NASA/TM–1998–206953

# Damping Mechanisms for Microgravity Vibration Isolation

(MSFC Center Director's Discretionary Fund Final Report, Project No. 94–07)

*M.S. Whorton, J.T. Eldridge, R.C. Ferebee, J.O. Lassiter, and J.W. Redmon, Jr.*
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***January 1998***

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National Aeronautics and
Space Administration

Marshall Space Flight Center

***January 1998***

## Acknowledgments

The authors wish to acknowledge Dr. Gerald Nuree for his vision, expertise, leadership, and support of the mg vibration isolation activities at Marshall Space Flight Center (MSFC) prior to his retirement in January 1997.

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TECHNICAL MEMORANDUM

# DAMPING MECHANISMS FOR MICROGRAVITY VIBRATION ISOLATION
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## 1. INTRODUCTION

As a research facility for microgravity (μg) science, the *International Space Station* (*ISS*) will be used for numerous investigations such as protein crystal growth, combustion, and fluid mechanics experiments which require a quiescent acceleration environment across a broad spectrum of frequencies. Examples of the acceleration requirements for these processes are shown in figure 1. Shown are the maximum magnitudes of desired accelerations, measured relative to Earth's gravity (g), versus frequency and the expected acceleration environment at the experiment. Note that these experiments are most sensitive to low-frequency accelerations and can tolerate much higher accelerations at a higher frequency. However, the anticipated acceleration environment on *ISS* significantly exceeds the requirements shown in figure 1. The ubiquity and difficulty in characterizing the disturbance sources precludes source isolation, requiring vibration isolation to attenuate the anticipated disturbances to an acceptable level.

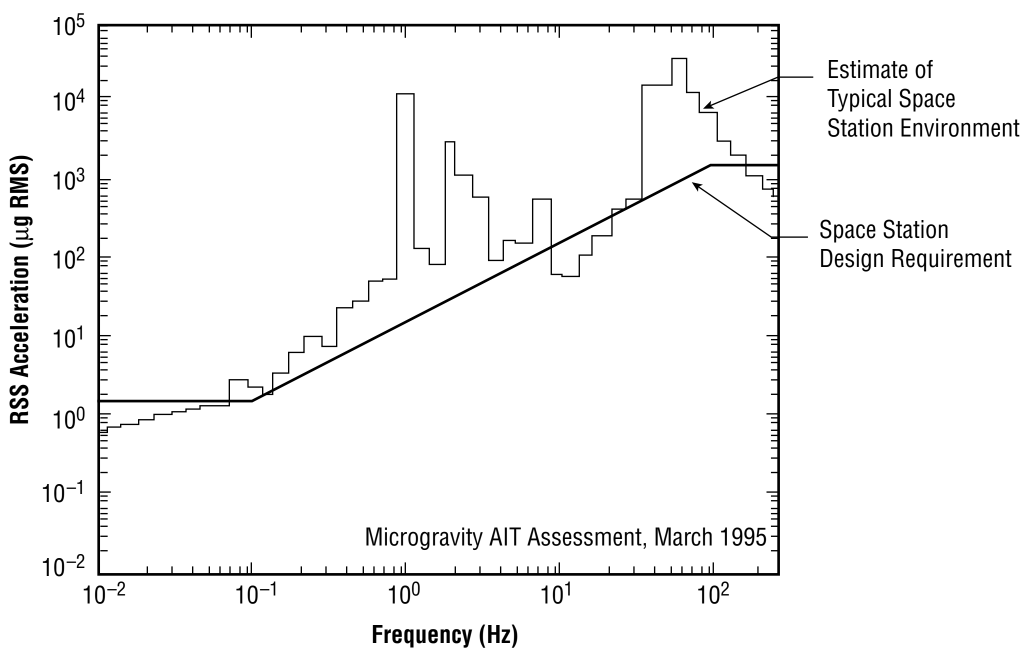


Figure 1. Microgravity acceleration requirements.

