g-LIMIT Design Definition Document (DDD)

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ABBREVIATIONS AND ACRONYMS

DOF	Degrees of Freedom
EPF	Experiment Parameter File
g-LIMIT	Glovebox Integrated Microgravity Isolation Technology
IM	Isolator Module
ISS	International Space Station
MSFC	Marshall Space Flight Center
MSG	Microgravity Science Glovebox
PIP	Power and Information Processor
PMS	Payload Mounting Structure
STABLE	Suppression of Transient Acceleration by Levitation Evaluation
TRIAX	Three Axis Reference Accelerometer
USML-2	United States Microgravity Lab-2

1.0 Introduction

The orbital environment provides a unique opportunity for studying phenomena in a manner not possible on earth. Earth-orbiting spacecraft provide the potential for a low-level acceleration environment enabling microgravity (µg) science experiments in disciplines such as life sciences, materials science, combustion, fundamental physics, and fluid mechanics. As a research laboratory, the International Space Station (ISS) will exploit the near-zero acceleration environment of low-earth orbit for unique state-of-the-art µg science investigations. However, due to a variety of vibro-acoustic disturbances on the ISS, the acceleration environment is expected to significantly exceed the requirements of many acceleration sensitive experiments. Figure 1 presents an estimate of the acceleration environment on the ISS along with the required acceleration levels for µg science from the ISS Microgravity Environment Specification.[1] Mitigation of the excessive acceleration environment requires the implementation of vibration isolation systems at either the disturbance source or the science payload. While an effort is being made to limit the induced disturbances, it is understood that the acceleration levels will not meet the environment requirement specification, thus requiring the use of vibration isolation at the payload/rack locations.

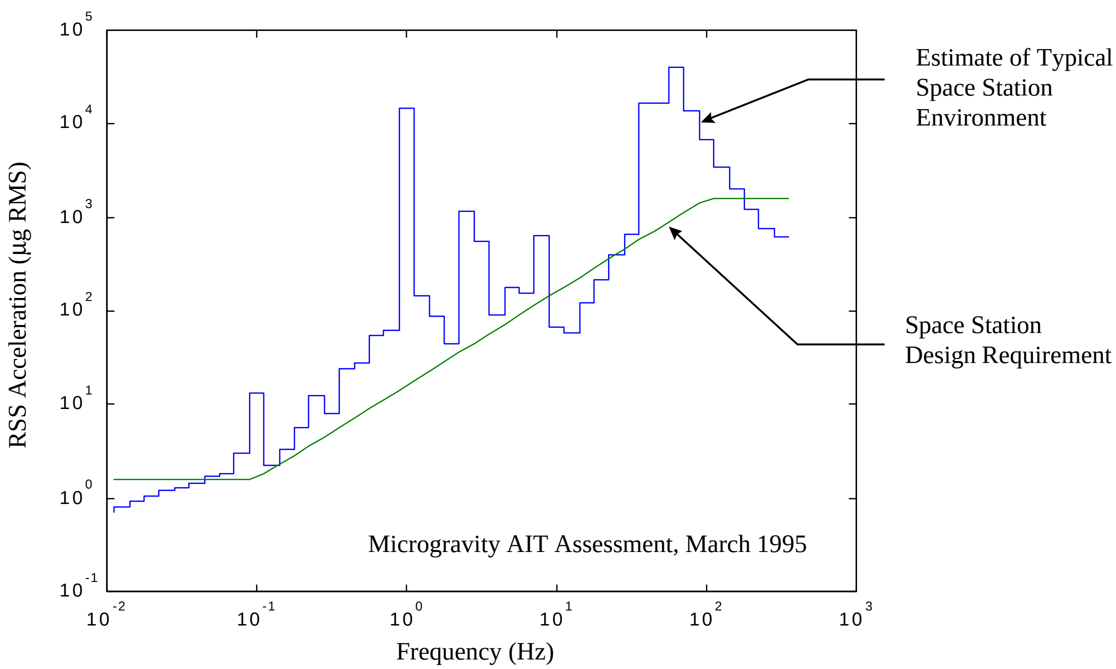

Figure 1: Space Station Required and Anticipated Environment

In view of the utility of the ISS as an orbiting science laboratory, the need for vibration isolation systems for acceleration sensitive experiments is gaining increasing visibility. To date, three active vibration isolation systems have been flight tested on shuttle flights: the

STABLE (Suppression of Transient Accelerations By Levitation) system, developed jointly by NASA Marshall Space Flight Center (MSFC) and The Boeing Corporation (formerly McDonnell Douglas Aerospace Corporation); the Microgravity Isolation Mount (MIM) developed by the Canadian Space Agency; and the Active Rack Isolation System (ARIS), developed by The Boeing Corporation. For a survey of the flight systems and a discussion of the fundamentals of microgravity vibration isolation, see Reference 2.

The Microgravity Science Glovebox (MSG) is being developed as a facility for microgravity science experiments on the ISS. To provide a more quiescent acceleration environment in the MSG, a vibration isolation system named g–LIMIT (GLovebox Integrated Microgravity Isolation Technology) is being designed. g-LIMIT is the next generation of technology developed for and demonstrated by STABLE on the USML-2 mission in October 1995. This technology evolution was accomplished in part through a NASA HQ/Code UG Advanced Technology Development (ATD) Program project (FY 97 – FY 99) entitled "Vibration Isolation and Control System for Small Payloads". g-LIMIT is scheduled for launch on the UF-1 mission and will be available to MSG investigators immediately after characterization testing.

1.1 Scope and Overview of Document

This document is written to describe the g-LIMIT system design philosophy and to define system requirements and mission objectives for g-LIMIT. This is a system level document in scope, from which subsystem requirements may be derived and the detailed design concept formulated. Any comments, corrections, or suggestions should be made to the author at (256) 544-1435 or mark.whorton@msfc.nasa.gov.

In Section 2, this document addresses an overall system description including active control philosophy, resources required, performance objectives, and science requirements. The experiment plan is presented in Section 3, which includes operational information such as data management (data description and analysis), test descriptions, and test scenario.

2.0 g-LIMIT System Overview

2.1 Hardware Description

In order to provide a quiescent acceleration environment to an experiment, an isolation system must sense and cancel the inertial accelerations applied to the experiment. With g–LIMIT, this is accomplished by six independent control actuation channels that provide six independent forces to a platform upon which the experiment resides. g–LIMIT is designed around three integrated isolator modules (IM), each of which is comprised of a dual axis actuator, two axes of acceleration sensing, two axes of position sensing, control electronics, and an IR data-link across the actuator gap. The isolator base plate is attached to the Power and Information Processor (PIP), which is attached to the MSG work volume floor. The isolator base plate houses connectors for MSG resources to be used by g-LIMIT and to interface with the g-LIMIT umbilical subsystem. The “base” portion of the IM is attached to the isolator base plate. Experiments are mounted to the isolated Payload Mounting Structure using the same pin pattern as the MSG work volume floor. Standard MSG structural and umbilical interfaces are used so minimize accommodation requirements for payloads. A set of connectors is attached to the Umbilical Interface Plate, which rigidly attaches to the “isolated” portion of the IM and the terminating end of the umbilical subsystem to the PMS. A snubber system is integrated into the base plate where a set of three bumpers are used to prevent relative motion between the PMS and base plate during installation and idle times. When in the operational configuration, the snubbers provide mechanical rattle-space constraints of approximately ±1 cm.

