Low Frequency Vibration Isolation Technology for Microgravity Space Experiments

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LOW FREQUENCY VIBRATION ISOLATION TECHNOLOGY FOR MICROGRAVITY SPACE EXPERIMENTS

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SUMMARY

The dynamic acceleration environment observed on Space Shuttle flights to date and predicted for the Space Station has complicated the analysis of prior microgravity experiments and prompted concern for the viability of proposed space experiments requiring long-term, low-g environments. Isolation systems capable of providing significant improvements in this environment exist, but have not been demonstrated in flight configurations. This paper presents a summary of the theoretical evaluation for two one degree-of-freedom (DOF) active magnetic isolators and their predicted response to both direct and base excitations, that can be used to isolate acceleration sensitive microgravity space experiments.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>C</td>
<td>capacitance</td>
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<tr>
<td>c</td>
<td>electro-magnet damping coeff.</td>
</tr>
<tr>
<td>F</td>
<td>isolator force</td>
</tr>
<tr>
<td>g</td>
<td>acceleration of the Earth at the surface</td>
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<tr>
<td>I_a</td>
<td>electro-magnet current (a velocity)</td>
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<tr>
<td>I_b</td>
<td>magnetic-circuit current bias</td>
</tr>
<tr>
<td>k</td>
<td>passive stiffness coefficient</td>
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<tr>
<td>k_a</td>
<td>magnetic-circuit current amplifier stiffness</td>
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<tr>
<td>k_c</td>
<td>magnetic-circuit Isolator stiffness</td>
</tr>
<tr>
<td>k_eq</td>
<td>magnetic-circuit proportional gain</td>
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<tr>
<td>k_i</td>
<td>magnetic-circuit current stiffness</td>
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<td>k_p</td>
<td>magnetic-circuit sensor amplifier gain</td>
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<tr>
<td>k_r</td>
<td>magnetic-circuit derivative gain</td>
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<tr>
<td>k_p</td>
<td>magnetic-circuit position stiffness</td>
</tr>
<tr>
<td>m</td>
<td>mass</td>
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<tr>
<td>N</td>
<td>number of ampere turns</td>
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<tr>
<td>R</td>
<td>resistance</td>
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<tr>
<td>u</td>
<td>position of base</td>
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<tr>
<td>x</td>
<td>position of payload</td>
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<tr>
<td>e</td>
<td>passive damping coefficient</td>
</tr>
<tr>
<td>t</td>
<td>time constant = RC</td>
</tr>
<tr>
<td>p</td>
<td>magnetic field strength</td>
</tr>
<tr>
<td>n</td>
<td>excitation frequency</td>
</tr>
<tr>
<td>w_n</td>
<td>active system resonance frequency</td>
</tr>
<tr>
<td>w_s</td>
<td>system resonance frequency</td>
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INTRODUCTION

Interest in vibration isolation for microgravity experiments has increased within the microgravity science community as the flight program has progressed and the small, but significant levels of residual acceleration on the Space Shuttle (STS) have become more widely recognized and documented (Hamacher, 1986: Workshop Proceedings, 1986). These background accelerations result from several sources characteristic of the orbiting carrier and the orbital environment. Very low frequency (10^-3 Hz to dc) accelerations due to drag, tidal effects, and gravity gradients contribute submicro-g levels. STS thruster activity can contribute 10^-4 to 10^-2 g/\(g_0\) accelerations with significant duration, but can be predicted and controlled. The most visible and troublesome contribution to most experiments is the moderate frequency (10^-3 to 100 Hz) dynamic spectrum of accelerations having magnitudes in the range 10^-5 to 10^-2 g/\(g_0\). This dynamic background is due substantially
to random excitations from manmade activity on the orbiter. However, orbiter structure and flight systems also contribute observable intermittent and resonant accelerations to the background as the orbiter interacts with its dynamic mechanical and thermal environment. The evolution of the Space Station design has led to many discussions of the potential limitations on long term, low gravity experimentation in this environment. It is now obvious that most of the true microgravity experiments will require "protection" from this random, milli-g environment if valid and reproducible results are to be expected. Because a large part of the transient disturbances have a frequency range from milli-Hz to 1 Hz. It is extremely difficult to design a passive isolation system with a frequency range at most $1/\sqrt{2}$ times the lowest excitation frequency of interest, namely the sub-Hz range.