The primary sources of vibration on *ISS* can be categorized into three characteristic frequency ranges. At low frequencies, approximately $10^{-3}$ Hz, the dominant accelerations are caused by gravity gradients and atmospheric drag. These low-frequency vibrations are determined by *ISS* configuration and orbit choices. These accelerations are nontransient in nature, either slowly varying or periodic. The acceleration caused by gravity gradient depends on the distance of the experiment from the center of mass, and on the *ISS* configuration. The total acceleration in this low-frequency range will be less than $10^{-5}$ g and can be made $<10^{-6}$ g for some experiments placed close to the *ISS* center of mass. At high frequencies, above ~1 Hz, the vibrations are caused by sinusoidal steady-state sources such as pumps, compressors, electric motors, and fans, as well as transient sources such as impacts, astronaut motion, and high-frequency components of thruster firings. This class of vibration sources has been measured on Spacelab and will require significant isolation to meet the desired vibration goals of *ISS*. Because of their relatively high frequency however, microgravity experiments can be isolated from these vibrations with relatively simple (possibly passive) vibration isolation systems. The third characteristic frequency range of vibrations is the intermediate range of $\sim 10^{-3}$ Hz to 1 Hz. The sources of acceleration in this range are mostly transient in nature, such as the motion of astronauts and payloads around the *ISS*, as well as the motion of the *ISS* caused by thrusters. Because of their transient nature, the effect of these vibrations on many experiments is difficult to analyze. The calculation of the resultant accelerations of the *ISS* at the upper end of this frequency range is also complicated by the interaction of these vibration sources with the structural modes of the *ISS*.

An example of these transient disturbances is the motion of the *ISS* crew. The large-scale motion of the crew leads to significant accelerations and displacements of the *ISS*. An example calculation results in peak accelerations of $9\times10^{-4}$ g for a 220,000 lbm *ISS*. During this soaring maneuver, the astronaut moves 48 ft and the *ISS* moves 0.4 in. In the high-frequency range, passive isolation techniques are often adequate to provide sufficient attenuation of vibration disturbances. However, isolation of low- and intermediate-frequency vibrations is not possible with passive isolation and therefore requires active isolation. Hence, the development of active isolation systems is imperative to provide a quiescent acceleration environment as required by many $\mu$ g science investigations.

Because vibration isolation plays such a significant role in MSFC's missions in $\mu$g science, the Center Director's Discretionary Fund (CDDF) Project Number 94–07 was initiated. This project, entitled "Damping Mechanisms for Microgravity Vibration Isolation," was undertaken to develop an expertise in vibration isolation systems for $\mu$g payloads. Three objectives were identified: first, survey the state of the art in $\mu$g isolation technology; second, develop testing capabilities for low-frequency, low-acceleration isolation systems; and third, perform component tests of existing isolator technologies.

