Active Vibration Isolation of Microgravity Experiments With Spring Umbilicals Using An Electrodynamic Actuator

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ABSTRACT

Microgravity experiments will require active vibration isolation in the low to mid frequency range of 0.1 Hz to 10 Hz. Approximately two orders of acceleration reduction (40 dB) will be required. Previous works have reported results for accelerations transmitted through the umbilical. This paper describes experimental and theoretical results for vibration isolation in one dimension (horizontal) where the simulated experiment is connected to the spacecraft by a spring umbilical. The experiment consisted of a spacecraft (shaker), experiment (mass), umbilical, accelerometer, control electronics, and Lorentz actuator. The experiment mass was supported in magnetic bearings to avoid any stiction problems. Acceleration feedback control was employed to obtain the vibration isolation. Three different spring umbilicals were employed. Acceleration reductions on the order of 40 dB were obtained over the frequency range of 0.1 Hz to 10 Hz. Good agreement was obtained between theory and experiment.

INTRODUCTION

Microgravity science experiments have often yielded poor results due to the presence of wideband vibration sources aboard the orbiter. These vibration disturbances are produced by astronaut movements, on-board machinery, thruster firings and other unavoidable factors, as noted by Nelson [1]. Typical acceleration environments on Skylab [2,3] and Spacelab [4] have been found to be of the order of 10^{-3} g_0 (g_0 is the gravitational constant for earth), while experiment specifications have been in the range of 10^{-5} to 10^{-6} g_ρ. Figure 1 shows the amplitude and frequency for a typical microgravity vibration specification (monochromatic) and an anticipated acceleration environment [5]. Note that a comparison of these environmental levels and the specifications indicate the need for vibration isolation on the order of 40 dB over the intermediate frequency range from 0.1 to 10 Hz.

The degree of isolation that can be obtained onboard the orbiter is fundamentally constrained by the actuator stroke. Knospe and Allaire have characterized the limits of microgravity isolation for both monochromatic sinusoidal [6] and stochastic [7] vibration disturbances. The actuator stroke most seriously affects the isolation of the payload from low frequency (in the quasi-steady range below 0.1 Hz) orbiter disturbances due to gravity gradient and atmospheric drag forces. Fortunately, most microgravity experiments do not require isolation in this range. For mid to high frequency vibrations (above 10 Hz) microgravity experiments can be isolated using passive techniques. It should be noted that passive devices cannot isolate microgravity payloads from both direct disturbances, where the disturbance is on the experiment platform, and indirect disturbances, those transmitted through the umbilicals or other connections to the spacecraft.

Further, payload isolation over the low to intermediate range cannot be achieved using passive isolation. Typically, the stiffness of umbilicals results in a corner frequency too high for effective passive isolation [1]. These issues are discussed in more detail in Knospe, et. al [8] where feedback controller design issues are explored. If the transfer function G(s) represents the plant, a loop shaping approach is proposed where the control loop feedback transfer function H(s) must be chosen so that G(s)H(s) is large. Also, gain and phase margins for system stability are discussed.

The choice of actuator to be employed is important. Non-contacting magnetic actuators, utilizing electromagnets or permanent magnets, are the best actuator solution for vibration isolation in the low to intermediate frequency range [9]. One reason for the use of non-contacting actuators is the avoidance

of friction and stiction associated with contacting actuators. Electrostatic levitation has also been considered for this application but typically, the size and force requirements preclude their use [10].

Several isolation systems have been built by researchers in the past decade. A single-axis electromagnetic actuator, similar to a magnetic thrust bearing, has been described by Havenhill and Kral [11]. Flux feedback was employed to accurately control the force produced independently of the air gap. Due to shaker and accelerometer limits, the lowest recorded frequency of their measured data was 5 Hz. Also umbilicals were not considered. This concept was extended to a six degree of freedom system called the Fluids Experiment Apparatus Magnetic Isolation System (FEAMIS) as reported in [12]. The system did not isolate disturbances below 2 Hz and did not consider umbilicals.

Grodsinsky [13] has reported a six degree of freedom active isolation system that employs relative and inertial sensors. A digital feedforward control system activated nine electromagnetic actuators with a stroke of ±0.3 in (0.76 cm). Another six degree of freedom system was developed by Fenn and Johnson [14] with a stroke of 0.4 in (1.002 cm). Nonlinear controls were also tested for a one degree of freedom testbed. Hibble, et. al [15] reported a Magnetic Isolation and Pointing System (MIPS) for the Space Station's Payload Pointing System. This system met the requirement of 0.01 g_0. The effect of umbilicals were not considered in any of these isolation systems.

Several researchers have employed a theoretical approach to examine the use of feedback control for active vibration isolation. Knospe, et. al [8] discussed the control issues of microgravity vibration when umbilicals are included and examined stability robustness. An investigation of acceleration control to reject disturbances caused by the compliance of an umbilical was considered by Jones, et. al [16]. The umbilical was assumed to have stiffness but not damping. As umbilical stiffness increased, the microgravity isolation quality deteriorated, as expected. Acceleration control was found to improve disturbance rejection significantly as compared to position control but at a cost of larger required gaps and forces. Hampton, et. al [17] presented a method for the design of robust feedback controllers using modern control synthesis methods. Constant state feedback gains and a quadratic cost function was employed used with an inverse frequency weighting approach which attenuates low frequency accelerations, below 50 Hz, by two orders of magnitude more than high frequency accelerations.

The purpose of this paper is to report on one dimensional long stroke microgravity vibration isolation results in the presence of spring umbilicals. Both a theoretical treatment and experimental results are presented. The objectives were three

fold: 1) construction of a one dimensional experimental test rig for microgravity vibration isolation, 2) achievement of mirocravity levels (1 to 10 μg_0) with spacecraft excitation levels on the order of 1 mg_0, and 3) a study of spring umbilical effects.