A key aspect of the g-LIMIT design is modularity. Incorporation of two axes of actuation, sensing (position and acceleration), and electronics into the IM results in a general-purpose system design. The IM forms the basis of g-LIMIT and also provides the capability for an off-the-shelf kit for other isolation applications such as lockers, drawers, and other small volumes. Use of a co-located control law results in configuration independent software and negligible interfaces. Vibration isolation of larger masses is easily accomplished with g-LIMIT (or the IM kits) as well.

Another novel feature of g-LIMIT is the patent-pending implicit position sensing technology which uses a drive coil to induce a signal on the actuation coil to sense motion much like a standard encoder. The g–LIMIT system will not only provide a quiescent environment for MSG investigations, but it will also have the capability to generate pristine accelerations as desired by certain classes of experiments such as protein crystal growth. In this mode, a user-prescribed acceleration forcing function (time response or frequency spectrum) will be applied to the experiment while providing isolation from the ambient MSG acceleration environment. An additional capability will be the accelerometer-independent measurement of quasi-steady accelerations as a by-product of the isolation control system. For a more general overview, see Reference 3.

2.2 Control Modes

g-LIMIT operates in one of three types of modes: Passive Mode, Standby Mode, and Active Mode. In passive mode, the position and acceleration control loops are open and self-test data is recorded. When in a standby mode, the position loop is closed with the acceleration loop open. Standby mode may be implemented either in local or central control and is used to test translation range, umbilical stiffness and bias, and quasi-steady acceleration estimation. In an active mode, both position and acceleration loops are closed. Active mode likewise may be implemented in local or central control and is used for vibration isolation. Each type of mode may be implemented with multiple control architecture options – i.e. the form of control laws and distribution of control laws between the PIP software (central control) and IM software (local control). These mode classes are summarized in Table 2-1.

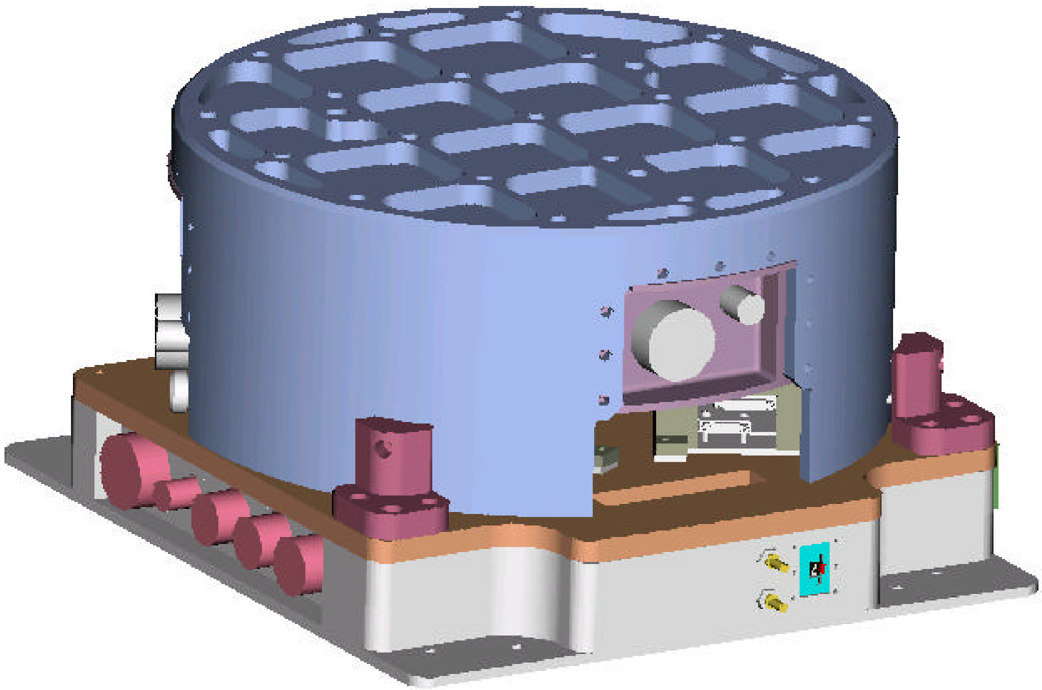

Figure 2: g-LIMIT System Assembly Drawing

Mode Type	Control Loops	Description
Passive	All control loops open	Used for self-test
Standby	Position control only	Used for system identification tests and transition to active mode
Active	All control loops closed	Nominal mode for isolation operations

Table 2-1: Operational Mode Classifications

For g-LIMIT characterization testing, the three classes of modes will be implemented using different control system architectures to evaluate a variety of control design methods. The control architectures to be implemented for standby and active modes are:

Mode Class	No.	Mode ID	Description
Passive Control Mode			
	1	PAS	Passive Mode
Standby Control Modes			
	2	LSS	Local SISO
	3	CSS	Central SISO

Active Control Modes			
	4	LSA	Local SISO
	5	DSA	Distributed SISO
	6	DMA	Distributed MIMO
	7	CSA	Central SISO
	8	CMA	Central MIMO

Table 2-2: Control Mode Definitions

A safety monitoring routine will be continuously operational in the PIP software to check for out-of-tolerance signals that would indicate improper functioning or off-nominal health status of the g-LIMIT system. In the event of an alert indication detected by the PIP software, the system will be placed in a passive mode. An abort feature will be available for the crew to initiate from the PAYLOAD LAPTOP crew displays.

Figure 3 presents the processor architecture implemented in g-LIMIT that is used to enable local control at the IM, central control in the PIP, or distributed control. Figure 3 also illustrates the signal flow through the components of g-LIMIT. Identical software is implemented on a TI C31 32 MHz DSP chip in each IM. A PC104 architecture will be used for the PIP which accommodates standard Pentium chips and peripherals. Depending on the control mode selected, acceleration and/or position control forces are computed at the PIP or IM. For more information on the control algorithms for g-LIMIT, see Reference 4.