The serious limitation of passive isolators is the absence of materials which have useful ranges of both low-modulus (providing low frequency) and appropriate damping (to avoid large amplitude oscillations). Two-stage passive isolators can decrease the frequency but limited damping leads to potentially unstable systems in the random excitation environment. It is apparent that a passive isolation system would not suffice because of the requirement of an extremely low stiffness for the isolation of small disturbance frequencies for the use of a microgravity test facility. On the other hand, when there are direct disturbances on the payload, a small value of stiffness is not desirable. Therefore, there is a trade-off, and an optimal design would need to compensate for both direct disturbances, if present, and low frequency base disturbances. Thus, active systems offer significant advantages over passive systems in the orbital environment, due to both the extremely small stiffness needs to isolate against such low frequency base disturbances and the ability to adapt to direct disturbances for the optimal isolation of the payload, since the responses to these two excitations require conflicting solutions.

Active systems require sensing of motion or position and a feedback control loop to counteract mechanical excitation and minimize motion of an isolated body. Such systems introduce the complexity of a high-gain control system, but offer significant advantages in versatility and performance (Ruzicka, 1969). This paper summarizes the theoretical evaluation of both a fully magnetic system and a passive static support system but with electromagnetic damping. The fully magnetically suspended system is evaluated using an attractive electromagnet, while the electromagnetically damped system is evaluated using a Lorentz magnet. These magnetic systems, specifically the attractive type, have been used for the suspension of rotating shafts for a number of years and the required negative feedback loops to control such systems have been discussed in numerous papers, giving the equivalent stiffness and damping coefficients for specific controllers. However, these studies have not been interested in the isolation of the suspended body from direct and base excitations. Thus, the response of such systems to these types of disturbances has not been documented. We evaluate the dynamic response to base and direct disturbances of both systems. A pictorial representation of both systems evaluated is shown in Fig. 1 where both systems can be represented by an isolator between a base support and the isolated payload. This isolator is simply an actuator which is driven in proportion to certain feedback signals. A specific feedback loop is used for this problem. Specifically, for the magnetic isolator, an attractive magnetic actuator was analyzed where both the stiffness and damping coefficients are derived from a relative position sensor and for the electromagnetic damping isolator a Lorentz actuator was analyzed where the damping coefficient was derived from an inertial sensor and the stiffness of the isolator is simply a constant spring stiffness of a passive spring. Presently, there are laboratory models of these theoretically represented one DOF isolation systems. However, the emphasis at NASA Lewis is to perform digital active control on dependent multidegrees of freedom. Currently, these systems are projected for test in a full six DOF free fall condition, provided by the NASA Lewis low gravity aircraft, in order to acquire the coupled response between all six DOF in a low gravity environment.

STATEMENT OF THE PROBLEM

To categorize the disturbances which are present in the Space Shuttle and will be present in the Space Station, one can group these accelerations into three frequency ranges (Jones et al., 1987):

(1) Quasi-Static External Disturbances
(2) Low Frequency Vibration Sources
(3) Medium-High Frequency Vibrations

The disturbances listed under the first category are aerodynamic drag, gravity gradient effects and photon pressure accelerations. These accelerations have frequency ranges less than a mHz and acceleration magnitudes of about 0.01 g's and lower. The category would include excitations due to large flexible space structures, crew motion, spacecraft attitude control, and robotic arms. These disturbances range from mHz to about the 10 Hz frequency range. The third category would list disturbances due to on-board equipment such as pumps and motors having a dynamic range of about 10 Hz and above. (See appendix (Hamacher, 1986; Ruzicka, 1969; Hamacher et al., 1986).)

OVERVIEW

The active isolators described in this paper are effective at a frequency range of about a tenth of a Hz and above. This constraint does not arise from a technology limitation, but from practical limitations due to the fact that the strokes needed to isolate against the very low frequency range are not obtainable because of the volume constraints in the shuttle and in the future Space Station manned environment laboratory modules. For example, an aerodynamic drag is a function of the atmospheric conditions during a specific mission, but an average magnitude of $10^{-9}$ g will be used for the sake of argument. Therefore, the frequency at which such a disturbance would act, in a
Due to this actuator's linear dependence with the con-
direction of current flow in the coil one can produce
a force in either a positive or negative direction.

In contrast. the Lorentz actuator can produce
forces bidirectionally. The force produced by a
Lorentz actuator is a vector quantity equal to the cur-
cent cross field, \( \psi \). Therefore, depending on the
direction of current flow in the coil one can produce
a force in either a positive or negative direction.

Due to this actuator's linear dependence with the con-
trol current and because it is not simply an attractive
system, the control law for this actuator is open loop
stable. The Lorentz actuator, being a linear device,
has advantages over the magnetic-circuit, but the power
needed to produce a certain force is higher for a
Lorentz actuator than for an attractive magnetic-circuit
configuration. However, due to the small forces needed
to control a payload in the weightless environment of
space, this inefficiency is not as limiting as in the
earth's gravitational field.