EXPERIMENTAL SET-UP

Figure 2 shows a one dimensional schematic diagram of a spacecraft (base), experiment (mass), umbilical with stiffness and damping coefficients, and an active isolator. A cylindrical mass, representing the experiment, is connected via springs, representing experiment umbilicals, to a shaker, representing the vibrating orbiter. An electrodynamic actuator is used to supply an active force creating the desired payload vibration isolation from disturbances produced by the shaker [18]. Figure 3 is a block diagram of the test rig. A non-contacting radial magnetic bearing support system ensures that the cylinder is free to move horizontally along its axis without stiction [19]. A large concrete base was employed to support the experiment and isolate the experiment from external building excitations.

The isolated mass (microgravity experiment) is a solid cylindrical mass with dimensions 58.4 cm (23 in) long and 9.6 cm (3.8 in) weighting 34 kg (75 lb). The shaker had a continuous force rating of 133.4 N (30 lb) in the frequency range from 0.1 to 20 Hz. It was operated in the voltage mode producing a constant velocity motion of the armature up to approximately 8 Hz where it had a resonance. Spring umbilicals were used to simulate experiment umbilicals. These are connected to both the experiment (mass) and spacecraft (shaker).

In the orbiter, there is a very high impedance at mid to low frequencies between the experiment and the orbiter due to the very large mass of the orbiter. The electrodynamic shaker employed in the laboratory experiment does not have a high impedance at low frequencies. Thus, in the laboratory experiment, the actuator was connected to an inertial plate, rather than directly to the shaker, to simulate experiment conditions in space. Connection directly to the shaker would change the impedance of the shaker armature and thus strongly influence the measurements.

The active isolation system consists of an accelerometer, accelerometer amplifier, controller, transconductance amplifier, and Lorentz actuator. A low frequency accelerometer, a Sundstrand Q-Flex QA-700, was used to sense the acceleration of the experiment. Another one was employed to monitor the acceleration of the shaker armature. These accelerometers use a quartz flexure seismic suspension system with a measured level of noise at 0.204 μg_0 and a signal to noise ratio of 4.9 at 1 μg_0. An acceleration amplifier is supplied with the unit. The analog

controller incorporates a continuously adjustable gain and some other components described in more detail in the later sections. The controller output drives a linear, bipolar transconductance amplifier. The one dimensional Lorentz actuator provides a force which is linear in response to the applied current. Because of the low frequencies involved, a long stroke was needed. The actuator was designed with a stroke of 2 inches. Experimental measurements showed that the stroke was nearly independent of position [18], as shown in Fig 4.

ACTIVE ISOLATION THEORY

The single degree of freedom isolation system described above for the spacecraft/experiment is considered here. The equation of motion for the system is

$$m \ddot{x} + c (\dot{x} - \dot{u}) + k(x - u) = F_d - F_a \tag{1}$$

The experiment is subject to accelerations due to their transmission through the connecting umbilicals from the spacecraft as well as direct force excitation F_d by a source on the experiment platform. Taking the Laplace transform yields

$$(m s^2 + c s + k) X(s) = (c s + k) U(s) + F_d(s) - F_a(s) \tag{2}$$

We are interested in accelerations rather than displacements yielding

$$\frac{(m s^2 + c s + k)}{s^2} \ddot{X}(s) = \frac{(c s + k)}{s^2} \ddot{U}(s) - F_a(s) \tag{3}$$

where the double dot over the symbol denotes acceleration. Figure 5 shows a block diagram of the control loop.

The direct disturbance force F_d is important for microgravity isolation and is treated in several works as discussed in the introduction so it will not be discussed in this paper. Thus the $F_d(s)$ term is set to zero. The open loop transfer function between the shaker (orbiter) acceleration and mass (microgravity experiment) acceleration (also called the open loop acceleration transmissibility) T_{OL} is

$$T_{OL} = \frac{\ddot{X}_{OL}(s)}{\ddot{U}(s)} = \frac{c\,s + k}{m\,s^2 + c\,s + k} \tag{4}$$

where X_{OL} denotes the open loop experiment displacement. In dimensionless pole-zero form this becomes

$$T_{OL} = \frac{2\,\zeta\omega_n\left(s + \dfrac{\omega_n}{2\zeta}\right)}{\left(s + 2\,\zeta\omega_n - 2\,i\,\omega_n\sqrt{1-\zeta^2}\right)\left(s + 2\,\zeta\omega_n + 2\,i\,\omega_n\sqrt{1-\zeta^2}\right)} \tag{5}$$

where the denominator is easily factored.

With acceleration feedback, the actuator force is given by

$$F_a(s) = H(s)\,\ddot{X}(s) \tag{6}$$

Substituting in Eq. (3) and solving for the closed loop transfer function (closed loop acceleration transmissibility) T_{CL} yields

$$T_{CL} = \frac{\ddot{X}_{CL}(s)}{\ddot{U}(s)} = \frac{c\,s + k}{[m + H(s)]\,s^2 + c\,s + k} \tag{7}$$

The closed loop transmissibility indicates the effectiveness of the feedback control loop in reducing the transmitted accelerations through the umbilicals. The objective is to find H(s) so that the magnitude of T_{CL} is small (at least -40 dB) in the frequency range where isolation is needed, 0.1 to 10 Hz.

Another effectiveness measure of the microgravity isolation system is the reduction ratio R of the open loop experiment acceleration to the closed loop experiment acceleration. R has the form

$$R = \frac{\ddot{X}_{OL}(s)}{\ddot{X}_{CL}(s)} = \frac{[m + H(s)]\,s^2 + c\,s + k}{m\,s^2 + c\,s + k} \tag{8}$$

This indicates how much improvement in the experiment acceleration level is achieved through active feedback control. Here the objective is to make R large, at least 100 (+40 dB), in the frequency range of 0.1 to 10 Hz. Note that the reduction ratio R indicates the improvement obtained with active control,

it does not directly indicate whether the overall isolation objective has been achieved.

FEEDBACK LOOP

The actuator force F_a is produced by a feedback loop which is examined next. The elements in the feedback loop are: 1) accelerometer, 2) controller circuit, 3) transconductance amplifier, and 4) Lorentz actuator.

