NASA Technical Memorandum 106496

5-10-94
E 8487

Final Report-Vibration Isolation Technology (VIT) ATD Project

Joseph F. Lubomski, Carlos M. Grodsinsky, Kirk A. Logsdon, and Douglas A. Rohn
Lewis Research Center
Cleveland, Ohio

and

N. Ramachandran
Marshall Space Flight Center
Huntsville, Alabama

March 1994

National Aeronautics and
Space Administration

FINAL REPORT

VIBRATION ISOLATION TECHNOLOGY (VIT) ATD PROJECT

Joseph F. Lubomski
Carlos M. Grodsinsky
Kirk A. Logsdon
Douglas A. Rohn
N. Ramachandran

NASA, Lewis Research Center
Cleveland, Ohio
LeRC Contacts: Dr. C. M. Grodsinsky, 216-433-2664
K. A. Logsdon, 216-433-2836
D. A. Rohn, 216-433-3325

NASA, Marshall Space Flight Center
Huntsville, AL
MSFC Contact: N. Ramachandran, 205-544-8308

June 28, 1993

Table of Contents

INTRODUCTION

A fundamental advantage for performing material processing and fluid physics experiments in an orbital environment is the reduction in gravity driven phenomena. However, experience with manned spacecraft such as the Space Transportation System (STS) has demonstrated a dynamic acceleration environment far from being characterized as a "microgravity" platform. Vibrations and transient disturbances from crew motions, thruster firings, rotating machinery etc. can have detrimental effects on many proposed microgravity science experiments. These same disturbances are also to be expected on the future space station. The Microgravity Science and Applications Division (MSAD) of the Office of Life and Microgravity Sciences and Applications (OLMSA), NASA Headquarters recognized the need for addressing this fundamental issue. As a result an Advanced Technology Development (ATD) project was initiated in the area of Vibration Isolation Technology (VIT) to develop methodologies for meeting future microgravity science needs.

The objective of the Vibration Isolation Technology ATD project was to provide technology for the isolation of microgravity science experiments by developing methods to maintain a predictable, well defined, well characterized, and reproducible low-gravity environment, consistent with the needs of the microgravity science community. Included implicitly in this objective was the goal of advising the science community and hardware developers of the fundamental need to address the importance of maintaining, and how to maintain, a microgravity environment. This document will summarize the accomplishments of the VIT ATD which is now completed.

There were three specific thrusts involved in the ATD effort. An analytical effort was performed at the Marshall Space Flight Center to define the sensitivity of selected experiments to residual and dynamic accelerations. This effort was redirected about half way through the ATD focusing specifically on the sensitivity of protein crystals to a realistic orbital environment. The other two thrusts of the ATD were performed at the Lewis Research Center. The first was to develop technology in the area of reactionless mechanisms and robotics to support the eventual development of robotics for servicing microgravity science experiments. This activity was completed in 1990. The second was to develop vibration isolation and damping technology providing protection for sensitive science experiments. In conjunction with the this activity, two workshops were held. The results of these were summarized and are included in this report.

BACKGROUND

The need for advanced vibration isolation systems for microgravity science experiments can be expected to increase as experiments and hardware become more complex and the science community develops an understanding of their specific acceleration environment needs relative to achievable acceleration environments aboard manned space craft. Achieving the documented microgravity requirement of the space station will require a multifaceted solution. An important aspect of this technology development will include acceleration environment control by preventing undesirable disturbances from perturbing the orbiter. To achieve this microgravity environment it will be necessary to define the problem by determining reasonable microgravity levels and providing the required technology to achieve this goal. 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 dynamic accelerations on the Space Transportation System became more widely recognized and documented.

The disturbances which are present in the space shuttle and will be present in the future space station, can be categorized into three frequency bands:

(1) quasi-static external disturbances,
(2) low-frequency vibration sources, and
(3) medium- to high-frequency vibrations.

The first category includes aerodynamic drag, gravity gradient effects, and photon pressure accelerations. The second category includes excitations due to large flexible space structures, crew motion, spacecraft attitude control, and robotic arms. The third category includes disturbances due to onboard equipment such as pumps and motors.

The evolution of the space station designs has led to potential limitations on long-term, low-gravity experimentation in this environment. Most of the true microgravity experiments will require isolation from this random milli-g environment if reproducible and useful 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 passive isolation systems with a resonance frequency of at most $1/\sqrt{2}$ times the lowest excitation frequency of interest. 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 oscillation). Two-stage passive isolators can decrease the frequency range, however, limited damping leads to potentially large amplitude oscillations in a random excitation environment.

Active systems offer significant advantages over passive systems in the orbital acceleration environment. This is due to the extremely small dynamic stiffnesses needed to isolate against such low frequency base disturbances and the added capability to adapt to direct disturbances for the optimal isolation of a payload. In addition, since the responses to these two excitations require conflicting solutions a closed loop system is dictated for the control of both types of excitation disturbances.

Active systems require sensing of motion or position, and a feedback and/or feedforward 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. To achieve a broad spectrum of isolation, both a feedforward and feedback control are discussed in the isolation system design presented. These approaches reference the isolated payload to an inertial frame rather than the payload's dynamic support structure.

DISCUSSION OF RESULTS

MSFC VIBRATION ISOLATION TECHNOLOGY (VIT) DEVELOPMENT

Objective

Crystal growth in space benefits both from the reduced gravity environment and from the absence of hydrostatic pressure. Gravity driven phenomena are thus reduced in strength, and a purely diffusive behavior can be attained (provided other non-gravity driven phenomena are minimized). While gravity related effects are definitely curtailed in spacecraft, they are nevertheless present to some degree due to the dynamic acceleration environment on board the orbital carrier (g-jitter). Causative factors include disturbances produced by spacecraft systems and crew activity, operational procedures and natural phenomena such as atmospheric drag and gravity gradient effects. These disturbances have been found to impact the outcome of "microgravity" materials experiments as substantiated by numerical studies and by specific experiments to some degree.

For example, several crystal growth experiments in the Protein Crystal Growth (PCG) area are expected to be carried out on future Shuttle flights and on space station. Vibration isolation techniques can be utilized to attenuate some of the detrimental frequencies and help in obtaining optimum growth conditions. However, the successful application of this technology requires the detailed analysis of candidate fluids experiments to gauge their response to g-jitter and determine their acceleration sensitivities.

The Marshal Space Flight Center (MSFC) ATD effort, initiated in July 1988, provided analytical/numerical support to the LeRC hardware initiative. The initial focus was on the effect of g-jitter on fluids experiments. A review of fluids experiments expected to be particularly sensitive to a vibration environment was completed. Fluid systems suspected to be sensitive to high or low frequency vibrations were selected and analyzed by detailed numerical modeling. New results were obtained for two basic experiment configurations: an enclosure type problem and a floating zone setup. In fiscal year 1990, the modeling effort was redirected to examine the effects of g-jitter on Protein Crystal Growth (PCG). In the initial familiarization phase, past PCG experiments were reviewed to understand the current experimental methodology, setup, time-line, difficulties, in-flight anomalies etc., and estimates for fluid properties were obtained. Subsequently, a detailed computational approach was planned and implemented.

Significant Results

The initial modeling effort looked at the thermocapillary convection in a float zone problem. Modeling work was completed in January, 1990. The response of three fluid experiments flown on previous shuttle flights, (silicone oil, methanol and silicon melt), to various residual, oscillatory and impulse type disturbances was investigated. The results showed that low frequency g-jitter(< 0.1 Hz) significantly modifies the flow and thermal fields in encapsulated float zones which could affect the crystal properties. The analysis of impulse type disturbances showed appreciable flow and thermal effects within the melt and also highlighted the long decay times associated with such transient events.

For the enclosure problem the numerical results of an investigation on the behavior of air, water and germanium melt enclosed in a container were summarized in August 1990. This effort was aimed at simulating a generic crystal growth system to discern the fluid mechanics associated with such configurations.

In December 1989 the numerical study of g-jitter impacts on the Protein Crystal Growth (PCG) experiment was initiated. The investigation comprised an Order of Magnitude (OMA) or scaling analysis followed by detailed computer simulations of g-jitter effects on PCG. The objectives of the investigation were:

(a) to computationally determine vibration sensitivities of Protein Crystal Growth experiments,
(b) determine if these experiments can benefit from vibration isolation techniques, and
(c) provide realistic requirements for vibration isolation technology.

The modeling and analysis of PCG experiments were carried out in three concurrent steps. In the familiarization phase, past PCG activities were reviewed with respect to the types of fluids/proteins used, flight hardware utilized, procedures followed, difficulties encountered, results obtained and inferences drawn from the specific experiments. Fluid properties and hardware operating conditions like temperature, concentration, etc., were noted during these Shuttle experiments. This initial phase was a continuous effort and fairly long term in nature, because several different proteins were involved and hardware was redesigned and these changes were included in the modeling effort. From this effort, a candidate protein (Lysozyme) was chosen for analysis and modeling. Results from this modeling effort served as a benchmark for future analyses.

The code development phase consisted of modifying the in-house 2-D code to model PCG. The modification included the introduction of the species equation to model solutal diffusion and convection, the input of a PCG geometry description, the addition of source terms to the Navier-Stokes momentum equations, accounting for solute induced buoyancy forces, and steady and unsteady code verification by comparison to benchmark solutions. Concurrently, an analytical effort was undertaken to obtain results from a scaling argument for a simplified model of PCG. This OMA technique involved choosing appropriate scaling factors for length, velocity, concentration, and other variables of importance to the experiment, while determining the dominant terms in the governing equations. Estimates of fluid sensitivity as a function of acceleration amplitude and frequency can be obtained, and these estimates can be used as a preliminary guide to more detailed computations.

The detailed modeling phase involved the numerical solution of the governing equations and boundary conditions for PCG. Several g-jitter scenarios were to be examined providing detailed results of the fluid response to the imposed excitations. While OMA allows only a single frequency input, the numerical model allows the flexibility of simulating multiple frequencies of different magnitudes and directions acting on the system. G-tolerance levels can be established, and the results can be used to determine if the experiment will benefit from vibration attenuation capabilities developed under the NASA Lewis inertial isolation approaches. Realistic requirements for Vibration Isolation Technology can also be established. The initial effort focused on a single candidate protein and simplified boundary conditions, where the simulations performed were for a worst case scenario with regard to the individual frequencies and their orientations. A typical Order of Magnitude curve for PCG is shown in Figure 1 along with g-tolerance curves for Space Station Freedom during routine crew activity and schedulable events. Also shown in the figure are measurements from Spacelab and simulated responses due to various events on-board a spacecraft. The figure clearly shows the susceptibility of PCG in the 0.1 to 10 Hz range. Figure 2 shows the solute field response to different residual or quasi-steady gravity levels including the purely diffusive case ($g = 0$). Velocity magnitudes and mass transfer rates (Sherwood numbers) are also listed for the specific cases. The figure shows that close to diffusion limited conditions are established for $g \approx 10^{-5}\ g_o$. Quantitative evidence of diffusive slute conditions is shown in Table 1 where the solute Peclet number is computed and the condition $Pe_M < 1$ is satisfied for $g = 10^{-5}\ g_o$. Detailed calculations for different g-jitter scenarios are presented in the journal paper (see publications list).