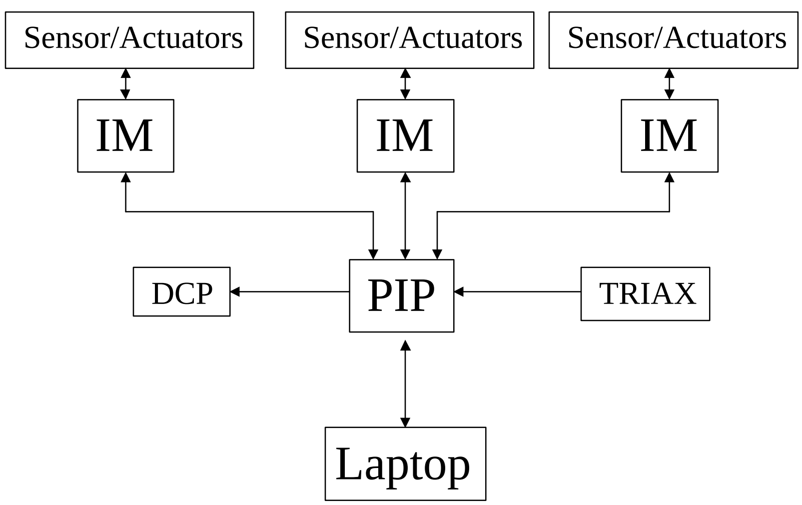

Figure 3: g-LIMIT Distributed Processor Architecture

2.3 MSG Interfaces to Payload

A primary design guideline of g-LIMIT is to minimize impacts on the payload resources. This objective motivates the use of the MSG 120VDC as primary power for g-LIMIT. The payload laptop computer will communicate to the g-LIMIT PIP via RS422. When operational, g–LIMIT is estimated to need approximately 100W peak and about 25W power nominally, derived from the 120V MSG power supply.

In order to make the isolation system transparent to the user with respect to interfaces, the structural, electrical, and data interfaces for a payload to g–LIMIT will be identical to the MSG. The glovebox provides a standard set of resources including power, data, video, heat dissipation, nitrogen, and vacuum. g–LIMIT will provide the experiments mounted to its isolated platform interfaces to a subset of the glovebox standard resources consisting of:

- one experiment electrical outlet (+/-12V, +28V, +5V)
- one MSG data port (4-bits digital in, 4 bits digital out, 4 channels differential analog input to MSG, RS422 and ethernet)
- two video channels.

3.0 g-LIMIT Characterization Test Requirements

In this section, the requirements for the g-LIMIT Characterization Test are described and success criteria for each are quantified. g-LIMIT requirements, elaborated on in the following subsections, are defined as:

R1: Provide attenuation of MSG induced accelerations

R2: Characterize attenuation of payload-induced accelerations.

R3: Generate user-specified pristine excitations to payload.

R4: Evaluate capability to measure quasi-steady accelerations from control law.

R5: Evaluate advanced vibration control technology.

R6: Validate the dynamic model of g-LIMIT.

R7: Characterize the acceleration environment of the MSG.

3.1 MSG Induced Vibration Isolation (R1)

Description:

Analytical estimates of the acceleration environment for ISS assembly complete indicate that the ISS ambient environment will exceed the design requirement across virtually all pertinent frequencies (Figure 1). This recognition led to the development of microgravity vibration isolation systems for acceleration-sensitive microgravity science experiments. The primary objective of g-LIMIT is to demonstrate attenuation of the ambient MSG acceleration environment to enable MSG science experiments. From Figure 1, an attenuation requirement curve can be derived by approximating the amount of attenuation needed to reduce the ISS accelerations to satisfy the design requirement. The attenuation requirement is quantified by the transmissibility curve in Figure 4. Three distinct frequency ranges define the requirement. Below 0.01 Hz, the isolation system must pass the quasi-steady accelerations of the MSG to the isolated payload. From 0.01 Hz to 10 Hz, the attenuation must increase one order of magnitude for every decade of frequency increase. Above 10 Hz, the attenuation requirement is constant at three orders of magnitude attenuation.

In the context of the g-LIMIT Characterization Test, attenuation is the reduction in magnitude of acceleration from the MSG-fixed (Base) reference accelerometer measurement to the isolated Payload Mounting Structure in one axis. The attenuation is the inverse of the magnitude of the transmissibility function, which is the transfer function from base acceleration to platform acceleration.

Whereas attenuation performance is a function of frequency and varies with each axis, the requirement may be applied to individual axes as well as to the root-sum-square (RSS) attenuation over all three translational axes. If the requirement is satisfied for each individual axis, then the RSS attenuation will likewise meet the requirement. Hence, performance will be evaluated for each axis for g-LIMIT. No requirement is specified for the rotational axes.

Success Criteria:

Successful completion of this requirement is control system dependent. That is, a variety of control systems will be tested, each with unique performance and stability characteristics, with the result that some will meet the requirement and some will not. This requirement will be met if one control system can be shown to satisfy the requirement curve in Figure 4.

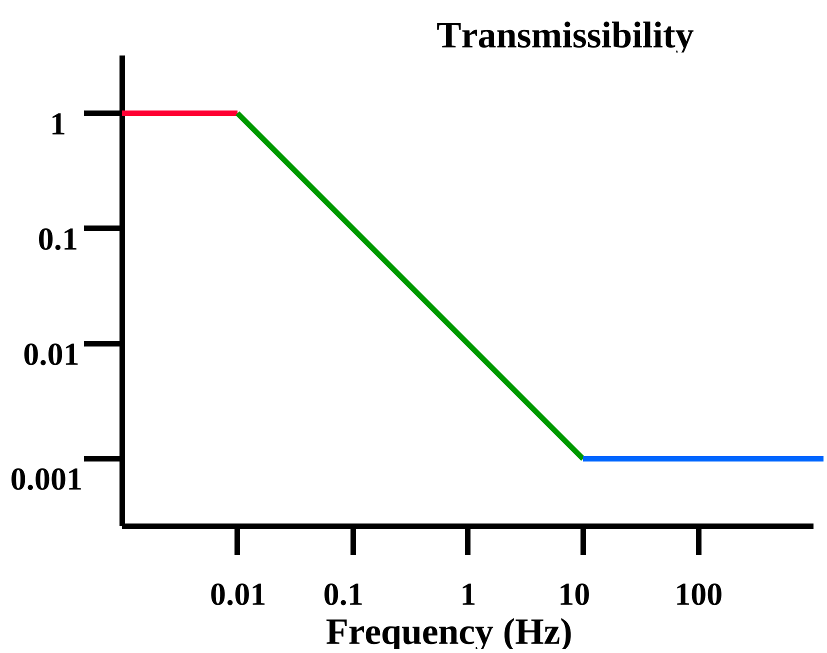

Fig. 4: Attenuation Performance Requirement

3.2 Payload Induced Vibration Isolation (R2)

Description:

A key objective of g-LIMIT is to reject directly applied inertial disturbances generated by the payload such as pumps, fans, and motors required by the experiment. Since these disturbances are applied to the payload, no passive attenuation is provided by the umbilicals. Additionally, since the platform is physically detached from the ISS vehicle, these forces react against the mass of the isolator and compliance of the umbilicals instead of reacting against the mass of the ISS and the compliance of the vehicle interface structure. The low mass of the isolator and compliance of the soft umbilicals results in more severe motion of the payload due to the "disturbance" forces generated by the payload. Thus, in order for a payload level isolation system to accommodate payloads that generate disturbances, the isolation system must reject these disturbances.