An accelerometer and its associated amplifier can be considered a pure gain in this frequency range with the voltage/acceleration constant K_a. The analog controller has the transfer function

$$\frac{V_c(s)}{V_a(s)} = \frac{K_c}{(1 + \tau_1 s)^2} \tag{9}$$

Here, K_c is the gain constant and the denominator represents a second order low pass filter, necessary to avoid exciting lightly damped high frequency modes of the space platform/experiment, with time constant τ_1 which has the value of 0.0072 sec. For the frequency range of interest, the transconductance amplifier has the gain constant K_t

$$\frac{I(s)}{V_c(s)} = K_t \tag{10}$$

and the Lorentz actuator has the gain constant α. The actuator provides a force which is very linear with respect to current and insensitive to displacement [18,19].

Combining all of these terms, the overall feedback transfer function is

$$\frac{F_a(s)}{\ddot{X}(s)} = \frac{V_a(s)}{\ddot{X}(s)} \frac{V_c(s)}{V_a(s)} \frac{I(s)}{V_c(s)} \frac{F_a(s)}{I(s)} \tag{11}$$

for the feedback part of the loop. Substituting for the individual components yields

$$\frac{F_a(s)}{\ddot{X}(s)} = H(s) = \frac{K_a K_c K_t \alpha}{(1 + \tau_1 s)^2} = \frac{K}{(1 + \tau_1 s)^2} \tag{12}$$

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where all of the constants can be condensed into one acceleration feedback gain K. In the actual control loop some additional compensation was employed at high frequency to avoid exciting high frequency modes of the system. The additional compensation was necessary to increase the system gain and phase margins [18] but did not affect the isolation properties in the frequency range of interest. Thus, due to length restrictions in the paper, a detailed discussion of that aspect is not presented here.

REDUCTION RATIO

The final open loop/closed loop acceleration ratio is given by

$$R = \frac{R_{num}}{R_{den}} \qquad (13)$$

where the numerator is

$$R_{num} = m \, \tau_1^2 \, s^4 + (2 \, m \, \tau_1 + c \, \tau_1^2) \, s^3$$

$$+ \, (m + K + 2 \, c \, \tau_1 + k \, \tau_1^2) \, s^2 + (c + 2 \, k \, \tau_1) \, s + k \qquad (14)$$

and the denominator is

$$R_{den} = m \, \tau_1^2 \, s^4 + (2 \, m \, \tau_1 + c \, \tau_1^2) \, s^3$$

$$+ \, (m + 2 \, c \, \tau_1 + k \, \tau_1^2) \, s^2 + (c + 2 \, k \, \tau_1) \, s + k \qquad (15)$$

This is the theoretical model of the active isolation system.

EXPERIMENTAL MEASUREMENTS

Experimental data was obtained by exciting the shaker with pseudo-random noise, band limited to 12.5 Hz. High resolution auto spectra were obtained providing 512 lines of frequency resolution. An averaged spectra were taken in each case presented with one hundred auto spectra per averaged plot.

The objective of the experimental measurements was to obtain acceleration auto spectra with a spring umbilical in place to determine the acceleration reduction and transmission ratios. A flat top window weighting function was chosen on the analyzer to make the time waveform be exactly periodic within the sample record length. The recorded plots are somewhat "jittery" due to

the nature of the shaker armature motion excited by the broadband pseudo-random noise input signal.

Three different cylindrical springs made of carbon steel were tested as umbilicals. The were connected from the shaker armature to the experiment mass. Each spring was in tension initially and throughout the testing in each case. It is assumed that the levitation magnetic bearings have negligible axial stiffness and damping because the simulated experiment mass was very long compared with the magnetic bearing length - there were no magnetic end effects.

The first case involved a spring umbilical with stiffness of 876 N/m (5 lb/in), verified by independent measurement. The overall gain constant was 9,000 and the calculated natural frequency ω_n, as in Eq. (5), equal to 0.81 Hz, and the damping ratio was equal to zero for the case of a spring. Figure 6 shows the acceleration of the mass with the controller off (top line) and on (bottom line) where the vertical axis is plotted in terms of the acceleration in decibels compared to 1 g_0. The upper line indicates spacecraft milligravity levels averaging about -80 dB (10^{-4} g_0) while the lower line indicates experiment microgravity levels approximately -120 dB (10^{-6} g_0).

Figure 7 plots the acceleration transmissibility T_{CL}, the ratio of experiment acceleration to spacecraft acceleration as transmitted by the spring umbilical, for the same case as above. With feedback control, over 30 dB of isolation is achieved over the entire frequency range from 0.1 to 10 Hz. Figure 8 shows a plot of the experimental reduction ratio R obtained from the ratio of the closed loop experiment acceleration to the open loop experiment acceleration. The reduction ratio is approximately 30 dB in the low frequency range, from 0.1 to 0.3 Hz and increases to approximately 50 dB in the range from 1 to 10 Hz. The theoretical results, based upon Eq. (16), are also plotted for comparison purposes, with relatively good agreement.

The second spring had a stiffness of 1226 N/m (7 lb/in). The overall controller gain constant was set at 9,000 and the calculated natural frequency of ω_n of 0.96 Hz. As with the first spring umbilical, the reduction is approximately 30 dB in the low frequency range and approximately 50 dB at higher frequencies [18]. Figure 9 gives the experiment/spacecraft acceleration transmissibility which is close to that for the first spring case. Figure 10 shows the reduction ratio for this case. The peak of reduction occurs at approximately 1 Hz. At 0.1 Hz, R = 26 dB and at 10 Hz R = 48 dB indicating that the desired reduction of 40 dB has been obtained for most of the frequency range. An overall controller gain constant of 9,000 produced an effective ratio of dynamic mass to actual mass of approximately 31.6 (30 dB).

The third spring had stiffness of 1488 N/m (8.5 lb/in). A gain of 9,000 was used again and the calculated natural frequency ω_n of 1.05 Hz. Acceleration plots and reduction ratio plots were generated for these cases [18]. They are rather similar to the previous two cases so they are not presented here. Figure 11 shows both the experimental transmissibility ratio and theoretical results from Eq. (16) for comparison purposes. Again, the results are in good agreement.

