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Frequency Weighted H_2 Control Design for the Glovebox Integrated Microgravity Isolation Technology (g-LIMIT)

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Abstract

The acceleration environment on the International Space Station (ISS) exceeds the requirements of many microgravity experiments. The Glovebox Integrated Microgravity Isolation Technology (g-LIMIT) has been built by the NASA Marshall Space Flight Center to attenuate the nominal acceleration environment and provide some isolation for microgravity science experiments. The g-LIMIT uses Lorentz (voice-coil) magnetic actuators to isolate a platform, for mounting science payloads, from the nominal acceleration environment. The system utilizes payload-acceleration, relative-position, and relative-orientation measurements in a feedback controller to accomplish the vibration isolation task. The controller provides current commands to six magnetic actuators, producing the required experiment isolation from the ISS acceleration environment. The present work documents the development of a candidate control law to meet the acceleration attenuation requirements for the g-LIMIT experiment platform. The controller design is developed using linear optimal control techniques for frequency-weighted H_2 norms. Comparison of performance and robustness to plant uncertainty for this control design approach is included in the discussion. System performance is demonstrated in the presence of plant modeling error.

Introduction

Space-science experiments on the ISS are subjected to a variety of vibratory disturbances in the frequency range above 0.01 Hz, including crew motion disturbances in the frequency band from 0.06 to 6 Hz (ref. 1). Microgravity experimenters will most likely require some attenuation of the nominal ISS acceleration environment. Three orders-of-magnitude attenuation of the induced accelerations on the experiment platform, with frequency roll-off of 20 db/decade over a range from 0.01 Hz to 10 Hz, has been established as a design requirement for a vibration isolation system (ref. 2).

The Glovebox Integrated Microgravity Isolation Technology (g-LIMIT) is designed to isolate experiments from medium-range frequency vibrations (between 0.01 and 10.0 Hz), while passing the quasi-static (<0.01 Hz) accelerations to the experiment (ref. 2). The acceleration-attenuation capability of g-LIMIT is limited primarily by two factors: (1) the character of the umbilical required between the g-LIMIT base (stator) and the g-LIMIT experiment platform (flotor), and (2) the allowed stator-to-flotor rattlespace. A primary goal in the design was to isolate at the individual experiment, rather than entire rack level. Ideally, only the sensitive elements of an experiment are isolated from the environment. This typically results in a stator-to-flotor umbilical that can be greatly reduced in size and in the services it must provide. The g-LIMIT employs three umbilicals to provide experiments with power, data-acquisition, and control services (ref. 2).

In order to design controllers for g-LIMIT it was necessary to develop an appropriate dynamic model of the system. The design methods employed for the controller described in this document require a linearized system model in state-space form. A six-degree-of-freedom (6-DOF) state model, augmented with absolute acceleration states, has been developed in a form appropriate for an optimal control design for g-LIMIT (ref. 3). The following section presents the model parameters used for the g-LIMIT flight system.

g-LIMIT State Space Model

Flotor and umbilical parameters for the g-LIMIT flight system, shown in table 1, were used to develop the state-space model for the controller design (ref. 3). The three g-LIMIT umbilicals are included in this model. The translational and rotational stiffness matrices for each umbilical have been assumed to be diagonal for an umbilical-fixed set of coordinate directions. These diagonal stiffness values are included in table 2. Similarity transformations of the diagonal stiffness matrices were performed to compute corresponding stiffness matrices in the stator-fixed frame. The umbilical coordinate directions used to diagonalize the stiffness matrices were assumed to diagonalize the corresponding damping matrices as well, with 3 percent damping. The diagonal stiffness terms are given in table 2. All stiffness and damping, translation/rotation cross-terms, that is, K_{tr}, K_{rt}, C_{tr}, and C_{rt}, were considered to be zero. Bias currents, required to produce a bias force and a bias moment to move the flotor from its assumed relaxed position to the home location, were included in the model. The flotor relaxed-position was assumed to be 2 mm from the home-position, and misaligned by approximately 2° about each stator-fixed coordinate axis. This resulted in the following set of bias current values: $I_{B2} = -0.264$ A, $I_{B4} = -0.159$ A, $I_{B6} = -0.123$ A, where the subscript, $B\#$, denotes bias value for the #th actuator.