To demonstrate the direct disturbance rejection capability of g-LIMIT, a Dynamic Characterization Payload (DCP) will be used. The DCP is basically a proof mass actuator that can be commanded to apply a specified forcing function to the g-LIMIT PMS. The DCP will also be used as a representative payload in terms of mass and inertia for isolation testing. Appendix B presents the design requirements for the DCP.

Success Criteria:
Successful completion of this requirement is control system dependent. Several control systems will be evaluated, each having different performance characteristics. This requirement is not intended to be met by all control designs, but only by the higher performance control system designs. Verification of this requirement can be done by comparing frequency response of the transfer functions from the DCP acceleration input (step, sine dwell, or sine sweep) and the measured acceleration.

3.3 Forced Excitation (R3)

Description:

In addition to providing a quiescent environment for MSG investigations by isolating the experiment from MSG and payload induced vibrations, g-LIMIT will also have the capability to generate or induce pristine accelerations as desired by certain classes of experiments such as protein crystal growth. In this mode, a user-prescribed acceleration forcing function (time response or frequency spectrum) will be applied to the experiment while providing isolation from the ambient MSG acceleration environment. Essentially, this mode provides a clean excitation "signal" against the background "noise" of the ambient MSG accelerations. This capability is provided by generating a reference acceleration (or position) command in the control system that is compared with the measurement to form an error signal, thus forcing the system to follow the reference command. Of course the ability to generate a forced response of the system is limited by the control bandwidth, measurement resolution and noise, and the force range of the actuators.

Using the same approach as above to determine the DCP constraints, the frequency of a sinusoidal forcing function generated by the actuators is given by

$$w = \sqrt{\frac{F}{md}}$$

An upper limit to the excitation frequency of 3.8 Hz is obtained by evaluating this equation with the maximum force of 5.6 N, the minimum displacement of 0.001 m, and a mass of 10 kg. (The maximum actuator force is obtained from the axis with minimum combined actuator force given by 2*cos(45^o)*4N, where 4N is the peak for an individual actuator.) For a 4 N peak force, 1 mm peak displacement, and 1 kg proof-mass, the excitation frequency is 10 Hz. A lower limit of 0.1 Hz is selected for the range of excitations.

Success Criteria:

Successful completion of this requirement is control system dependent. Several control systems will be evaluated, each having different performance characteristics. This requirement is not intended to be met by all control designs, but only by the higher performance control system designs. Verification of this requirement can be done by comparing frequency response functions or time histories of the error between the reference acceleration command (step, sine dwell, or sine sweep) and the measured acceleration. As a benchmark for success criteria, this requirement is satisfied if one control system tracks a reference sine dwell at 1 Hz with error less than 10% in peak magnitude (after transients decay).

3.4 Quasi-steady Acceleration Measurement (R4)

Description:

Another unique aspect of this system is the capability of measuring the absolute acceleration of the experiment during isolated operation. Since a requirement of the control system is to pass through quasi-steady accelerations, the quasi-steady (e.g. below 0.05 Hz) components of the platform acceleration can be extracted from the position control algorithm independent of accelerometer measurements, and hence, independent of accelerometer biases. The position control law operates at a very low frequency to generate an estimate of the bias forces and the accelerometer bias measurement based on the position sensor measurements. Since the true accelerations (g-jitter, gravity gradient, and drag) and bias sources have unique frequency and/or position dependence, frequency and time response analysis of the position control law digital computations can be used to estimate the unbiased absolute acceleration of the station at the experiment location without accelerometer measurements.

Success Criteria:

Long-duration time history data will be filtered and processed both in the time domain and frequency domain to determine low-frequency averages of the estimated acceleration and measured acceleration. Successful completion of this requirement is simply the evaluation of how accurate the acceleration can be estimated and an assessment of contributing error factors such as position sensor measurements and umbilical uncertainty.

3.5 Advanced Vibration Control Technology (R5)

Description:

g-LIMIT utilizes a high-frequency control loop to cancel the inertial accelerations and a low frequency position loop to center the platform in the sway space while following the quasi-steady motion of the vehicle. By sensing relative position and absolute acceleration of the platform the active feedback control system forces the platform to follow the very-low-frequency motion of the base while attenuating the base motion at higher frequencies. High bandwidth acceleration feedback essentially increases the "effective mass" and inertial damping for disturbance rejection. Demonstration of this level of performance in six DOF cannot be accomplished on the ground due to gravitational coupling, but requires testing in a μg environment. Long periods of experimentation (on the order of hundreds of seconds) are necessary to characterize the low-frequency behavior, which is the most critical frequency range for active vibration isolation. During flight investigation, various control designs will be tested to determine performance and robustness characteristics.

The two key issues characterizing an active control system are stability and performance. Stability is the tendency for a system to return to equilibrium when disturbed. Performance is simply a measure of the degree to which stated objectives are achieved with the active control system. Stability and performance are in opposition such that the greater amount of performance for which one designs, the lesser the amount of stability (margin) the system possesses. Robustness of the control system is also important since it is a measure of how much variation from nominal can be tolerated while preserving stability or performance.

One control design approach that emphasizes stability robustness over performance is "local control". In a "local control" implementation, the two axes of control in each IM are uncoupled by using co-located acceleration and position feedback to each axis of control actuation. Local control is known to possess good stability robustness when co-located acceleration or velocity is used for feedback. However, local control neglects the interaction between control channels and the dynamic coupling between axes, hence, emphasizing robust stability at the expense of performance. This is also an asset of local control in terms of implementation, interfaces, and utilization since the parameters are independent of the system properties to a great extent and need not be modified for different payload configurations. In local control, a fixed, configuration independent hardware/software design may be implemented. This feature results in the modularity and general utility of g-LIMIT.

Alternatively, “centralized” control will be implemented as well. “Central control” uses the distributed acceleration measurements to compute the rigid body accelerations in a platform-fixed coordinate system, computes control forces resolved at the origin of the platform coordinate system (typically the center of mass), and appropriately distributes the force commands to the actuators. Central control depends on knowledge of the system properties such as mass, inertia, and umbilical stiffness to determine the appropriate control forces and the correct force distribution among axes. Each axis may be treated independently, but the rigid body coupled motion of the system including the control force of each actuator is taken into account. It should be stated that central control designs can be more robust than local control designs, but the configuration of the actuators and sensors must be known to implement central control. Hence the software for central control is configuration specific.

A third control structure is “distributed control” which implements a central acceleration control law and local position control laws. Distributed control is the most efficient implementation from a computational perspective since the low-authority position control law computations are performed at the IM, thus reserving the PIP computational capacity for the higher performance acceleration control laws. A detailed description of the control algorithms is given in Reference 4.