CONCLUSIONS

Microgravity experiments will require active vibration isolation in the expected acceleration environment for spacecraft. This paper has demonstrated the reduction of milli-g spacecraft acceleration levels, transmitted to the experiment via spring umbilicals, to μ-g_0 levels. A magnetic bearing supported experiment mass was constructed to simulate a zero-g environment and avoid stiction problems that would be encountered with other support systems. An acceleration feedback control system using an accelerometer, controller, and non-contacting actuator to implement the control force was developed. Experimental results were presented demonstrating over 30 dB attenuation for a tethered microgravity experiment in the low to mid frequency range of 0.1 to 10 Hz. This is the first combined theoretical/experimental study that the authors are aware of to carry out such isolation as a function of different umbilicals.

Three different spring umbilicals were used in the study, with spring stiffnesses of 876, 1226, and 1488 N/m (5, 7, and 8.5 lbf/in). Accelerations of the simulated spacecraft were at milli-g levels averaging about -80 dB (10^{-4} g_0) due to shaker excitations. With the controller on, experiment accelerations were at microgravity levels of approximately -120 dB (10^{-6} g_0). These isolation levels were obtained for all of the three spring umbilicals tested. The controller attained an average level of transmissibility reduction of two orders of magnitude over the frequency range from 0.1 to 10 Hz with somewhat lower levels in the lower end of this frequency range. The controller also attained reduction ratios averaging approximately 40 dB over the same frequency range. A linear theoretical model of the system was developed and agreed reasonably well with the experimental results. It is expected that this model could be used to design microgravity controllers in general, if umbilical nonlinearities are not too large.

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NOMENCLATURE

c	Umbilical Damping
F_a	Actuator Force
F_d	Disturbance Force
H	Feedback Transfer Function
I	Actuator Current
k	Umbilical Spring Stiffness
K	Acceleration Feedback Gain
K_c	Controller Gain
K_t	Transconductance Amplifier Gain
m	Experiment Mass
R	Reduction Ratio
s	Complex Frequency
T	Acceleration Transmissibility
u	Spacecraft Displacement
V_a	Accelerometer Voltage
V_c	Controller Voltage
x	Experiment Displacement
α	Lorentz Actuator Constant
τ	Controller Time Constant
ω_n	Natural Frequency $= (k/m)^{1/2}$
ζ	Damping Ratio $= c/2m\omega_n$

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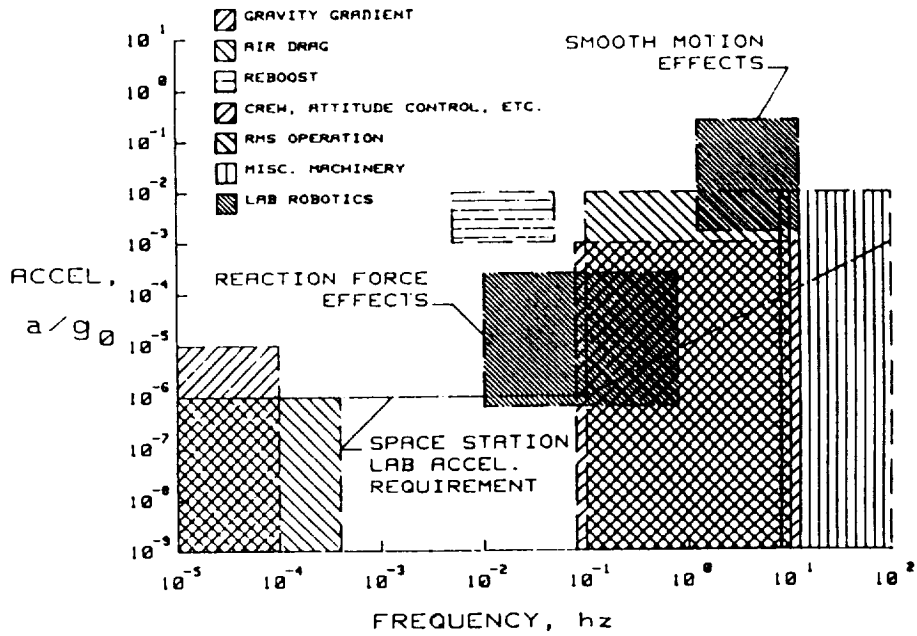
POTENTIAL DISTURBANCES

Figure 1. Typical Microgravity Experiment Requirements and Anticipated Acceleration Environment
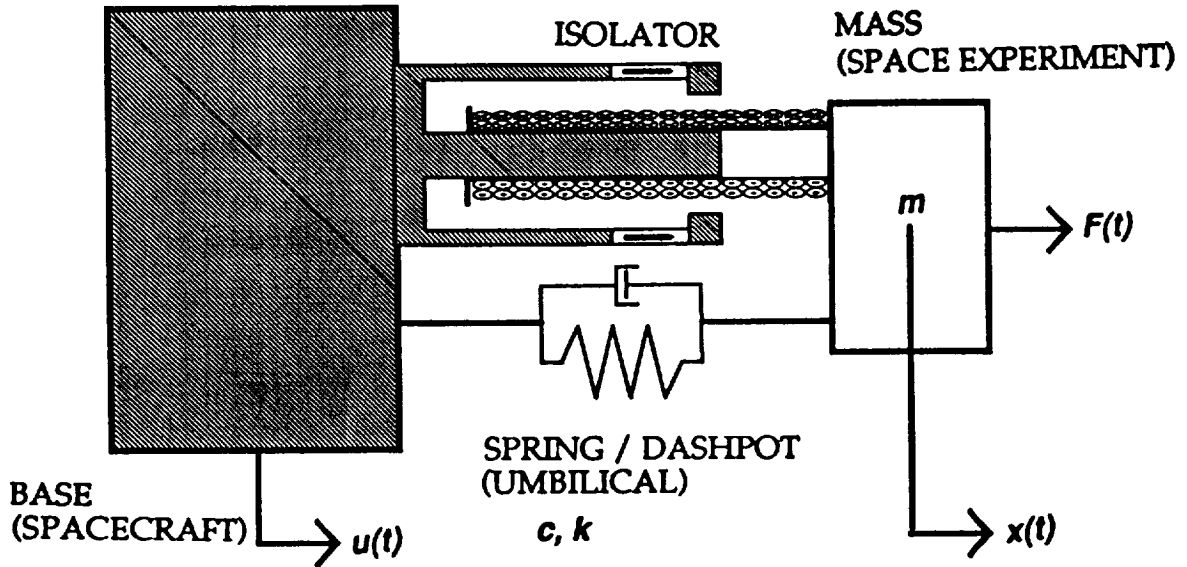

