    Threshold                 "st3ig+62"
  }
  Block {
    BlockType                 Fcn
    Name                      "Thrust Tail off"
    Position          [250, 20, 310, 50]
    Expr                      "u[2]*exp(-(u[1]-(st3ig+62)))"
  }
  Block {
    BlockType                 Outport
    Name                      "St3Thrust"
    Position          [485, 70, 505, 90]
    Port                      "1"
    OutputWhenDisabled        held
    InitialOutput             "0"
  }
  Line {
    SrcBlock          "St3 Thrust"
    SrcPort           1
    Points            [25, 0]
    Branch {
      DstBlock                "Product"
      DstPort         2
    }
    Branch {
      Points          [55, 0]
      DstBlock                "Switch"
      DstPort         3
    }
  }
  Line {
    SrcBlock          "Switch"
    SrcPort           1
    DstBlock          "St3Thrust"
    DstPort           1
  }
  Line {
    SrcBlock          "Mux"
    SrcPort           1
    DstBlock          "Thrust Tail off"
    DstPort           1
  }
  Line {
    SrcBlock          "Step"
    SrcPort           1
    DstBlock          "Mux"
    DstPort           2
  }
  Line {
    SrcBlock          "Thrust Tail off"
    SrcPort           1
    DstBlock          "Product"
    DstPort           1
  }
  Line {
    SrcBlock          "Product"
    SrcPort           1
    Points            [5, 0]
```

```
          DstBlock          "Switch"
          DstPort           1
        }
        Line {
          SrcBlock          "Time"
          SrcPort           1
          Points            [15, 0]
          Branch {
            DstBlock                 "Mux"
            DstPort           1
          }
          Branch {
            Points            [0, 55]
            DstBlock                 "Switch"
            DstPort           2
          }
        }
  }
}
Block {
  BlockType                  SubSystem
  Name              "St0 Thrust"
  Ports             [2, 1, 1, 0, 0]
  Position                   [210, 226, 340, 259]
  ShowPortLabels    on
  System {
        Name                         "St0 Thrust"
        Location          [297, 547, 819, 829]
        Open                         off
        ScreenColor                  white
        Block {
          BlockType                  Inport
          Name                       "Altitude"
          Position          [30, 200, 50, 220]
          Port                       "1"
          PortWidth                  "-1"
          SampleTime                 "-1"
        }
        Block {
          BlockType                  Inport
          Name                       "Time"
          Position          [30, 80, 50, 100]
          Port                       "2"
          PortWidth                  "-1"
          SampleTime                 "-1"
        }
        Block {
          BlockType                  EnablePort
          Name                       "Enable"
          Ports                      [0, 0, 0, 0, 0]
          Position          [30, 25, 50, 45]
          StatesWhenEnabling held
          ShowOutputPort    off
        }
        Block {
          BlockType                  SubSystem
          Name                       "Atmospere Model1"
          Ports                      [1, 1, 0, 0, 0]
          Position          [70, 192, 175, 228]
          ShowPortLabels    on
          MaskType                   "Atmosphere Model"
          MaskDescription   "Calculates exponential pressure "
                                     "and density based on isothermal "
                                     "atmosphere. T=249K.\n\nu(1)=pressure"
                                     "\nu(2)=density"
          MaskIconFrame              on
          MaskIconOpaque    on
          MaskIconRotate    none
```

```
MaskIconUnits            autoscale
System {
 Name               "Atmospere Model1"
 Location                 [167, 351, 502, 483]
 Open               off
 ScreenColor              white
 Block {
  BlockType               Inport
  Name              "Altitude"
  Position                [25, 58, 55, 72]
  Port              "1"
  PortWidth               "-1"
  SampleTime        "-1"
 }
 Block {
  BlockType               Fcn
  Name              "Pressure"
  Position                [120, 25, 180, 55]
  Expr              "101325*exp((-1.3728e-4)*u)"
 }
 Block {
  BlockType               Outport
  Name              "pres"
  Position                [280, 58, 310, 72]
  Port              "1"
  OutputWhenDisabled  held
  InitialOutput     "0"
 }
 Line {
  Labels            [1, 0]
  SrcBlock                "Altitude"
  SrcPort                 1
  Points            [15, 0; 0, -25]
  DstBlock                "Pressure"
  DstPort                 1
 }
 Line {
  SrcBlock                "Pressure"
  SrcPort                 1
  Points            [20, 0; 0, 15; 55, 0; 0, 10]
  DstBlock                "pres"
  DstPort                 1
 }
}
}
Block {
 BlockType                Mux
 Name                     "Mux"
 Ports                    [2, 1, 0, 0, 0]
 Position           [135, 82, 170, 118]
 Inputs             "2"
}
Block {
 BlockType                Product
 Name                     "Product"
 Ports                    [2, 1, 0, 0, 0]
 Position           [280, 92, 310, 123]
 Inputs             "2"
}
Block {
 BlockType                Fcn
 Name                     "St0 Thrust"
 Position           [195, 195, 255, 225]
 Expr                     "1313900+(1-u/101325)*336100"
}
Block {
 BlockType                Step
 Name                     "Step"
```

```
    Position		[85, 95, 115, 125]
    Time			"[74.5 81.5]"
    Before		"[0 1]"
    After			"[1 0]"
  }
  Block {
    BlockType		Switch
    Name			"Switch"
    Position		[335, 160, 365, 190]
    Threshold		"74.5"
  }
  Block {
    BlockType		Fcn
    Name			"Thrust Tail off"
    Position		[195, 85, 255, 115]
    Expr			"u[2]*exp(-(u[1]-74.5))"
  }
  Block {
    BlockType		Outport
    Name			"St0Thrust"
    Position		[410, 165, 430, 185]
    Port			"1"
    OutputWhenDisabled	held
    InitialOutput		"0"
  }
  Line {
    SrcBlock		"Mux"
    SrcPort		1
    DstBlock		"Thrust Tail off"
    DstPort		1
  }
  Line {
    SrcBlock		"Step"
    SrcPort		1
    DstBlock		"Mux"
    DstPort		2
  }
  Line {
    SrcBlock		"Atmospere Model1"
    SrcPort		1
    DstBlock		"St0 Thrust"
    DstPort		1
  }
  Line {
    SrcBlock		"Altitude"
    SrcPort		1
    DstBlock		"Atmospere Model1"
    DstPort		1
  }
  Line {
    SrcBlock		"Switch"
    SrcPort		1
    DstBlock		"St0Thrust"
    DstPort		1
  }
  Line {
    SrcBlock		"Thrust Tail off"
    SrcPort		1
    DstBlock		"Product"
    DstPort		1
  }
  Line {
    SrcBlock		"St0 Thrust"
    SrcPort		1
    Points		[0, 0]
    Branch {
      Points		[60, 0]
      DstBlock		"Switch"
```

```
	    DstPort		3
	  }
	  Branch {
	    Points		[0, -95]
	    DstBlock			"Product"
	    DstPort		2
	  }
	}
	Line {
	  SrcBlock		"Product"
	  SrcPort		1
	  Points		[5, 0]
	  DstBlock		"Switch"
	  DstPort		1
	}
	Line {
	  SrcBlock		"Time"
	  SrcPort		1
	  Points		[15, 0]
	  Branch {
	    DstBlock			"Mux"
	    DstPort		1
	  }
	  Branch {
	    Points		[0, 85]
	    DstBlock			"Switch"
	    DstPort		2
	  }
	}
  }
}
Block {
  BlockType		SubSystem
  Name		"Stl Thrust"
  Ports		[2, 1, 1, 0, 0]
  Position		[210, 172, 340, 203]
  NamePlacement	alternate
  ShowPortLabels	on
  System {
	Name			"Stl Thrust"
	Location		[265, 309, 802, 476]
	Open			off
	ScreenColor		white
	Block {
	  BlockType		Inport
	  Name			"Altitude"
	  Position		[110, 110, 130, 130]
	  Port			"1"
	  PortWidth		"-1"
	  SampleTime		"-1"
	}
	Block {
	  BlockType		Inport
	  Name			"Time"
	  Position		[85, 15, 105, 35]
	  Port			"2"
	  PortWidth		"-1"
	  SampleTime		"-1"
	}
	Block {
	  BlockType		EnablePort
	  Name			"Enable"
	  Ports			[0, 0, 0, 0, 0]
	  Position		[35, 15, 55, 35]
	  StatesWhenEnabling	held
	  ShowOutputPort	off
	}
	Block {
```

```
  BlockType               Mux
  Name                    "Mux"
  Ports                   [2, 1, 0, 0, 0]
  Position          [190, 17, 225, 53]
  Inputs            "2"
}
Block {
  BlockType               Fcn
  Name                    "Pressure"
  Position          [175, 105, 235, 135]
  Expr                    "101325*exp((-1.3728e-4)*u)"
}
Block {
  BlockType               Product
  Name                    "Product"
  Ports                   [2, 1, 0, 0, 0]
  Position          [355, 27, 385, 58]
  Inputs            "2"
}
Block {
  BlockType               Fcn
  Name                    "St1 Thrust"
  Position          [270, 105, 330, 135]
  Expr                    "298032+(1-u/101325)*186854"
}
Block {
  BlockType               Step
  Name                    "Step"
  Position          [140, 30, 170, 60]
  Time                    "[147.7 154.7]"
  Before            "[0 1]"
  After                   "[1 0]"
}
Block {
  BlockType               Switch
  Name                    "Switch"
  Position          [410, 65, 440, 95]
  Threshold               "147.7"
}
Block {
  BlockType               Fcn
  Name                    "Thrust Tail off"
  Position          [250, 20, 310, 50]
  Expr                    "u[2]*exp(-(u[1]-147.7))"
}
Block {
  BlockType               Outport
  Name                    "St1Thrust"
  Position          [485, 70, 505, 90]
  Port                    "1"
  OutputWhenDisabled      held
  InitialOutput           "0"
}
Line {
  SrcBlock          "St1 Thrust"
  SrcPort           1
  Points            [5, 0]
  Branch {
    DstBlock                "Product"
    DstPort           2
  }
  Branch {
    Points            [55, 0]
    DstBlock                "Switch"
    DstPort           3
  }
}
Line {
```

```
      SrcBlock        "Switch"
      SrcPort         1
      DstBlock        "St1Thrust"
      DstPort         1
    }
    Line {
      SrcBlock        "Mux"
      SrcPort         1
      DstBlock        "Thrust Tail off"
      DstPort         1
    }
    Line {
      SrcBlock        "Step"
      SrcPort         1
      DstBlock        "Mux"
      DstPort         2
    }
    Line {
      SrcBlock        "Thrust Tail off"
      SrcPort         1
      DstBlock        "Product"
      DstPort         1
    }
    Line {
      SrcBlock        "Product"
      SrcPort         1
      Points          [5, 0]
      DstBlock        "Switch"
      DstPort         1
    }
    Line {
      SrcBlock        "Time"
      SrcPort         1
      Points          [15, 0]
      Branch {
        DstBlock                "Mux"
        DstPort         1
      }
      Branch {
        Points          [0, 55]
        DstBlock                "Switch"
        DstPort         2
      }
    }
    Line {
      SrcBlock        "Pressure"
      SrcPort         1
      DstBlock        "St1 Thrust"
      DstPort         1
    }
    Line {
      SrcBlock        "Altitude"
      SrcPort         1
      DstBlock        "Pressure"
      DstPort         1
    }
  }
}
Block {
  BlockType               Switch
  Name            "Switch"
  Position                [220, 25, 250, 55]
  ShowName                off
  Threshold               "st3ig+69"
}
Block {
  BlockType               Switch
  Name            "Switch1"
```