Table 1. g-LIMIT Parameters

Parameter	Symbol	Value
Flotor Mass	m	17.85 kg
Flotor Moments of Inertia	I_{xx} I_{yy} I_{zz}	0.17 kg m^2 0.16 kg m^2 0.23 kg m^2
Flotor Products of Inertia	I_{xy} I_{xz} I_{yz}	−3e−6 kg m^2 2e−4 kg m^2 −2.5e−4 kg m^2
Umbilical Locations (3 Umbilicals)	${}^{(F)}\underline{r}_{F^* F_u}$	[0.0, −0.12, −0.032] m [0.1, 0.06, −0.032] m [−0.1,0.06, −0.032] m
Actuator Coil Current Direction Vectors (6 Actuator Coils)	${}^{(S)}\hat{\underline{I}}_i$	[0.0, 0.0, 1.0] [−1.0, 0.0, 0.0] [0.0, 0.0, 1.0] [0.5, 0.866, 0.0] [0.0, 0.0, 1.0] [0.5, −0.866, 0.0]
Actuator Magnet B-Field Direction Vectors (3 Actuator Magnets)	${}^{(F)}\hat{\underline{B}}_i$	[0.0 1.0 0.0] [0.0 1.0 0.0] [0.866 −0.5 0.0] [0.866 −0.5 0.0] [−0.866 −0.5 0.0] [−0.866 −0.5 0.0]
Actuator Constant	$\left(L_i\, B_i\right)$	1.0 N/Amp

Table 2. Diagonal Stiffness Parameters

	Translational	Rotational
	[N/m]	[N-m/rad]
Umbilical X-axis	25.0	2.0
Umbilical Y-axis	25.0	2.0
Umbilical Z-axis	50.0	1.0

Candidate H_2 Control Design

A well-designed microgravity vibration-isolation controller must (1) maintain the flotor within its rattlespace constraints (i.e., preclude flotor-to-stator physical contact) at low frequencies (<0.01 Hz), (2) attenuate the absolute acceleration of the flotor at mid-range frequencies (from 0.01 Hz up to 10.0 Hz), and (3) "turn off" the control effort at some high frequency (20 to 30 Hz). The rattlespace requirement means the flotor must track the stator motion at low frequencies. Since the motion of the stator will be significant at low frequencies (i.e., ISS motion is very large at orbital frequency), the stator-to-flotor closed-loop acceleration transmissibility must be unity over the low-frequency range. To meet the science requirements the absolute flotor acceleration transmissibility should be attenuated by three orders of magnitude, with a frequency roll-off of 20 dB/decade over a range from 0.01 to 10 Hz. Above this frequency the controller should "turn off," so that the closed-loop transmissibility curve rejoins the open-loop transmissibility curve. This will avoid excitation of any high-frequency vibrational modes. The above design criteria should be met while limiting the actuator control effort to less than 40 amps/micro-g over the entire frequency range (ref. 4).

Feedback of the absolute acceleration of the flotor was used for candidate g-LIMIT controller design. Any controller using only acceleration feedback to attenuate indirect disturbances will also automatically result in attenuation of direct disturbances (ref. 4). This attenuation stems from the increase in effective mass due to an acceleration-only feedback controller. Thus, the choice of acceleration-only feedback allows the designer to focus on attenuation of indirect disturbances while attenuation of direct disturbances will be realized as a consequence. The increase in effective mass has the additional advantage of improving the stability robustness, because the desired attenuation is achieved by increasing effective mass rather than by adding negative stiffness.

An optimal controller design strategy using a frequency-weighted linear quadratic regulator (LQR), along with a full order Kalman filter, was chosen for g-LIMIT (ref. 4). Recent research demonstrated the usefulness of this method for designing SDOF controllers to meet the vibration isolation criteria (ref. 4). The method was subsequently applied for the design of controllers for multi-input multi-output (MIMO), multi-degree-of-freedom (MDOF) systems (ref. 5). In particular, the method has been applied to a full-order state-space model for the g-LIMIT design (refs. 3 and 5). A rational approach to selecting the state weighting filters, previously developed and demonstrated in a SDOF case study, was shown to achieve similar results for the MDOF, multi-axis system (refs. 4 and 5). The technique provided an intuitive approach for steering the designer's choice of frequency weighting, so as to avoid (via unnecessarily conflicting demands) poor conditioning of the Riccati-equations used for controller optimization.