Success Criteria:
As shown in Table 2-2, a total of eight modes have been defined, seven of which represent closed loop control. These different modes represent control architectures for implementing various control designs. A miminum of one test per closed loop control mode is required for success. However, to evaluate advanced control design methods, multiple controllers must be implemented for selected modes. Hence, succesful completion of this requirement is an evaluation of at least 10 control designs (where controller evaluation consists of execution of Test 7 from Table 4-2).

3.6 g-LIMIT Dynamic Model Validation (R6)

Description:
Standard control design methods are “model-based”, meaning that an accurate model of the system to be controlled is used in the design and analysis of the control system. A dynamic model of g-LIMIT has been developed to facilitate control design for the Characterization Test. Anticipating the use of g-LIMIT for future science payloads, this dynamic model will be used with a payload model for control design and evaluation. Thus, the dynamic model must be verified and validated with flight data.

Success Criteria:
Model validation will be conducted with flight data and simulated data compared on the basis of metrics such as time domain averages, frequency responses, and system parameters. The validation process successfully completes this requirement.

3.7 MSG Acceleration Environment Characterization (R7)

Description:
To design control systems for future payloads in the MSG, an understanding of the ambient acceleration environment in the MSG is necessary.

Success Criteria:
Environment analysis will be conducted with flight data in the form of time domain averages and frequency responses. The analysis process successfully completes this requirement.

4.0 g-LIMIT Characterization Test Plan

The purpose of this section is to provide a detailed description of the g-LIMIT experiment plan including objectives, operations, test execution, data sets, and flight data analysis. In order to facilitate crew training and operations, common terminology associated with the Boeing Active Rack Isolation System (ARIS) is used where appropriate related to crew operations.

4.1 Isolation Performance Assessment

g-LIMIT isolation performance is determined by comparing the measured acceleration levels of the MSG base and the isolated platform. Platform measurements are resolved into three translational and three rotational accelerations at the platform center of mass. The six base accelerations are resolved into a parallel set of axes. A set of 36 transmission responses may be calculated. For simplicity, attenuation of the direct transmission in each translational axis will be the primary performance metric although this method neglects multiple axis coupling of the transmission. In addition to the attenuation of each axis, a root-sum-square average of three axes will be determined for the frequency response analysis. Multiple input-multiple output isolation performance will be analyzed post-flight using system identification methods. Isolation performance will also be determined by commanding acceleration sine sweeps to each axis and comparing the measured closed-loop acceleration response to the commanded input. Tests will be performed in both local and centralized control to assess performance of each.

Two classes of data analysis will be used to quantify the isolation performance of g-LIMIT. Averages and peak values will be used to measure time domain isolation performance. Frequency domain analysis will be used to estimate the isolation performance as a function of frequency and includes attenuation function estimation, power spectrums, cumulative power spectrums, and one-third octave band integrated power spectrums.

4.2 Data Management

In order to demonstrate mission success and quantify the performance of g-LIMIT, a significant amount of data must be measured and archived for processing. Characterization data will be archived on orbit and down-linked to the greatest extent possible. During each test the data will be stored on a PCMCIA Flash Memory card in the PIP with lower rate data sent to the PAYLOAD LAPTOP for real-time display and telemetry. The current baseline flash memory card has a 440 MB capacity, which determines the limitations on test duration, frequency of sampling, number of bits for each parameter saved, etc. Note that the permanent archival of data will be on the PCMCIA Flash Memory card, but the archive data files will be copied to the PAYLOAD LAPTOP for down-link via ethernet when available. After successfully downlinking a file, the file will be deleted from the PAYLOAD LAPTOP hard disk. A log file will be created on the PAYLOAD LAPTOP to document test execution.

The archival data file will contain the unprocessed, raw measurements in integer counts, except for computed values such as actuator commands, which will be stored as floating point numbers.

Table 4-1 defines the data available to be archived during g-LIMIT testing. The data has the following characteristics:

- Disclaimer: Note that the following values are nominal settings. The actual values will depend on electronics components tolerance which will result in a small variation from these nominal design values.
- Two sample rates will be implemented:
  - Major frame sampled at 1 kHz, 8 pole filter at 250 Hz.
  - Minor frame sampled at 25 Hz, 4 filter poles at 6.25 Hz; 2 poles at 30-50 Hz (for clock pulse)
  - Options exist by hardware modification to change the minor frame rate to 100 Hz (25 Hz filter) and 12.5 Hz (3.125 Hz filter).
- Accelerations:
  - Sampled each major frame with 16 bits
  - Acceleration channels have selectable gains according to the following table, with a nominal value of 10:

gain	lsb (µg)	peak (mg)	
1	0.010	0.328	
10	0.10	3.28	<-- Nominal for Isolated Accels
100	1.0	32.8	<-- Nominal for Base Accels
1000	10	328	

- Positions:
  - Sampled each minor frame with 12 bits
  - Position channel gains will be fixed with 0.0060 mm lsb and ±12.29 mm range
- Temperatures:
  - Sampled each minor frame with 16 bits
  - Temperature channels have an lsb of 0.0010 degC for the range 0-65.5 degC

    - Assuming that the accelerometer bias temperature sensitivity is 10 μg/C, the nominal acceleration increment due to temperature change is 0.01 μg, which is less than the nominal acceleration lsb.
- Actuator Currents:
    - Sampled each minor frame with 12 bits
    - Actuator channels have fixed gains with lsb = 2.40 mA and ±4.92A range.
- Internal to the PIP, the data can further decimated for extended duration tests.
- A log file will be stored with each test containing test parameter specifications.
- Although data may be sampled at 12 bits, for ease of processing the data will be archived in 16 bit words.

Table 4-1: Sampled Data Definitions

g-LIMIT Data	#	Rate (Hz)	Description
Onboard IM Accels	6	1000	Acceleration measurements at sensor location in engineering units
Onboard Accel Temps	6	25	Accelerometer temperature measurements
PIP Accels	3	1000	Reference base acceleration measurements at sensor location
PIP Accel Temps	3	25	Accelerometer temperature measurements
Remote Triax Accels	3	1000	Triax remote sensor acceleration measurements
Remote Triax Accel Temps	3	25	Triax temperature measurements
Control Force Commands	6	1000	Total force commands to actuator in actuator frame from controller
IM Actuator Currents	6	25	Measured actuator currents
IM Positions	6	25	Relative positions measured at actuator gap
Umbilical Bias Estimates	6	25	Bias force estimate computed in position control loop
Accel Bias Estimates	6	25	Measured bias estimates on platform

