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# Vibration Isolation Technology: An Executive Summary of Systems Development and Demonstration

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# VIBRATION ISOLATION TECHNOLOGY: AN EXECUTIVE SUMMARY OF SYSTEMS DEVELOPMENT AND DEMONSTRATION

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## Abstract

In 1987 the Microgravity Science and Applications Division, of the Office of Space Science and Applications, organized Advanced Technology Development (ATD) programs in order to develop the enabling technologies needed for the use of Space Station Freedom as a viable microgravity experimental platform. One of these development programs was the Vibration Isolation Technology (VIT), ATD. This technology development program grew because of increased awareness that the acceleration disturbances present on the Space Transportation System (STS) orbiter can and are detrimental to many microgravity experiments proposed for STS, and in the future, Space Station Freedom (SSF). This paper will cover the overall technological organization of the VIT ATD program. Emphasis will be given to the results from development and demonstration of enabling technologies to achieve the acceleration requirements perceived as those most likely needed for a variety of microgravity science experiments. In so doing, a brief summary of general theoretical approaches to controlling the acceleration environment of an isolated space based payload and the design/performance of two prototype six degree of freedom active magnetic isolation systems will be presented.

## Introduction

The need for advanced vibration isolation systems or components for microgravity science experiments can be expected to grow as experiments and available hardware become more complex and the science community develops an understanding of their specific acceleration environment needs, relative to an achievable environment, on manned space missions. Achieving the documented microgravity requirement of the Space Station Freedom (SSF) will be and is a multi-faceted problem. An important aspect of this technology development will include, but not be limited to, environment control by preventing undesirable disturbances from perturbing their support structures. To achieve this "microgravity" environment it will be necessary to define the problem by determining reasonable acceleration levels and providing the required technology to achieve these levels.

The evolution of the Freedom Station design has led to potential limitations on long-term, low-gravity experimentation in this environment. It is now obvious that 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, mainly the sub-Hz range. The serious limitation of passive isolators is the absence of materials which have useful ranges of both low modulus (providing low frequency) and appropriate damping (to avoid large amplitude oscillation). Two-stage passive isolators can decrease the frequency range; however, limited damping leads to potentially large

amplitude oscillations in the random excitation environment.

Active systems offer significant advantages over passive systems in the orbital acceleration environment. Active systems require sensing of motion or position, and a feedback or feedforward control loop, or both, to counteract mechanical excitation and minimize acceleration of an isolated body. Such systems can introduce the complexity of a high-gain control system, but offer significant advantages in versatility and performance [ref. 1]. To achieve a broad spectrum of isolation, both feedforward and feedback control loops are used in the isolation system design presented.

The Microgravity Sciences and Applications Division (MSAD) at NASA Headquarters has recognized the need for addressing this issue and initiated the Advanced Technology Development (ATD) Program to address this and other MSAD technology needs. The Vibration Isolation Technology (VIT) Project ATD is funded by MSAD and was initiated in 1987.

The objective of the VIT ATD project was to provide the technology for the isolation of "microgravity" science experiments by developing methods and systems to maintain a predictable, well defined, well characterized, and reproducible low-gravity environment, consistent with the science needs of the microgravity community.

Included implicitly in the 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 in a manned orbiter.

This paper will summarize the theoretical and experimental findings from the VIT ATD project and will cover the three organizational topics results and conclusions. The organization structure of the technology research was based on three phases of development: (1) technology requirements, (2) technology development, and (3) technology demonstration.

Specifically, this paper will also present the general form of active controllers used in isolating a payload from low frequency base and direct disturbances. In addition, the prototype design for a six degree of freedom (DOF) active digital magnetic isolation system will be discussed and some overall performance data from the two prototype isolation systems developed will be presented. Future goals of this technology development work will be the attempt to foster support and advocacy, to push the next logical phase of such a research program: the verification of this technology in an orbital environment and to validate the g-jitter sensitivity research which has proliferated in the last five years.

## VIT Project Organization and Technical Approach

The VIT project was conducted in three concurrent phases: (1) technology requirements definition, (2) technology development, and (3) technology

The technology demonstration phase of the VIT ATD project was an in-house effort consisting of a proof-of-concept demonstration in a laboratory environment and then a systems demonstration during low gravity parabolic trajectories using the NASA Lewis Research Center's Learjet aircraft. A vibration isolation testbed was also 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. Then an 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.