More realistic and complex boundary conditions, other proteins, and different g-jitter orientations remain to be investigated in future studies.

The salient results from the investigation are as follows:

1. G-jitter dominates the spacecraft acceleration environment. It is comprised of a myriad of frequencies and displays no preferred orientation. The g-jitter magnitude can be as high as 1 milli-g.

2. Impulsive type disturbances are random in nature and hence unpredictable. The solutal field response to impulsive forces is especially long term and considerable. Impulse type disturbances are also deleterious to PCG in other respects (e.g., drop dislodgment, multiple crystals, crystal crack, etc). It is therefore prudent to take remedial measures to safeguard against their pernicious effects on materials processing.

3. PCG observations and analyses indicate susceptibility to g-jitter.

4. Calculations show the PCG flow field to be susceptible to the 0.1-10 Hz Frequency range.

5. PCG will benefit from vibration isolation technology. NASA Lewis has developed active isolation techniques with the capabilities to have significant attenuation and roll-off by 0.1 Hz and have demonstrated these systems in a reduced gravity environment to a cut-off frequency of 0.3 Hz.

6. A minimum recommendation would be to investigate the use of a passive isolation system. An active system would most certainly benefit PCG.

The most recent results from the study were presented at the 'Fourth International Conference on Crystal Growth of Biological Macromolecules', August 18-23, 1991, Freiburg, Germany. A comprehensive paper summarizing the results is under preparation for the Journal of Crystal Growth.

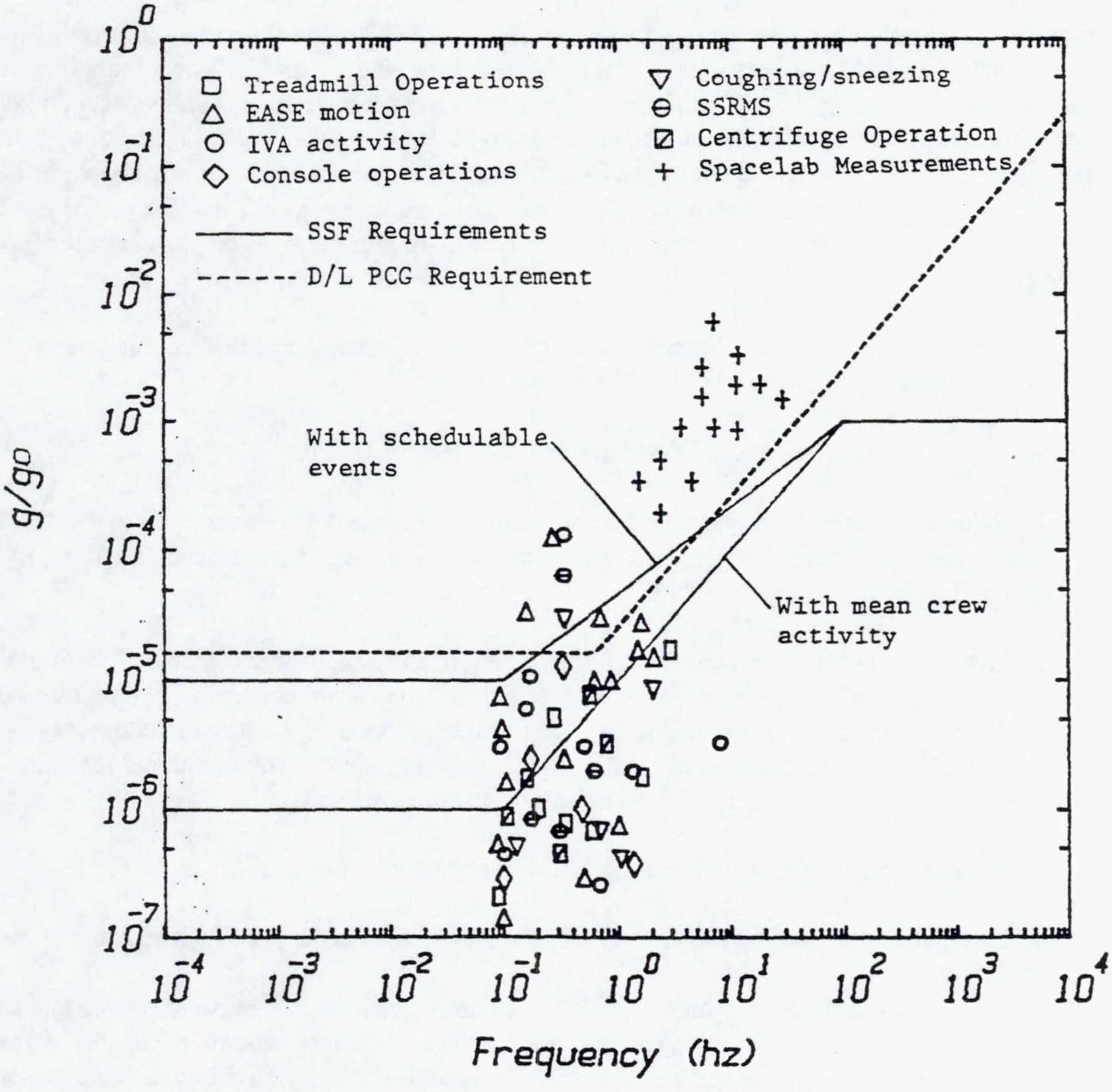
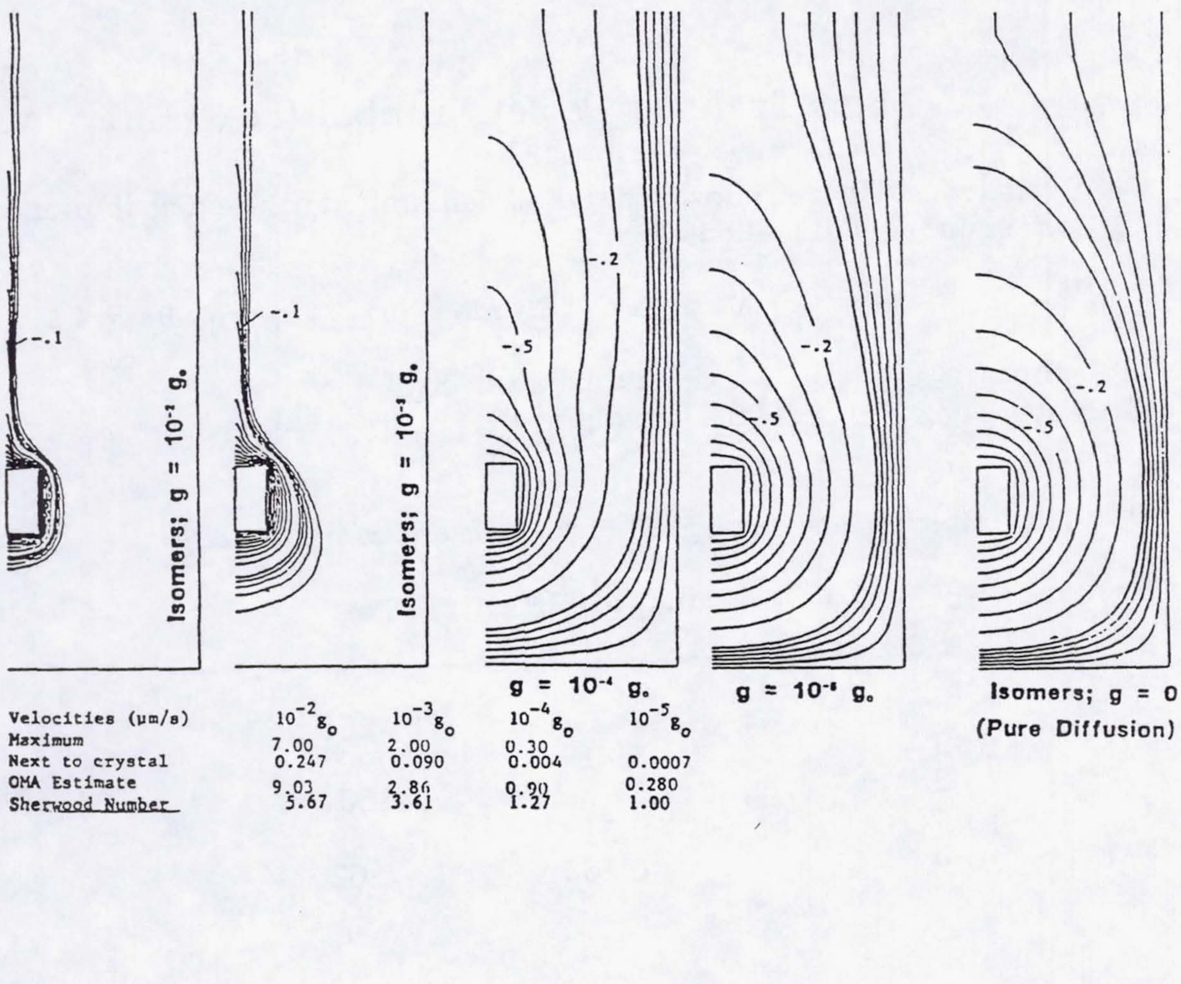


Figure 1: Spacecraft Acceleration Environment.

PCG Numerical Modeling (Residual Accelerations)



Velocities (µm/s)	$10^{-2} g_o$	$10^{-3} g_o$	$10^{-4} g_o$	$10^{-5} g_o$
Maximum	7.00	2.00	0.30	
Next to crystal	0.247	0.090	0.004	0.0007
OMA Estimate	9.03	2.86	0.90	0.280
Sherwood Number	5.67	3.61	1.27	1.00

Figure 2: PCG Numerical Modeling Simulations.

Mass Transfer Peclet Number (Pe_M) Calculations

❶ Motakef (1990) has shown that diffusion limited solute distribution is establishec directional solidification when

Mass Peclet Number ($u_{max} r_c/D$), $Pe_M < 1$

where u_{max} : Maximum axial velocity
r_c : Charge radius
D : Diffusivity of solute

❷ This criterion can be applied to the present computations

Gravity (g_o)	u_{max} ($\mu m/s$)	Pe_M
1	247	1235
10^{-2}	58.1	290
10^{-3}	32.8	160
10^{-4}	0.518	2.59
10^{-5}	0.135	0.675 ✓

Table 1: Mass Transfer Peclet Number (Pe_M) Calculations.