4.3 Data Archiving

The archival data file will contain the measurements in raw 16 bit integers (counts) and will be converted to engineering units during post-processing. Two fixed data storage rates are implemented: a high frequency storage rate of 1 kHz and a low frequency storage rate of 25 Hz. All data will be archived as raw integer counts in 16 bit words, except for the actuator force commands which be a 32 bit floating point number. Two Archive Data Formats will be implemented and are defined below:
- Isolation Test Data Archive Format (ITA)
- System Test Data Archive Format (STA)

Isolation Test Data Archive Format:

Parameter	# Parameters	Sample rate
Frame Count Word 1	1	1 kHz
Frame Count Word 2	1	1 kHz
IM accelerations	6	1 kHz
Base accelerations	6	1 kHz
Actuator Force Command Word 1	6	1 kHz
Actuator Force Command Word 2	6	1 kHz
PIP Frame Overruns	1	1 kHz
IM1 Frame Overruns	1	1 kHz
IM2 Frame Overruns	1	1 kHz
IM3 Frame Overruns	1	1 kHz
Control Mode	1	1 kHz
Status Word 1	1	1 kHz
Status Word 2	1	1 kHz
IM accelerometer temps	6	25 Hz
Base accelerometer temps	6	25 Hz
Relative positions	6	25 Hz
Actuator currents	6	25 Hz
System Power	1	25 Hz

Data file size: 67.25 KB/sec

System Test Data Archive Format:

Parameter	# Parameters	Sample rate
Frame Count Word 1	1	25 Hz
Frame Count Word 2	1	25 Hz
IM accelerations	6	25 Hz
Base accelerations	6	25 Hz
Actuator Force Command Word 1	6	25 Hz
Actuator Force Command Word 2	6	25 Hz
PIP Frame Overruns	1	25 Hz
IM1 Frame Overruns	1	25 Hz
IM2 Frame Overruns	1	25 Hz
IM3 Frame Overruns	1	25 Hz
Control Mode	1	25 Hz
Status Word 1	1	25 Hz
Status Word 2	1	25 Hz
IM accelerometer temps	6	25 Hz
Base accelerometer temps	6	25 Hz
Relative positions	6	25 Hz
Actuator currents	6	25 Hz
System Power	1	25 Hz

Data file size: 2.9 KB/sec

PIP to Laptop Data Packet:

Low rate sampled data will be packetized by the PIP and transferred to the PAYLOAD LAPTOP once per second for display to the crew and real-time downlink via the ISS 1553 telemetry stream. Each sampled measurement will be transferred as raw 16 bit integer numbers except for the computed values, which will be 16 bit floating point numbers. The following table is a partial list of the PIP-laptop data packet contents:

Parameter	# Parameters	Sample rate
IM accelerations	6	25 Hz
IM accelerometer temps	6	1 Hz
Base accelerations	6	25 Hz
Base accelerometer temps	6	1 Hz
Control Force Word 1	6	1 Hz
Control Force Word 2	6	1 Hz
Actuator currents	6	1 Hz
Relative positions	6	1 Hz
Status Word 1	1	1 Hz
Status Word 2	1	1 Hz
Frame Count	1	1 Hz
Control Mode	1	1 Hz
Test ID	1	1 Hz

1 Hz Data packet size: 682 Bytes/sec

Each parameter in the above table will be sampled once per second with the exception of the six IM accelerations and the three Base accelerations. Although sent once per second, the 12 accelerations measurements in the data packet will be sampled at 25 Hz. Each major frame measurement of the accelerations will be processed through a fourth order low pass filter with a 10 Hz break frequency in order to prevent aliasing in the 25 Hz decimated acceleration data in the PIP-Laptop data packet. Hence, each minor frame, the output of each acceleration low-pass filter will be written to the data packet.

4.4 Test Descriptions

In view of the significant crew workload during g-LIMIT testing, the system is being designed to operate in an autonomous mode (excluding setup and initialization) once test execution is initiated. Experiment execution may be either initiated from the ground via telemetry or from the PAYLOAD LAPTOP with crew participation. Once the experiment commences, the test will operate autonomously without need for crew intervention. Experiment execution is initiated by creating an experiment parameter file (EPF) which is transferred to the PIP from the PAYLOAD LAPTOP either by crew or by ground command. The format of the EPF file is given in Appendix A. Table 4.2 presents a summary of the tests to be performed and is followed by a detailed description of each g-LIMIT characterization test.

In Table 4.2, the last column indicates which requirement is associated with a particular test. An "S" indicates a stability test, a "C" indicates a system characterization test, and Ri" indicates that this test objective is verification of requirement Ri as defined in Section 3 of this document.

TABLE 4.2: Summary of Characterization Tests

Test No.	Test	Description	Duration (hh:mm:ss)	Data (MB)	Reqmt
1	Position Control Test	Position stability; bias estimation	00:05:00	0.87	S
2	Umbilical Stiffness Test	Estimate umbilical stiffness	00:22:00	3.83	C
3	Range Test	Measure range of travel	00:13:00	2.62	C
4	Mass & Inertia Test	Estimate mass properties	00:13:00	2.62	C
5	Recovery Test	Verify anti-bump function	00:11:00	1.91	S
6	Acceleration Control Test	stability of accel control	00:01:30	6.05	S
7	Quiescent Isolation Test	Isolation performance	01:10:00	282.45	R1, R6
8	Disturbance Rejection Test	Disturbance rejection performance	00:13:20	53.80	R2, R6
9	Forced Response Test	Pristine excitation performance	00:20:00	80.70	R3
10	MSG Isolation Test	MSG induced disturbance rejection	01:45:00	423.68	R1, R7
11	Quasi-steady Acceleration Test	Estimation of quasi-steady acceleration	15:00:00	156.60	R4

Test 1: Position Control Test

Purpose: This test is used to verify stability of the Standby Mode position controller and estimate the bias force of the umbilical system.

Method: Begin test in Standby mode and command g-LIMIT to null position. This test should be done while ISS accelerations are relatively quiescent.

Success Criteria: PMS does not violate sway space constraints with stable control.

Test Duration: 00:05:00

Archive Data Format: STA
Archive Data File Size: 0.87 MB

Test 2: Umbilical Stiffness Test

Purpose: Stiffness characterization test.

Method: Begin test in Central Standby mode (CSS) for 100 seconds and command g-LIMIT to null position. After 100 second initialization, begin 0.05 Hz sinusoid position command, 75% full-scale in axis 1 for 120 seconds. After 120 second command completed, command null position for 100 seconds and repeat sinusoid position command for axes 2 – 6 sequentially.

Success Criteria: Positions and force commands measured for ground estimation of stiffness matrix

Test Duration: 00:22:00

Archive Data Format: STA
Archive Data File Size: 3.83 MB

Test 3: Range Test

Purpose: Determine range of travel in all six axes.

Method: Begin test in Central Standby mode (CSS) for 100 seconds and command g-LIMIT to null position with anti-bump control off. After 100 second initialization, command position to 110% full-scale in axis 1 for 30. After 30 second command completed, command null position for 100 seconds and repeat sinusoid position command for axes 2 – 6 sequentially.