The basic concept behind these active isolation
techniques is the sensing of position, velocity and/or
acceleration, and driving an actuator 180° out of phase
with this signal in order to cancel a disturbance to
the payload. If there is some knowledge about certain
disturbances, a feed forward loop could also be employed
to anticipate an excitation and react to it without an
error signal. These active isolation techniques can
be implemented using either analog or digital control
schemes to close the feedback or feed forward control
loops.

To summarize the linearized control law for a
one DOF magnetic-circuit isolator and the linear con-
trol law for a Lorentz electromagnetically damped one
DOF system, one can give their transmissibilities and
effectiveness in isolating against both base and direct
disturbances. First, the response or transmissibili-
ties of both systems will be generated for harmonic
base excitations, using the active isolation system's
differential equations of motion. These equations of
motion were written using Newton's first and second
laws. Where \( u \) is actually a time function so
\( u = u(t) \) with the same implied for a directly applied
force, such that in actuality \( F = F(t) \). Therefore,
for a spring mass damper system, the equations of
motion for base excitation become:

Magnetic-circuit Isolator

\[
m \frac{d^2x}{dt^2} + k \left[ (x - u) + c \left( \frac{dx}{dt} - \frac{du}{dt} \right) \right] = 0
\]  
(1)

Electromagnetic damping Isolator

\[
m \frac{d^2x}{dt^2} + c \frac{dx}{dt} + Kx = Ku
\]  
(2)

These systems look very similar to passive vis-
coelastic systems with the exception that, for all
practical purposes, the stiffness and damping of both
the magnetically suspended isolator and the electro-
magnetic damping case can be set at whatever coefficient is desired for an appropriate response to an
excitation source. Therefore, these systems can be
easily configured for an adaptive system where, by
using sensed information from the disturbance environ-
ment, the control law could be changed to optimize the
isolation of the payload. In using the magnetic-
circuit actuator as an isolator, the stiffness and
damping are not purely independent. However, this
dependency is minimal if certain control parameters
are not violated, these isolation parameters can be
assumed to be independent. To achieve a purely damped
response independent of stiffness, be it active or
passive stiffness, one would need to use a Lorentz
actuator. In contrast, for the magnetic-circuit case,
a certain amount of damping is needed in order to
overcome open loop instability.

In defining the dynamic base motion equations for
both systems, the stiffness and damping terms can be
solved by using the appropriate control law needed for
a stable negative feedback system. In summary, the
stiffness coefficient for the magnetic-circuit becomes:
Thus, the transfer functions in terms of frequency response are vectors in the complex plane and the magnitudes of vibrations measured on the isolated payload resulting from a sinusoidal excitation \( \sin(\omega t) \) is the vector length of \( X(j\omega) \). This value is a scalar, since the phase angle is not used, and is called the transmissibility function of the system. The transmissibility is generally written as

\[
T = \left| \frac{X}{U(j\omega)} \right|
\]

Therefore, the transmissibility functions for both systems of interest become:

**Magnetic-circuit Transmissibility Function**

\[
T = \left| \frac{X}{U(j\omega)} \right| = \sqrt{1 + \left( \frac{2\zeta \omega_{n}}{\omega_{n}} \right)^{2} + \left( \frac{2\zeta \omega_{h}}{\omega_{h}} \right)^{2}}
\]

**Electromagnetic Damping Transmissibility Function**

\[
T = \left| \frac{X}{U(j\omega)} \right| = \sqrt{1 + \left( \frac{2\zeta \omega_{h}}{\omega_{h}} \right)^{2} + \left( \frac{2\zeta \omega_{h}}{\omega_{h}} \right)^{2}}
\]