LeRC-REACTIONLESS MICROGRAVITY MECHANISMS AND ROBOTICS

Objective

Future space missions will require the development and operation of facilities to conduct long-duration microgravity experiments. Efficient utilization of these orbiting laboratories, as well as the future commercialization of space, may depend on robotic manipulators for conducting experiments and performing processes. Robot systems could enhance manned-laboratory utilization and enable autonomous facility operation. Studies undertaken with standard industrial robots which included measuring both base and end-effector reactions, found that poorly controlled robot movements have the potential of causing critical disturbances as a result of these reactions. Thus, new technologies are needed to develop robotic systems ensuring that motion of the robot itself does not disturb the quiescent microgravity environment of an experiment or of the entire facility. The key issue is to minimize reaction forces transmitted to the robot's surroundings through attachment points. The simplest method for reduction of the base reactions is to move the robot arm so slowly that forces are maintained within acceptable levels. This obviously will increase task time. Another approach is to use mechanisms and control strategies to compensate for, or cancel possible reactions. Use of reaction control techniques will improve robot productivity in situations that permit high accelerations at the end-effector, such as the transportation of non-sensitive test equipment or supplies.

A program based on the latter approach was undertaken at NASA Lewis Research Center to develop motion and acceleration control technology for use in the microgravity laboratory environment. This program involved analysis of potential robotic disturbances, evaluation of smooth-acting roller-driven joints, and optimization of joint trajectories to minimize reaction forces. The goal of these efforts was to develop reaction compensation technology. This program was funded by the Vibration Isolation Technology ATD from FY1987 through FY1990.

Reaction Compensation Technology

Roller Driven Joints

Roller, or traction, driven actuators provide significant benefits to servomechanism applications in space by offering: zero backlash, high torsional stiffness, low starting friction, low torque ripple, potential for nonlubricated operation (due to low sliding), and over-torque protection (ability to slip at predetermined traction limits). These characteristics are important for the smooth control of robot joints.

A manipulator arm was designed for a Laboratory Telerobotic Manipulator (LTM) which incorporated a 2-DOF roller-driven joint. To simplify the control system and provide the necessary fineness of control, drive system backlash was eliminated. The rollers were made of hardened steel with ion-gold plating to allow for dry operation. This permitted operation in a vacuum. This joint design was incorporated into a test bed at NASA Lewis and tested to demonstrate the characteristics of roller-driven robot joints.

Joint Trajectory Planning

Dynamics and control technologies can be utilized to limit the reactions transmitted by a robot through its base to the orbiting laboratory. Several methods for momentum compensation were investigated under a grant funded through the ATD at Case Western Reserve. The basis for the reaction minimization strategy used in this project is joint trajectory planning through the use of redundant degrees of freedom (DOF). Manipulators used in space applications may have kinematic redundancy in order to facilitate the performance of tasks. In certain applications, the redundant degrees of freedom may also be used to minimize base reactions. A method was developed for trajectory design which employs kinematic redundancy (extra degrees of freedom) for base reaction minimization. The method involves moving the extra sections of the manipulator in an inertially opposite direction as compared to the movement of the end-effector in order to minimize base reactions. This procedure employs an optimization strategy for identifying the joint motion solution set which minimizes the resulting base reactions.

The effect of various weighting functions on the base forces and moments were investigated analytically. From these results it was determined that a suitable weighting matrix could be constructed by using average values of base moments and forces. This weighting function can also be tailored to minimize a partial set of reaction components (i.e., only the forces or moments).

This strategy was incorporated into a general computer program to simulate and control manipulators with any number of links, joints, and degrees of redundancy. It was found that it is possible to design manipulators through the proper selection of redundancy which would be capable of operating with minimal base reactions. Typical results from the program are shown in Figure 3. An arbitrary planar manipulator, with no redundancy, would exhibit a base reaction force and moment response for an arbitrary end effector motion that is off the scale of the figure. For the same motion, with one redundancy, the response is as shown. For two redundancies, Figure 3 demonstrates the ability to have a resulting zero net base reaction. However, in most cases, it is not possible to completely eliminate base reactions. It was analytically shown that these techniques could be employed to lower robotic disturbances to below the published space station "microgravity" acceleration requirement, as shown in Figure 4.

Implementation of the above control strategies on a multi-DOF test bed was done by generating a set of joint angles as a function of time for a desired robot end-motion from the output of the optimization code. This set-point file was downloaded to the control computer. The manipulator was then commanded through the motion under robotic-control using position-feedback mode, during which six-axis reaction and joint angle data was acquired. Static, gravity-induced moment loads were removed from the data by subtracting a non-linear function of joint angles based on known physical dimensions and the measured joint angles. It was recognized that the test bed had only a 4-DOF arm, so the possible end-effector positions and orientations as well as available redundancies and corresponding joint trajectories was limited.

Initial experimental validation showed that the robot tracked commanded trajectories imprecisely, and that unacceptable levels of base reaction were present at all times. In order to determine whether tracking errors were introducing the unacceptable levels of base reaction forces, system parameters were measured through a series of static and dynamic tests. From these parameters, the control system was tuned for best achievable performance. While this did improve tracking performance, the base reaction disturbances were still at least an order of magnitude higher than theory would predict for any manipulator motion, whether optimized to use redundancy to cancel reactions, or not.

It was determined that the manipulator performance was limited by the combined effects of friction and the presence of mechanical compliance between the friction and the actuating motors. While the friction in the joint was not high compared to other robot joints, the combination of any level of friction with the drive train compliance results in a system which operates in a characteristic stick-slip or "stiction" fashion. The traction driven 2-DOF joints incorporate a roller-loading device which applies a normal load to the rollers in proportion to the applied torque. This has the effect of reducing friction at low torques and increasing bearing and roller life. However, it requires torsional wind-up of the loading mechanism to apply the roller loads in addition to the elastic deflection of the components.

Comparison tests were made to determine whether this stiction was unique to this testbed manipulator. Several industrial and research robots in other laboratories were surveyed using a high resolution accelerometer near the robots' end effectors. The data showed that while performing a simple 0.2 Hz circular motion, all of the robot designs produced a non-smoothness in the range of 5 to 75 milli-g. Further, similar measurements using a human subject showed that these levels are as smooth a human capabilities. Overall, these tests show that for true low-disturbance microgravity operations, robots will require smoother drive systems than currently employed.

Currently, efforts supported by other sources are underway to complete the laboratory measurements to help address the problem of precise motion, friction and compliance in the drive train, and to evaluate the roller-driven joint concept. This will include exploring the effects of trading off higher friction for lower compliance, which is inherent in the design. One of the results of this current evaluation indicates that in moving any robot arm slowly, stiction in the elements is more pronounced and the motion is not smooth.

Summary

The goal of the microgravity robotics technology program at NASA Lewis Research Center was to develop reaction-control technology for use in robots for microgravity laboratories. Roller drive design, analysis, and experimentation are still underway to provide smooth robotic drive systems under a variety of environmental and dynamic conditions. Optimization schemes have been developed which can control reactions in a redundant-joint robot. The need for low-friction, smooth-motion manipulators has been identified. These and future results will help prevent excessive disturbances to the on-orbit microgravity environment of future space laboratories.

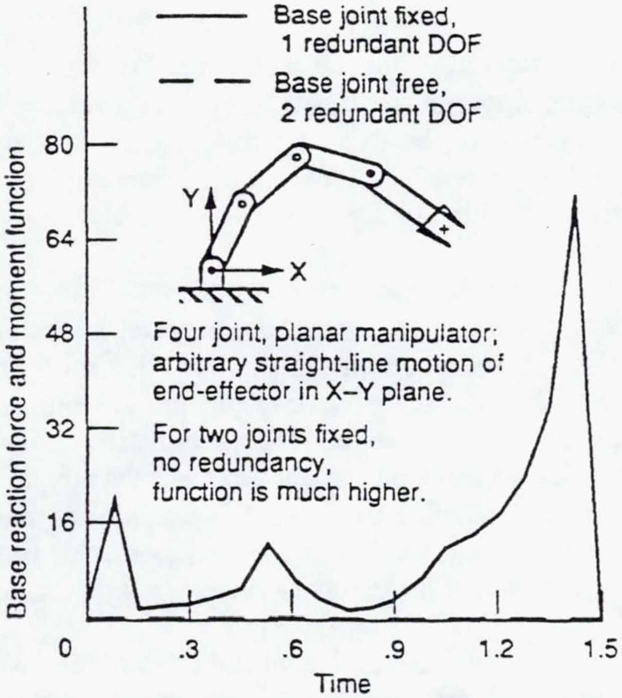


Figure 3: Typical optimization of base reactions for four-joint planar manipulator over arbitrary trajectory, with one and two redundancies. Base reaction function is defined as a weighted sum of the squares of reaction and moments.

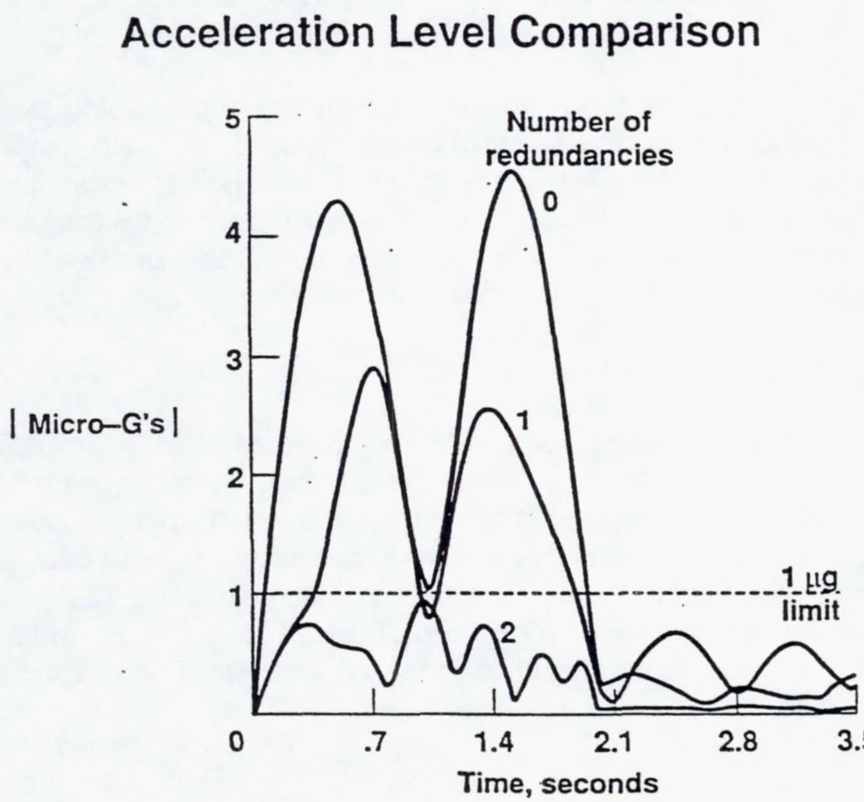


Figure 4: Acceleration level comparison for 0, 1, and 2 redundancies.