```
    Position                    [275, 60, 305, 90]
    ShowName                    off
    Threshold                   "st3ig"
  }
  Block {
    BlockType                   Switch
    Name                "Switch2"
    Position                    [330, 95, 360, 125]
    ShowName                    off
    Threshold                   "80.7+st2ig"
  }
  Block {
    BlockType                   Switch
    Name                "Switch3"
    Position                    [385, 130, 415, 160]
    ShowName                    off
    Threshold                   "st2ig"
  }
  Block {
    BlockType                   Switch
    Name                "Switch4"
    Position                    [440, 165, 470, 195]
    ShowName                    off
    Threshold                   "154.7"
  }
  Block {
    BlockType                   Switch
    Name                "Switch5"
    Position                    [495, 200, 525, 230]
    ShowName                    off
    Threshold                   "81.5"
  }
  Block {
    BlockType                   Switch
    Name                "Switch6"
    Position                    [140, 200, 170, 230]
    ShowName                    off
    Threshold                   "154.7"
  }
  Block {
    BlockType                   Outport
    Name                "Thrust"
    Position                    [550, 208, 580, 222]
    Port                "1"
    OutputWhenDisabled    held
    InitialOutput       "0"
  }
  Line {
    SrcBlock                    "Switch5"
    SrcPort                     1
    DstBlock                    "Thrust"
    DstPort                     1
  }
  Line {
    SrcBlock                    "Switch"
    SrcPort                     1
    Points              [0, 25]
    DstBlock                    "Switch1"
    DstPort                     1
  }
  Line {
    SrcBlock                    "Switch1"
    SrcPort                     1
    Points              [0, 25]
    DstBlock                    "Switch2"
    DstPort                     1
  }
  Line {
```

```
    Labels              [0, 0]
    SrcBlock                      "Switch2"
    SrcPort                       1
    Points              [0, 25]
    DstBlock                      "Switch3"
    DstPort                       1
  }
  Line {
    SrcBlock                      "Switch3"
    SrcPort                       1
    Points              [0, 25]
    DstBlock                      "Switch4"
    DstPort                       1
  }
  Line {
    SrcBlock                      "Switch4"
    SrcPort                       1
    Points              [0, 25]
    DstBlock                      "Switch5"
    DstPort                       1
  }
  Line {
    Labels              [1, 0]
    SrcBlock                      "Motor Off"
    SrcPort                       1
    Points              [5, 0]
    Branch {
          Points                          [0, -70]
          Branch {
            DstBlock          "Switch1"
            DstPort           3
          }
          Branch {
            Points            [0, -55]
            DstBlock          "Switch"
            DstPort           1
          }
    }
    Branch {
          DstBlock           "Switch3"
          DstPort                     3
    }
  }
  Line {
    SrcBlock                      "St 2 Thrust"
    SrcPort                       1
    DstBlock                      "Switch2"
    DstPort                       3
  }
  Line {
    SrcBlock                      "St 3 Thrust"
    SrcPort                       1
    Points              [0, -20]
    DstBlock                      "Switch"
    DstPort                       3
  }
  Line {
    SrcBlock                      "St0 Thrust"
    SrcPort                       1
    Points              [0, -20]
    DstBlock                      "Switch5"
    DstPort                       3
  }
  Line {
    SrcBlock                      "Time"
    SrcPort                       1
    Points              [25, 0]
    Branch {
```

```
	Points			[0, 30]
	Branch {
	 DstBlock		"St 3 Thrust"
	 DstPort		1
	}
	Branch {
	 Points			[0, 50]
	 Branch {
	  DstBlock			"St 2 Thrust"
	  DstPort		1
	 }
	 Branch {
	  Points		[0, 95]
	  Branch {
	   DstBlock			"Switch6"
	   DstPort			2
	  }
	  Branch {
	   Points		[0, 35; 80, 0]
	   Branch {
		DstBlock		"St0 Thrust"
		DstPort				2
	   }
	   Branch {
		Points				[0, -55]
		DstBlock		"St1 Thrust"
		DstPort				2
	   }
	  }
	 }
	}
}
Branch {
	Points			[100, 0]
	Branch {
	 Points			[0, 35; 55, 0]
	 Branch {
	  Points		[0, 35; 55, 0]
	  Branch {
	   Points		[0, 35; 55, 0]
	   Branch {
		Points				[0, 35; 55, 0]
		Branch {
		 Points			[0, 35]
		 DstBlock		"Switch5"
		 DstPort		2
		}
		Branch {
		 DstBlock		"Switch4"
		 DstPort		2
		}
	   }
	   Branch {
		DstBlock		"Switch3"
		DstPort				2
	   }
	  }
	  Branch {
	   DstBlock			"Switch2"
	   DstPort			2
	  }
	 }
	 Branch {
	  DstBlock			"Switch1"
	  DstPort		2
	 }
	}
	Branch {
```

```
        DstBlock          "Switch"
        DstPort           2
       }
    }
   }
   Line {
    SrcBlock              "Switch6"
    SrcPort               1
    Points            [100, 0]
    Branch {
        DstBlock          "St1 Thrust"
        DstPort                 enable
    }
    Branch {
        DstBlock          "St0 Thrust"
        DstPort                 enable
    }
   }
   Line {
    SrcBlock              "Constant1"
    SrcPort               1
    DstBlock              "Switch6"
    DstPort               1
   }
   Line {
    SrcBlock              "Constant"
    SrcPort               1
    DstBlock              "Switch6"
    DstPort               3
   }
   Line {
    SrcBlock              "Altitude"
    SrcPort               1
    Points            [135, 0]
    Branch {
        DstBlock          "St1 Thrust"
        DstPort                 1
    }
    Branch {
        DstBlock          "St0 Thrust"
        DstPort                 1
    }
   }
   Line {
    SrcBlock              "St1 Thrust"
    SrcPort               1
    DstBlock              "Switch4"
    DstPort               3
   }
  }
}
Block {
 BlockType            Trigonometry
 Name                 "Trigonometric\nFunction"
 Ports                [1, 1, 0, 0, 0]
 Position         [460, 315, 490, 345]
 ShowName             off
 Operator         sin
}
Block {
 BlockType            Trigonometry
 Name                 "Trigonometric\nFunction1"
 Ports                [1, 1, 0, 0, 0]
 Position         [460, 360, 490, 390]
 ShowName             off
 Operator         cos
}
Block {
```

```
  BlockType                  Fcn
  Name                       "local gee"
  Position          [275, 290, 335, 320]
  Orientation                left
  Expr                       "9.81*(6378135^2/(6378135+u)^2)"
}
Block {
  BlockType                  Outport
  Name                       "Thrust"
  Position          [695, 52, 725, 68]
  Port                       "1"
  OutputWhenDisabled         held
  InitialOutput              "0"
}
Block {
  BlockType                  Outport
  Name                       "CG Vel"
  Position          [695, 163, 725, 177]
  Port                       "2"
  OutputWhenDisabled         held
  InitialOutput              "0"
}
Block {
  BlockType                  Outport
  Name                       "Density"
  Position          [695, 17, 725, 33]
  Port                       "3"
  OutputWhenDisabled         held
  InitialOutput              "0"
}
Block {
  BlockType                  Outport
  Name                       "Drag Force"
  Position          [320, 15, 340, 35]
  Port                       "4"
  OutputWhenDisabled         held
  InitialOutput              "0"
}
Line {
  SrcBlock          "Vibes"
  SrcPort           1
  Points            [230, 0]
  DstBlock          "Mux1"
  DstPort           10
}
Line {
  SrcBlock          "CG Range"
  SrcPort           1
  DstBlock          "Terminator26"
  DstPort           1
}
Line {
  SrcBlock          "Switch"
  SrcPort           1
  Points            [5, 0]
  DstBlock          "CG Alpha"
  DstPort           1
}
Line {
  SrcBlock          "Alpha Dot"
  SrcPort           1
  Points            [0, 10]
  DstBlock          "Switch"
  DstPort           1
}
Line {
  SrcBlock          "Product1"
  SrcPort           1
```

```
  DstBlock              "CG Range"
  DstPort               1
}
Line {
  SrcBlock              "Sum"
  SrcPort               1
  Points                [0, 0]
  Branch {
    DstBlock                      "Trigonometric\nFunction"
    DstPort             1
  }
  Branch {
    DstBlock                      "Trigonometric\nFunction1"
    DstPort             1
  }
}
Line {
  SrcBlock              "local gee"
  SrcPort               1
  Points                [-10, 0]
  Branch {
    Points              [-115, 0]
    DstBlock                      "Mux"
    DstPort             1
  }
  Branch {
    Points              [0, -130]
    DstBlock                      "Mux1"
    DstPort             6
  }
}
Line {
  SrcBlock              "Mux"
  SrcPort               1
  DstBlock              "Alpha Dot"
  DstPort               1
}
Line {
  SrcBlock              "Constant"
  SrcPort               1
  Points                [30, 0]
  DstBlock              "Switch"
  DstPort               3
}
Line {
  SrcBlock              "Trigonometric\nFunction1"
  SrcPort               1
  Points                [5, 0]
  Branch {
    Points              [5, 0]
    Branch {
      DstBlock                    "Product1"
      DstPort                     1
    }
    Branch {
      Labels            [2, 0]
      Points            [0, 30; -370, 0; 0, -65]
      DstBlock                    "Mux"
      DstPort                     4
    }
  }
  Branch {
    Points              [0, -105; -230, 0; 0, -75]
    DstBlock                      "Mux1"
    DstPort             8
  }
}
Line {
```

```
    SrcBlock            "Product"
    SrcPort             1
    Points              [5, 0]
    Branch {
      DstBlock                      "CG Altitude"
      DstPort             1
    }
    Branch {
      Points              [0, -60; -300, 0; 0, -60]
      DstBlock                      "Mux1"
      DstPort             9
    }
    Branch {
      Points              [0, 90; -435, 0; 0, -65]
      DstBlock                      "Mux"
      DstPort             5
    }
  }
  Line {
    SrcBlock            "Trigonometric\nFunction"
    SrcPort             1
    Points              [0, 0]
    Branch {
      Points              [10, 0]
      Branch {
        DstBlock                      "Product"
        DstPort                       2
      }
      Branch {
        Points              [0, -50; -240, 0; 0, -95]
        DstBlock                      "Mux1"
        DstPort                       7
      }
    }
    Branch {
      Points              [0, 70; -350, 0]
      DstBlock                      "Mux"
      DstPort             6
    }
  }
  Line {
    SrcBlock            "CG Altitude"
    SrcPort             1
    Points              [0, -40]
    Branch {
      Points              [-280, 0]
      Branch {
        DstBlock                      "local gee"
        DstPort                       1
      }
      Branch {
        Points              [-95, 0]
        Branch {
              Points                        [-125, 0]
              Branch {
                Points              [0, -100]
                DstBlock            "Thrust\nProgram"
                DstPort             2
              }
              Branch {
                Points              [0, 35]
                DstBlock            "Mux"
                DstPort             2
              }
        }
        Branch {
              Points                        [0, -120]
              DstBlock            "Mux1"
```