By plotting these transmissibilities, one can see the effect of changing the stiffness or damping of either system. As can be seen from the stiffness coefficients for the magnetic suspension case, using the attractive magnetic-circuit actuator, the natural frequency of the system is frequency dependent on the excitation source. However, for small disturbance frequencies of 100 Hz and below, this dependence is negligible and \( \omega_{n} \) is assumed constant. The transmissibility curve for the first case is illustrated in Fig. 3. Figure 3 demonstrates the effect of increasing the damping coefficient of the magnetic-circuit isolator system. As can be seen by the curves in Fig. 3, increasing the velocity feedback gain, \( K_{r} \), the system can become overly damped, which gives rise to the damped response at resonance and less isolation at excitation frequencies above \( \sqrt{2} \) times \( \omega_{n} \) than would be achievable with a less damped system. The effect of increasing the position gain would shift the natural frequency of the system to the right because of the increase in equivalent stiffness of the system, while the opposite would result by decreasing the position gain \( K_{p} \). The subsequent electromagnetic damping case is illustrated in Fig. 4. Figure 4 shows the effect of increasing the damping coefficient of the Lorentz electromagnetic damping system. The curves show the response of the system to increasing the velocity feedback term and thus, increasing the damped response of the system. The advantage of active damping feedback, derived from an inertial reference, is that it can remove the resonant response, broadening and smoothing the transition between the low frequency and high frequency regions, while reducing both the transmission and the response, particularly in the low frequency range of interest. The effects of such a system for large values of velocity feedback gain can be understood by considering that it is equivalent to having a passive damper attached to the isolated mass and a virtual inertial reference. As the friction in the damper is increased, the isolated mass becomes more and more tightly coupled to the (motionless) ideal inertial reference. Unlike the passive...
damper, the stronger the coupling, the better the isolation. This arises because the velocity proportional noise is determined from the integration of an inertial sensor signal. This type of response is not seen in the pure suspension case because the velocity term was determined from the derivative of a relative position sensor giving rise to the response shown in Fig. 3.

\[ \xi = \frac{K_i K_g K_p (K_g + K_r) - K_g 1.022110^{-3}}{(1 - R C \omega^2)^2 + (R C + \tau_f)^2 \omega^2} \]

\[ u_n^2 = K_0 + \frac{K_i K_g K_p (K_g (1 - R C \omega^2) + (K_g + K_r) (R C \omega^2) + (K_g + K_r) R C \omega^2)}{(1 - R C \omega^2)^2 + (R C + \tau_f)^2 \omega^2} \]

points show the effect of filtering this "mechanical noise" through such an isolator and the resultant "worst case" line.

As explained previously, these curves demonstrate system response to base excited harmonic motions. However, disturbances may also be generated directly on the payload itself. The sensitivity of

In order to relate these curves to the microgravity environment, one can use a \( g/g_0 \) versus frequency plot, which was generated from typical Microgravity Science Laboratory acceleration data (refs. 1 and 2), and superimpose these transmissibility curves on this data, to predict the isolation performance achievable for such disturbances, measured on an earlier shuttle flight. By superimposing these curves, one can get a rough idea of the capability of such techniques in isolating against such low frequency disturbances. These curves are presented in Fig. 5 (Hamacher, 1989; Ruzicka, 1969). Figure 5 shows selected peak accelerations (open data points) typical of those observed on STS missions (Hamacher, 1989; Ruzicka, 1969) and an upperbound (line with positive slope) that is intended to reflect the "worst case" limit for a transmissibility curve of a theoretical isolator. The filled data

the isolated payload to a disturbing force will be characterized by a term called the isolated payload mobility. The mobility of the payload is the vector magnitude of \( \mathbf{X}(s) \mathbf{F}(s) \). This parameter measures the amplitude of the payload deflection per unit of force amplitude. The equations of motion for both systems, for direct disturbance only are:

\[ M \frac{d^2 \mathbf{X}}{dt^2} = \mathbf{F}(t) - \mathbf{K} \mathbf{eq} - \mathbf{C} \mathbf{eq} \frac{d \mathbf{X}}{dt} \]  \hspace{1cm} \text{(12)}
TYPICAL MSL DATA

A MAGNITUDE OF PREDICTED ISOLATION

1° TRANSMISSIBILITY

LIMIT

LOG OF ACCELERATION

PREDICTED ISOLATION LIMIT

FREQUENCY, Hz

FIGURE 5.

Electromagnetic Damping Equation of Motion

\[ M \frac{d^2x}{dt^2} = F(t) - Kx - c \frac{dx}{dt} \]  \hspace{1cm} (13)

These equations can be placed in the Laplace operation format and from the definition of the vector magnitude \( X(s)/F(s) \), one can write the mobility equation for both cases as follows:

Magnetic-circuit Mobility Equation

\[ \frac{X(s)}{F(s)} = \frac{1}{Ms^2 + C_{eq}s + K_{eq}} \]  \hspace{1cm} (14)

Electromagnetic Damping Mobility Equation

\[ \frac{X(s)}{F(s)} = \frac{1}{Ms^2 + cs + K} \]  \hspace{1cm} (15)