LeRC-ISOLATION AND DAMPING

The Isolation and Damping portion of the VIT ATD project was conducted in three concurrent phases:

(1) technology requirements definition,
(2) technology development,
(3) technology demonstration.

Technology Requirements Definition

The technology requirements definition phase consisted of informally surveying potential microgravity users as to their requirements as well as discussions with industry to determine the current state-of-the-art in vibration isolation. A VIT workshop was held in September 1988 to bring users together with industry and technologists in order to establish a dialogue between the two groups to better define needs and requirements. In addition, an element of the VIT ATD project conducted at Marshall Space Flight Center (MFSC), discussed previously, supported the requirements definition phase. The results of the technology requirements definition phase and the initial VIT workshop were used to focus vibration isolation technology development on critical needs of vibration sensitive microgravity experiments.

The first workshop was conducted to ascertain the state-of-the-art in isolation technology, to determine the perceived science requirements for vibration isolation, and to organize the VIT ATD project to best meet these needs. The workshop discussions were centered around two working groups: a Science and Users group, and a Technology group.

The Science and Users Working group concluded that there were two principal issues. One issue, relating to the microgravity environment recommended a systematic documentation, in a meaningful data format, of the existing environment onboard shuttle and an early definition of the proposed space station environment. A strong recommendation for source control was given for the space station, similar to the approach proposed for the European free-flyer Eureca. A second issue regarding requirements had two parts. The first was the recommendation that users should address "real" science needs systematically and realistically, and secondly, the engineering limitations on meeting these needs must be defined, especially with regard to the impact of umbilicals.

The Technology Working group recommendations were that vibration isolation technology be developed to extend capabilities into the sub-Hertz frequency, and microgravity range, and that this technology should be demonstrated. In conjunction with these recommendations, actuator technology to support the control developments must be successfully demonstrated within a multi-DOF system in a low gravity environment. The limitations of passive isolation should also be considered. It was also recommended that the problem of umbilicals be addressed, the use of non-contacting methods be encouraged, and spring rates of other umbilicals be characterized. The use of umbilicals on sensitive experiments should be evaluated early in the design to minimize their effects and control strategies to cancel these umbilical effects should be explored. Using these findings, the Vibration Isolation Technology ATD project was focused on the high priority recommendations. Concurrently other efforts were initiated throughout the world space community to accomplish similar goals. Coordination in mutual areas of interest was established between participants to keep abreast of developments and to safe guard against duplication of effort. Eventually, as it became obvious that a considerable amount of work was being carried out in the area of Vibration Isolation Technology for Microgravity Science applications, an International Workshop sponsored by MSAD and hosted by the NASA Lewis Research Center's Space Experiments Division was held in Cleveland, Ohio in April of 1991. The purpose of this workshop was to generate a dialogue to specifically evaluate the relevance of the current work in progress, and to make recommendations as to what needs must be addressed in the future to create a meaningful microgravity environment in order to assure productive international microgravity science programs. The subject matter and results of this Workshop are summarized below.

Summary of Workshop

The international workshop had 80 attendees, representing U.S. and international industry, universities, and several governments. Seven NASA installations were represented, as were the Canadian Space Agency (CSA), the European Space Agency (ESA), and the Nippon Space Development Agency of Japan (NASDA). The presentation part of the workshop consisted of four sessions.

Session 1:

Session 1 was dedicated to the "Sensitivity of Microgravity Science Experiments." Two presentations were made summarizing current NASA efforts: (1) numerical modeling to predict the behavior of fluid experiments and protein crystals exposed to g-jitter, and (2) an examination of the anticipated g-jitter effects on the space station.

Session 2:

Session 2 was dedicated to "Isolation Technology Development," which was the main theme of the workshop and thus the longest session. Eight presentations were made summarizing the work being sponsored by ESA, CSA, NASDA, and NASA in the area of Vibration Isolation Technology for "Microgravity" Science experiments. A common element in all of the programs was the use of active, magnetic isolation techniques. There were variations in controller concepts and types of actuators, but the selection of these components will be a function of the particular application. The scope of each technology presentation is outlined below.

ESA's major effort is the development of the Microgravity Isolation Mount (MGIM), which is a facility for providing active vibration isolation for sensitive experiments to be flown on the Columbus Attached Laboratory and the Columbus Free-Flyer Laboratory. The facility is designed to be accommodated in a standard Columbus rack, and interfaces with existing rack utility services. The facility design is based on a non-contacting strategy, which includes services to the experiment. The concept was developed for ESA by a team at the University College of North

Wales in the United Kingdom. This facility is the only known microgravity science facility being developed to counter the effects of g-jitter on the science payload.

CSA's work in progress involves the development of a Large Motion Isolation Mount (LMIM) for providing a high quality environment of 10^{-4} g for 5 to 15 seconds on the KC-135. The work is being conducted by the Canadian Astronaut Program Office with the University of British Columbia. CSA and NASA/MSAD are sponsoring the work, with NASA/JSC and NASA/MSFC participating.

NASDA has an extensive vibration isolation program in progress to develop isolation concepts for use in the Japanese Experiment Module (JEM). A unique aspect of the NASDA effort includes an investigation into rack passive damping methods, as well as investigating active, electromagnetic methods for isolating the payload. Validation of the performance of the various concepts being developed has been done using both ground-based laboratory testing and low gravity aircraft flights. In principle, the NASDA work in progress in active magnetic isolation is similar to the NASA Vibration Isolation Technology ATD in-house effort.

The NASA work had several elements, most of which were done within the MSAD-sponsored ATD. The in-house work conducted at the Lewis Research Center had the objective of developing and demonstrating the proof of concept of a six degree of freedom active magnetic isolation prototype system for low frequency sub-Hertz applications. This was done by developing the necessary control and actuator concepts in a laboratory, building a laboratory six degree of freedom prototype for validation of performance, and then building a demonstration system that was flown in a reduced gravity flight test program. In addition to the in-house work, grants were funded with two universities. This NASA Lewis in-house research and the two NASA funded grants will be discussed in detail separately.

There were also two Phase II Small Business Innovative Research (SBIR) contracts funded through Code C that contributed to the NASA Vibration Isolation Technology effort. NASA Lewis managed a Phase II SBIR conducted by Applied Technology Associates of Albuquerque, New Mexico, which developed an innovative inertial actuator concept for stabilization in "microgravity". The inertial actuator concept is best suited for the control of direct disturbances from entering the environment (e.g., isolating exercise equipment). NASA Marshall Space Flight Center also had a Phase II SBIR conducted by SatCon Technology of Cambridge Massachusetts. This effort developed a six degree of freedom Lorentz force vibration isolator with a nonlinear controller. The concept was validated in the laboratory by off loading the weight of the isolated platform.

Session 3:

The theme of the third session was the Microgravity Environment. Two presentations were made concerning the effects of cyclic exercise equipment onboard the shuttle and space station. Dr. W. Thornton of the Astronaut Office made a presentation entitled, "Shock and Vibration Isolation for Cyclic Exercise in Space Craft." The need for cyclic exercise was discussed and the resultant disturbing forces of the various exercises were presented. Concepts for isolating and minimizing the effects of these forces were also presented. Disturbances generated by exercise equipment are direct disturbances that, as stated previously, are best controlled or stabilized by using inertial actuation devices. It was concluded that for long duration space flight, cyclic exercise is mandatory, but will need source isolation to minimize effects on the carrier environment.

The second presentation of this session was prepared by Level II of the Space Station Office and was entitled "Space Station Freedom Microgravity Environment Requirements and Assessment Methods." There was considerable interest in this area. The program status and the space station microgravity requirements were discussed, as well as quasi-steady, low frequency and vibro-acoustic assessment techniques.

Session 4:

Session 4 was entitled, "Microgravity Measurements," and consisted of three presentations. A presentation on the Space Acceleration Measurement System (SAMS), entitled "Early Mission Science Support," described the SAMS hardware, the capabilities of SAMS, and detailed the configurations to be used in the missions over the next two years.

The presentation entitled, "Microgravity Accelerometer Characterization on Columbia STS-32 Mission" discussed the use of the Honeywell In-Space Accelerometer (HISA) on the STS-32 mission in support of the Microgravity Disturbance Experiment (MDE). A description of the HISA, along with the principle of operation and performance specifications were given. The objective of the MDE was to investigate the effects of various disturbances (e.g., crew motion, treadmill operation, thruster firings, etc.) on the microstructure of an Indium crystal grown using a float zone method. The Fluid Experiment Apparatus (FEA) was used to grow the crystal and the HISA, mounted on the front side of the FEA, measured and recorded the disturbance levels.

The final presentation in Session 4 entitled, "Development of a Residual Acceleration Data Reduction and Dissemination Plan," addressed the developing problem area of how to handle the large volume of data that will be generated by various accelerometer systems. This work is being performed by the University of Alabama in Huntsville in support of the ACAP program. Gigabytes of data will be generated on each mission flown with a measurement system. The approach being taken is: (1) to first identify the experiment characteristics and those mission events that are meaningful so as to limit the amount of accelerometer data an investigator would be interested in, and (2) to determine how the data will be processed so that it will be meaningful and relevant to the experiment objectives.

Session 5:

Session 5 was a split session consisting of two working groups, one involved with isolation technology needs and the other with science requirements and the environment definition.

Isolation Technology Working Group

In the first workshop held in 1988, this working group felt that the three most important issues to be addressed were:

(1) Control Technology
(2) Actuators
(3) Umbilicals.

During this workshop these same areas were still deemed important, however, the order of importance had changed-the first and third area were switched. These issues were then followed by source vibration control, sensor technology, active versus passive methods, cost effectiveness, and specifications or requirements. The umbilical problem was considered the most important issue since control technology and actuators have been addressed extensively in all of the international programs, while the umbilical problem has not. The working group concluded that in the absence of umbilicals, (contacting services), the problem of successfully isolating a science payload or any payload had been solved. In 1988, the lower frequency limit on state-of-the-art hardware was about two or three Hz. As a result of several international programs, the technology is now available to isolate down to near 0.01 Hz and microgravity levels. The lower frequency range is not limited by the technology but by volumetric constraints of any realistic isolation system.