Figure 2. One Dimensional Acceleration Isolation Test Rig for Microgravity Experiments with an Umbilical
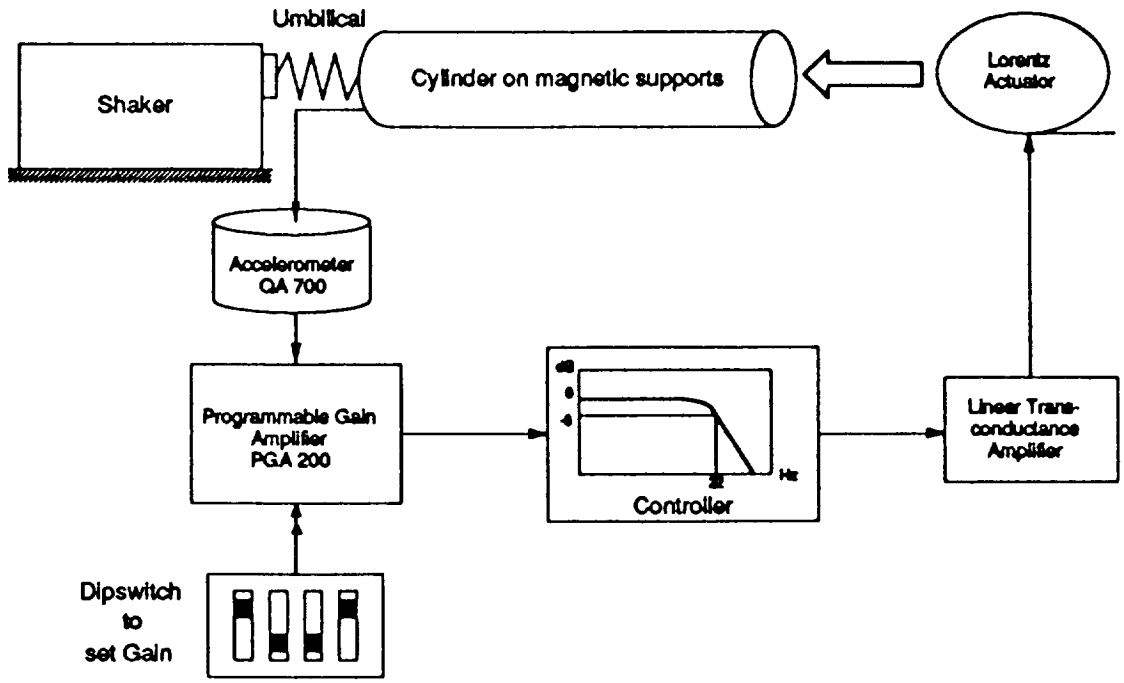
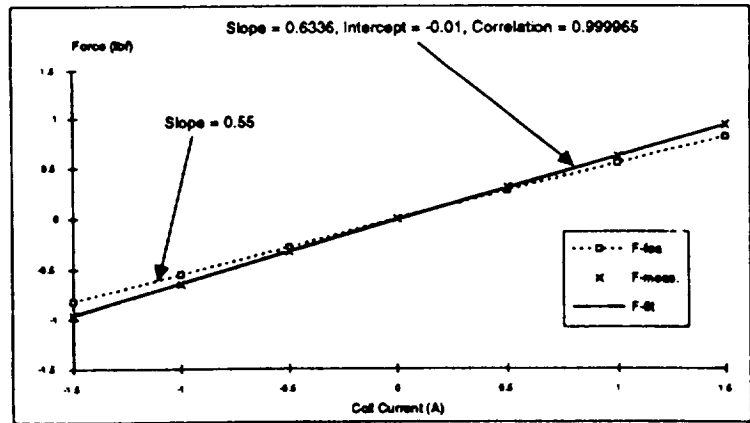Figure 3. Block Diagram of Microgravity Isolation Test Rig