In order to evaluate the effectiveness of these active systems, the ratio of \( X(s)/F(s) \) active to \( X(s)/F(s) \) for an equivalent passive system will be used. This ratio will be called the mobility effectiveness \( X_F(s) \). Therefore, if \( X_F(s) \) is unity, the active system does nothing. If \( X_F(s) \) is zero, no motion of the payload results from a finite applied force. If \( X_F(s) \) is greater than unity, then the active system amplifies the effect of the applied force, increasing the payload motion. The equations for the effectiveness function for both cases, in terms of frequency response, where the vector length of \( X_F(s) \) is \([X_F(j\omega)]\), become:

Magnetic Circuit Effectiveness

\[ X_F[j\omega] = \frac{\omega_n}{\omega_{na}} \sqrt{\frac{1 - [\omega/\omega_n]^2}{1 - [\omega/\omega_{na}]^2} + [2\xi_1 \omega/\omega_n]^2} \]  \hspace{1cm} (16)

Where: for small excitation frequencies \( \omega_{na} = \omega_n \); \( \xi_1 \) = damping coefficient of passive spring (\( A \) value of 0.05 was used for \( \xi_1 \).)

Active: \( \omega_n = \sqrt{\frac{K}{M} - \frac{C_{eq}}{M} = 2\xi_0 \) \( \omega_n \)

Electromagnetic Damping Effectiveness

\[ X_F[j\omega] = \sqrt{\frac{1 - [\omega/\omega_n]^2}{1 - [\omega/\omega_{na}]^2} + [2\xi_0 \omega/\omega_n]^2} \]  \hspace{1cm} (17)

Where:

\[ \xi_0 = 2\xi_0 \cdot \omega_n \cdot \sqrt{\frac{K}{M} \cdot \frac{1}{G}} \cdot \sqrt{\frac{1}{K}} \]
$\xi_1 = \text{damping coefficient of passive spring (A value of 0.05 was used for } \xi_1).$

These effectiveness functions are plotted in Figs. 6 and 7. Figures 6 and 7 present the effectiveness of the active feedback, force actuated vibration isolation systems as compared to a passive system with a critical damping coefficient of 0.05, which is typical of passive systems of the type utilized with low frequency system resonances.

CONCLUDING REMARKS

In conclusion, it is apparent that the active magnetic systems described here have advantages over passive isolators due to their ability to isolate against the low frequency regime of the orbital carriers, as well as their ability to implement an adaptive control to isolate against both the direct and base excitations which will be present in all pressurized modules. Therefore, the optimal isolation of a microgravity science payload will eventually need an adaptive digitally controlled system in order to optimize isolation coefficients to most effectively prevent disturbances from perturbing the isolated payload. In order to lower the corner frequencies of such an active system one would need to use actuators with larger and larger strokes. However, this would be impossible due to the volume constraints present in space flight vehicles. Thus, such an isolated payload will have to follow these very low steady-state accelerations such as aerodynamic drag and gravity gradient effects. In order to achieve the microgravity requirements imposed on the Space Station facility (Fig. 8), for any significant length of time, microgravity vibration isolation will have to become a systems engineered solution as well as an experiment specific concern. Thus, these requirements for acceleration sensitive microgravity space experiments will dictate multi-stage isolation concepts which will combine both passive and active systems where the control of the center of gravity of the Space Station will be closed around microgravity steady-state accelerations.
REFERENCES


APPENDIX

The range of accelerations which have been observed on several SSS missions or estimated for the accessible orbit are summarized below (Hamacher, 1986; Ruzicka, 1969; Hamacher, et al., 1986).

Quasi-Steady or "DC" Acceleration Disturbances

\[ \frac{g}{g_0} \quad \text{Frequency,} \quad \text{Source} \]

\[ \begin{align*}
 10^{-7} & \quad 0 \text{ to } 10^{-3} \quad \text{Aerodynamic drag} \\
 10^{-8} & \quad 0 \text{ to } 10^{-3} \quad \text{Light pressure} \\
 10^{-7} & \quad 0 \text{ to } 10^{-3} \quad \text{Gravity gradient}
\end{align*} \]

Periodic Acceleration Disturbances

\[ \begin{align*}
 2 \times 10^{-2} & \quad \text{Thruster fire (orbital)} \\
 2 \times 10^{-3} & \quad \text{Crew motion} \\
 2 \times 10^{-4} & \quad \text{Ku band antenna}
\end{align*} \]

Nonperiodic Acceleration Disturbances

\[ \begin{align*}
 10^{-4} & \quad \text{Thruster fire (attitude)} \\
 10^{-4} & \quad \text{Crew push off}
\end{align*} \]
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Abstract
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Key Words (Suggested by Author(s))
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