Success Criteria: Full range determined in each of six axes

Test Duration: 00:13:00

Archive Data Format: STA
Archive Data File Size: 2.62 MB

Test 4: Mass & Inertia Test

Purpose: mass properties characterization test.

Method: Begin test in Central Standby mode (CSS) for 100 seconds and command g-LIMIT to null position with anti-bump control off. After 100 second initialization, command a 1 Hz, 10 milli-g sinusoid acceleration command in axis 1 for 30 seconds. After 30 second command completed, command null position for 100 seconds and repeat sinusoid acceleration command for axes 2 – 6 sequentially.

Success Criteria: Mass and Inertia Matrix estimated

Test Duration: 00:13:00

Archive Data Format: STA
Archive Data File Size: 2.62 MB

Test 5: Recovery Test

Purpose: Verify functionality of the Anti-bump feature of the position control law.

Method: Begin test in Central Standby mode (CSS) for 100 seconds and command g-LIMIT to null position with anti-bump control on. After 100 second initialization, command position to 110% full-scale in axis 1 for 10 seconds. After 10 second command completed, command null position for 100 seconds and repeat for axes 2 – 6 sequentially.

Success Criteria: Stable convergence to null position and mode flags switch correctly.

Test Duration: 00:11:00

Archive Data Format:	STA
Archive Data File Size:	1.91 MB

Test 6: Acceleration Control Stability Test

Purpose: Verify stability of acceleration and position control loops.

Method: Begin test in standby mode for 30 seconds and then transition to the specified active control mode for 60 seconds.

Success Criteria:	Control loops stable and PMS does not violate sway space constraints.

Test Duration: 00:01:30

Archive Data Format:	ITA
Archive Data File Size:	6.05 MB

Test 7: Quiescent Isolation Test

Purpose: Characterize isolation performance from base-motion disturbances with MSG in quiescent mode.

Method: Begin test in standby mode for 30 seconds and then transition to the specified active control mode for 4100 seconds.

Success Criteria: Control loops stable and PMS does not violate sway space constraints.

Test Duration: 01:10:00

Archive Data Format: ITA
Archive Data File Size: 282.45 MB

Test 8: Payload Disturbance Rejection Test

Purpose: Characterize isolation performance from payload-induced disturbances.

Method: Begin test in standby mode for 30 seconds and then transition to the specified active control mode. Wait 30 seconds and command DCP to generate acceleration input in axis 1 using a logarithmic sine sweep from 0.5 Hz to 10 Hz, 25 points, 20 cycle dwell each. Command DCP to null position for 30 seconds, then command DCP to generate acceleration input in axis 2 as described above. After second axis excitation complete, command DCP to null position and continue for duration of test.

Success Criteria: Control loops stable and PMS does not violate sway space constraints.

Test Duration: 00:13:20

Archive Data Format: ITA
Archive Data File Size: 53.80 MB

Test 9: Acceleration Forced Response Test

Purpose: Characterize performance of user-specified forcing function.

Method: Begin test in standby mode for 30 seconds and then transition to the specified active control mode. Wait 30 seconds and generate acceleration commands according to specified acceleration input spectrum in specified control axis. This test is only performed with central control.

Success Criteria: Control loops stable and tracking input command with TBD error.

Test Duration: 00:20:00

Archive Data Format: ITA
Archive Data File Size: 80.70 MB

Test 10: MSG Disturbance Rejection Test

Purpose: Characterize isolation performance from base-motion disturbances with MSG in maximum disturbance operations.

Method: Begin test in standby mode for 30 seconds and then transition to the specified active control mode for 4100 seconds. After 1 minute, the MSG facility will be sequentially transitioned to a "high ambient vibration" state. Near the end of the test, the MSG facility will be sequentially returned to a "low ambient vibration" state for the duration of the test. The crew members must note the times at which various facility settings are changed.

Success Criteria: Control loops stable and PMS does not violate sway space constraints.

Test Duration: 01:45:00

Archive Data Format: ITA
Archive Data File Size: 423.68 MB

Test 11: Quasi-Steady Acceleration Estimation Test

Purpose: Characterize performance of acceleration estimation function.

Method: Begin test in Standby mode and command g-LIMIT to null position. This test should be conducted during a crew sleep period or otherwise quiet time. For this test, the high_store_rate is set to 250 Hz.

Success Criteria: Control loops stable, PMS does not violate sway space constraints and data acquired.

Test Duration: 15:00:00

Archive Data Format: STA
Archive Data File Size: 156.60 MB

5.5 Test Set Classifications:

Test Set #1: System Characterization Tests

Test No.	Description	# runs
1	Position Control	6
2	Umbilical Stiffness	2
3	Range	1
4	Mass & Inertia	1
5	Recovery	3

- Total Experiment Time: 02:13:00
- Total Data Volume: 23.85 MB

Test Set #2: Isolation Characterization Tests

Test No.	Description	# runs
6	Acceleration Stability	1
7	Quiescent Isolation	1
8	Payload Disturbance Rejection	1
9	Forced Response	1
10	MSG Disturbance Rejection	1

- Total Experiment Time: 03:29:50
- Total Data Volume: 846.68 MB

Test Set #3: Quasi-Steady Characterization Tests

Test No.	Description	# runs
11	Quasi-Steady Acceleration Est.	1

- Total Experiment Time: 15:00:00
- Total Data Volume: 156.60 MB

Test Timeline Sequence:

Day 1: Test Set # 1
Day 2 – 16: Test Set # 2, Controller #1 - #15
Day 17: Test Set # 13

- Total Archived Test Data Volume: 12.88 GB

General Test Scenario Comments:

- The only exception to the above test sequence is Test Set # 3. This test set can be performed at any time after successful completion of Test Set #1 and should be performed during the most quiescent period possible, preferably during crew sleep.
- Initial system hardware setup will require an estimated 45 min. crew time.
- Hardware deactivation and stow will require an estimated 45 min. crew time.
- Time for experiment execution does not include setup and test initiation (file transfer, test selection, etc).
- The nominal test plan includes placeholders for controllers that are to be designed during the mission based on down-linked archive data. These controllers will be tuned to optimize performance based on data analysis results.

5.0 References

1. Boeing Defense & Space Group Missiles and Space Division, "System Specification for the International Space Station," Specification #41000D, Nov. 1, 1995.
2. Grodsinsky, Carlos M. and Whorton, Mark S., "A Survey of Active Vibration Isolation Systems for Microgravity Applications," *Journal of Spacecraft and Rockets*, submitted for publication.
3. Whorton, Mark S. "g–LIMIT: A VIBRATION ISOLATION SYSTEM FOR THE MICROGRAVITY SCIENCE GLOVEBOX," AIAA Paper 99-0577, 37th AIAA Aerospace Sciences Meeting, Reno, NV, January 11-14, 1999.
4. Whorton, Mark S. "Development of Control Algorithms for g-LIMIT."