## 2. LITERATURE SEARCH

Much work has been done during the past several years toward the development of active isolation systems for $\mu$g payloads. The NASA Lewis Research Center (LeRC) conducted an Advanced Technology Development Project in Vibration Isolation Technology from 1987 through 1992 which sponsored in-house technology and funded numerous contractor studies and hardware development.[1] A six degree-of-freedom (DOF) laboratory test-bed was developed to evaluate concepts and control strategies which led to an aircraft test-bed system that was successfully tested on the NASA LeRC Learjet. Based on two decades of experience in active suspension systems, the Honeywell Corporation (formerly Sperry) developed the first isolation system for space shuttle flight applications called the Fluids Experiment Apparatus Magnetic Isolation System (FEAMIS) to support Rockwell's Fluid Experiment Apparatus (FEA).[2] However, FEAMIS was never flown. McDonnell Douglas Aerospace Corporation (MDAC) developed a six DOF active isolation system using piezoelectric polymer film actuators.[3] In early 1995, MSFC joined with MDAC to develop a vibration isolation system called Suppression of Transient Accelerations By Levitation (STABLE).[4] STABLE utilized noncontact electromagnetic actuators developed for a helicopter imaging system. The STABLE flight experiment on STS–73 was the first successful $\mu$g vibration isolation system to be flown in space and was made possible, in part, by the technology developed through this CDDF project. The Canadian Space Agency has developed a system called the Microgravity Vibration Isolation Mount (MIM). MIM began operation aboard the Russian *Mir Space Station* during 1996 and was flight-tested on the space shuttle flight STS–85 in August 1997. The design approach selected as part of the *ISS* $\mu$g control plan is to provide isolation to an entire rack using the Active Rack Isolation System (ARIS) developed by The Boeing Corp.[5] ARIS uses voice-coil actuators with pushrods to attenuate disturbances transmitted through the utility umbilicals to the isolated rack. Based on the large mass and low stiffness of the umbilicals and actuator flexures, ARIS relies on passive attenuation above frequencies in the 5-Hz range. ARIS was flight-tested on STS–79 in September 1996.[6] An isolation system, called the Microgravity Isolation Mount (MGIM) was developed by the European Space Agency and tested in the laboratory to support Space Station research.[7] Satcon Corp. developed a ground test version of a six DOF vibration isolation system as did Applied Technology Associates, Inc. with a three DOF system. With the exception of the ARIS voice-coil/pushrod actuator and the MDAC piezoelectric polymer film actuator, each of the systems described above uses noncontacting electromagnetic actuators to isolate an individual experiment.

The other objectives of the CDDF project were to develop $\mu$g isolation test capabilities and perform component testing. Toward this end, a $\mu$g vibration control laboratory was developed. The first phase of this lab facility consisted of a pendulous "gallows" support structure mounted on an isolation table. By suspending both the isolated portion and the nonisolated base, the transmissibility of an isolation system could be tested in as many as three DOF. This facility was used to perform functional verification tests on the STABLE flight hardware. During STABLE verification testing, several deficiencies with this approach were observed. Testing for vibration isolation at the microgravity level is not a trivial task due to gravitational coupling and environmental disturbances. One particular problem was the coupling between translation and rotation of the suspended platform. Since a unit $\mu$ radian angular displacement from the horizontal plane is measured as a unit $\mu$g disturbance acceleration, the coupling introduced errors that were too large for the control system to overcome. Also, longitudinal flexure of the suspension cables transmitted undesirable disturbances to the suspended platform. As a result of lessons learned during STABLE verification testing, a second phase of this facility is under development which utilizes air pads on an isolation table for suspension of the platform.

## 3. VIBRATION ISOLATION FUNDAMENTALS

The basic objective of a vibration isolation system is to attenuate the accelerations of an experiment transmitted from umbilicals or other disturbances. As illustrated in figure 2, the umbilicals, represented by a linear spring with stiffness $k$, and a dashpot with damping coefficient $d$, provide a disturbance transmission path from the base to the isolated platform (with mass $m$). The inertial displacement of the base is $x_0$ and the inertial displacement of the platform is $x$. Base motion may be due to several sources such as crew motion, vehicle attitude control, or mechanical systems. In addition, disturbance forces which are transmitted directly to the platform, independent of the umbilicals, are indicated in figure 2 by $f_{dist}$. These direct inertial forces may result from crew contact or payload-generated sources such as pumps, fans, motors, and structural vibration of the isolated experiment. An actuator used for active control is represented by the control force $f_{act}$.