Figure 4. Force vs. Current In Lorentz Actuator of Microgravity
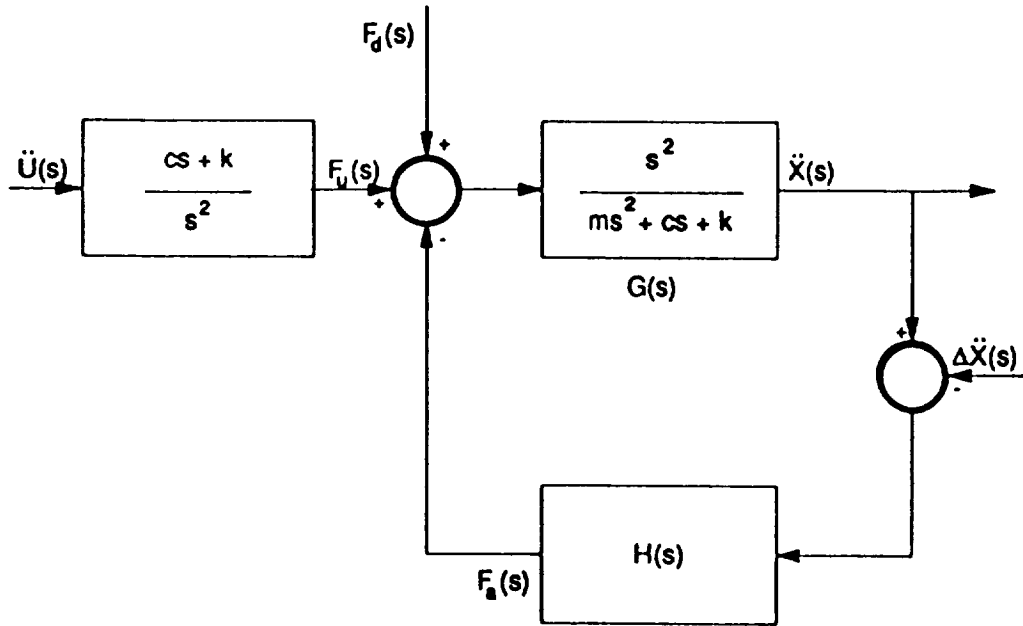Isolation Test Rig
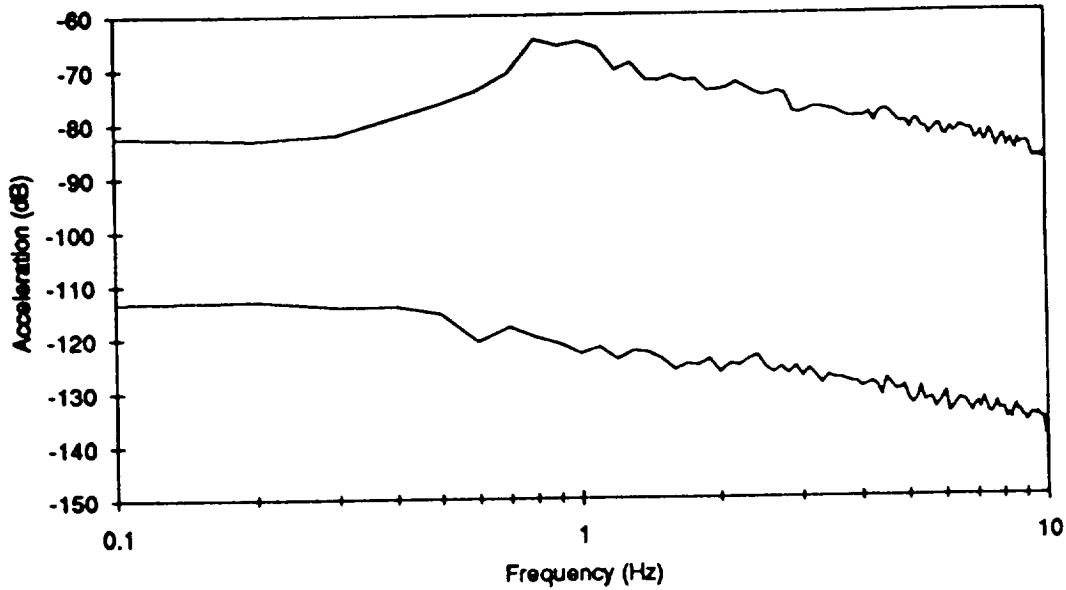
Figure 5. Control Loop Block Diagram

Figure 6. Microgravity Experiment Accelerations without Isolation Controller (Top Line) and with Isolation Controller (Bottom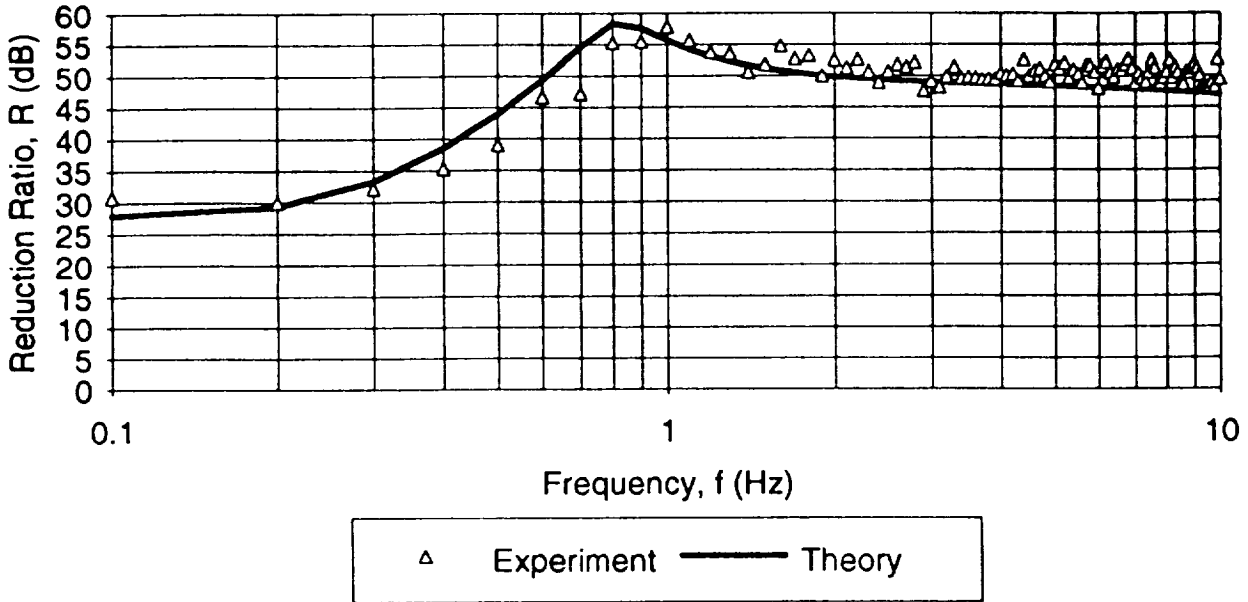 Line) for Umbilical Spring Stiffness of 876 N/m (5 lbf/in). Note: 0 dB equals 1.0 g_0 and -120 dB equals 1.0 μg_0.
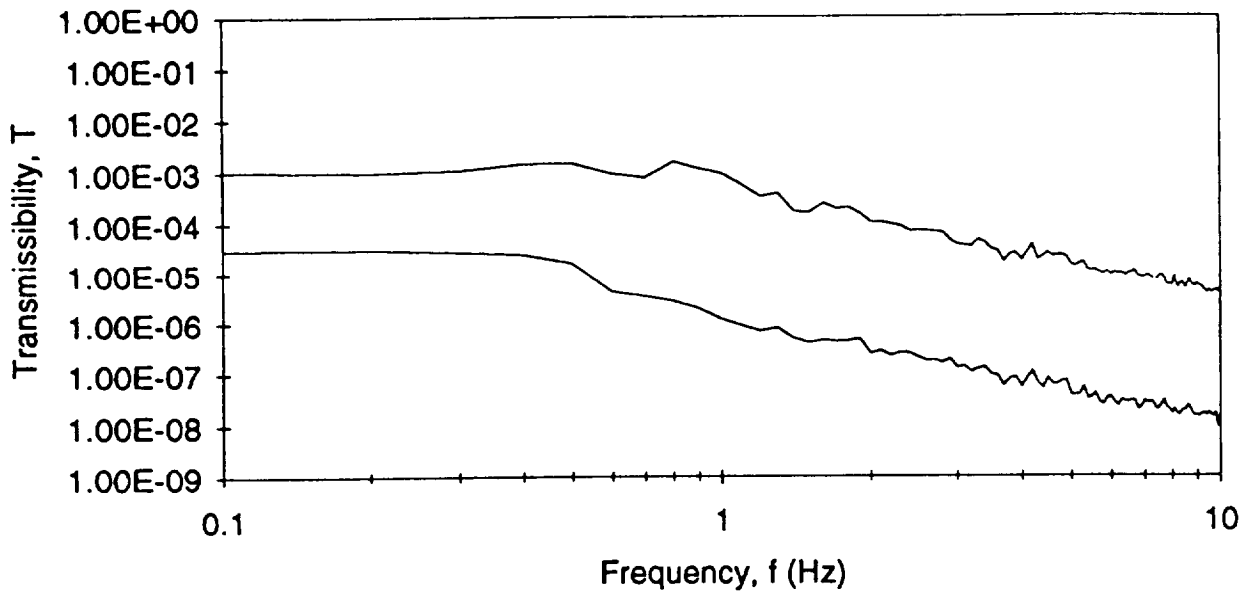
Figure 7. Microgravity Experiment Transmissibility Between Spacecraft and Experiment without Isolation Controller (Top Line) and with Isolation Controller (Bottom Line) for Umbilical Spring Stiffness of 876 N/m (5 lbf/in).