```
          DstPort                    5
    }
   }
  }
  Branch {
   Points              [0, -195]
   DstBlock                      "Atmospere Model"
   DstPort             1
  }
 }
 Line {
  SrcBlock            "Pitch Program"
  SrcPort             1
  Points              [35, 0]
  DstBlock            "Sum"
  DstPort             2
 }
 Line {
  SrcBlock            "CG Alpha"
  SrcPort             1
  DstBlock            "Sum"
  DstPort             1
 }
 Line {
  SrcBlock            "CG Vel Dot"
  SrcPort             1
  DstBlock            "CG Velocity"
  DstPort             1
 }
 Line {
  SrcBlock            "Drag"
  SrcPort             1
  Points              [-15, 0]
  Branch {
   Points              [0, 55]
   DstBlock                      "Mux1"
   DstPort             4
  }
  Branch {
   Points              [0, -75]
   DstBlock                      "Drag Force"
   DstPort             1
  }
 }
 Line {
  SrcBlock            "Mux1"
  SrcPort             1
  DstBlock            "CG Vel Dot"
  DstPort             1
 }
 Line {
  SrcBlock            "Mux2"
  SrcPort             1
  DstBlock            "Drag"
  DstPort             1
 }
 Line {
  SrcBlock            "CG Velocity"
  SrcPort             1
  Points              [30, 0]
  Branch {
   Points              [0, 0]
   Branch {
    Points              [0, 145]
    Branch {
          Points                    [0, 75]
          Branch {
           Points              [0, 20; -380, 0; 0, -80]
```

```
        DstBlock        "Mux"
        DstPort         3
      }
      Branch {
        DstBlock        "Product1"
        DstPort         2
      }
    }
    Branch {
      DstBlock          "Product"
      DstPort           1
    }
  }
  Branch {
    Points              [0, -50; -105, 0]
    Branch {
      Points            [-120, 0]
      DstBlock          "Mux1"
      DstPort           1
    }
    Branch {
      DstBlock          "Mux2"
      DstPort           2
    }
  }
}
Branch {
  DstBlock              "CG Vel"
  DstPort               1
}
}
Line {
  SrcBlock              "Thrust\nProgram"
  SrcPort               1
  Points                [0, -20; 15, 0]
  Branch {
    Points              [45, 0]
    DstBlock            "Mux1"
    DstPort             3
  }
  Branch {
    Points              [0, -90]
    DstBlock            "Thrust"
    DstPort             1
  }
}
Line {
  SrcBlock              "Atmospere Model"
  SrcPort               1
  Points                [-10, 0]
  Branch {
    DstBlock            "Mux2"
    DstPort             1
  }
  Branch {
    Points              [0, -65]
    DstBlock            "Density"
    DstPort             1
  }
}
Line {
  SrcBlock              "Time"
  SrcPort               1
  Points                [70, 0]
  Branch {
    DstBlock            "Thrust\nProgram"
    DstPort             1
  }
```

```
          Branch {
            Points              [0, 210]
            Branch {
              Points              [150, 0; 0, -10]
              DstBlock                    "Switch"
              DstPort                     2
            }
            Branch {
              Points              [0, 80]
              DstBlock                    "Pitch Program"
              DstPort                     1
            }
          }
        }
        Line {
          SrcBlock            "Sys Mass"
          SrcPort             1
          Points              [180, 0; 0, 15]
          DstBlock            "Mux1"
          DstPort             2
        }
  }
}
Block {
  BlockType                   SubSystem
  Name                "Mass Matrix \nInverter"
  Ports               [6, 1, 0, 0, 0]
  Position                    [430, 187, 505, 278]
  ShowPortLabels      on
  System {
        Name                          "Mass Matrix \nInverter"
        Location              [586, 190, 851, 416]
        Open                          off
        ScreenColor                   white
        Block {
          BlockType                     Inport
          Name                          "Total"
          Position            [25, 18, 55, 32]
          Port                          "1"
          PortWidth                     "-1"
          SampleTime                    "-1"
        }
        Block {
          BlockType                     Inport
          Name                          "Lower"
          Position            [15, 53, 45, 67]
          Port                          "2"
          PortWidth                     "-1"
          SampleTime                    "-1"
        }
        Block {
          BlockType                     Inport
          Name                          "Upper"
          Position            [15, 83, 45, 97]
          Port                          "3"
          PortWidth                     "-1"
          SampleTime                    "-1"
        }
        Block {
          BlockType                     Inport
          Name                          "Inert"
          Position            [15, 113, 45, 127]
          Port                          "4"
          PortWidth                     "-1"
          SampleTime                    "-1"
        }
        Block {
          BlockType                     Inport
```

```
      Name                  "Payload"
      Position              [15, 143, 45, 157]
      Port                  "5"
      PortWidth             "-1"
      SampleTime            "-1"
    }
    Block {
      BlockType             Inport
      Name                  "SC1"
      Position              [30, 173, 60, 187]
      Port                  "6"
      PortWidth             "-1"
      SampleTime            "-1"
    }
    Block {
      BlockType             Fcn
      Name                  "Fcn4"
      Position              [90, 66, 120, 84]
      ShowName              off
      Expr                  "1/u"
    }
    Block {
      BlockType             Fcn
      Name                  "Fcn5"
      Position              [90, 81, 120, 99]
      ShowName              off
      Expr                  "1/u"
    }
    Block {
      BlockType             Fcn
      Name                  "Fcn6"
      Position              [90, 96, 120, 114]
      ShowName              off
      Expr                  "1/u"
    }
    Block {
      BlockType             Fcn
      Name                  "Fcn7"
      Position              [90, 111, 120, 129]
      ShowName              off
      Expr                  "1/u"
    }
    Block {
      BlockType             Fcn
      Name                  "Fcn8"
      Position              [90, 128, 120, 142]
      ShowName              off
      Expr                  "1/u"
    }
    Block {
      BlockType             Fcn
      Name                  "Fcn9"
      Position              [90, 141, 120, 159]
      ShowName              off
      Expr                  "1/u"
    }
    Block {
      BlockType             Mux
      Name                  "Mux"
      Ports                 [6, 1, 0, 0, 0]
      Position              [145, 62, 185, 163]
      Inputs                "6"
    }
    Block {
      BlockType             Outport
      Name                  "M inv"
      Position              [210, 108, 240, 122]
      Port                  "1"
```

```
    OutputWhenDisabled        held
    InitialOutput             "0"
  }
  Line {
    SrcBlock          "SC1"
    SrcPort           1
    Points            [0, -30]
    DstBlock          "Fcn9"
    DstPort           1
  }
  Line {
    SrcBlock          "Payload"
    SrcPort           1
    Points            [0, -15]
    DstBlock          "Fcn8"
    DstPort           1
  }
  Line {
    SrcBlock          "Inert"
    SrcPort           1
    DstBlock          "Fcn7"
    DstPort           1
  }
  Line {
    SrcBlock          "Mux"
    SrcPort           1
    DstBlock          "M inv"
    DstPort           1
  }
  Line {
    SrcBlock          "Upper"
    SrcPort           1
    Points            [0, 15]
    DstBlock          "Fcn6"
    DstPort           1
  }
  Line {
    SrcBlock          "Lower"
    SrcPort           1
    Points            [0, 30]
    DstBlock          "Fcn5"
    DstPort           1
  }
  Line {
    SrcBlock          "Total"
    SrcPort           1
    Points            [0, 50]
    DstBlock          "Fcn4"
    DstPort           1
  }
  Line {
    SrcBlock          "Fcn4"
    SrcPort           1
    DstBlock          "Mux"
    DstPort           1
  }
  Line {
    SrcBlock          "Fcn5"
    SrcPort           1
    DstBlock          "Mux"
    DstPort           2
  }
  Line {
    SrcBlock          "Fcn6"
    SrcPort           1
    DstBlock          "Mux"
    DstPort           3
  }
```

```
      Line {
        SrcBlock            "Fcn7"
        SrcPort             1
        DstBlock            "Mux"
        DstPort             4
      }
      Line {
        SrcBlock            "Fcn8"
        SrcPort             1
        DstBlock            "Mux"
        DstPort             5
      }
      Line {
        SrcBlock            "Fcn9"
        SrcPort             1
        DstBlock            "Mux"
        DstPort             6
      }
  }
}
Block {
  BlockType           SubSystem
  Name                "Mass Properties"
  Ports               [1, 6, 0, 0, 0]
  Position            [90, 184, 190, 281]
  ShowPortLabels      on
  MaskType            "Mass Properties"
  MaskPromptString    "2nd Stage Ignition Time|3rd Stage Ignition "
                      "Time|Payload Mass|Axial Subcomponent Mass|Latera"
                      "l Subcomponent Moment of Inertia"
  MaskStyleString     "edit,edit,edit,edit,edit"
  MaskVariables       "st2ig=@1;st3ig=@2;plm=@3;mass1=@4;mass2=@5;"
  MaskIconFrame       on
  MaskIconOpaque      on
  MaskIconRotate      none
  MaskIconUnits       autoscale
  MaskValueString     "166.8|635|1780|1|1"
  System {
      Name                "Mass Properties"
      Location            [95, 439, 1151, 983]
      Open                off
      ScreenColor         white
      Block {
        BlockType           Inport
        Name                "Time"
        Position            [135, 93, 165, 107]
        Port                "1"
        PortWidth           "-1"
        SampleTime          "-1"
      }
      Block {
        BlockType           Sum
        Name                "Active Stage Mass"
        Ports               [4, 1, 0, 0, 0]
        Position            [530, 269, 555, 336]
        Orientation         left
        Inputs              "+---"
      }
      Block {
        BlockType           Demux
        Name                "Demux"
        Ports               [1, 5, 0, 0, 0]
        Position            [290, 118, 325, 192]
        Outputs             "5"
      }
      Block {
        BlockType           Demux
        Name                "Demux1"
```

```
    Ports                   [1, 4, 0, 0, 0]
    Position                [460, 412, 495, 448]
    NamePlacement           alternate
    ShowName                off
    Outputs                 "4"
   }
   Block {
    BlockType               Demux
    Name                    "Demux2"
    Ports                   [1, 4, 0, 0, 0]
    Position                [460, 452, 495, 488]
    ShowName                off
    Outputs                 "4"
   }
   Block {
    BlockType               Step
    Name                    "Fairing"
    Position                [665, 420, 695, 450]
    Time                    "st2ig+3"
    Before                  "205"
    After                   "0"
   }
   Block {
    BlockType               Step
    Name                    "Fairing\nMass"
    Position                [575, 125, 605, 155]
    Time                    "st2ig+3"
    Before                  "0"
    After                   "-205"
   }
   Block {
    BlockType               Fcn
    Name                    "Fcn"
    Position                [440, 290, 500, 320]
    Orientation             left
    Expr                    "u/2"
   }
   Block {
    BlockType               Fcn
    Name                    "Fcn1"
    Position                [860, 265, 920, 295]
    Expr                    "u-mass1"
   }
   Block {
    BlockType               Sum
    Name                    "Inert\nMass"
    Ports                   [4, 1, 0, 0, 0]
    Position                [760, 325, 790, 455]
    Inputs                  "++++"
   }
   Block {
    BlockType               Integrator
    Name                    "Mass Flow"
    Ports                   [1, 1, 0, 0, 0]
    Position                [690, 210, 720, 240]
    ExternalReset           none
    InitialConditionSource  internal
    InitialCondition        "71600"
    LimitOutput             off
    UpperSaturationLimit    "inf"
    LowerSaturationLimit    "-inf"
    ShowSaturationPort      off
    ShowStatePort           off
    AbsoluteTolerance       "auto"
   }
   Block {
    BlockType               Constant
    Name                    "Mass1"
```