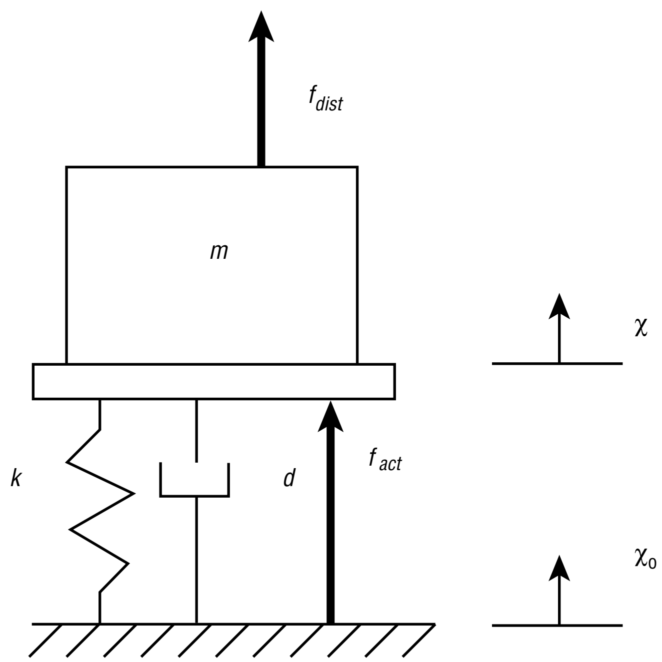


Figure 2. One degree-of-freedom example.

The required attenuation can be derived from the anticipated disturbance environment and required acceleration levels as shown in figure 1. To provide the desired environment requires that the isolation system pass through the quasi-steady accelerations while providing attenuation above 0.01 Hz. At frequencies above 10 Hz, the required attenuation level is –60 dB, or three orders of magnitude. To accomplish this isolation in the presence of stiff umbilicals while rejecting direct disturbances requires an active isolation system. By sensing relative position and absolute acceleration of the platform, the isolation system can constrain the platform to follow the very low frequency motion of the base while attenuating the base motion above 0.01 Hz. High-bandwidth acceleration feedback, in essence, effectively increases the dynamic mass of the platform which reduces the response to direct disturbances. Demonstration of this level of performance in six DOF cannot be accomplished on the ground due to gravitational coupling, but requires testing in a $\mu$g environment. Long periods of experimentation are necessary to characterize the low-frequency behavior, which is the most critical frequency range for active vibration isolation.

In general, an active vibration isolation system can be characterized by three parameters: required stroke, maximum isolation frequency, and force. If the isolation system were required to reduce the residual acceleration of the isolated mass to zero, the required stroke for each of the vibration sources would be the peak-to-peak displacement of *ISS* resulting from these sources. For the low-frequency disturbances, such as the attitude control, gravity gradient, and reboost thrust, the actuator strokes required to reduce the accelerations to zero are prohibitively large, >1 m. Isolation of these lower frequency disturbances is not practical since excessively large stroke actuators would be required. Isolation from higher frequency steady-state vibration sources such as pumps, machinery, etc. requires only a relatively small gap (stroke) suspension of <1 cm. The hardest vibrations to isolate in order to meet the formal *ISS* requirement are the transient vibrations caused by crew motion. Elimination of these transient vibrations may require isolators with strokes over 1 cm.

The limited gap (stroke) of any isolation system requires that it force the isolated body to follow the *ISS* at low frequencies, which sets the break frequency of the transmissibility function. Since isolation below $10^{-3}$ Hz will require strokes exceeding a few centimeters, a reasonable isolator transmissibility function will have a break frequency of ~$10^{-2}$ Hz. The control system bandwidth determines the spectrum of direct disturbances that may be attenuated. This bandwidth is limited typically to between 5 and 50 Hz in order to prevent undesirable excitation of structural modes and amplification of measurement noise.

The third basic parameter needed to design the isolation system is the maximum force it must produce. A reasonable estimate of this force is simply the maximum acceleration times the isolated mass. For a 100-kg (220-lbm) experiment meeting the formal *ISS* isolation goal, this requires a force capability of ~0.0025 lbf. Although this is enough force capability for normal operation, there may be some short-duration, high-acceleration transients that require higher forces. Transient vibrations caused by crew motion, resulting in an acceleration of $9\times10^{-4}$, could be isolated with a force capability of ~0.25 lbf for a 220-lbm experiment. Of course the actuator must be able to maintain this dynamic force range in addition to whatever bias forces are transmitted by the umbilical system when the isolated payload is centered in the swayspace. A secondary “bias elimination” stage could be employed to deform the umbilicals in the appropriate manner to remove the bias force required by the isolation stage. The necessity of this coarse stage would be determined by the characteristics of the umbilical system.