A summary of the state frequency weighting guidelines is presented below (ref. 4).

State-Weighting Design Guidelines

1. Use the relative-position and relative-velocity state-weighting matrices for shaping the closed-loop acceleration transmissibilities in the low-frequency region, to call for near-unity relative accelerations.

2. Use the acceleration state-weighting matrix for shaping the mid-range closed-loop acceleration transmissibilities, to attenuate flotor accelerations at intermediate frequencies.

3. Choose all state-weighting filters to call for roll-off of pseudo-sensitivity and pseudo-complementary-sensitivity functions (*S* and *T*, respectively) at high frequencies, for high-frequency controller "turn-off."

These state frequency-weighting guidelines were applied to the SDOF system in a case study, to determine the effect of various state-weighting, measurement-noise, and process-noise design choices (ref. 4). The case studies provided examples of the logical application of the methodology, and proved effective in meeting the design objectives. This same basic state-weighting-filter selection process was then applied to the 6-DOF vibration control for g-LIMIT (ref. 5).

Figure 1 shows state-weighting selections used for the respective axes in a candidate MDOF controller design for g-LIMIT (ref. 5). For the translational degrees of freedom, band-pass filters (with consecutive legs having slopes +1, 0, -2) were used on each absolute acceleration state; flat filters (i.e., constant weightings), on each relative-position state; and open filters, on each relative-velocity state. Flat filters, with the same weighting magnitude as the relative-position states, were used for the relative-angular-position states, along with open filters for the relative-angular-velocity states. Control weightings were chosen to be flat filters with a magnitude of 100 for each actuator. Figure 2 shows the corresponding weightings on *S* and *T*.

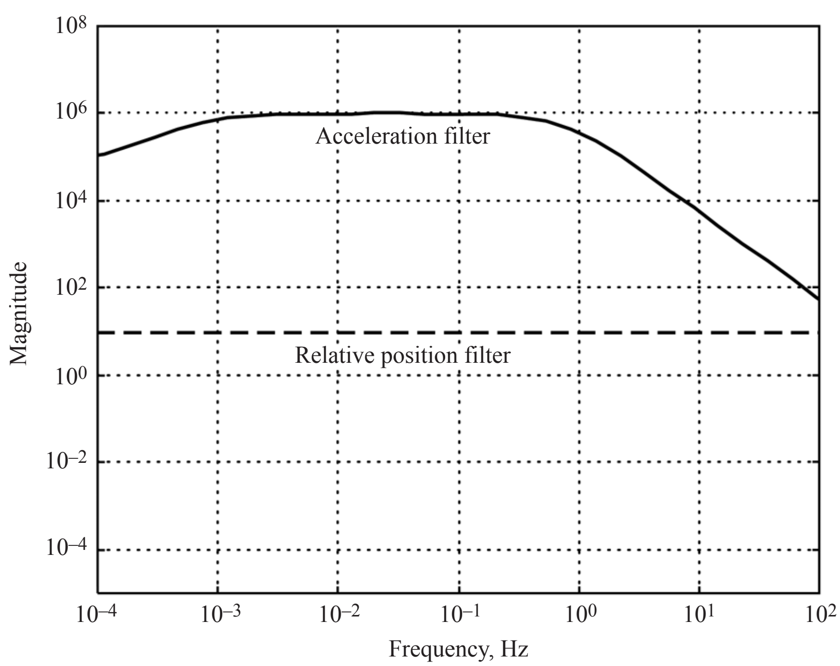

Figure 1. Design weighting filters (all degrees of freedom).