```
 Position        [880, 425, 935, 445]
 Value                    "mass1"
}
Block {
 BlockType                Step
 Name                     "Neg Nozzle"
 Position        [400, 455, 430, 485]
 Time                     "[0;81.5;st2ig;st3ig]"
 Before          "[-795.3;-235.4;-118.7;-52.8]"
 After                    "[0;0;0;0]"
}
Block {
 BlockType                Constant
 Name                     "Payload Mass"
 Position        [355, 50, 410, 70]
 Value                    "plm"
}
Block {
 BlockType                Step
 Name                     "Pos Nozzle"
 Position        [400, 415, 430, 445]
 NamePlacement            alternate
 Time                     "[81.5;154.7;st2ig+80.7;st3ig+69]"
 Before          "[795.3;235.4;118.7;52.8]"
 After                    "[0;0;0;0]"
}
Block {
 BlockType                Step
 Name                     "St0 Mass"
 Position        [425, 65, 455, 95]
 Time                     "81.5"
 Before          "0"
 After                    "-4211"
}
Block {
 BlockType                Step
 Name                     "St1"
 Position        [705, 330, 735, 360]
 Time                     "81.5"
 Before          "14020"
 After                    "0"
}
Block {
 BlockType                Step
 Name                     "St1 Mass"
 Position        [475, 85, 505, 115]
 Time                     "154.7"
 Before          "0"
 After                    "-1868"
}
Block {
 BlockType                Step
 Name                     "St2"
 Position        [665, 360, 695, 390]
 Time                     "154.7"
 Before          "3370"
 After                    "0"
}
Block {
 BlockType                Step
 Name                     "St2 Mass"
 Position        [525, 105, 555, 135]
 Time                     "st3ig"
 Before          "0"
 After                    "-345"
}
Block {
 BlockType                Step
```

```
  Name                  "St3"
  Position              [700, 390, 730, 420]
  Time                  "st3ig"
  Before                "985"
  After                 "100"
}
Block {
  BlockType             Step
  Name                  "St3 Mass"
  Position              [620, 150, 650, 180]
  Time                  "st3ig+129"
  Before                "0"
  After                 "-203"
}
Block {
  BlockType             Sum
  Name                  "Sum"
  Ports                 [8, 1, 0, 0, 0]
  Position              [530, 406, 565, 494]
  Inputs                "++++++++"
}
Block {
  BlockType             Sum
  Name                  "Sum1"
  Ports                 [2, 1, 0, 0, 0]
  Position              [365, 342, 395, 373]
  Orientation           left
  Inputs                "++"
}
Block {
  BlockType             Switch
  Name                  "Switch1"
  Position              [375, 85, 405, 115]
  ShowName              off
  Threshold             "st3ig+69"
}
Block {
  BlockType             Switch
  Name                  "Switch2"
  Position              [425, 110, 455, 140]
  ShowName              off
  Threshold             "st3ig"
}
Block {
  BlockType             Switch
  Name                  "Switch3"
  Position              [475, 135, 505, 165]
  ShowName              off
  Threshold             "st2ig+80.7"
}
Block {
  BlockType             Switch
  Name                  "Switch4"
  Position              [625, 210, 655, 240]
  ShowName              off
  Threshold             "81.5"
}
Block {
  BlockType             Switch
  Name                  "Switch5"
  Position              [525, 160, 555, 190]
  ShowName              off
  Threshold             "st2ig"
}
Block {
  BlockType             Switch
  Name                  "Switch6"
  Position              [575, 185, 605, 215]
```

```
    ShowName                    off
    Threshold                   "154.7"
  }
  Block {
    BlockType                   Sum
    Name                        "System Mass"
    Ports                       [7, 1, 0, 0, 0]
    Position            [760, 127, 790, 233]
    Inputs              "+++++++"
  }
  Block {
    BlockType                   Constant
    Name                        "mdot's"
    Position            [30, 144, 270, 166]
    Value                       "[-11.3333;-37.48451;-166.0109;-598.8834;0]"
  }
  Block {
    BlockType                   Outport
    Name                        "Tot Mass"
    Position            [970, 170, 990, 190]
    Port                        "1"
    OutputWhenDisabled          held
    InitialOutput               "0"
  }
  Block {
    BlockType                   Outport
    Name                        "Lower"
    Position            [320, 350, 340, 370]
    Orientation                 left
    NamePlacement               alternate
    Port                        "2"
    OutputWhenDisabled          held
    InitialOutput               "0"
  }
  Block {
    BlockType                   Outport
    Name                        "Upper"
    Position            [320, 295, 340, 315]
    Orientation                 left
    Port                        "3"
    OutputWhenDisabled          held
    InitialOutput               "0"
  }
  Block {
    BlockType                   Outport
    Name                        "Inert"
    Position            [960, 380, 980, 400]
    Port                        "4"
    OutputWhenDisabled          held
    InitialOutput               "0"
  }
  Block {
    BlockType                   Outport
    Name                        "Payload"
    Position            [955, 270, 975, 290]
    Port                        "5"
    OutputWhenDisabled          held
    InitialOutput               "0"
  }
  Block {
    BlockType                   Outport
    Name                        "SC1"
    Position            [960, 425, 980, 445]
    Port                        "6"
    OutputWhenDisabled          held
    InitialOutput               "0"
  }
  Line {
```

```
    SrcBlock            "Fcn1"
    SrcPort             1
    DstBlock            "Payload"
    DstPort             1
  }
  Line {
    SrcBlock            "Fairing"
    SrcPort             1
    DstBlock            "Inert\nMass"
    DstPort             4
  }
  Line {
    SrcBlock            "St2"
    SrcPort             1
    DstBlock            "Inert\nMass"
    DstPort             2
  }
  Line {
    SrcBlock            "Time"
    SrcPort             1
    Points              [190, 0]
    Branch {
      Points            [0, 25; 50, 0]
      Branch {
        Points          [0, 25; 50, 0]
        Branch {
          Points        [0, 25; 50, 0]
          Branch {
            Points      [0, 25; 50, 0]
            Branch {
              Points    [0, 25]
              DstBlock  "Switch4"
              DstPort   2
            }
            Branch {
              DstBlock  "Switch6"
              DstPort   2
            }
          }
          Branch {
            DstBlock    "Switch5"
            DstPort     2
          }
        }
        Branch {
          DstBlock      "Switch3"
          DstPort       2
        }
      }
      Branch {
        DstBlock        "Switch2"
        DstPort         2
      }
    }
    Branch {
      DstBlock          "Switch1"
      DstPort           2
    }
  }
  Line {
    SrcBlock            "Switch1"
    SrcPort             1
    DstBlock            "Switch2"
    DstPort             1
  }
  Line {
    SrcBlock            "Switch2"
    SrcPort             1
```

```
    DstBlock		"Switch3"
    DstPort		1
  }
  Line {
    SrcBlock		"Switch3"
    SrcPort		1
    DstBlock		"Switch5"
    DstPort		1
  }
  Line {
    SrcBlock		"Switch5"
    SrcPort		1
    DstBlock		"Switch6"
    DstPort		1
  }
  Line {
    SrcBlock		"Switch6"
    SrcPort		1
    DstBlock		"Switch4"
    DstPort		1
  }
  Line {
    SrcBlock		"Switch4"
    SrcPort		1
    DstBlock		"Mass Flow"
    DstPort		1
  }
  Line {
    SrcBlock		"Mass Flow"
    SrcPort		1
    DstBlock		"System Mass"
    DstPort		7
  }
  Line {
    SrcBlock		"St3 Mass"
    SrcPort		1
    Points		[5, 0; 0, 45]
    DstBlock		"System Mass"
    DstPort		6
  }
  Line {
    SrcBlock		"Fairing\nMass"
    SrcPort		1
    Points		[55, 0; 0, 55]
    DstBlock		"System Mass"
    DstPort		5
  }
  Line {
    SrcBlock		"St2 Mass"
    SrcPort		1
    Points		[110, 0; 0, 60]
    DstBlock		"System Mass"
    DstPort		4
  }
  Line {
    SrcBlock		"St1 Mass"
    SrcPort		1
    Points		[165, 0; 0, 65]
    DstBlock		"System Mass"
    DstPort		3
  }
  Line {
    SrcBlock		"St0 Mass"
    SrcPort		1
    Points		[220, 0; 0, 70]
    DstBlock		"System Mass"
    DstPort		2
  }
```

```
Line {
  SrcBlock        "mdot's"
  SrcPort         1
  DstBlock        "Demux"
  DstPort         1
}
Line {
  SrcBlock        "Demux"
  SrcPort         1
  Points          [20, 0; 0, -15]
  DstBlock        "Switch1"
  DstPort         3
}
Line {
  SrcBlock        "Demux"
  SrcPort         2
  Points          [20, 0; 0, 20]
  DstBlock        "Switch3"
  DstPort         3
}
Line {
  SrcBlock        "Demux"
  SrcPort         3
  Points          [15, 0; 0, 55]
  DstBlock        "Switch6"
  DstPort         3
}
Line {
  SrcBlock        "Demux"
  SrcPort         4
  Points          [10, 0; 0, 65]
  DstBlock        "Switch4"
  DstPort         3
}
Line {
  Labels          [1, 0]
  SrcBlock        "Demux"
  SrcPort         5
  Points          [25, 0]
  Branch {
    Points          [0, -50]
    Branch {
      Points          [0, -45]
      DstBlock                  "Switch1"
      DstPort                   1
    }
    Branch {
      DstBlock                  "Switch2"
      DstPort                   3
    }
  }
  Branch {
    DstBlock                  "Switch5"
    DstPort         3
  }
}
Line {
  SrcBlock        "System Mass"
  SrcPort         1
  Points          [25, 0]
  Branch {
    DstBlock                  "Tot Mass"
    DstPort         1
  }
  Branch {
    Points          [0, 100]
    DstBlock                  "Active Stage Mass"
    DstPort         1
```

```
    }
  }
  Line {
    SrcBlock            "Payload Mass"
    SrcPort             1
    Points              [270, 0]
    Branch {
      Points            [0, 75]
      DstBlock                    "System Mass"
      DstPort           1
    }
    Branch {
      Points            [150, 0; 0, 220]
      Branch {
        DstBlock                  "Fcn1"
        DstPort                   1
      }
      Branch {
        Points          [0, 15]
        DstBlock                  "Active Stage Mass"
        DstPort                   2
      }
    }
  }
  Line {
    SrcBlock            "Pos Nozzle"
    SrcPort             1
    DstBlock            "Demux1"
    DstPort             1
  }
  Line {
    SrcBlock            "Neg Nozzle"
    SrcPort             1
    DstBlock            "Demux2"
    DstPort             1
  }
  Line {
    SrcBlock            "Demux1"
    SrcPort             1
    DstBlock            "Sum"
    DstPort             1
  }
  Line {
    SrcBlock            "Demux1"
    SrcPort             2
    DstBlock            "Sum"
    DstPort             2
  }
  Line {
    SrcBlock            "Demux1"
    SrcPort             3
    DstBlock            "Sum"
    DstPort             3
  }
  Line {
    SrcBlock            "Demux1"
    SrcPort             4
    DstBlock            "Sum"
    DstPort             4
  }
  Line {
    SrcBlock            "Demux2"
    SrcPort             1
    DstBlock            "Sum"
    DstPort             5
  }
  Line {
    SrcBlock            "Demux2"
```

```
    SrcPort           2
    DstBlock          "Sum"
    DstPort           6
  }
  Line {
    SrcBlock          "Demux2"
    SrcPort           3
    DstBlock          "Sum"
    DstPort           7
  }
  Line {
    SrcBlock          "Demux2"
    SrcPort           4
    DstBlock          "Sum"
    DstPort           8
  }
  Line {
    SrcBlock          "Active Stage Mass"
    SrcPort           1
    DstBlock          "Fcn"
    DstPort           1
  }
  Line {
    SrcBlock          "Sum1"
    SrcPort           1
    DstBlock          "Lower"
    DstPort           1
  }
  Line {
    SrcBlock          "St3"
    SrcPort           1
    DstBlock          "Inert\nMass"
    DstPort           3
  }
  Line {
    SrcBlock          "St1"
    SrcPort           1
    DstBlock          "Inert\nMass"
    DstPort           1
  }
  Line {
    SrcBlock          "Mass1"
    SrcPort           1
    DstBlock          "SC1"
    DstPort           1
  }
  Line {
    SrcBlock          "Sum"
    SrcPort           1
    Points            [25, 0; 0, -85]
    Branch {
      DstBlock                  "Sum1"
      DstPort           2
    }
    Branch {
      Points            [0, -40]
      DstBlock                  "Active Stage Mass"
      DstPort           4
    }
  }
  Line {
    SrcBlock          "Inert\nMass"
    SrcPort           1
    Points            [15, 0]
    Branch {
      DstBlock                  "Inert"
      DstPort           1
    }
```