Appendix A:
Experiment Parameter File

Name	Type	Description
iDataArchiveFormat	Integer	Indicates format of archived data 1 – System Test Archive Format 2 – Isolation Test Archive Format
iTestDuration	Integer	Duration of the test in seconds
iStartOffset	Integer	Used by MSG-FL to indicate time between ENTER_LSS_MODE and START_TEST
iControlMode	Integer	Indicates control mode for the test
fAccGain[12]	Real array of size 12	Electronics gain for each channel
fAccScale[12]	Real array of size 12	EU conversion for each channel
fAccBias[12]	Real array of size 12	DC bias for each accelerometer
fTempScale[12]	Real array of size 12	EU conversion for each accelerometer
fTempCal[12]	Real array of size 12	Accelerometer temp calibration
fPosScale[6]	Real array of size 6	EU conversion for each position channel
fCurrentScale[6]	Real array of size 6	EU conversion for each actuator channel
iAntiBump	Integer	Flag to indicate if Anti-bump control on
fSwitchThreshold	Real array of size 12	Switch Thresholds for Anti-bump control
iExcitationFlag	Integer	Used to indicate Reference Command: 0 – None 1 – Position 2 – Acceleration 3 – DCP
iExcitationAxis[6]	Integer Array of size 6	Used to indicate which axes to be commanded
iExcitationType	Integer	Used to indicate Reference Command: 1 – Step 2 – Sine Dwell 3 – Sine Sweep
fExcitationAmplitude	Real	Amplitude of Reference Command
iExcitationDuration	Integer	How long to shake it
iExcitationStartTime	Integer Array of size 6	When to start shaking each axis
filename	Char array of size 16	8.3 notation. DOS 6.2.2 filenaming convention
TBD 1	Real	Placeholder
TBD 2	Real	Placeholder
TBD 3	Real	Placeholder
TBD 4	Real	Placeholder
TBD 5	Real	Placeholder
ControllerFilename	Char array of size 16	Name of file containing control parameters
fControlParameters	TBD	

Appendix B:
Dynamic Characterization Payload Design Requirements

A key objective of g-LIMIT is to reject directly applied inertial disturbances generated by the payload such as pumps, fans, and motors required by the experiment. To demonstrate the direct disturbance rejection capability of g-LIMIT, a Dynamic Characterization Payload (DCP) will be used. The DCP is basically a proof mass actuator that can be commanded to apply a specified forcing function to the g-LIMIT PMS. The DCP will also be used as a representative payload in terms of mass and inertia for isolation testing. A design requirement of the DCP is that the mass must be locked when not in use. The following subsections derive the design requirements for the DCP.

Frequency Constraints

The frequency of a sinusoidal forcing function with magnitude *F* applied to a mass, *m*, with a peak displacement of *d* is given by

$$w = \sqrt{\frac{F}{md}}$$

An upper limit to the excitation frequency is obtained by evaluating this equation with the maximum force and the minimum displacement and mass. For a 4 N peak force, 1 mm peak displacement, and 1 kg proof-mass, the excitation frequency is 10 Hz.

The lower-limit of the excitation frequency is a function of the actuator mass load and the force or acceleration produced. The force generated by the DCP should be sufficient to produce an excitation on the g-LIMIT platform of sufficient magnitude to measure the attenuation. As a first cut, the DCP force should generate an acceleration of the platform that is two orders of magnitude above the Space Station Requirement shown in Figure 1. At 1 Hz, the requirement is 16 μg, which implies the DCP must generate a platform acceleration of 1.6 mg.

The acceleration of the platform due to the DCP force is equal to the acceleration of the DCP mass multiplied by the mass ratio $\frac{M_{DCP}}{M_{platform}}$. Thus the required acceleration of the platform may be used to derive a requirement on the acceleration of the DCP mass. For a peak displacement of 1 cm, the maximum DCP acceleration is given as a function of the excitation frequency of the DCP by the following plot in Figure B-1. The dashed line on this plot is the derived requirement on DCP acceleration assuming a platform mass to DCP mass ratio of 10. From Figure 5, a lower limit of 0.4 Hz is derived for the DCP excitation. Increasing the mass load on the DCP will reduce the mass ratio, which in turn will reduce the derived requirement. For example, if the DCP mass was equal to the platform mass, the derived acceleration requirement would be reduced by a factor of ten, resulting in a lower limit on excitation frequency. However, higher force levels would then be required to generate the acceleration level. Force and power constraints must be taken into account as well.33

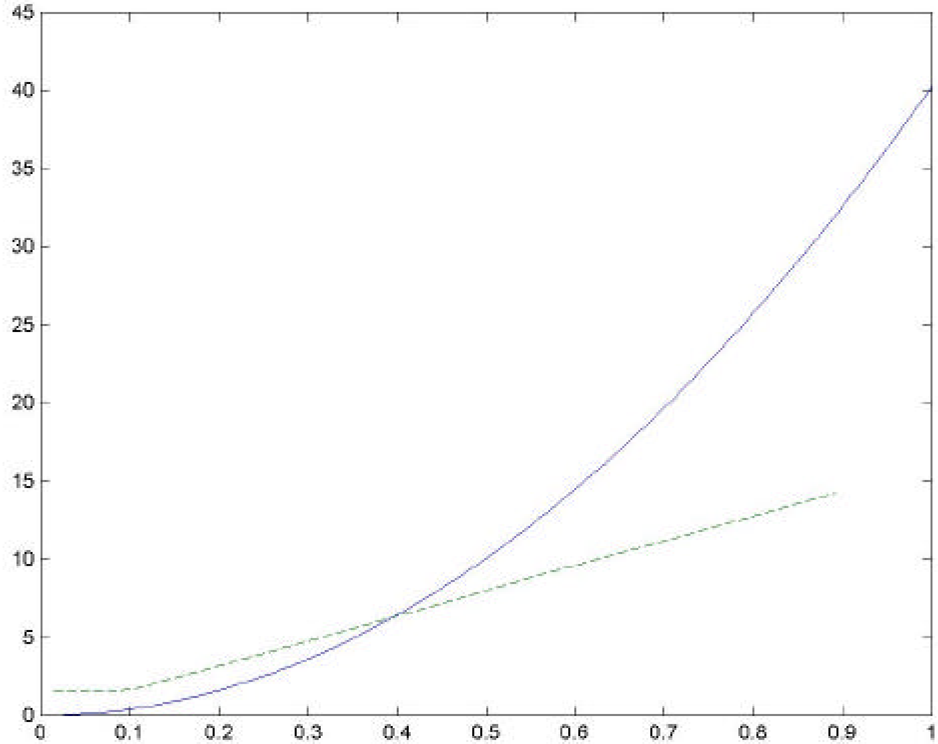

Figure B-1: Excitation Frequency and Derived Requirement as a Function of DCP