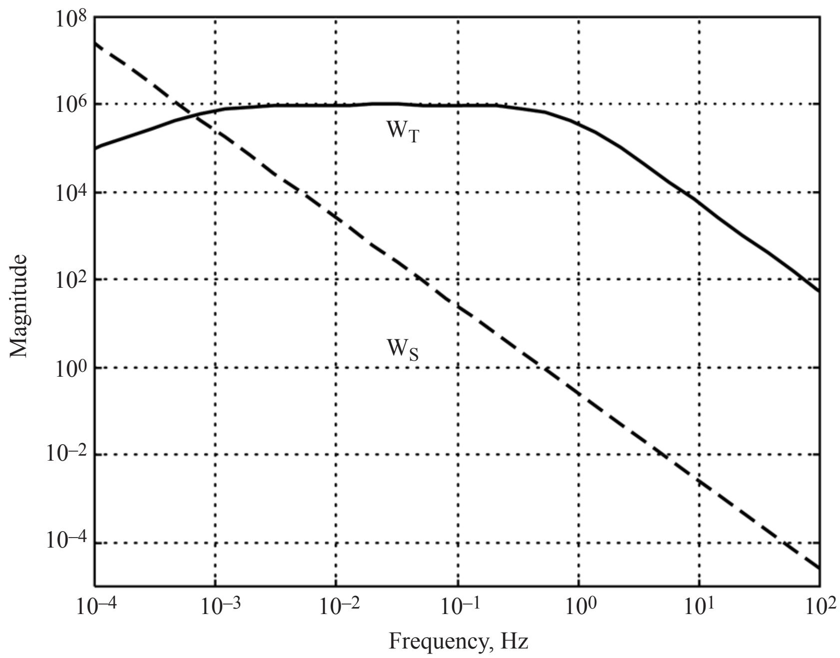

Figure 2. Pseudo-sensitivity- and pseudo-complementary-sensitivity function weighting.

Controller Design Modification

The candidate controller design described above was considered for implementation in the g-LIMIT flight system. However, the resulting controller state matrices contained some rather large high-frequency modes. The maximum real part of the eigenvalues associated with the controller state matrices was about 1.9e5 rad/s. This value is much larger than the 500-Hz sampling frequency for the controller update (ref. 2). The result is a nonrealizable compensator, because the largest frequency associated with the controller must be smaller than half the sampling rate to avoid aliasing. Further, the numerical integration step-size for these high frequencies places excessive demands on computational resources. Upon examination of the controller eigenvalues it was determined that these undesirable high-frequency modes were associated with the full-state Kalman Filter. (State estimation is necessary for the controller implementation because only measurements of absolute acceleration are used for feedback.)

Several modifications to the state frequency weighting were attempted to resolve this eigenvalue problem. First, the upper corner frequency of the band-pass filter, used for acceleration state weighting, was lowered in an attempt to reduce controller bandwidth. This achieved the desired effect on the controller eigenvalues. Unfortunately, the modification also led to inadequate closed-loop attenuation over the desired isolation frequencies. In fact, the resulting closed-loop response approached the open-loop response, so that the controller did not achieve the required level of vibration isolation. Several other options were considered in an attempt to improve the controller performance. These included lowering the gains on the state weightings, and changing the acceleration weighting-filter slopes on the lower and upper legs. None of these changes resulted in adequate controller performance.

For accelerations to be represented as states in the model used for controller design the dynamic equations of motion had been augmented with low-pass filtered absolute acceleration measurements (ref. 3). A simple first-order low-pass filter was used for this realization. The corner frequency was initially set to 10 Hz (i.e., to encompass the isolation frequency range). Lowering the corner frequency was found to reduce the maximum controller eigenvalue, while maintaining adequate closed-loop system isolation. Table 3 shows the maximum controller eigenvalue for each of several such modifications to the g-LIMIT controller design. For each design the corner frequency of the low-pass filter on accelerometer measurements used the values shown in table 3. Design #1 is not realizable since the maximum eigenvalue is much larger than the controller sample frequency. The roll-off frequency of the low-pass filter was reduced until the maximum eigenvalue was less than half the controller sample rate. The resulting modified controller designs each had a maximum eigenvalue in the range of 45 to 180 Hz. To reduce the maximum controller eigenvalue to 100 Hz (1/5 of the sample rate) required the corner frequency of the accelerometer filter to be an unacceptably low 25 milli-Hz. This filtering of the measurement seemed excessive because it ignored accelerometer information in the frequency range of interest.