It may be necessary to make a sensitive experiment self-contained by including the required services onboard the isolated platform. In most cases this will not be feasible, so it was felt that the umbilical problem needs to be addressed, particularly when dealing with vacuum lines and mass transport services such as fluids. The following suggestions or recommendations were made:

(1) obtain a better quantitative understanding of the dynamics of umbilicals (stiffness and damping values),
(2) develop the technology to make smart umbilicals, such that they track the payload,
(3) originate or emanate the umbilical connection from a breakout box and isolate that box actively, and
(4) incorporate the umbilical into the isolation actuator.

The actuator issue resolved into two issues. First, if there is a need to handle large strokes, (> 2 cm), to handle the large motions required for the lower frequencies, and if so whether this should be done in stages or with one actuator. The consensus was that for most applications the range of motion requirements can be handled with current technologies, but there may be instances where a large motion actuator (e.g., a Stewart platform) may be needed. The other issue discussed was the preference for the Lorentz, or voice coil actuator, versus the attractive electromagnetic actuator. There are preferences for both types. Both have the capabilities needed and would work well in the orbital environment. Both have advantages and disadvantages. The issue is really a matter of personal preference and should be determined on a case-by-case basis.

There were no major control issues. The discussions centered around using position feedback or inertial feedback/feedforward. With no direct disturbances position feedback would be adequate. With direct disturbances and/or umbilicals, inertial feedback is required.

Source control of vibration disturbances was generally accepted, however, how much source control versus payload isolation to be used was an issue. In principle, source control is common sense planning. In designing equipment it is sensible to use techniques and components that will tend to be quiet. The problem can be handled by setting limits on equipment builders, but exactly what these limits should be may be hard to define. Actively isolating all sources is not feasible. The effort of the space station Level II office to try to institute a vibro-acoustic plan for the space station was highly endorsed.

Sensor technology discussion focused on the fact that any active isolation system is now limited by the performance of the sensor being used. It is recommended that some effort be expanded to develop lower cost sensors with better performance.

The issue of active versus passive isolation techniques was brought up again. Passive isolation will be most cost effective, but for only specific requirements and limited in its low frequency effectiveness. It was suggested that consideration be given to exploring improved passive system performance or hybrid systems be explored for introducing position control or damping into a very soft suspension.

The cost effectiveness can be manifested in simple ways, such as using passive isolation mounts on racks to reduce disturbance transfer or develop low cost hardware and sensors. A facility such as the ESA MGIM, which takes into account vibration isolation, should be cost effective in the long term as opposed to experiment specific hardware.

The issue of specifications, or requirements basically is summarized into what is really needed by the experimentallists. Requirements, to date, have been generated based on simple analyses. Their applicability is constantly being challenged. It is understood that this issue will not be resolved without in orbit acceleration sensitivity experimentation.

Science Requirements and Environment Definition Working Group

The discussions in this working group centered around the space station microgravity requirements. The principle outcome of these discussions was that the "Nauman" or lower curve in the requirement is necessary to do meaningful science for some experiments, particularly for sensitive crystal growth experiments.

The original monochromatic requirements curve has been discussed and criticized, primarily because it only represents a part of the problem, (i.e., a single monochromatic source). The actual environment is and will be quite complex, consisting of many sources that will have random, periodic, and impulsive components. The approach being taken for the space station uses Power Spectral Density (PSD), narrow band and transient analyses to account for the major elements of the vibro-acoustic environment.

It was pointed out that the high frequency end of the current requirement is unrealistic since the displacements involved are in the nanometer range. It also became apparent that isolation will be required in some instances, but this must be done cost effectively, and that a vibro-acoustic plan be implemented.

An issue of major importance to most people defining requirements and effects is the critical need for a well designed, coordinated experimental and numerical effort to validate modeling techniques. The vast majority of current modeling is being done with simple models and methods, and there is uncertainty in the results. Some of this experimental effort could be accomplished using ground-based, off-loading means, (i.e., low gravity trajectories, etc.).

The working group discussed the issue of whether users understand what they really need and whether they have a clear understanding of what the actual environment for the STS and space station are and will be. The concern is that a set of requirements can be established on paper for a carrier but this does not ensure that there will not be disturbances exceeding these requirements. The users would be prudent to realize this and plan for it.

Free-flyer concepts were discussed, and it was concluded that these carriers should be pursued for those experiments requiring long duration pristine acceleration environments.

Session 6:

Session 6 was a plenary session, wherein the findings and recommendations of the working groups were summarized and discussed.

The detailed results of this international workshop and the presentations given in each session have been published in a NASA Conference Publication (CP) entitled, "International Workshop on Vibration Isolation Technology for Microgravity Science Applications," NASA CP-10094.

Technology Development

NASA Lewis In-House Effort

The Technology Development phase of the VIT ATD was conducted in-house and through university grants. This phase concentrated on low frequency actuator development and the associated control technologies. These specific technology areas emerged from the initial VIT workshop as the critical technologies for vibration isolation of microgravity experiments. Analytical studies from the requirements definition phase indicated that the critical frequency regime for crystal growth experiments and fluid experiments are in the quasi-static to 1 Hz range. This frequency regime was determined to be below the present capability of passive isolators and the current commercial state-of-the-art active isolation systems. To successfully isolate an experiment in this frequency regime an active isolation system would be required with larger stroke capabilities and advanced control techniques.

In response to the technological needs addressed in the VIT workshop, an active six degree-of-freedom (DOF) magnetic isolation system was developed in laboratory and Learjet flight configurations. These digitally controlled isolation systems were used as tools to evaluate control algorithms, developed under the technology development phase, to attenuate the acceleration environment of a payload. The use of a generic active digital isolation system allowed the application of numerous optimal and classical control approaches to the microgravity isolation problem. The control approaches are based on the specific scientific acceleration requirements and the optimal control strategies for a specific disturbance environment.

The active control approaches developed can, in general, be separated into inertial feedback and inertial feedforward isolation techniques, or a combination of the two. These techniques can be implemented using advanced optimal control strategies, which have also been studied under university grants, where a performance index, or cost function, is defined and an optimal controller designed to minimize this function. These functions can be frequency weighted in order to shape the response as a function of frequency dependent on the requirements or spectrum of concern. In addition, a specified transfer function can be defined and an appropriate stable closed-loop controller designed to meet this transfer function.

In order to give a general qualitative description of the advantages in isolating a payload by the proposed active inertial means, a simple one DOF spring-mass-damper system, shown in Figure 5, will be discussed. Figure 5 can be described by a simple equation of motion where F_s is a servo force proportional to the inertial position and velocity of the support structure and the isolated payload mass. The feedforward terms in the servo force are derived by referencing an actuator to the first and second integrals of an accelerometer attached to the support structure. The feedback terms are derived from an accelerometer attached to the payload mass in a similar way. Using the following definitions, $\omega_n^2 = K/m$, where ω_n is the natural frequency of vibration for the system, and x the viscous damping factor, additional terms will be defined as $c/m = 2\xi\omega_n$, $A_{vfb} \equiv a_{vfb}c$, $A_{afb} \equiv a_{afb}m$, $B_{pff} \equiv b_{pff}K$, and $B_{vff} \equiv b_{vff}c$, where the subscripts vfb, afb, pff, and vff, represent velocity feedback, acceleration feedback, velocity feedforward, and position feedforward scale factors, respectively.

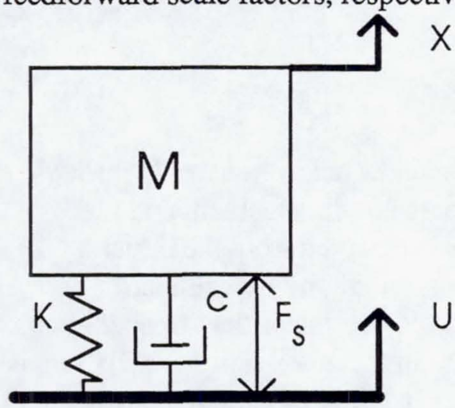


Figure 5

The magnitude of the transfer function for such a defined system is defined as the transmissibility of the isolated system to a harmonic base disturbance. Therefore, the following transfer function can be written which depicts the various possibilities of actively controlling a single DOF system through various inertial means. In addition, the relative active control parameters are shown, which determine the dynamic stiffness and damping values.

As depicted by the following equation, the feedforward techniques attempt to cancel out the dynamic transmission due to the relative terms in the equation of motion, (i.e., the relative spring and viscous damping terms), while the inertial feedback term increases the dynamic mass of the system and the inertial viscous term references the payload through a viscous damper to an inertial reference frame. In practice, the feedforward and feedback terms, derived from accelerometers attached to the payload and support structure, will have bandwidth and linearity limitations and thus, these terms will be functions of frequency. By calibrating the control sensors and bandwidth limiting the controller, one can arrive at an optimal controller performance in order to meet bandwidth and noise floor requirements.

$$\left|\frac{X}{U}(j\omega)\right| = \left(\frac{\left(1-b_{pff}\right)^2 + \left(2\xi\frac{\omega}{\omega_n}\right)^2 \left(1-b_{vff}\right)^2}{\left(1-\left(1+a_{afb}\right)\left(\frac{\omega}{\omega_n}\right)^2\right)^2 + \left(2\xi\frac{\omega}{\omega_n}\right)^2 \left(1+a_{vfb}\right)^2} \right)^{1/2}$$

Inertial feedforward cancellation of the base transmission provides a means of attenuating a broadband disturbance throughout the bandwidth of the controller, limited only by the volumetric constraints imposed on the translational and rotational motion of the inertially referenced payload. Without these constraints there would be an infinite theoretical attenuation of base disturbances achievable. However, the noise floor of the sensors limit the overall attenuation of any active control system.

Inertial acceleration feedback increases the dynamic mass of the system. The natural frequency of the closed-loop system is lowered electronically, making the system appear more massive. Inertial damping feedback removes 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 effect of such a system for large values of inertial velocity feedback gain can be understood by noting that it is equivalent to having a passive damper attached between the isolated mass and a virtual inertial reference. As the damping is increased, the isolated mass becomes more and more tightly coupled to the (motionless) ideal inertial reference. In other words, the stronger the damping, the better the isolation. 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.

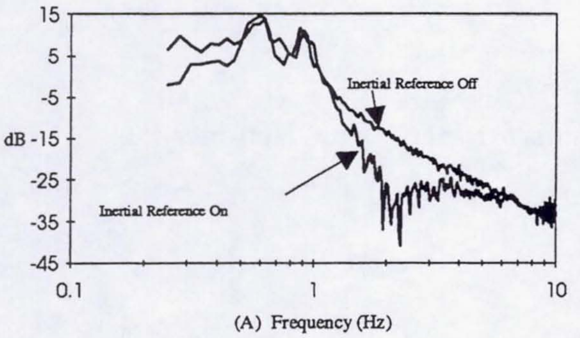


Figure 6: Inertial and Non-inertial Control Transfer Function.