```
	  Branch {
	    Points		    [0, -80]
	    DstBlock		    "Active Stage Mass"
	    DstPort		    3
	  }
	}
	Line {
	  SrcBlock		  "Fcn"
	  SrcPort		  1
	  Points		  [-25, 0]
	  Branch {
	    DstBlock		    "Upper"
	    DstPort		    1
	  }
	  Branch {
	    DstBlock		    "Sum1"
	    DstPort		    1
	  }
	. }
  }
}
Block {
  BlockType		  SubSystem
  Name			  "Noise\nGenerator"
  Ports			  [3, 1, 0, 0, 0]
  Position		  [440, 58, 560, 112]
  ShowPortLabels	  on
  MaskType		  "Noise Generator"
  MaskDescription	  "Set band limited noise power."
  MaskPromptString	  "Aero Noise Power|Resonant Burn Frequency|Resonan"
			  "t Burn Amplitude|Combustion Noise Power|Noise "
			  "Filter Numerator|Noise Filter Denominator"
  MaskStyleString	  "edit,edit,edit,edit,edit,edit"
  MaskVariables		  "wind=@1;freq=@2;respower=@3;power=@4;bp=@5;ap=@6"
			  ";"
  MaskIconFrame		  on
  MaskIconOpaque	  on
  MaskIconRotate	  none
  MaskIconUnits		  autoscale
  MaskValueString	  "5.0e5|50|5e4|1e2|bp|ap"
  System {
	Name			"Noise\nGenerator"
	Location		[371, 513, 932, 883]
	Open			off
	ScreenColor		white
	Block {
	  BlockType		  Inport
	  Name			  "Thrust"
	  Position		  [20, 215, 40, 235]
	  Port			  "1"
	  PortWidth		  "-1"
	  SampleTime		  "-1"
	}
	Block {
	  BlockType		  Inport
	  Name			  "Velocity"
	  Position		  [20, 250, 40, 270]
	  Port			  "2"
	  PortWidth		  "-1"
	  SampleTime		  "-1"
	}
	Block {
	  BlockType		  Inport
	  Name			  "Density"
	  Position		  [20, 285, 40, 305]
	  Port			  "3"
	  PortWidth		  "-1"
	  SampleTime		  "-1"
```

```
}
Block {
 BlockType              Reference
 Name                   "Band-Limited\nWhite Noise"
 Ports                  [0, 1, 0, 0, 0]
 Position         [20, 150, 50, 180]
 SourceBlock            "simulink/Sources/Band-Limited\nWhite Noise"
 SourceType             "Continuous White Noise."
 Cov                    "[1 wind]"
 Ts                     "1/400"
 seed                   "[12312 34985]"
}
Block {
 BlockType              SubSystem
 Name                   "Combustion Noise"
 Ports                  [2, 1, 0, 0, 0]
 Position         [210, 132, 290, 183]
 NamePlacement          alternate
 ShowPortLabels   on
 System {
  Name             "Combustion Noise"
  Location              [576, 28, 871, 203]
  Open             off
  ScreenColor           white
  Block {
   BlockType            Inport
   Name            "Noise In"
   Position             [20, 55, 40, 75]
   Port            "1"
   PortWidth            "-1"
   SampleTime      "-1"
  }
  Block {
   BlockType            Inport
   Name            "Thrust"
   Position             [20, 115, 40, 135]
   Port            "2"
   PortWidth            "-1"
   SampleTime      "-1"
  }
  Block {
   BlockType            Fcn
   Name            "Fcn"
   Position             [160, 60, 220, 90]
   Expr            "u[1]*u[2]/1650000"
  }
  Block {
   BlockType            Mux
   Name            "Mux"
   Ports           [2, 1, 0, 0, 0]
   Position             [105, 57, 140, 93]
   Inputs          "2"
  }
  Block {
   BlockType            Outport
   Name            "Noise Out"
   Position             [240, 68, 270, 82]
   Port            "1"
   OutputWhenDisabled   held
   InitialOutput   "0"
  }
  Line {
   SrcBlock             "Thrust"
   SrcPort              1
   Points          [45, 0]
   DstBlock             "Mux"
   DstPort              2
  }
```

```
    Line {
      SrcBlock              "Noise In"
      SrcPort               1
      DstBlock              "Mux"
      DstPort               1
    }
    Line {
      SrcBlock              "Mux"
      SrcPort               1
      DstBlock              "Fcn"
      DstPort               1
    }
    Line {
      SrcBlock              "Fcn"
      SrcPort               1
      DstBlock              "Noise Out"
      DstPort               1
    }
  }
}
Block {
  BlockType             Demux
  Name                  "Demux"
  Ports                 [1, 2, 0, 0, 0]
  Position          [80, 147, 115, 183]
  Outputs           "2"
}
Block {
  BlockType             Gain
  Name                  "Gain"
  Position          [320, 144, 380, 176]
  Gain                  "power"
}
Block {
  BlockType             Mux
  Name                  "Mux"
  Ports                 [2, 1, 0, 0, 0]
  Position          [455, 132, 490, 168]
  Inputs            "2"
}
Block {
  BlockType             Product
  Name                  "Product"
  Ports                 [2, 1, 0, 0, 0]
  Position          [185, 32, 215, 63]
  Inputs            "2"
}
Block {
  BlockType             Product
  Name                  "Product1"
  Ports                 [2, 1, 0, 0, 0]
  Position          [195, 257, 225, 288]
  ShowName              off
  Inputs            "2"
}
Block {
  BlockType             Sin
  Name                  "Resonant Burn"
  Position          [125, 60, 155, 90]
  Amplitude             "respower"
  Frequency             "(freq)*2*pi"
  Phase                 "0"
  SampleTime            "0"
}
Block {
  BlockType             Step
  Name                  "Step"
  Position          [125, 15, 155, 45]
```

```
    Time                "[81.5]"
    Before      "[1]"
    After               "[0]"
  }
  Block {
    BlockType           Sum
    Name                "Sum"
    Ports               [2, 1, 0, 0, 0]
    Position    [400, 71, 430, 104]
    Inputs      "++"
  }
  Block {
    BlockType           TransferFcn
    Name                "Transfer Fcn"
    Position    [140, 165, 175, 205]
    Numerator           "bp"
    Denominator         "ap"
  }
  Block {
    BlockType           TransferFcn
    Name                "Transfer Fcn1"
    Position    [140, 125, 175, 165]
    NamePlacement       alternate
    Numerator           "bp"
    Denominator         "ap"
  }
  Block {
    BlockType           SubSystem
    Name                "Transonic Scale Factor"
    Ports               [2, 1, 0, 0, 0]
    Position    [75, 251, 175, 304]
    ShowPortLabels      on
    System {
      Name      "Transonic Scale Factor"
      Location          [125, 273, 644, 597]
      Open      off
      ScreenColor       white
      Block {
        BlockType       Inport
        Name    "Velocity"
        Position        [15, 88, 45, 102]
        Port    "1"
        PortWidth       "-1"
        SampleTime      "-1"
      }
      Block {
        BlockType       Inport
        Name    "Density"
        Position        [15, 223, 45, 237]
        Port    "2"
        PortWidth       "-1"
        SampleTime      "-1"
      }
      Block {
        BlockType       Fcn
        Name    "Dynamic Pressure"
        Position        [150, 205, 210, 235]
        Expr    "(u[2]*u[1]^2)/2"
      }
      Block {
        BlockType       Gain
        Name    "Gain"
        Position        [245, 136, 285, 164]
        Gain    "12"
      }
      Block {
        BlockType       Fcn
        Name    "Mach (V/c) "
```

```
 Position                          [80, 80, 140, 110]
 Expr                    "u/(1.4*287.05*249)^0.5"
}
Block {
 BlockType                         Fcn
 Name                    "Mach Effects"
 Position                          [250, 90, 310, 120]
 Expr                    "1/(0.5+(abs(1-u[1]^2))^0.5)"
}
Block {
 BlockType                         Mux
 Name                    "Mux"
 Ports                   [2, 1, 0, 0, 0]
 Position                          [185, 87, 220, 123]
 Inputs                  "2"
}
Block {
 BlockType                         Mux
 Name                    "Mux1"
 Ports                   [2, 1, 0, 0, 0]
 Position                          [95, 202, 130, 238]
 Inputs                  "2"
}
Block {
 BlockType                         Product
 Name                    "Product"
 Ports                   [2, 1, 0, 0, 0]
 Position                          [415, 112, 445, 143]
 Inputs                  "2"
}
Block {
 BlockType                         Fcn
 Name                    "Scale Pressure"
 Position                          [75, 135, 135, 165]
 Expr                    "u/101325"
}
Block {
 BlockType                         Sum
 Name                    "Sum"
 Ports                   [2, 1, 0, 0, 0]
 Position                          [345, 102, 375, 133]
 Inputs                  "++"
}
Block {
 BlockType                         Outport
 Name                    "Scale"
 Position                          [480, 123, 510, 137]
 Port                    "1"
 OutputWhenDisabled      held
 InitialOutput           "0"
}
Line {
 SrcBlock                          "Dynamic Pressure"
 SrcPort                           1
 Points                  [0, -35; -155, 0]
 DstBlock                          "Scale Pressure"
 DstPort                           1
}
Line {
 SrcBlock                          "Velocity"
 SrcPort                           1
 Points                  [5, 0]
 Branch {
        Points                            [0, 115]
        DstBlock                "Mux1"
        DstPort                           1
 }
 Branch {
```

```
	DstBlock		"Mach (V/c) "
	DstPort			1
 }
}
Line {
 SrcBlock		"Mux1"
 SrcPort		1
 DstBlock		"Dynamic Pressure"
 DstPort		1
}
Line {
 SrcBlock		"Sum"
 SrcPort		1
 DstBlock		"Product"
 DstPort		1
}
Line {
 SrcBlock		"Mach (V/c) "
 SrcPort		1
 DstBlock		"Mux"
 DstPort		1
}
Line {
 SrcBlock		"Scale Pressure"
 SrcPort		1
 Points		[5, 0]
 Branch {
	Points			[0, -35]
	DstBlock		"Mux"
	DstPort			2
 }
 Branch {
	DstBlock		"Gain"
	DstPort			1
 }
}
Line {
 SrcBlock		"Mux"
 SrcPort		1
 DstBlock		"Mach Effects"
 DstPort		1
}
Line {
 SrcBlock		"Gain"
 SrcPort		1
 Points		[40, 0]
 DstBlock		"Sum"
 DstPort		2
}
Line {
 SrcBlock		"Mach Effects"
 SrcPort		1
 Points		[15, 0]
 DstBlock		"Sum"
 DstPort		1
}
Line {
 SrcBlock		"Product"
 SrcPort		1
 DstBlock		"Scale"
 DstPort		1
}
Line {
 SrcBlock		"Density"
 SrcPort		1
 Points		[25, 0]
 Branch {
	DstBlock		"Mux1"
```