## 4. CONTROL SYSTEM DESIGN CONSIDERATIONS

To illustrate the need for active isolation, consider the one-DOF spring-mass-damper system in figure 2. The response of the platform to base motion and direct inertial disturbances is

$$m\ddot{x} + d\left(\dot{x} - \dot{x}_0\right) + k\left(x - x_0\right) = f_{dist} + f_{act} \quad . \tag{1}$$

The transmissibility function is defined as the ratio of platform acceleration to base acceleration and may be obtained by taking Laplace transforms of equation (1), resulting in

$$\frac{X(s)}{X_0(s)} = \frac{2\zeta\omega s + \omega^2}{s^2 + 2\zeta\omega s + \omega^2} \quad , \tag{2}$$

where the natural (or break) frequency is $\omega = \sqrt{\frac{k}{m}}$ and $\zeta = \frac{d}{2\sqrt{km}}$ is the percent damping ratio. This passive system behaves like a low-pass filter, transferring disturbances with frequencies below the damped natural frequency, $\omega_d = \omega\sqrt{1-\zeta^2}$, and attenuating disturbances above $\omega_d$. The slope of the attenuation function above $\omega_d$ depends on the damping, but for an undamped system is –40 dB/decade. Thus, better isolation is obtained by decreasing the umbilical stiffness, *k*, or increasing the platform/payload mass, *m*. It is typically not desirable to increase the payload mass, so the umbilicals are designed to minimize stiffness. However, for small payload masses, achieving isolation at frequencies lower than 1 Hz by reducing stiffness is not possible with reasonable rattlespace constraints (±1 cm).

To improve upon the attenuation of direct disturbances by the passive system shown in figure 2, either the platform mass must increase or a *stiff* spring must connect the platform to the base (or better, to inertial space). Obviously the objectives of base motion isolation and direct disturbance rejection are in opposition for a small payload mass and cannot be achieved with passive isolation. That is not the case with an actively controlled isolation system.

For example, consider a control law using feedback of absolute acceleration, relative velocity, and relative position described by

$$f_{act} = -K_a\left(\ddot{x} - \ddot{x}_0\right) - K_v\left(\dot{x} - \dot{x}_0\right) - K_p\left(x - x_0\right) \quad . \tag{3}$$

Substituting equation (3) into equation (1) yields the closed-loop equations of motion:

$$\left(m + K_a\right)\ddot{x} + \left(d + K_v\right)\left(\dot{x} - \dot{x}_0\right) + \left(k + K_p\right)\left(x - x_0\right) = f_{dist} \quad . \tag{4}$$

Taking Laplace transforms results in the closed-loop transmissibility function

$$\frac{X(s)}{X_0(s)} = \frac{2\zeta_{CL}\omega_{CL}s + \omega_{CL}^2}{s^2 + 2\zeta_{CL}\omega_{CL}s + \omega_{CL}^2} \quad , \tag{5}$$

where the closed-loop natural frequency is

$$\omega_{CL} = \sqrt{\frac{k + K_p}{m + K_a}} \tag{6}$$

and the closed-loop damping ratio is

$$\zeta_{CL} = \frac{d + K_v}{2\sqrt{\left(k + K_p\right)\left(m + K_a\right)}} \quad . \tag{7}$$

Comparing the open-loop (passive) system with the closed-loop system indicates that the gains ($K_a$, $K_v$, $K_p$) may be viewed as effective mass, damping, and stiffness, respectively, and may be used to modify the dynamic response of the system. For a fixed umbilical stiffness and payload mass, the break frequency can be reduced by either using positive position feedback ($K_p < 0$) to negate the spring stiffness or by using high gain acceleration feedback (large $K_a$). Stiffness cancellation is not a sound approach for stability reasons and acceleration feedback is preferable. Acceleration feedback is also beneficial for attenuating direct disturbances by effectively increasing the dynamic mass of the isolated payload.