Based on a relative feedback and inertial feedforward controller design a laboratory prototype six DOF system was designed and built for verification of one of the isolation approaches developed. The relative and inertial motion of the active suspension system, (i.e., the displacement of the isolated payload with respect to its support environment and the acceleration of the support structure), are measured using eddy current probes and proof mass accelerometers, respectively.

In order to demonstrate the feasibility of using a feedback/feedforward control algorithm the frequency response of the prototype isolation hardware was measured with a multi-DOF forcing function in the horizontal plane. Only the three horizontal DOFs were analyzed because of the large one g bias in the vertical dimension which limited the acceleration magnitude range of testing. However, the system was under full suspension and every attempt was made to constrain the swept sinusoidal forcing function to the horizontal plane. Two triaxial accelerometers were used to record the acceleration spectrums of the payload and the forced platform. These spectrums were then used to calculate the frequency response of the isolated payload for both relative feedback and inertial feedforward control. The natural frequency of the suspension system for both frequency response curves was set at about 0.65 Hz. As shown in Figure 6, the relative feedback control shows a typical soft suspension system response with a roll-off of about 40 dB/decade, while the inertially referenced control curve, for the same relative parameters, shows a substantial increase in roll-off, about 110 dB/decade. The response of both system tends to flatten out at about 26 to 33 dB where the 12 bit control resolution limit dominates. This controller limitation is translated into the suspended payload's acceleration noise floor performance by the resolution of the relative control loop. In order to demonstrate this, input and output power spectrums from the frequency response calculations in Figure 6 are shown in Figure 7. Figure 7 gives the input power spectrum of an accelerometer in the horizontal direction and the corresponding response of the actively isolated payload for both relative and inertial control. Superimposed on this plot are the theoretical closed loop resolution limits for a 12 and 16 bit single DOF suspension control loop. The attenuation performance of the active suspension is and will be limited by the digital resolution of the controller.

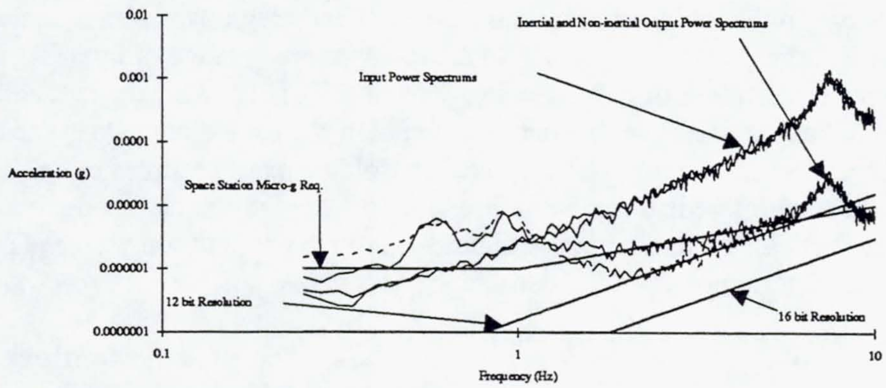


Figure 7: Input and Output Spectrums for Inertial and Non-inertial Control.

Universtiy Grants

The grant with the University of Virginia concluded in October of 1991. The goals of this grant were to develop new actuators for use in microgravity isolation systems, investigate the design of controllers for multi-degree-of-freedom (MDOF) active isolation, and to construct a single degree-of-freedom (SDOF) test rig with an umbilical. Under the actuator development studies two actuator designs were examined: a large gap attractive electromagnetic actuator and a large stroke Lorentz force actuator. It was concluded that SDOF electromagnetic actuator was not as robust or flexible in its design, so the Lorentz force actuator was pursued as the actuator of preference. The Lorentz actuator was designed and built for the SDOF test rig using magnetic circuit and finite element analysis tools to optimize its magnetic design.

This grant also examined the design of actuators for MDOF systems. This consisted of a design for an integrated 1 cm gap six-DOF non-contacting magnetic suspension system and a "coarse" follower to permit the practical extension of magnetic suspension to larger strokes. The thrust of the controller designs for these systems consisted of feedback/feedforward controllers using modern control synthesis techniques. The feedback/feedforward controller design proceeded through the use of Linear Quadratic Gaussian control theory. Several new additions to the theory were made including the computation of suboptimal feedforward terms directly from the Linear Quadratic Regulator (LQR) solution and the solution of the combined stochastic and deterministic disturbance accommodation problem.

The Pennsylvania State University grant for the development of active vibration isolation algorithms to maintain a microgravity environment was concluded and a final report was received on December 19, 1991. The grant period of performance was extended to June 14, 1991 under a no cost extension from the original conclusion date of December 1990. Under this grant new control algorithms were developed to achieve the desired acceleration transmissibility function for microgravity isolation systems. The relative displacement and acceleration of the isolated mass were used as feedback signals for the control of the isolated mass. For a system with known parameters, two approaches were developed to find the controller transfer function in the Z-domain, which yields the desired transmissibility at each frequency. These two control approaches lead to the desired transmissibility function. The approaches developed are superior to the standard phase lead/lag compensator approach, both in meeting the desired transmissibility function and minimizing the required control effort. For a system with unknown parameters, a model reference adaptive control (MRAC) algorithm was developed for a single DOF system. A reference system can be derived from the desired transmissibility. The control law is composed of the inertial velocity (or the integral of payload acceleration) and relative displacement feedbacks together with adjustable gains. To adjust these controller gains, an adaptive control law is designed to reduce the difference between the responses of the reference model and actual system to a given input.

Technology Demonstration

The technology demonstration phase of the VIT ATD project was an in-house effort consisting of a system demonstration during low gravity parabolic trajectories using the LeRC Learjet. A vibration isolation testbed was developed for installation in the Learjet to be used as an evaluation tool for component and system performance of both active and passive devices. Initially a constrained passive three DOF system was flown to evaluate the dynamic characteristics of this testbed. The active system concept, developed under the technology development phase of the VIT ATD project, was flown for the evaluation of a fully active flight-type digital system. This active testbed hardware is envisioned as being a useful tool to evaluate vibration isolation components and subsystems. A Data Acquisition System (DAS) was also built in-house for use with the vibration isolation testbed system. This DAS includes six SAMS triaxial heads fitted with QA-2000 sensors.

The objective of the isolation and damping portion of the VIT ATD project was to demonstrate an active inertial isolation system in a reduced gravity environment. Since an orbital isolation experiment was not logistically feasible during the coarse of the VIT ATD, it was decided to attempt a hardware proof-of-concept demonstration during low gravity flight trajectories. A 16 bit digitally controlled isolation system similar to the one developed during the technology development phase of the project was designed and built.

The six DOF demonstration hardware was flown through low gravity Keplarien trajectories to acquire performance data in an off-loaded environment. Although the low gravity environment is limited in time and the non-stationary aspects of the maneuver cause limitations in bandwidth and system control parameter testing, this environment allowed the testing of the full six DOF with comparable control and equilibrium states for both vertical and horizontal motions. This allowed the analysis of the data in the full three dimensional configuration where comparisons could be made in the multi-axis performance of the hardware.

The duration of these aircraft maneuvers typically lasts 10 to 15 seconds using the NASA Lewis Learjet aircraft. Therefore, the system testing bandwidth is constrained, mainly on the low end, by the trajectory duration. A typical parabolic trajectory begins with an initial 5^{o} dive followed by a 2 to 3 g pull up maneuver. Subsequently , after a few seconds through the push-over phase of the trajectory, the off-loaded reference frame of the aircraft is controlled from an inertial sensor in the rear of the aircraft. During this phase of the trajectory the active 16 bit demonstration hardware was activated, stabilized, and data was acquired to calculate the frequency response of the payload. In order to best recreate the dynamics of both the actively controlled payload and its support structure, two data acquisition systems (DAS) were flown. A slaved autonomous six channel DAS was attached to the suspended platform, while a master 14 channel DAS was flown for the Learjet acceleration and rotational environment time histories. A total of 18 acceleration and two gyroscopic data channels where digitized by a 14 bit converter at a speed of approximately 142 Hz. A total of approximately 70 to 80 active six DOF magnetic suspension trajectories were successfully performed generating approximately 30 megabytes of acceleration and gyroscopic data.

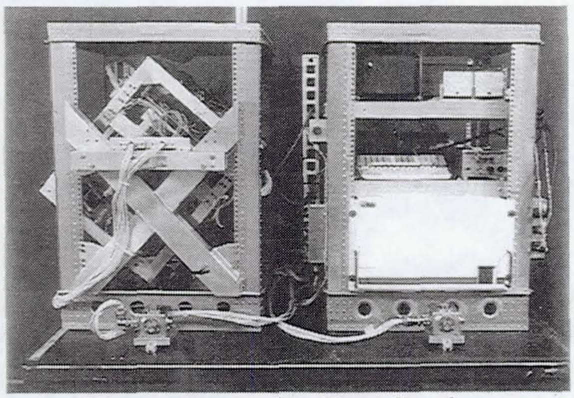


Figure 8: Active Test Section

The Learjet demonstration hardware was housed in a standard Learjet rack. These racks have standard instrumentation interfaces with T-rail mountings to attach to the aircraft fuselage. The Learjet hardware consisted of two instrumentation racks, one for the levitated test section and the second housing the control computer, dc power supplies, and support electronics. The levitated test section was interfaced with a trunnion support package housed internal to a standard rack allowing the experimental package to pivot about a trunnion support shaft. Figure 8 is a photograph of the two experiment racks mounted in the Learjet. The trunnioned support is shown pivoted about its support shaft. The electronics rack shows the control computer with the proximitor, accelerometer, and magnet dc power supplies. The master DAS was also housed in this rack. In addition, a computer monitor and two current meters were attached to the electronics rack, where the current meters gave the total magnetic actuator's current draw. The trunnion-attached hardware consisted of the levitated platform, three actuation pods, the control sensors, and the magnetic actuator's current control power amplifiers. Figure 9 is a photograph showing an end view of the trunnioned payload. The top part of the trunnioned cube housed the twelve power amplifiers and the proximitor drive signal conditioning circuits. The bottom of the trunnioned volume housed the actual isolation system. The isolated payload consisted of a ferromagnetic structure where the autonomous six channel DAS was housed and slaved to the master DAS. The autonomous slaved system was time synchronized with the master DAS. The two data acquisition systems were triggered by the press of a button prior to entering the low gravity portion of the Keplarien trajectories. This configuration gave the ability to control the six rigid body degrees of freedom.