```
	DstPort		2
    }
    Branch {
	Points		[0, 35; 325, 0]
	DstBlock	"Product"
	DstPort		2
    }
   }
  }
 }
 Block {
  BlockType		Outport
  Name			"Noise\nAccelerations"
  Position		[510, 140, 530, 160]
  Port			"1"
  OutputWhenDisabled	held
  InitialOutput		"0"
 }
 Line {
  SrcBlock		"Product1"
  SrcPort		1
  Points		[210, 0]
  DstBlock		"Mux"
  DstPort		2
 }
 Line {
  SrcBlock		"Product"
  SrcPort		1
  Points		[165, 0]
  DstBlock		"Sum"
  DstPort		1
 }
 Line {
  SrcBlock		"Velocity"
  SrcPort		1
  Points		[15, 0]
  DstBlock		"Transonic Scale Factor"
  DstPort		1
 }
 Line {
  SrcBlock		"Density"
  SrcPort		1
  Points		[15, 0]
  DstBlock		"Transonic Scale Factor"
  DstPort		2
 }
 Line {
  SrcBlock		"Transonic Scale Factor"
  SrcPort		1
  DstBlock		"Product1"
  DstPort		2
 }
 Line {
  SrcBlock		"Sum"
  SrcPort		1
  Points		[5, 0]
  DstBlock		"Mux"
  DstPort		1
 }
 Line {
  SrcBlock		"Resonant Burn"
  SrcPort		1
  Points		[10, 0]
  DstBlock		"Product"
  DstPort		2
 }
 Line {
  SrcBlock		"Step"
```

```
      SrcPort            1
      Points             [10, 0]
      DstBlock           "Product"
      DstPort            1
     }
     Line {
      SrcBlock           "Mux"
      SrcPort            1
      DstBlock           "Noise\nAccelerations"
      DstPort            1
     }
     Line {
      SrcBlock           "Combustion Noise"
      SrcPort            1
      DstBlock           "Gain"
      DstPort            1
     }
     Line {
      SrcBlock           "Band-Limited\nWhite Noise"
      SrcPort            1
      DstBlock           "Demux"
      DstPort            1
     }
     Line {
      SrcBlock           "Gain"
      SrcPort            1
      DstBlock           "Sum"
      DstPort            2
     }
     Line {
      SrcBlock           "Thrust"
      SrcPort            1
      Points             [150, 0]
      DstBlock           "Combustion Noise"
      DstPort            2
     }
     Line {
      SrcBlock           "Transfer Fcn"
      SrcPort            1
      DstBlock           "Product1"
      DstPort            1
     }
     Line {
      SrcBlock           "Transfer Fcn1"
      SrcPort            1
      DstBlock           "Combustion Noise"
      DstPort            1
     }
     Line {
      SrcBlock           "Demux"
      SrcPort            1
      Points             [5, 0]
      DstBlock           "Transfer Fcn1"
      DstPort            1
     }
     Line {
      SrcBlock           "Demux"
      SrcPort            2
      Points             [5, 0]
      DstBlock           "Transfer Fcn"
      DstPort            1
     }
 }
}
Block {
 BlockType               SubSystem
 Name           "PID Controller"
 Ports          [1, 1, 0, 0, 0]
```

```
Position		[700, 268, 820, 302]
Orientation	left
ShowPortLabels	on
MaskType		"PID Controller"
MaskPromptString	"Proportional Gain|Integral Gain|Derivative Gain"
MaskStyleString	"edit,edit,edit"
MaskVariables	"prop=@1;int=@2;deriv=@3;"
MaskIconFrame	on
MaskIconOpaque	on
MaskIconRotate	none
MaskIconUnits	autoscale
MaskValueString	"5e-10|3e-10|8e-11"
System {
	Name			"PID Controller"
	Location		[673, 441, 1098, 623]
	Open			off
	ScreenColor		white
	Block {
	 BlockType		Inport
	 Name			"Acceleration"
	 Position		[370, 80, 400, 94]
	 Orientation		left
	 Port			"1"
	 PortWidth		"-1"
	 SampleTime		"-1"
	}
	Block {
	 BlockType		Demux
	 Name			"Demux1"
	 Ports			[1, 5, 0, 0, 0]
	 Position		[310, 70, 345, 100]
	 Orientation		left
	 ShowName		off
	 Outputs		"5"
	}
	Block {
	 BlockType		Derivative
	 Name			"Derivative"
	 Position		[200, 125, 230, 155]
	 Orientation		left
	}
	Block {
	 BlockType		Gain
	 Name			"Gain"
	 Position		[140, 25, 170, 55]
	 Orientation		left
	 Gain			"prop"
	}
	Block {
	 BlockType		Gain
	 Name			"Gain1"
	 Position		[140, 75, 170, 105]
	 Orientation		left
	 Gain			"int"
	}
	Block {
	 BlockType		Gain
	 Name			"Gain2"
	 Position		[140, 125, 170, 155]
	 Orientation		left
	 Gain			"deriv"
	}
	Block {
	 BlockType		Integrator
	 Name			"Integrator"
	 Ports			[1, 1, 0, 0, 0]
	 Position		[200, 75, 230, 105]
	 Orientation		left
```

```
  ExternalReset           none
  InitialConditionSource  internal
  InitialCondition        "0"
  LimitOutput             off
  UpperSaturationLimit    "inf"
  LowerSaturationLimit    "-inf"
  ShowSaturationPort      off
  ShowStatePort           off
  AbsoluteTolerance       "auto"
 }
 Block {
  BlockType               Sum
  Name                    "Sum"
  Ports                   [3, 1, 0, 0, 0]
  Position                [80, 74, 110, 106]
  Orientation             left
  Inputs                  "---"
 }
 Block {
  BlockType               Outport
  Name                    "Control Force"
  Position                [20, 85, 50, 99]
  Orientation             left
  Port                    "1"
  OutputWhenDisabled      held
  InitialOutput           "0"
 }
 Line {
  SrcBlock                "Sum"
  SrcPort                 1
  DstBlock                "Control Force"
  DstPort                 1
 }
 Line {
  SrcBlock                "Acceleration"
  SrcPort                 1
  DstBlock                "Demux1"
  DstPort                 1
 }
 Line {
  SrcBlock                "Demux1"
  SrcPort                 4
  Points                  [-40, 0]
  Branch {
   Points                 [0, 50]
   DstBlock               "Derivative"
   DstPort                1
  }
  Branch {
   DstBlock               "Integrator"
   DstPort                1
  }
  Branch {
   Points                 [0, -50]
   DstBlock               "Gain"
   DstPort                1
  }
 }
 Line {
  SrcBlock                "Integrator"
  SrcPort                 1
  DstBlock                "Gain1"
  DstPort                 1
 }
 Line {
  SrcBlock                "Derivative"
  SrcPort                 1
  DstBlock                "Gain2"
```

```
      DstPort            1
    }
    Line {
      SrcBlock           "Gain2"
      SrcPort            1
      Points             [-10, 0]
      DstBlock           "Sum"
      DstPort            3
    }
    Line {
      SrcBlock           "Gain1"
      SrcPort            1
      DstBlock           "Sum"
      DstPort            2
    }
    Line {
      SrcBlock           "Gain"
      SrcPort            1
      Points             [-10, 0]
      DstBlock           "Sum"
      DstPort            1
    }
  }
}
Block {
  BlockType              Scope
  Name                   "Scope"
  Ports                  [1, 0, 0, 0, 0]
  Position               [975, 35, 1005, 65]
  Floating               off
  Location               [675, 92, 1217, 470]
  Open                   off
  Grid                   on
  TickLabels             on
  ZoomMode               on
  TimeRange              "auto"
  YMin                   "-100          "
  YMax                   "100           "
  SaveToWorkspace        off
  SaveName               "ScopeData"
  LimitMaxRows           off
  MaxRows                "5000"
  Decimation             "1"
  SampleInput            off
  SampleTime             "0"
}
Block {
  BlockType              Terminator
  Name                   "Terminator25"
  Position               [885, 150, 905, 170]
  ShowName               off
}
Block {
  BlockType              Terminator
  Name                   "Terminator26"
  Position               [885, 195, 905, 215]
  ShowName               off
}
Block {
  BlockType              ToWorkspace
  Name                   "To Workspace"
  Position               [950, 100, 1010, 130]
  VariableName           "hybpid38"
  Buffer                 "inf"
  Decimation             "1"
  SampleTime             "1/400"
}
Block {
```

```
BlockType		SubSystem
Name		"Vibration\nDynamics"
Ports		[2, 3, 0, 0, 0]
Position		[755, 89, 855, 231]
ShowPortLabels	on
MaskType		"Vibration Dynamics"
MaskPromptString	"Klu|Kui|Kip|Kp1|Clu|Cui|Cip|Cp1"
MaskStyleString	"edit,edit,edit,edit,edit,edit,edit,edit"
MaskVariables	"klu=@1;kui=@2;kip=@3;kp1=@4;clu=@5;cui=@6;cip=@7"
		";cp1=@8;"
MaskIconFrame	on
MaskIconOpaque	on
MaskIconRotate	none
MaskIconUnits	autoscale
MaskValueString	"4e8|1e8|(freq*2*pi)^2*1779|(50*2*pi)^2|90000|450"
		"0|0|4*0.01*pi*freq|4*0.01*pi*50"
System {
	Name		"Vibration\nDynamics"
	Location	[129, 148, 507, 430]
	Open		off
	ScreenColor	white
	Block {
	  BlockType	Inport
	  Name		"Forcing \nFunction\nVector"
	  Position	[25, 38, 55, 52]
	  Port		"1"
	  PortWidth	"-1"
	  SampleTime	"-1"
	}
	Block {
	  BlockType	Inport
	  Name		"Reciprocal Mass Vector"
	  Position	[180, 255, 210, 270]
	  Orientation	up
	  Port		"2"
	  PortWidth	"-1"
	  SampleTime	"-1"
	}
	Block {
	  BlockType	SubSystem
	  Name		"Damping"
	  Ports		[2, 1, 0, 0, 0]
	  Position	[95, 143, 180, 172]
	  Orientation	left
	  ShowPortLabels	on
	  System {
	    Name	"Damping"
	    Location	[89, 423, 725, 837]
	    Open	off
	    ScreenColor	white
	    Block {
	      BlockType	Inport
	      Name	"Xdot"
	      Position	[15, 80, 35, 100]
	      Port	"1"
	      PortWidth	"-1"
	      SampleTime	"-1"
	    }
	    Block {
	      BlockType	Inport
	      Name	"Mass"
	      Position	[15, 210, 35, 230]
	      Port	"2"
	      PortWidth	"-1"
	      SampleTime	"-1"
	    }
	    Block {
	      BlockType	Demux
```

```
    Name                "Demux"
    Ports               [1, 5, 0, 0, 0]
    Position                     [65, 33, 100, 147]
    ShowName                     off
    Outputs                      "5"
   }
   Block {
    BlockType                    Demux
    Name                "Demux1"
    Ports               [1, 6, 0, 0, 0]
    Position                     [65, 175, 105, 260]
    Outputs                      "6"
   }
   Block {
    BlockType                    Gain
    Name                "Gain16"
    Position                     [260, 235, 290, 265]
    ShowName                     off
    Gain                "[-clu clu+cui -cui 0 0]"
   }
   Block {
    BlockType                    Gain
    Name                "Gain17"
    Position                     [260, 275, 290, 305]
    ShowName                     off
    Gain                "[0 -cui cui+cip -cip 0]"
   }
   Block {
    BlockType                    Gain
    Name                "Gain18"
    Position                     [260, 315, 290, 345]
    ShowName                     off
    Gain                "[0 0 -cip cip+cp1 -cp1]"
   }
   Block {
    BlockType                    Gain
    Name                "Gain19"
    Position                     [260, 355, 290, 385]
    ShowName                     off
    Gain                "[0 0 0 -cp1 cp1]"
   }
   Block {
    BlockType                    Gain
    Name                "Gain28"
    Position                     [260, 200, 290, 230]
    ShowName                     off
    Gain                "[clu -clu 0 0 0]"
   }
   Block {
    BlockType                    Mux
    Name                "Mux"
    Ports               [5, 1, 0, 0, 0]
    Position                     [140, 196, 175, 254]
    Inputs              "5"
   }
   Block {
    BlockType                    Product
    Name                "Product"
    Ports               [2, 1, 0, 0, 0]
    Position                     [420, 12, 450, 43]
    ShowName                     off
    Inputs              "2"
   }
   Block {
    BlockType                    Product
    Name                "Product1"
    Ports               [2, 1, 0, 0, 0]
    Position                     [420, 47, 450, 78]
```