Table 3. Controller Modifications to Low-Pass Filter Corner Frequency

Design #	Maximum Eigenvalue	Corner Frequency
1	31000 Hz	10 Hz
2	180 Hz	0.050 Hz
3	100 Hz	0.025 Hz
4	64 Hz	0.015 Hz
5	45 Hz	0.010 Hz

A controller modification was needed that reduced the maximum controller eigenvalue, without significantly lowering the corner frequency of the accelerometer filter, while providing performance similar to that of the original design. This was achieved by the addition of frequency weighting on the disturbance inputs. A first-order low-pass filter with a corner frequency of 0.2 Hz was used to weight each direct and indirect disturbance input. The effect of this low-pass disturbance weighting was to provide an overall reduction in the controller effort over the high-frequency range. In consequence, high-frequency modes of the controller were reduced, while the frequency weightings on *S* and *T* remained unchanged. Using a 5-Hz roll-off for the acceleration filtering resulted in closed-loop transmissibility for the modified design that was virtually the same as for the original design. These modifications resulted in an increase in controller order by nine states, one for each indirect and direct translational disturbance, and one for each direct rotational disturbance. This resulted in a state dimension of 33 for the controller: 15 of these were for the full state observer and 9 more for the acceleration state weightings. Figures 3 and 4 show vertical direction transmissibility to indirect and direct translational disturbances, respectively. On-axis indirect disturbances are attenuated by at least 20 db/decade starting at slightly above 0.01 Hz. The closed-loop response remains attenuated by at least three orders of magnitude above 1 Hz, thus meeting the isolation requirements. Off-axis responses are significantly reduced over the same frequency range. Transmissibility responses in other directions, not shown, demonstrated similar performance.

Controller Robustness

The controller performance robustness to umbilical stiffness modeling error was evaluated by varying the diagonal stiffness values for each umbilical over a wide range. Simultaneously, the umbilical coordinate directions corresponding to diagonalized stiffness matrices were misaligned by up to 40° from the stator-fixed coordinate directions. This resulted in significant off-diagonal terms in the system translational and rotational stiffness matrices. The results of one of these cases are presented in this section to demonstrate apparent controller robustness to modeling error. The following summarizes the umbilical modeling error used in this robustness test case.

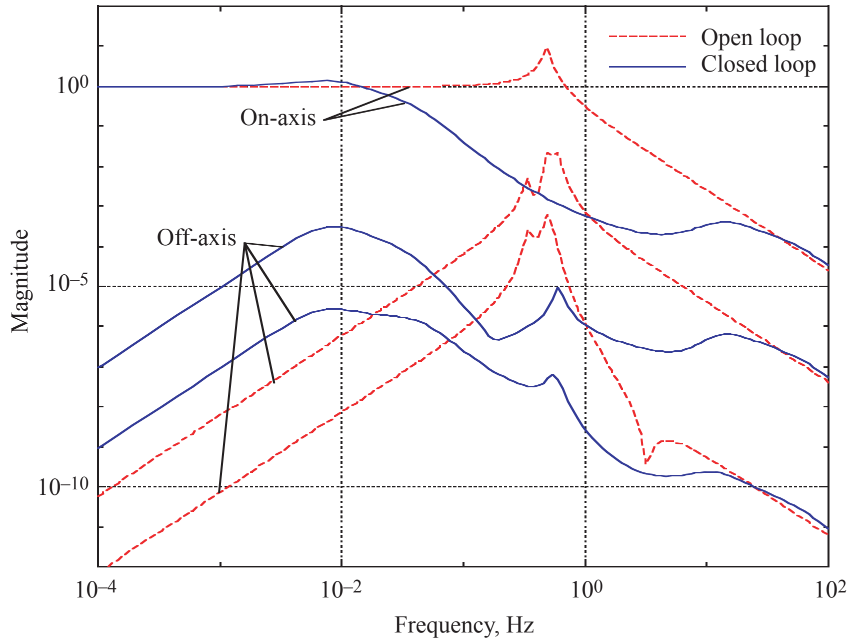

Figure 3. Transmissibility for vertical-axis indirect acceleration disturbances.