Figure 8. Microgravity Reduction Ratio for Experiment with
Isolation Controller vs. Frequency for Umbilical Spring Stiffness
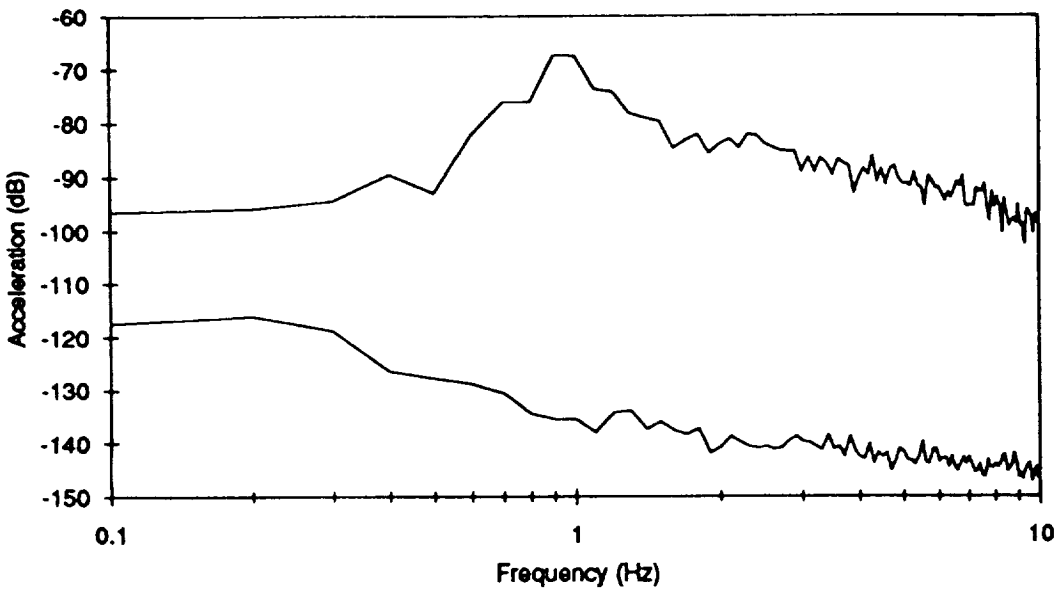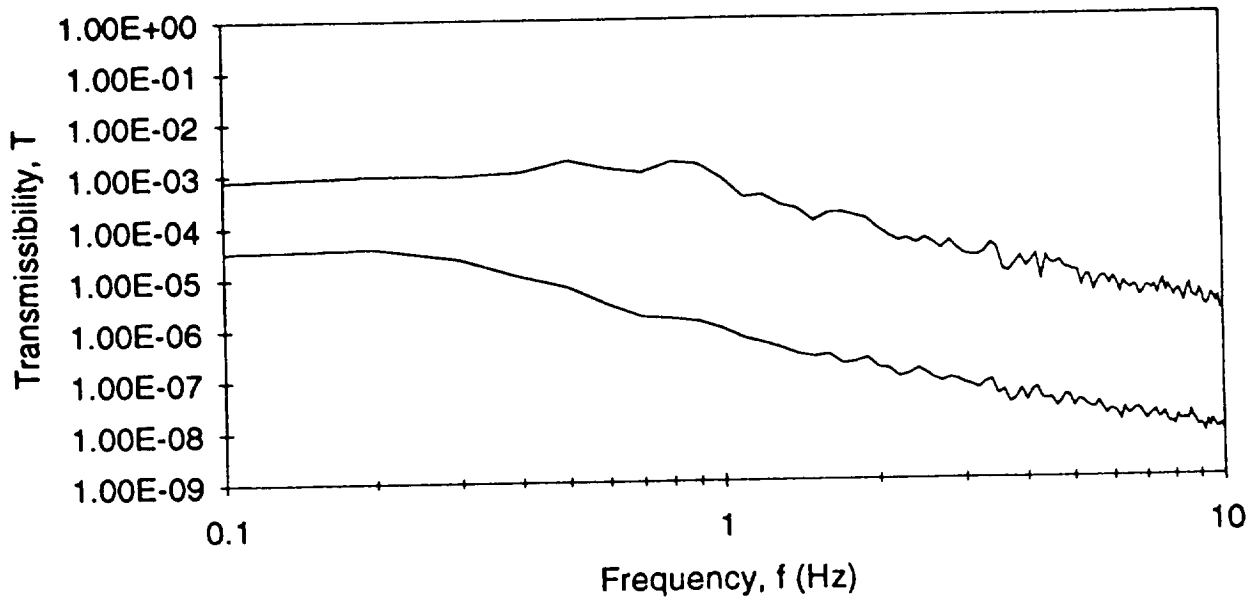of 876 N/m (5 lbf/in).