```
    ShowName              off
    Inputs          "2"
  }
  Block {
    BlockType             Product
    Name            "Product2"
    Ports           [2, 1, 0, 0, 0]
    Position              [420, 82, 450, 113]
    ShowName              off
    Inputs          "2"
  }
  Block {
    BlockType             Product
    Name            "Product3"
    Ports           [2, 1, 0, 0, 0]
    Position              [420, 117, 450, 148]
    ShowName              off
    Inputs          "2"
  }
  Block {
    BlockType             Product
    Name            "Product4"
    Ports           [2, 1, 0, 0, 0]
    Position              [420, 152, 450, 183]
    ShowName              off
    Inputs          "2"
  }
  Block {
    BlockType             Sum
    Name            "Sum"
    Ports           [5, 1, 0, 0, 0]
    Position              [490, 76, 520, 124]
    Inputs          "+++++"
  }
  Block {
    BlockType             Terminator
    Name            "Terminator"
    Position              [150, 160, 170, 180]
  }
  Block {
    BlockType             Outport
    Name            "Damping Force"
    Position              [550, 90, 570, 110]
    Port            "1"
    OutputWhenDisabled    held
    InitialOutput   "0"
  }
  Line {
    SrcBlock              "Sum"
    SrcPort               1
    DstBlock              "Damping Force"
    DstPort               1
  }
  Line {
    SrcBlock              "Product4"
    SrcPort               1
    Points          [20, 0]
    DstBlock              "Sum"
    DstPort               5
  }
  Line {
    SrcBlock              "Product3"
    SrcPort               1
    Points          [15, 0; 0, -25]
    DstBlock              "Sum"
    DstPort               4
  }
  Line {
```

```
    SrcBlock            "Demux"
    SrcPort             4
    Points        [0, 15]
    DstBlock            "Product3"
    DstPort             1
  }
  Line {
    SrcBlock            "Demux"
    SrcPort             5
    Points        [200, 0; 0, 30]
    DstBlock            "Product4"
    DstPort             1
  }
  Line {
    SrcBlock            "Product1"
    SrcPort             1
    Points        [15, 0; 0, 25]
    DstBlock            "Sum"
    DstPort             2
  }
  Line {
    SrcBlock            "Product"
    SrcPort             1
    Points        [20, 0]
    DstBlock            "Sum"
    DstPort             1
  }
  Line {
    SrcBlock            "Product2"
    SrcPort             1
    DstBlock            "Sum"
    DstPort             3
  }
  Line {
    SrcBlock            "Demux"
    SrcPort             3
    DstBlock            "Product2"
    DstPort             1
  }
  Line {
    SrcBlock            "Demux"
    SrcPort             1
    Points        [205, 0; 0, -30]
    DstBlock            "Product"
    DstPort             1
  }
  Line {
    SrcBlock            "Demux"
    SrcPort             2
    Points        [0, -15]
    DstBlock            "Product1"
    DstPort             1
  }
  Line {
    SrcBlock            "Xdot"
    SrcPort             1
    DstBlock            "Demux"
    DstPort             1
  }
  Line {
    SrcBlock            "Gain28"
    SrcPort             1
    Points        [75, 0; 0, -180]
    DstBlock            "Product"
    DstPort             2
  }
  Line {
    Labels        [1, 0]
```

```
  SrcBlock            "Gain16"
  SrcPort             1
  Points        [80, 0; 0, -180]
  DstBlock            "Product1"
  DstPort             2
}
Line {
  SrcBlock            "Gain17"
  SrcPort             1
  Points        [85, 0; 0, -185]
  DstBlock            "Product2"
  DstPort             2
}
Line {
  Labels        [1, 0]
  SrcBlock            "Gain18"
  SrcPort             1
  Points        [90, 0; 0, -190]
  DstBlock            "Product3"
  DstPort             2
}
Line {
  SrcBlock            "Gain19"
  SrcPort             1
  Points        [95, 0; 0, -195]
  DstBlock            "Product4"
  DstPort             2
}
Line {
  SrcBlock            "Mass"
  SrcPort             1
  DstBlock            "Demux1"
  DstPort             1
}
Line {
  SrcBlock            "Demux1"
  SrcPort             1
  Points        [25, 0]
  DstBlock            "Terminator"
  DstPort             1
}
Line {
  SrcBlock            "Demux1"
  SrcPort             2
  Points        [15, 0]
  DstBlock            "Mux"
  DstPort             1
}
Line {
  SrcBlock            "Demux1"
  SrcPort             3
  Points        [15, 0]
  DstBlock            "Mux"
  DstPort             2
}
Line {
  SrcBlock            "Demux1"
  SrcPort             4
  DstBlock            "Mux"
  DstPort             3
}
Line {
  SrcBlock            "Demux1"
  SrcPort             5
  Points        [0, -5]
  DstBlock            "Mux"
  DstPort             4
}
```

```
Line {
 SrcBlock		"Demux1"
 SrcPort		6
 Points		[15, 0]
 DstBlock		"Mux"
 DstPort		5
}
Line {
 SrcBlock		"Mux"
 SrcPort		1
 Points		[65, 0]
 Branch {
	DstBlock		"Gain28"
	DstPort		1
 }
 Branch {
	Points		[0, 25]
	Branch {
	 DstBlock		"Gain16"
	 DstPort		1
	}
	Branch {
	 Points		[0, 40]
	 Branch {
	  DstBlock		"Gain17"
	  DstPort		1
	 }
	 Branch {
	  Points		[0, 40]
	  Branch {
	   DstBlock		"Gain18"
	   DstPort		1
	  }
	  Branch {
	   DstBlock		"Gain19"
	   DstPort		1
	  }
	 }
	}
 }
}
}
}
Block {
 BlockType		SubSystem
 Name		"Stiffness"
 Ports		[2, 1, 0, 0, 0]
 Position		[95, 196, 180, 229]
 Orientation		left
 ShowPortLabels	on
 System {
  Name		"Stiffness"
  Location		[173, 99, 811, 552]
  Open		off
  ScreenColor		white
  Block {
   BlockType		Inport
   Name		"X"
   Position		[35, 105, 55, 125]
   Port		"1"
   PortWidth		"-1"
   SampleTime		"-1"
  }
  Block {
   BlockType		Inport
   Name		"Mass"
   Position		[35, 230, 55, 250]
   Port		"2"
```

```
      PortWidth               "-1"
      SampleTime      "-1"
    }
    Block {
      BlockType               Demux
      Name            "Demux"
      Ports           [1, 5, 0, 0, 0]
      Position                [85, 58, 120, 172]
      ShowName                off
      Outputs                 "5"
    }
    Block {
      BlockType               Demux
      Name            "Demux1"
      Ports           [1, 6, 0, 0, 0]
      Position                [80, 195, 120, 280]
      Outputs                 "6"
    }
    Block {
      BlockType               Gain
      Name            "Gain16"
      Position                [280, 260, 310, 290]
      ShowName                off
      Gain            "[-klu klu+kui -kui 0 0]"
    }
    Block {
      BlockType               Gain
      Name            "Gain17"
      Position                [280, 300, 310, 330]
      ShowName                off
      Gain            "[0 -kui kui+kip -kip 0]"
    }
    Block {
      BlockType               Gain
      Name            "Gain18"
      Position                [280, 340, 310, 370]
      ShowName                off
      Gain            "[0 0 -kip kip+kp1 -kp1]"
    }
    Block {
      BlockType               Gain
      Name            "Gain19"
      Position                [280, 380, 310, 410]
      ShowName                off
      Gain            "[0 0 0 -kp1 kp1]"
    }
    Block {
      BlockType               Gain
      Name            "Gain28"
      Position                [280, 225, 310, 255]
      ShowName                off
      Gain            "[klu -klu 0 0 0]"
    }
    Block {
      BlockType               Mux
      Name            "Mux"
      Ports           [5, 1, 0, 0, 0]
      Position                [155, 216, 190, 274]
      Inputs          "5"
    }
    Block {
      BlockType               Product
      Name            "Product"
      Ports           [2, 1, 0, 0, 0]
      Position                [440, 37, 470, 68]
      ShowName                off
      Inputs          "2"
    }
```

```
Block {
 BlockType               Product
 Name            "Product1"
 Ports           [2, 1, 0, 0, 0]
 Position                [440, 72, 470, 103]
 ShowName                off
 Inputs          "2"
}
Block {
 BlockType               Product
 Name            "Product2"
 Ports           [2, 1, 0, 0, 0]
 Position                [440, 107, 470, 138]
 ShowName                off
 Inputs          "2"
}
Block {
 BlockType               Product
 Name            "Product3"
 Ports           [2, 1, 0, 0, 0]
 Position                [440, 142, 470, 173]
 ShowName                off
 Inputs          "2"
}
Block {
 BlockType               Product
 Name            "Product4"
 Ports           [2, 1, 0, 0, 0]
 Position                [440, 177, 470, 208]
 ShowName                off
 Inputs          "2"
}
Block {
 BlockType               Sum
 Name            "Sum"
 Ports           [5, 1, 0, 0, 0]
 Position                [510, 101, 540, 149]
 Inputs          "+++++"
}
Block {
 BlockType               Terminator
 Name            "Terminator"
 Position                [165, 185, 185, 205]
}
Block {
 BlockType               Outport
 Name            "Spring Force"
 Position                [570, 115, 590, 135]
 Port            "1"
 OutputWhenDisabled      held
 InitialOutput           "0"
}
Line {
 SrcBlock                "Sum"
 SrcPort                 1
 DstBlock                "Spring Force"
 DstPort                 1
}
Line {
 SrcBlock                "Product4"
 SrcPort                 1
 Points          [20, 0]
 DstBlock                "Sum"
 DstPort                 5
}
Line {
 SrcBlock                "Product3"
 SrcPort                 1
```

```
      Points              [15, 0; 0, -25]
      DstBlock                        "Sum"
      DstPort                         4
    }
    Line {
      SrcBlock                        "Demux"
      SrcPort                         4
      Points              [0, 15]
      DstBlock                        "Product3"
      DstPort                         1
    }
    Line {
      SrcBlock                        "Demux"
      SrcPort                         5
      Points              [200, 0; 0, 30]
      DstBlock                        "Product4"
      DstPort                         1
    }
    Line {
      SrcBlock                        "Product1"
      SrcPort                         1
      Points              [15, 0; 0, 25]
      DstBlock                        "Sum"
      DstPort                         2
    }
    Line {
      SrcBlock                        "Product"
      SrcPort                         1
      Points              [20, 0]
      DstBlock                        "Sum"
      DstPort                         1
    }
    Line {
      SrcBlock                        "Product2"
      SrcPort                         1
      DstBlock                        "Sum"
      DstPort                         3
    }
    Line {
      SrcBlock                        "Demux"
      SrcPort                         3
      DstBlock                        "Product2"
      DstPort                         1
    }
    Line {
      SrcBlock                        "Demux"
      SrcPort                         1
      Points              [200, 0; 0, -30]
      DstBlock                        "Product"
      DstPort                         1
    }
    Line {
      Labels              [0, 0]
      SrcBlock                        "Demux"
      SrcPort                         2
      Points              [0, -15]
      DstBlock                        "Product1"
      DstPort                         1
    }
    Line {
      SrcBlock                        "X"
      SrcPort                         1
      DstBlock                        "Demux"
      DstPort                         1
    }
    Line {
      SrcBlock                        "Gain28"
      SrcPort                         1
```