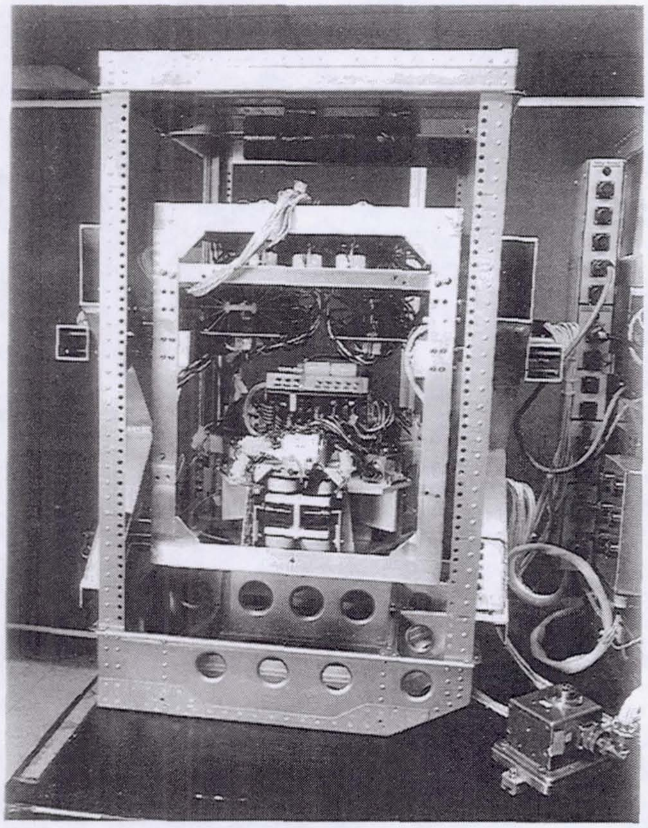
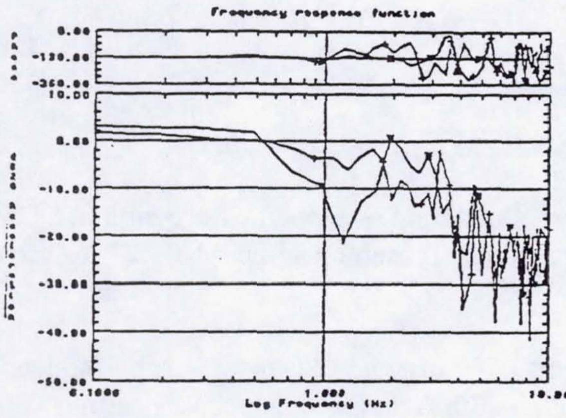


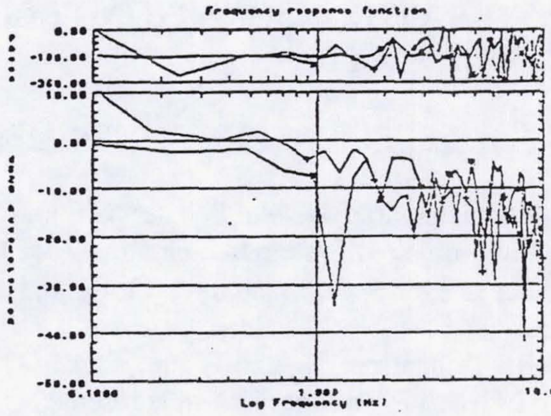
Figure 9: Learjet Active Isolation Testbed.

The natural frequency of the demonstration hardware was set at about 0.6 Hz as was the prototype laboratory hardware. However, the demonstration flights posed considerable environmental challenges. Therefore, the system was intentionally over damped in order to insure the stabilization of the platform after the initial conditions seen during the push-over phase of the parabolic flight. Figure 11 shows the frequency response curves for two typical trajectories where the active system is under closed-loop relative/inertial, feedback/feedforward control. These frequency response curves are given for the vertical direction where the acceleration spectrum of the payload is compared to that of the support structure.

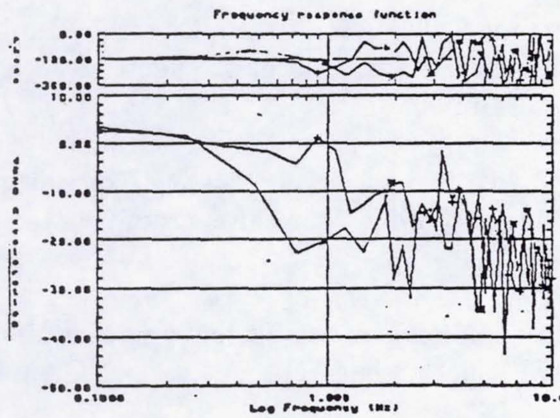
The relative and inertial frequency response curves were calculated from 17 and 14 second low gravity time histories, respectively. In order to get a fairly representative frequency response function for both cases, the elements per ensemble, with a 50% Hanning window, were set to generate the plotted curves with stable results. This gave a frequency resolution of 0.2 and 0.24 Hz for the relative and inertial cases, respectively. Figure 10 shows the response functions of a soft, well-damped system with a natural frequency of about 0.5 to 0.6 Hz. The inertially referenced curves as compared to the relative feedback curves show the system's increased roll-off and attenuation as a function of frequency. The expected increase in attenuation of inertial feedforward compared to relative control was masked in the bandwidth from 2 to 10 Hz due to directly induced vibrations from the onboard DAS equipment. Since the inertial feedforward and relative control does not control onboard disturbances, the excited DAS was a source of performance limitations for the system in the frequency band mentioned. However, the proof of concept demonstration for the active control of a space qualifiable six DOF inertially referenced payload was a success. The data conclusively demonstrated the increase in attenuation and roll-off of the system response for comparable relative parameters. The limitation of setting a lower cut-off frequency for the system in an inertial or relative control mode is a function of the testing environment as well as the performance limitations caused by the airborne energy seen during all trajectories. To the best of our knowledge this active inertial six DOF system was the first fully active isolation system demonstrated in a reduced gravity environment. The difficulty of ground-based testing six DOF systems to the sub-Hertz frequency range is self-evident, however, the control bandwidth tested during the course of the VIT ATD project has demonstrated the technology, both its advantages and disadvantages. The full validation of such systems can only be successfully attempted in a prolonged on-orbit low gravity environment.



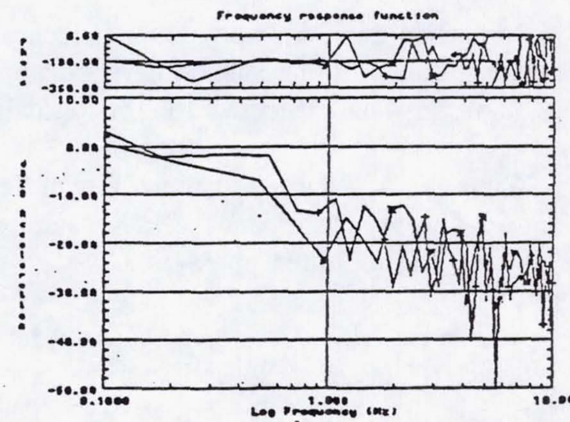
(10a) Location 6 on platform vs.
location 1 on trunnion.



(10b) Location 6 on platform vs.
location 2 on trunnion.



(10c) Location 6 on platform vs.
location 3 on aircraft fuselage.



(10d) Location 6 on platform vs.
location 4 on aircraft fuselage.

Figure 10: Frequency response of demonstration hardware in vertical dimension for inertial and relative control.

VIBRATION ISOLATION TECHNOLOGY (ATD) PROJECT PUBLICATIONS

MSFC PUBLICATIONS, EXPERIMENT SENSITIVITY

Ramachandran, N., and Schafer, C.F.: "Numerical Simulation of Forced Convection in a Two Fluid Layered System in a Floating Zone Configuration." Presented at the AIAA 27th Aerospace Sciences Meeting, January 9-12, Reno, Nevada, 1989.

Ramachandran, N., and Winter, C.A.: "The Effects of G-Jitter and Surface Tension Induced Convection on Float Zones." Presented at the AIAA 28th Aerospace Sciences Meeting, January 8-11, Reno. Nevada, 1990. AIAA Journal of Spacecraft and Rockets, 1990 (in press).

Ramachandran, N., "Buoyancy and Marangoni Convection in a Two Fluid Layered System-A Numerical Study." Presented at the AIAA 28th Aerospace Sciences Meeting, January 8-11, 1990 Reno, Nevada. AIAA Journal of Thermophysics and Heat Transfer, (in press).

Ramachandran, N., "G-Jitter Convection in Enclosures." 9th International Heat Transfer Conference, August 19-24, 1990, Jerusalem, ISRAEL. Paper 8-MC-03, Vol.3, pp 277-282.

Ramachandran, N., "Thermal Buoyancy and Solutal Convection due to G-Jitter." AIAA 29th Aerospace Science Meeting, January 9-10, 1991.

Ramachandran, N., "Convection Effects and Vibration Isolation for Protein Crystal." Fourth International Conference on Crystallization of Biological Macromolecules, August 18-24, 1991. Manuscript under preparation for Journal of Crystal Growth.

Winter, C.A., "Vibration Sensitivity of Selected Fluids and Materials Processing Experiments to Low-Gravity Disturbances." In Research and Technology 1989, Annual Report of the Marshall Space Flight Center, pp 72-74.

Alexander, J.I.D., Zhang, Y.Q., and Adebiyi, A., "Vibration Isolation Technology: Sensitivity of Selected Classes of Space Experiments to Residual Accelerations." NASA Research Grant NAG-8-724, First Annual Report, 1989.

Alexander, J.I.D., "Vibration Isolation Technology: Sensitivity of Selected Classes of Space Experiments to Residual Accelerations." NASA Research Grant NAG8-724, Semi-annual Report, January, 1990.

LeRC PUBLICATIONS, ISOLATION AND DAMPING

Grodsinsky, C.M. and Brown G.V., "Low Frequency Vibration Isolation Technology for Microgravity Science Experiments", NASA TM 101488. Presented at the 12th ASME Biennial Conference on Mechanical Vibration and Noise, Montreal, CANADA, September 17-20, 1989

Grodsinsky, C.M. and Brown, G.V., "Nonintrusive Inertial Vibration Isolation Technology for Microgravity Science Experiments", NASA TM- 102386. Presented at the 28th AIAA Aerospace Sciences Meeting, Reno, Nevada, January 8-11, 1990.

Logsdon, K.A., Grodsinsky, C.M., and Brown G.V., "Development of a Vibration Isolation Prototype System for Microgravity Space Experiments", NASA TM 103664
Presented at the COSPAR XXVIII, The Hague, NETHERLANDS, June 26-29, 1990.

Grodsinsky, C.M., "Development and Approach to Low Frequency Microgravity Isolation Systems", NASA TP 2984, July 1990.