Additional performance and stability improvements can be made by using more advanced optimal control techniques. Frequency-weighted linear-quadratic-Gaussian (LQG) design seeks to minimize a quadratic cost functional (an $H_2$ norm) that is related to the energy of the system response and the energy of the control system input. Since an objective of vibration isolation is to minimize the mean-square acceleration of the payload, $H_2$ methods are well suited for control design.[8–10]

A key shortcoming of $H_2$ methods is the lack of stability and performance robustness with respect to model errors. A robust control design approach for $\mu$g vibration isolation must account for uncertainties in umbilical properties, mass, *cg* location, actuator/sensor dynamics, and uncertain or unmodeled plant dynamics. Using an $H_\infty$ norm framework, optimal controllers may be designed to provide robust stability and performance guarantees for bounded model errors. However, the $H_\infty$ norm is related to the system gain so that the resulting controller seeks to minimize the peak frequency response magnitude.[11,12] This performance metric is typically not as well suited to the vibration isolation problem as the $H_2$ norm. $H_\infty$ design also tends to be overly conservative when the uncertainty has structure such as is encountered with parametric uncertainty or when designing for robust performance. This conservatism is somewhat lessened using $\mu$–synthesis methods which modify the $H_\infty$ design plant with frequency-varying weights that are optimized with respect to the uncertainty structure.[13–15]

Recent advancements in control theory have addressed designing for nominal performance using an $H_2$ norm and robust stability using an $H_\infty$ norm. This so-called mixed $H_2/H_\infty$ control design methodology is a combined approach which seeks to maximize $H_2$ performance subject to robust stability constraints. Mixed $H_2/H_\infty$ control design is well suited for vibration isolation and has been applied to controlling the structural vibration of buildings subject to earthquake excitation[16] as well as pointing control of flexible space structures.[17] The application of mixed $H_2/H_\infty$ control design to the $\mu$g vibration isolation problem is in progress.

## 5. STABLE HARDWARE DESCRIPTION

As a result of the technology developed through this CDDF effort, MSFC teamed with MDAC in early 1995 to jointly develop a $\mu$g vibration isolation system called STABLE. This effort culminated in the first flight of an active $\mu$g vibration isolation system on STS–73/USML–02 in late 1995. Having been given authorization to proceed in mid-January 1995, the schedule required delivery of flight hardware to the NASA Kennedy Space Center during the first week of June 1995. This unprecedented aggressive schedule required design, analysis, fabrication, procurement, integration, testing, and delivery of qualified flight hardware in less than 5 months. A successful delivery and flight experiment was made possible in part by the technology and $\mu$g vibration isolation system test capabilities developed at MSFC through this CDDF project.

The STABLE system provides component-level isolation as an alternative to the rack-level approach. The concept of isolating only the vibration-sensitive portion of a payload minimizes the number and size of any utility umbilicals, since the floating portion of the payload is not necessarily connected to all onboard support systems. In multiexperiment racks, it also protects each individual payload regardless of disturbances produced by nearby experiments, including servicing activities by the crew. Component-level isolation also eliminates the potential for disturbances due to accidental crew contact with the rack or its enclosure.

The STABLE hardware, in the configuration successfully flown on STS–73, provided an uninterrupted $\mu$g environment for a fluid dynamics experiment dubbed "CHUCK." Both experiments were contained within a single middeck locker. In addition to providing a $\mu$g environment to the onboard experiment, STABLE transferred power, data, and video signals to the platform by flexible umbilical cables. The platform and CHUCK were levitated by three MDAC dual-axis, wide-gap electromagnetic actuators.