```
    Points              [75, 0; 0, -180]
    DstBlock            "Product"
    DstPort             2
  }
  Line {
    Labels              [1, 0]
    SrcBlock            "Gain16"
    SrcPort             1
    Points              [80, 0; 0, -180]
    DstBlock            "Product1"
    DstPort             2
  }
  Line {
    SrcBlock            "Gain17"
    SrcPort             1
    Points              [85, 0; 0, -185]
    DstBlock            "Product2"
    DstPort             2
  }
  Line {
    Labels              [1, 0]
    SrcBlock            "Gain18"
    SrcPort             1
    Points              [90, 0; 0, -190]
    DstBlock            "Product3"
    DstPort             2
  }
  Line {
    SrcBlock            "Gain19"
    SrcPort             1
    Points              [95, 0; 0, -195]
    DstBlock            "Product4"
    DstPort             2
  }
  Line {
    SrcBlock            "Mass"
    SrcPort             1
    DstBlock            "Demux1"
    DstPort             1
  }
  Line {
    SrcBlock            "Demux1"
    SrcPort             1
    Points              [25, 0]
    DstBlock            "Terminator"
    DstPort             1
  }
  Line {
    SrcBlock            "Demux1"
    SrcPort             2
    Points              [15, 0]
    DstBlock            "Mux"
    DstPort             1
  }
  Line {
    SrcBlock            "Demux1"
    SrcPort             3
    Points              [15, 0]
    DstBlock            "Mux"
    DstPort             2
  }
  Line {
    SrcBlock            "Demux1"
    SrcPort             4
    DstBlock            "Mux"
    DstPort             3
  }
  Line {
```

```
    SrcBlock                "Demux1"
    SrcPort                 5
    Points          [15, 0]
    DstBlock                "Mux"
    DstPort                 4
   }
   Line {
    SrcBlock                "Demux1"
    SrcPort                 6
    Points          [15, 0]
    DstBlock                "Mux"
    DstPort                 5
   }
   Line {
    SrcBlock                "Mux"
    SrcPort                 1
    Points          [65, 0; 0, 5]
    Branch {
          Points                    [0, -10]
          DstBlock          "Gain28"
          DstPort                   1
    }
    Branch {
          Points                    [0, 25]
          Branch {
           DstBlock          "Gain16"
           DstPort           1
          }
          Branch {
           Points            [0, 40]
           Branch {
            DstBlock                  "Gain17"
            DstPort           1
           }
           Branch {
            Points            [0, 40]
            Branch {
             DstBlock                 "Gain18"
             DstPort                  1
            }
            Branch {
             Points           [0, 40]
             DstBlock                 "Gain19"
             DstPort                  1
            }
           }
          }
    }
   }
  }
}
Block {
 BlockType                  Integrator
 Name                       "X"
 Ports                      [1, 1, 0, 0, 0]
 Position           [225, 60, 255, 90]
 ExternalReset              none
 InitialConditionSource  internal
 InitialCondition       "0"
 LimitOutput                off
 UpperSaturationLimit       "inf"
 LowerSaturationLimit       "-inf"
 ShowSaturationPort   off
 ShowStatePort              off
 AbsoluteTolerance      "auto"
}
Block {
 BlockType                  Integrator
```

```
  Name                          "X*"
  Ports                         [1, 1, 0, 0, 0]
  Position              [145, 60, 175, 90]
  ExternalReset                 none
  InitialConditionSource internal
  InitialCondition      "0"
  LimitOutput                   off
  UpperSaturationLimit          "inf"
  LowerSaturationLimit          "-inf"
  ShowSaturationPort    off
  ShowStatePort                 off
  AbsoluteTolerance     "auto"
 }
 Block {
  BlockType                     Sum
  Name                          "X**"
  Ports                         [3, 1, 0, 0, 0]
  Position              [80, 27, 110, 123]
  Inputs                "+--"
 }
 Block {
  BlockType                     Outport
  Name                          "Accelerations"
  Position              [155, 15, 175, 35]
  Port                          "1"
  OutputWhenDisabled            held
  InitialOutput                 "0"
 }
 Block {
  BlockType                     Outport
  Name                          "Velocities"
  Position              [230, 15, 250, 35]
  Port                          "2"
  OutputWhenDisabled            held
  InitialOutput                 "0"
 }
 Block {
  BlockType                     Outport
  Name                          "Positions"
  Position              [305, 65, 325, 85]
  Port                          "3"
  OutputWhenDisabled            held
  InitialOutput                 "0"
 }
 Line {
  SrcBlock              "Stiffness"
  SrcPort               1
  Points                [-30, 0; 0, -140]
  DstBlock              "X**"
  DstPort               2
 }
 Line {
  SrcBlock              "X*"
  SrcPort               1
  Points                [20, 0]
  Branch {
   Points               [0, 75]
   DstBlock                     "Damping"
   DstPort              1
  }
  Branch {
   Points               [0, 0]
   Branch {
    DstBlock                    "X"
    DstPort                     1
   }
   Branch {
    Points              [0, -50]
```

```
          DstBlock              "Velocities"
          DstPort               1
        }
      }
    }
    Line {
      SrcBlock          "Damping"
      SrcPort           1
      Points            [-25, 0]
      DstBlock          "X**"
      DstPort           3
    }
    Line {
      SrcBlock          "Reciprocal Mass Vector"
      SrcPort           1
      Points            [0, -30]
      Branch {
        DstBlock                "Damping"
        DstPort           2
      }
      Branch {
        DstBlock                "Stiffness"
        DstPort           2
      }
    }
    Line {
      SrcBlock          "Forcing \nFunction\nVector"
      SrcPort           1
      DstBlock          "X**"
      DstPort           1
    }
    Line {
      SrcBlock          "X**"
      SrcPort           1
      Points            [10, 0]
      Branch {
        DstBlock                "X*"
        DstPort           1
      }
      Branch {
        Points            [0, -50]
        DstBlock                "Accelerations"
        DstPort           1
      }
    }
    Line {
      SrcBlock          "X"
      SrcPort           1
      Points            [0, 0]
      Branch {
        Points            [0, 130]
        DstBlock                "Stiffness"
        DstPort           1
      }
      Branch {
        DstBlock                "Positions"
        DstPort           1
      }
    }
  }
}
Line {
  SrcBlock                "Vibration\nDynamics"
  SrcPort                 1
  Points          [15, 0]
  Branch {
        Points                  [0, -70]
        DstBlock          "Demux"
```

```
      DstPort                 1
    }
    Branch {
      Points                  [40, 0]
      Branch {
        DstBlock              "To Workspace"
        DstPort               1
      }
      Branch {
        Points                [0, 170]
        DstBlock              "PID Controller"
        DstPort               1
      }
    }
  }
  Line {
    SrcBlock                  "Demux"
    SrcPort                   4
    DstBlock                  "Scope"
    DstPort                   1
  }
  Line {
    SrcBlock                  "Vibration\nDynamics"
    SrcPort                   3
    DstBlock                  "Terminator26"
    DstPort                   1
  }
  Line {
    SrcBlock                  "PID Controller"
    SrcPort                   1
    Points              [-95, 0]
    DstBlock                  "Axial Forcing\nFunctions"
    DstPort                   5
  }
  Line {
    SrcBlock                  "Vibration\nDynamics"
    SrcPort                   2
    DstBlock                  "Terminator25"
    DstPort                   1
  }
  Line {
    SrcBlock                  "Noise\nGenerator"
    SrcPort                   1
    Points              [5, 0]
    Branch {
      DstBlock                "Axial Forcing\nFunctions"
      DstPort                 2
    }
    Branch {
      Points                  [0, 95; -330, 0]
      DstBlock                "LV CG Dynamics"
      DstPort                 3
    }
  }
  Line {
    SrcBlock                  "LV CG Dynamics"
    SrcPort                   2
    DstBlock                  "Noise\nGenerator"
    DstPort                   2
  }
  Line {
    Labels              [2, 0]
    SrcBlock                  "LV CG Dynamics"
    SrcPort                   1
    Points              [0, -5; 60, 0]
    Branch {
      DstBlock                "Noise\nGenerator"
      DstPort                 1
```

```
 }
 Branch {
        DstBlock              "Axial Forcing\nFunctions"
        DstPort                       1
 }
}
Line {
 SrcBlock                        "Clock"
 SrcPort                         1
 Points              [20, 0]
 Branch {
        Points                        [180, 0]
        DstBlock              "LV CG Dynamics"
        DstPort                       1
 }
 Branch {
        Points                        [0, 170]
        DstBlock              "Mass Properties"
        DstPort                       1
 }
}
Line {
 SrcBlock                        "Axial Forcing\nFunctions"
 SrcPort                         1
 DstBlock                        "Vibration\nDynamics"
 DstPort                         1
}
Line {
 SrcBlock                        "LV CG Dynamics"
 SrcPort                         3
 Points              [60, 0]
 DstBlock                        "Noise\nGenerator"
 DstPort                         3
}
Line {
 SrcBlock                        "Mass Properties"
 SrcPort                         2
 DstBlock                        "Mass Matrix \nInverter"
 DstPort                         2
}
Line {
 SrcBlock                        "Mass Properties"
 SrcPort                         3
 DstBlock                        "Mass Matrix \nInverter"
 DstPort                         3
}
Line {
 SrcBlock                        "Mass Properties"
 SrcPort                         4
 DstBlock                        "Mass Matrix \nInverter"
 DstPort                         4
}
Line {
 SrcBlock                        "Mass Properties"
 SrcPort                         5
 DstBlock                        "Mass Matrix \nInverter"
 DstPort                         5
}
Line {
 SrcBlock                        "Mass Properties"
 SrcPort                         6
 DstBlock                        "Mass Matrix \nInverter"
 DstPort                         6
}
Line {
 SrcBlock                        "Mass Matrix \nInverter"
 SrcPort                         1
 Points              [80, 0]
```

```
    Branch {
          Points                          [150, 0]
          DstBlock                "Vibration\nDynamics"
          DstPort                         2
    }
    Branch {
          Points                          [0, -70]
          DstBlock                "Axial Forcing\nFunctions"
          DstPort                         4
    }
   }
   Line {
    SrcBlock                    "Mass Properties"
    SrcPort                     1
    Points               [35, 0]
    Branch {
          DstBlock                "Mass Matrix \nInverter"
          DstPort                         1
    }
    Branch {
          Points                          [0, -90]
          DstBlock                "LV CG Dynamics"
          DstPort                         2
    }
   }
   Line {
    SrcBlock                    "LV CG Dynamics"
    SrcPort                     4
    Points               [210, 0; 0, -30]
    DstBlock                    "Axial Forcing\nFunctions"
    DstPort                     3
   }
  }
 }
```

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For this study, a launch vehicle/satellite computer model was developed to explore various types of passive and hybrid isolation systems. Hybrid isolation techniques explored the use of PID anfd PPF control. The different control systems available offer different benefits. Research is being conducted into determining which one is most effective overall. The results of this research will point the way to a hybrid isolator design that will be implemented on a future space launch. The results conclude that passive isolation creates major improvements over a baseline vibration load on a satellite. The hybrid results were mixed. Whole satellite isolation improved, while a satellite subcomponent suffered substantially increased loading.

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