Figure 9. Microgravity Experiment Accelerations without Isolation
Controller (Top Line) and with Isolation Controller (Bottom Line)
for Umbilical Spring Stiffness of 1226 N/m (7 lbf/in). Note: 0
dB equals 1.0 g_0 and -120 dB equals 1.0 μg_0.

Figure 10. Microgravity Experiment Transmissibility Between
Spacecraft and Experiment without Isolation Controller (Top Line)
and with Isolation Controller (Bottom Line) for Umbilical Spring
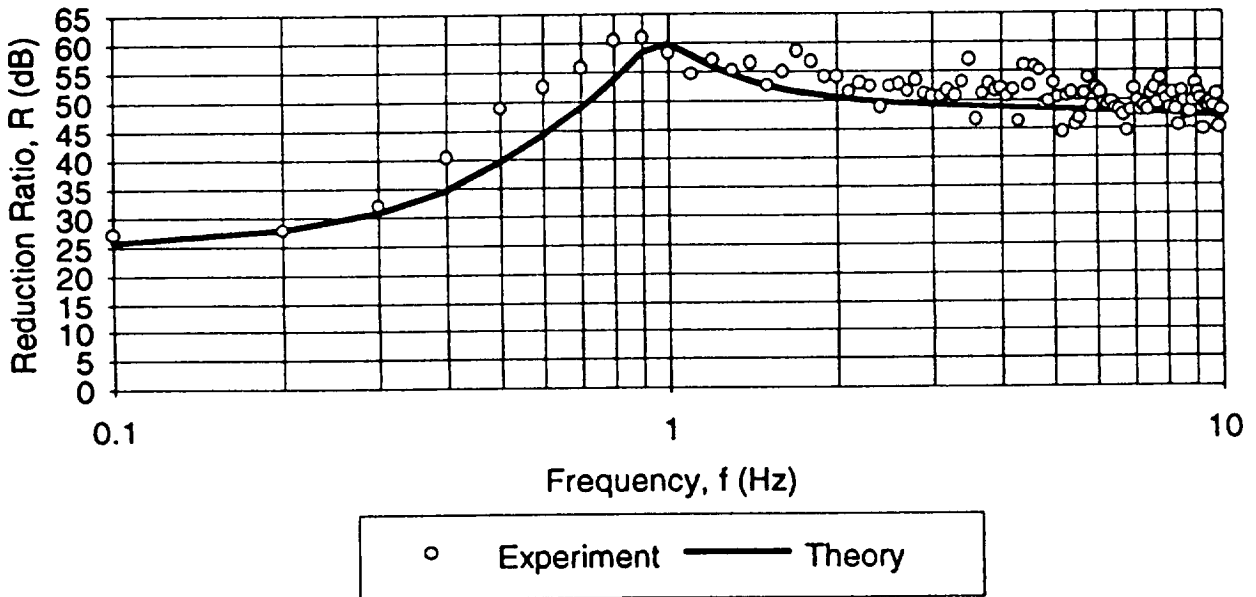Stiffness of 1226 N/m (7 lbf/in).

Figure 11. Microgravity Reduction Ratio for Experiment and with
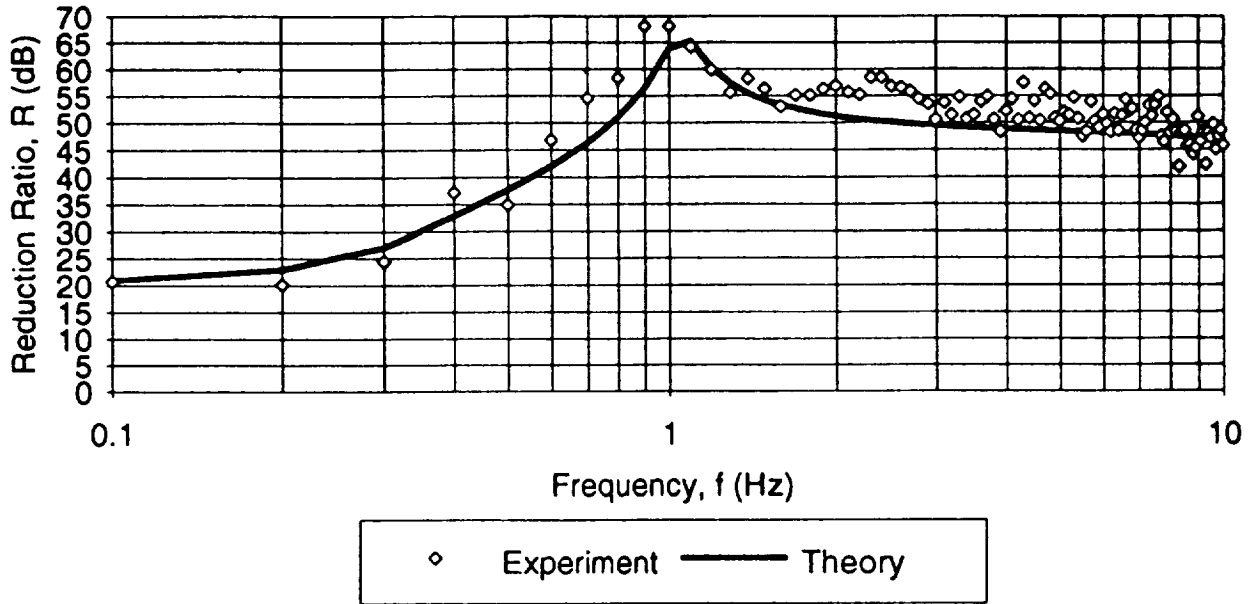Isolation Controller for Umbilical Spring Stiffness of 1226 N/m
(7 lbf/in).

Figure 12. Microgravity Reduction Ratio for Experiment with
Isolation Controller for Umbilical Spring Stiffness of 1488 N/m
(8.5 lbf/in).