STABLE isolates by floating a platform on electromagnetic actuators that apply forces to counteract those that are transmitted through umbilicals or that originate within the experiment itself. Accelerations caused by these disturbing forces are measured by accelerometers on the platform, and these signals are used by a high-bandwidth feedback controller to command the counteracting actuator forces. In addition to the acceleration controller, there is a very low-bandwidth position loop that tends to keep the platform centered. Signals from three, two-axis optical sensors measure the position of the platform with respect to the base and are used to maintain centering. The centering function compensates for the extremely low-frequency disturbances for which adequate rattle space cannot be provided.

## 6. RELATED RESEARCH AND DEVELOPMENT

The technology developed during the CDDF Project Number 94–07 laid a foundation for continuing activities in the area of $\mu$g vibration isolation. The foremost significant development resulting from the CDDF project has been the first successful $\mu$g vibration isolation flight experiment, STABLE. As a result of the expertise developed during the CDDF 94–07 and STABLE projects, team members were tasked to perform an independent technical assessment of the Boeing ARIS for the Space Station. Additional technical support has been given to the ARIS team in test, verification, and flight operations for the ARIS Risk Mitigation Flight Experiment on STS–79 in September 1996. Technical support for ARIS in preparation for space station operation is currently ongoing. Additionally, an Advanced Technology Development (ATD) project has been funded by NASA Headquarters Code UG/Microgravity Science and Applications Division for fiscal years 1997–1999. The objective of this ATD project is to develop the technology and ground test a small, modular vibration isolation system that can be used in the space station glovebox. A proposal to develop a flight hardware version for use in the Space Station glovebox has been approved with delivery anticipated during FY2000.

## REFERENCES


1. Lubomski, J.F.; Grodsinsky, C.M.; Logsdon, K.A.; Rohn, D.A.; and Ramachanadran, N.: "Final Report—Vibration Isolation Technology (vit) ATD Project." *NASA Technical Memorandum 106496*, March 1994.

2. Allen, T.S.; Havenhill, D.D.; and Kral Feamis, K.D.; "A Magnetically Suspended Isolation System for Space-Based Materials Processing." In AAS Guidance and Control Conference, Keystone, CO, February 1986.

3. Edberg, D.L.; and von Flotow, A.: "Design Considerations for a Microgravity Vibration Isolation System." In *Proceedings of The AIAA/AHS/ASEE Aerospace Design Conference*, Irvine, CA, February 1993. AIAA Paper 93–1116.

4. Edgerg, D.; Boucher, R.; Schenck, D.; Nurre, G.; Whorton, M.; Kim, Y.; and Alhorn, D.: "Results of the Stable Microgravity Vibration Isolation Flight Experiment." R.D. Culp and M. Odefey, editors, *Guidance and Control 1996*, Vol. 92, *Advances in the Astronautical Sciences*, 1996. AAS Paper 96–071.

5. Microgravity Control Plan, International Space Station Program. NASA Johnson Space Center, February 1997. Revision B, Draft.

6. Bushnell, G.: STS–79 Quick-Look Report, RME-1313. Document No. sk683–62235–1, Boeing Defense & Space Group, Research & Technology, 1996.

7. Owen, R.G.; Jones, D.I.; and Owens, A.R.: "Mechanical Design and Simulation of a Microgravity Isolation Mount for Columbus." *Journal of Spacecraft and Rockets*, Vol. 30, No. 4, 1993.

8. Knospe, C.R.; Hampton, R.D.; and Allaire, P.E.: "Control Issues of Microgravity Vibration Isolation." *Acta Astronautica*, Vol. 25, No. 11, pp. 687–697, 1991.

9. Hampton, R.D., Knospe, C.R.; and Grodsinsky, C.: "Microgravity Isolation System Design: A Modern Control Synthesis Framework." *Journal of Spacecraft and Rockets*, Vol. 33, No. 1, pp. 101–109, 1996.