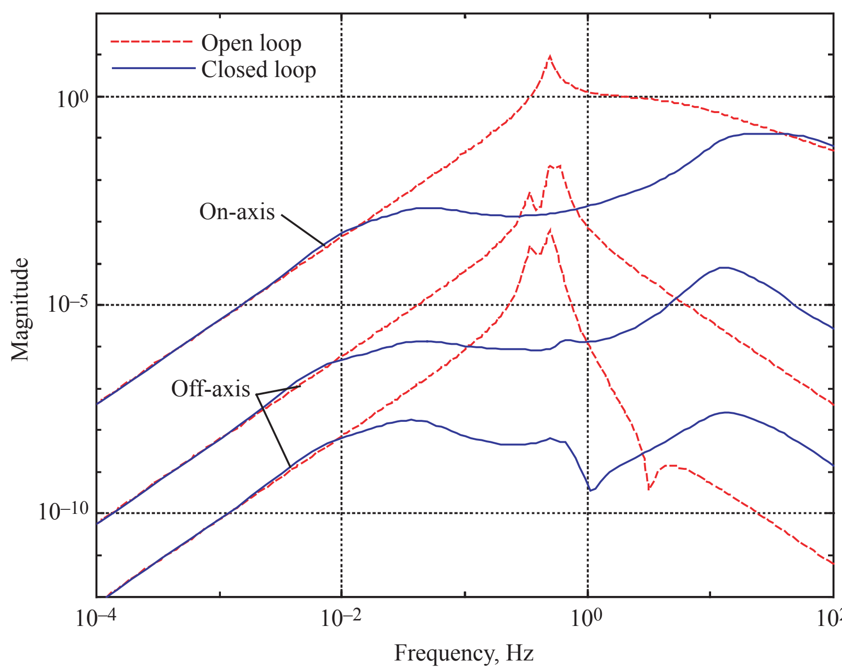

Figure 4. Transmissibility for vertical-axis direct acceleration disturbances.

1. The diagonal umbilical stiffness values were increased by 50 percent over those used for the design.

2. The umbilical coordinate systems were misaligned by –20°, +20°, and +40°, respectively, from the orientations used for the design.

Figures 5 and 6 show vertical direction transmissibilities to indirect and direct translational disturbances, respectively, for this robustness test case. On-axis indirect disturbances are attenuated by at least 20 db/decade starting at slightly above the roll-off shown in the nominal case. The closed-loop response remains attenuated by at least three orders of magnitude above 1 Hz, thus meeting the isolation requirements. Off-axis responses are significantly reduced over the same frequency range. The off-axis response to indirect disturbance is increased over the low-frequency range but remains below the on-axis response over the entire frequency range. Response to direct-disturbance inputs also demonstrates good performance in this off-nominal case. Transmissibility responses in other directions, not shown, demonstrated similar performance.

The robustness of the H_2 controller was evaluated over a wide range of diagonal stiffness values and umbilical- to stator-frame misalignment angles. Adequate performance was achieved over a range of diagonal-stiffness modeling error from about −50 to +50 percent and a range of ±45° misalignment angles. System stability was maintained for all these cases. Overall the H_2 control design using frequency weighting performed well.