Grodsinsky, C.M., and Logsdon, K.A., "Development and Design of a Magnetic Inertially Referenced Isolation System for Microgravity Experimentation", NASA CP 10066, Proceedings of the Workshop on Aerospace Applications of Magnetic Suspension Technology, Hampton VA., September 25-27, 1990.

Knospe, C.R., Hampton, R.D., "Control Issues of Microgravity Vibration Isolation", NASA CP 10066, Proceedings of the Workshop on Aerospace Applications of Magnetic Suspension Technology, Hampton VA., September 25-27, 1990.

Hampton, R.D., Grodsinsky C.M., Allaire, P.E., Lewis, D.W., Knospe, C.R.,"Microgravity Vibration Isolation: An Optimal Control Law for the One Dimensional Case," NASA TM 105146, October 1991.

Banerjee, B.B., Allaire, P.E., Knospe, C.R., "Vibration Isolation of Science Experiments in Space-Design of a Laboratory Test Setup", NASA CP 10066, Proceedings of the Workshop on Aerospace Applications of Magnetic Suspension Technology, Hampton, VA, September 25-27, 1990.

Grodsinsky, C.M., and Sutliff, T.J., "The Vibro-Acoustic Mapping of Low Gravity Trajectories on a Learjet Aircraft", NASA TM 103103. Presented at the Second Workshop on Microgravity Experimentation, National Research Council of Canada, Ottawa, May 8-9, 1990.

Knospe, C.R. and Allaire, Univ. of Virginia, "Limits on the Isolation of Stochastic Vibration for Microgravity Space Experiments", AIAA Journal of Spacecraft and Rockets, 28(2): 229-237, March-April 1991.

Allan, A.P. and Knospe, C.R., Univ. of Virginia, "A Six Degree-of-Freedom Actuator Design for Microgravity Vibration Isolation", Proceedings of the International Symposium on Magnetic Suspension Technology, August 1991.

Hampton, R.D., Knospe, C.R., and Grodsinsky, C.M., "Controller Design for Microgravity Vibration Isolation Systems," IAF-92-0969, World Space Congress, Washington D.C., Aug. 28-Sept. 5, 1992.

Sinha, A. Kao,C.K. and Grodsinsky, C.M., " A New Approach to Controller Design for Microgravity Isolation Systems", Acta Astronautica, Vol 21, 1990:771-775.

Sinha, A., Wang, Y.P., Tsai, N.C., and Kao,C.K., Pennsylvania State University, "Active Vibration Isolation Algorithm to Maintain Microgravity Environment in Space Station", Final Report NASA Grant NAG3-949, December 1991.

Lubomski, J.F., "Proceeding of the Vibration Isolation Technology Workshop for Microgravity Science Experiments." Cleveland, OH., September 28-29, 1988.

Lubomski, J.F., "Proceedings of the International Workshop on Vibration Isolation Technology for Microgravity Science Applications." Cleveland, OH, April 23-25,1991. NASA CP-10094.

Hampton, R.D., Knospe, C.R., Grodsinsky, C.M., Allaire, P.E., and Lewis D.W., "Microgravity Vibration Isolation: Optimal Preview and Feedback Control." NASA TM 105673, May 1992.

LeRC PUBLICATIONS, REACTIONLESS MICROGRAVITY MECHANISMS AND ROBOTICS.

Rohn, D. A., Lawrence, C, and Brush, A. S.: "Microgravity Robotics Technology Program," ISA 88-1642, 1988.

Harman, P. E. and Rohn, D. A.: "The Impact of an IVA Robot on the Space Station Microgravity Environment," Proceedings, NASA/Army Space and Military Applications of Robotics Conference, Huntsville, AL, June 21-23, 1988.

Dodd, W. R., Badgley, M. B., and Konkel, C. R.: "User Needs, Benefits, and Integration of Robotic Systems in a Space Station Laboratory," NASA CR-185150, October 1989.

Brush, A. S.: "Microgravity Manipulator Demonstration," LST'88, NASA CP-3003-VOL 1, May 1988, pp. 217-227

Quinn, R. D. and Lawrence, C.: "Robots for Manipulation in a Microgravity Environment,"Sixth VPI&SU/AIAA Symposium on Dynamics and Control of Large Structures, June 6, 1987.

DeSilva, C. W., Chung, C. L., and Lawrence, C.: "Trajectory Design for Robotic Manipulators in Space Applications," submitted to International Journal of Robotics Research.

Chung, C. L. and Desa, S.: "Base Reaction Optimization of Redundant Manipulators For Space Applications," ASME Mechanisms Conference, Orlando, FL, Sept. 25-28, 1988.

Quinn, R. D., Chen, J. L., and Lawrence, C: "Redundant Manipulators for Momentum Compensation in a Micro-Gravity Environment," AIAA Guidance and Control Conference, Minneapolis, MN, August 1988.

Chung, C. L. and Desa, S.: "A Global Approach for Using Kinematic Redundancy to Minimize Base Reactions of Manipulators Used in Microgravity Environments," IEEE Robotics and Automation Conference, 1988.

Chang, R.Y.: "Simulation and Modeling of Multidegree of Freedom Mechanical System for Space Applications." MS Thesis, Department of Mechanical Engineering , Case Western Reserve University, Cleveland, OH, 1987.

Chen, J.L.: "Control of Reactionless Robots." MS Thesis, Department of Mechanical Engineering, Case Western Reserve University, Cleveland, OH, 1988.

Lin, N.J.: "Trajectory Optimization and Control of Robots in a Microgravity Environment." MS Thesis, Department of Mechanical Engineering, Case Western Reserve University, Cleveland, OH 1988

Chung, C.L.: "A Unified Motion Planning Approach for Redundant and Non-Redundant Manipulators with Actuator Constraints." Ph.D. Dissertation , Department of Mechanical Engineering, Carnegie-Mellon University, Pittsburgh, PA 1990.

DeSilva, C.W., Chung, C.L., and Lawrence, C.: "Base Reaction Optimization of Robotic Manipulators for Space Applications." Proc. International Symposium on Robots, Sydney, AUSTRALIA, November 1988.

Herndon, J.N., Gassell, R.L., Butler, P.L., Williams, D.W., Rohn, D.A. and Miller, J.H.: "Manipulator Hardware for Microgravity Research." Proceedings of the 38th Conference on Remote Systems Technology, American Nuclear Society 1990, Vol. 2, pp. 161-168.

Miller, J.H., Lawrence, C., and Rohn, D.A.: "The Dynamic Effects of Internal Robots on Space Station Freedom." AIAA Guidance, Navigation, and Control Conference, New Orleans, LA August 12-14, 1991, NASA TM-104345.

Newman, W.S., Glosser, G.D., Miller, J.H., and Rohn, D.A.: "The Detrimental Effect of Friction on Space Microgravity Robotics." IEEE International Conference on Robotics and Automation, Nice, FRANCE, May 1992.

Quinn, R.D., and Lin, N.J.:"New Results Concerning the Use of Kinematically Redundant Manipulators in Microgravity Environments." AIAA Guidance, Navigation, and Control Conference, Boston,MA, August 14-16, 1989.

Rohn, D.A.: "Microgravity Mechanisms and Robotics Program." Lewis Structures Technology-1988, Vol.1-Structural Dynamics, NASA CP-3003, pp 1-143 to 1-156, 1988.

Rohn, D.A.: "Roller Drive Materials Performance." Lewis Structures Technology-1988, Vol.1-Structural Dynamics, NASA CP-3003, pp 1-203 to 1-216, 1988.

Rohn, D.A., Lawrence, C., and Miller, J.H.: Reaction-Compensation Technology for Microgravity Laboratory Robotics." i-SAIRAS '90 International Symposium on Artificial Intelligence Robotics, and Automation in Space, Kobe, JAPAN, November 18-20, 1990, NASA TM-103271.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	March 1994	Technical Memorandum

4. TITLE AND SUBTITLE

Final Report-Vibration Isolation Technology (VIT) ATD Project

5. FUNDING NUMBERS

WU-694-03-0C

6. AUTHOR(S)

Joseph F. Lubomski, Carlos M. Grodsinsky, Kirk A. Logsdon,
Douglas A. Rohn, and N. Ramachandran

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E-8487

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, D.C. 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM-106496

11. SUPPLEMENTARY NOTES

Joseph F. Lubomski, Carlos M. Grodsinsky, Kirk A. Logsdon, and Douglas A. Rohn, NASA Lewis Research Center; and N. Ramachandran, NASA Marshall Space Flight Center, Huntsville, Alabama 35812. Responsible person, Carlos M. Grodsinsky, organization code 6720, (216) 433-2664.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Category 01

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

A fundamental advantage for performing material processing and fluid physics experiments in an orbital environment is the reduction in gravity driven phenomena. However, experience with manned spacecraft such as the Space Transportation System (STS) has demonstrated a dynamic acceleration environment far from being characterized as a "microgravity" platform. Vibrations and transient disturbances from crew motions, thruster firings, rotating machinery etc. can have detrimental effects on many proposed microgravity science experiments. These same disturbances are also to be expected on the future space station. The Microgravity Science and Applications Division (MSAD) of the Office of Life and Microgravity Sciences and Applications (OLMSA), NASA Headquarters recognized the need for addressing this fundamental issue. As a result an Advanced Technology Development (ATD) project was initiated in the area of Vibration Isolation Technology (VIT) to develop methodologies for meeting future microgravity science needs. The objective of the Vibration Isolation Technology ATD project was to provide technology for the isolation of microgravity science experiments by developing methods to maintain a predictable, well defined, well characterized, and reproducible low-gravity environment, consistent with the needs of the microgravity science community. Included implicitly in this objective was the goal of advising the science community and hardware developers of the fundamental need to address the importance of maintaining, and how to maintain, a microgravity environment. This document will summarize the accomplishments of the VIT ATD which is now completed. There were three specific thrusts involved in the ATD effort. An analytical effort was performed at the Marshall Space Flight Center to define the sensitivity of selected experiments to residual and dynamic accelerations. This effort was redirected about half way through the ATD focusing specifically on the sensitivity of protein crystals to a realistic orbital environment. The other two thrusts of the ATD were performed at the Lewis Research Center. The first was to develop technology in the area of reactionless mechanisms and robotics to support the eventual development of robotics for servicing microgravity science experiments. This activity was completed in 1990. The second was to develop vibration isolation and damping technology providing protection for sensitive science experiments. In conjunction with the this activity, two workshops were held. The results of these were summarized and are included in this report.

14. SUBJECT TERMS

Active magnetic suspension; Microgravity isolation systems; Microgravity sensitivity; Microgravity mechanisms

15. NUMBER OF PAGES

36

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	