10. Hyde, T.T.; and Crawley, E.F.: "$H_2$ Synthesis for Active Vibration Isolation." In *Proceedings of the American Controls Conference*, Seattle, WA, June 1995.

11. Francis, B.A.: *A Course in $H_\infty$ Control Theory*. Springer-Verlag, Berlin, 1987.

12. Doyle, J.C.; Glover, K.; Khargonekar, P.P.; and Francis, B.A.: "State-Space Solutions to Standard $H_2$ and $H_\infty$ Control Problems." *IEEE Transactions on Automatic Control*, Vol. 34, No. 8, pp. 831–947, August 1989.

13. Doyle, J.C.: "Analysis of Feedback Systems With Structured Uncertainties." In *Proceedings IEE–D 129*, 1982.

14. Doyle, J.C.: Lecture notes on advances in multivariable control. *Technical Report, ONR/Honeywell Workshop on Advances in Multivariable Control*, Minneapolis, MN, October 1984.

15. Doyle, J.C.; and Chu, C.C.: "Robust Control of Multivariable and Large Scale Systems." *Technical Report, AFOSR,* March 1986. Final Technical Report for Contract No. F49620–84–C–0088.

16. Whorton, M.S.; Calise, A.J.; and Hsu, C.C.: A Study of Fixed Order Mixed Norm Designs for a Benchmark Problem in Structural Control. *Earthquake Engineering and Structural Dynamics*. To be published.

17. Whorton, M.S.: *High Performance, Robust Control of Flexible Space Structures*. Ph.D. Thesis, Georgia Institute of Technology, Atlanta, GA, August 1997.

# REPORT DOCUMENTATION PAGE

*Form Approved*
*OMB No. 0704-0188*



| 1. AGENCY USE ONLY *(Leave Blank)* | 2. REPORT DATE | 3. REPORT TYPE AND DATES COVERED |
|---|---|---|
| | January 1998 | Technical Memorandum |

**4. TITLE AND SUBTITLE**
Damping Mechanisms for Microgravity Vibration Isolation (MSFC Center Director's Discretionary Fund Final Report, Project No. 94–07)

**5. FUNDING NUMBERS**

**6. AUTHORS**
M.S. Whorton, J.T. Eldridge, R.C. Ferebee, J.O. Lassiter, and J.W. Redmon, Jr.

**7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)**
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

**8. PERFORMING ORGANIZATION REPORT NUMBER**
M–849

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**
National Aeronautics and Space Administration
Washington, DC 20546-0001

**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
NASA/TM—1998–206953

**11. SUPPLEMENTARY NOTES**
Prepared by Structures and Dynamics Laboratory, Science and Engineering Directorate

**12a. DISTRIBUTION/AVAILABILITY STATEMENT**
Unclassified–Unlimited
Subject Category 18
Nonstandard Distribution

**12b. DISTRIBUTION CODE**

**13. ABSTRACT** *(Maximum 200 words)*

As a research facility for microgravity science, the *International Space Station* (*ISS*) will be used for numerous investigations such as protein crystal growth, combustion, and fluid mechanics experiments which require a quiescent acceleration environment across a broad spectrum of frequencies. These experiments are most sensitive to low-frequency accelerations and can tolerate much higher accelerations at higher frequency. However, the anticipated acceleration environment on *ISS* significantly exceeds the required acceleration level. The ubiquity and difficulty in characterization of the disturbance sources precludes source isolation, requiring vibration isolation to attenuate the anticipated disturbances to an acceptable level. This memorandum reports the results of research in active control methods for microgravity vibration isolation.

**14. SUBJECT TERMS**
microgravity vibration isolation, robust control

**15. NUMBER OF PAGES**
20

**16. PRICE CODE**
A03

| 17. SECURITY CLASSIFICATION OF REPORT | 18. SECURITY CLASSIFICATION OF THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT |
|---|---|---|---|
| Unclassified | Unclassified | Unclassified | Unlimited |

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18
298-102