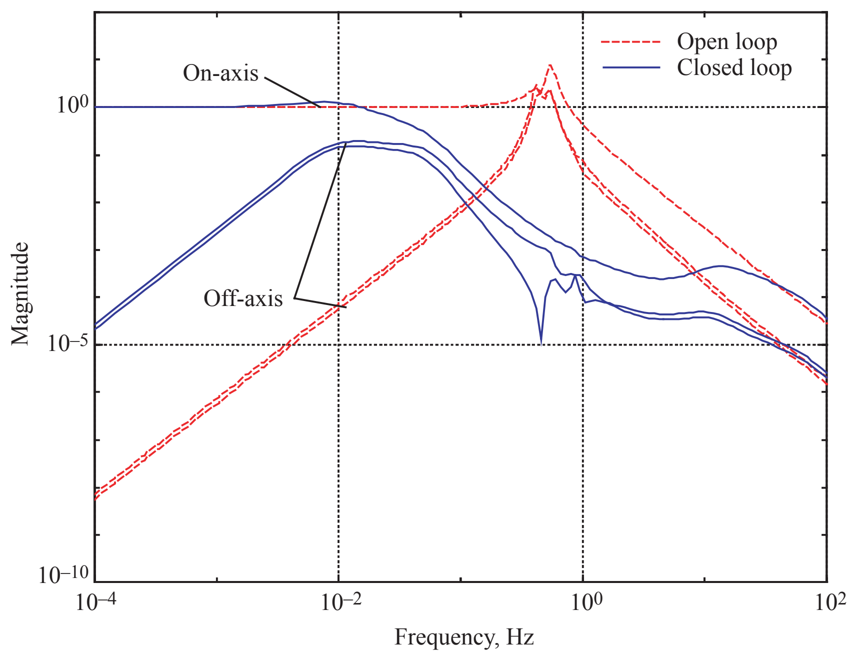

Figure 5. Transmissibilities for vertical-axis indirect acceleration disturbances. (Robustness Test)

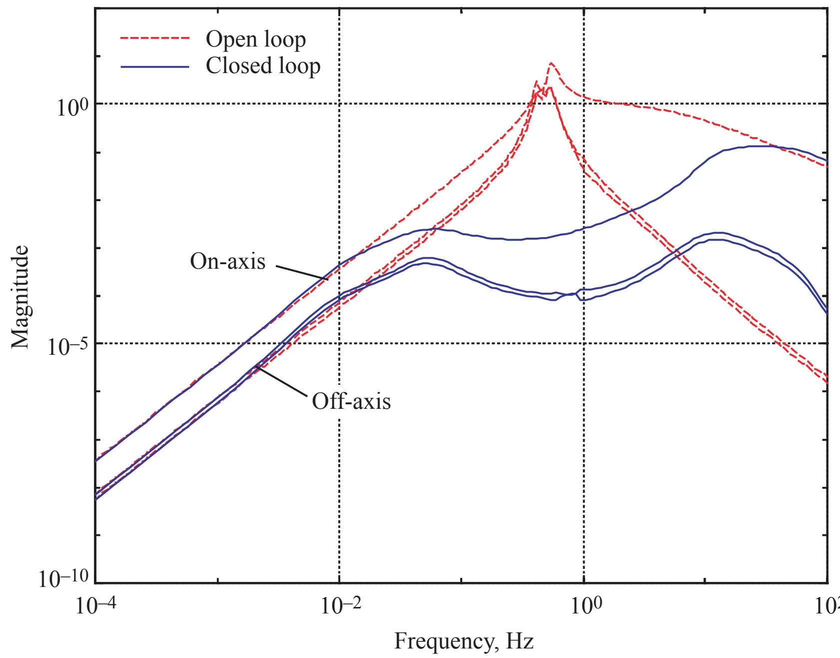

Figure 6. Transmissibilities for vertical-axis direct acceleration disturbances. (Robustness Test)

Simulation Study

The H_2 controller design performance was evaluated using a nonlinear MDOF simulation of the g-LIMIT equations of motion (ref. 3). The simulation was developed in Matlab/Simulink and utilized a variable-step fourth-order Runga-Kutta method for integration of the equations of motion. The controller update rate and measurement sample rate were 500 Hz. To evaluate the controller performance the flotor was subjected to both direct and indirect acceleration disturbances. These disturbances were simulated using band-limited white noise sources. Figures 7 and 8 show vertical direction transmissibilities to indirect and direct translational disturbances, respectively, for the simulated nominal design. On-axis indirect disturbances are attenuated by at least 20 db/decade starting at 0.03 Hz. The closed-loop response remains attenuated by at least three orders of magnitude between 1 and 10 Hz, thus meeting the isolation requirements. Response to direct-disturbance inputs also demonstrates good performance within the 10-Hz specification, although slight amplification occurred at frequencies above 30 Hz.

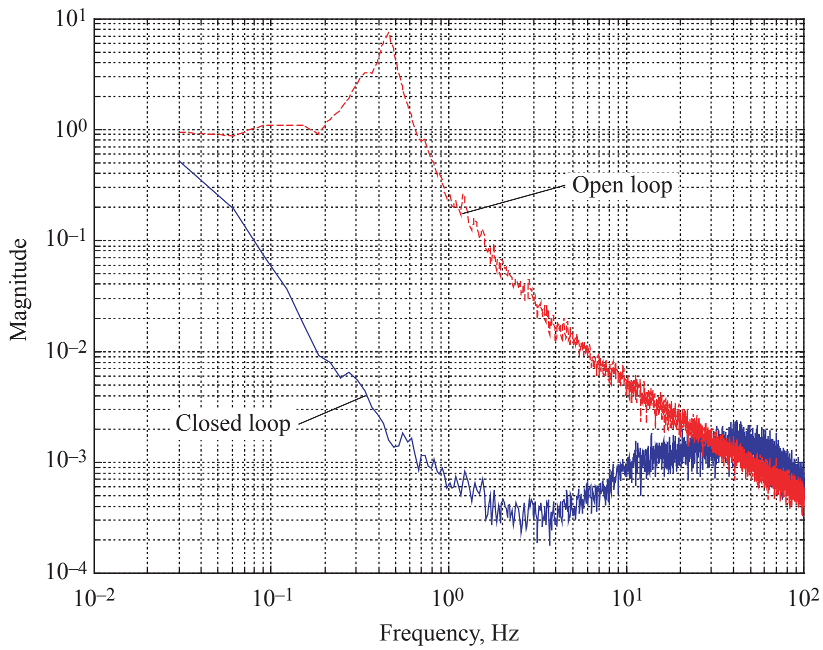

Figure 7. Transmissibilities for vertical-axis indirect acceleration disturbances. (Simulation Test)

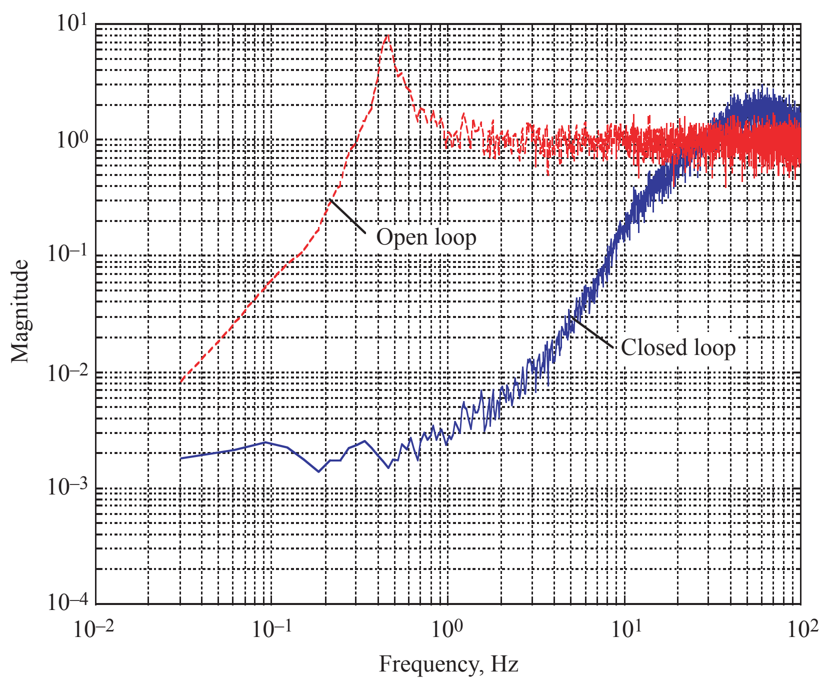

Figure 8. Transmissibilities for vertical-axis direct acceleration disturbances. (Simulation Test)

Concluding Remarks

This document presents a candidate design for a microgravity vibration isolation controller for g-LIMIT. It addresses a controller implementation problem in an underlying design, namely large controller eigenvalues. The desired performance was achieved by slightly lowering the corner frequency of the low-pass filter used on the acceleration measurements, and adding frequency weighting for disturbance inputs. An H_2 control methodology was evaluated for g-LIMIT using linear analysis and MDOF nonlinear simulation. An approach to selecting the state weighting filters, previously developed and demonstrated in SDOF and MDOF case studies (refs. 4 and 5), was shown to achieve adequate performance for the modified controller. The final controller performed well in all disturbance-loading conditions. On-axis closed-loop responses to each disturbance-loading direction were shown to meet the design objectives and demonstrated robustness to umbilical stiffness modeling error. Off-axis transmissibility to disturbances was increased somewhat over low-frequency ranges but was held below the on-axis response.

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