### VIT Technology Development: Theory, Results and Discussion

In order to demonstrate the advantages of isolating a payload by proposed active inertial feedforward/feedback controller designs. A simple one degree-of-freedom spring-mass-damper system, shown in figure 1, can be solved, where  $F_s$  is a servo force proportional to the inertial position and velocity of the support structure and the isolated payload mass. Specifically,  $F_s$  can be defined

as;  $F_s \equiv B_{pff}\dot{u} + B_{vfb}\dot{x} + A_{afb}\ddot{x} + A_{vfb}\ddot{x}$ . 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 of the mass. While the feedback terms are derived from an accelerometer attached to the payload mass and the first integral of the sensor, giving the inertial velocity feedback term. The equation of motion for this system is:

$$m\ddot{x} + c(\dot{x} - \dot{u}) + k(x - u) + F_s = 0 \quad (1)$$

and substituting the defined servo force into (1),

$$\ddot{x}(1 + A_{afb}/m) + c/m(\dot{x} - \dot{u}) + b_{vfb}\dot{x} + a_{vfb} + k/m(x - u + b_{pff}u) = 0. \quad (2)$$

Using the following definitions,  $\omega_n^2 = k/m$ , where  $\omega_n$  is the natural frequency of vibration for the system, and  $\xi$  the viscous damping factor. The additional terms in equation (2) are defined as follows,  $c/m = 2\xi\omega_n$ ,  $A_{vfb} \equiv a_{vfb}m$ ,  $A_{afb} \equiv a_{afb}m$ ,  $B_{pff} \equiv b_{pff}k$ , and  $B_{vfb} \equiv b_{vfb}c$ , where the subscripts vfb, afb, pff, and vff stand for velocity feedback, acceleration feedback, velocity feedforward, and position feedforward, respectively. Equation (2) can be put into vibration notation using the above definitions giving the following form:

$$\ddot{x}(1 + a_{afb}) + 2\xi\omega_n\dot{x}(1 + a_{vfb}) + \omega_n^2x = u\omega_n^2(1 - b_{pff}) + \dot{u}2\xi\omega_n(1 - b_{vfb}) \quad (3)$$

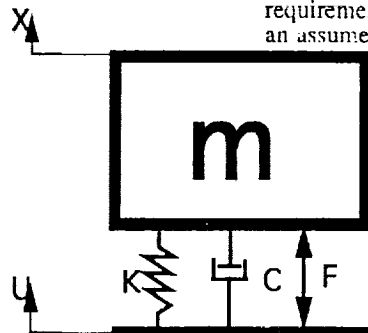


Figure 1: One Degree-of-freedom Inertial Feedforward/Feedback Physical Description.

demonstration. The technology requirements definition phase initially consisted of informally surveying potential users as to their requirements as well as discussions with industry to determine the current state-of-the-art capabilities. A VIT workshop was held and the proceedings published [4] to bring the users together with industry and university technologists to establish a dialogue between the two groups to better define needs and requirements. The results of the technology requirements definition phase were then used to focus vibration isolation technology development on the critical needs of vibration sensitive microgravity experiments.

An international Vibration Isolation Technology for Microgravity Science and Applications Symposia and Workshop was held April of 1991 as a culmination of the technology requirements definition phase of the VIT project. This Symposia/workshop was to present and evaluate the efforts of the various international organizations involved in VIT research, and to formulate plans to develop mutually beneficial cooperative efforts in the pursuit of VIT technology developments. This workshop was also used to evaluate NASA's future efforts in the VIT area, specific to MSAD's technology involvement. [ref. 2]

The technology development phase was conducted in-house and through university grants. This phase concentrated on low frequency actuator development and the associated control technologies. These specific research areas emerged from the initial VIT workshop as the critical technologies to be addressed for the vibration isolation of sensitive microgravity experiments. Analytic studies from the requirements definition phase indicate that the critical frequency regime for many microgravity experiments are in the quasi-static to 1 Hz range. [ref. 3] 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 will be required with larger stroke capabilities and more advanced control technologies than those of present day commercial systems.

In response to the technology needs addressed in the VIT workshop the design, fabrication and test of an active six DOF magnetic isolation system was developed, in laboratory and Learjet parabolic flight configurations. These digital isolation systems were used as tools to evaluate control algorithms, developed under the technology development phase in order to attenuate the acceleration environment of a payload. This approach enabled the use of a generic active digital isolation system with numerous optimal, and classical control approaches to the microgravity isolation problem. These control approaches are based on the scientific acceleration requirement limits and the optimal control strategies for an assumed disturbance environment.

If we take the Laplace transforms of  $x$ , and  $u$ , equation (3) becomes:

$$s^2 X(s)(1 + a_{fb}) + 2\xi\omega_n s X(s)(1 + a_{fb}) + \omega_n^2 X(s) = \omega_n^2 U(s)(1 - b_{ff}) + s2\xi\omega_n U(s)(1 - b_{ff}) \quad (4)$$

Taking the frequency response of the transfer function in the  $s$  domain, and calculating the magnitude of this function, one arrives at the following equation, giving the frequency response transfer function or transmissibility of the isolated payload to a harmonic base disturbance. Therefore, the following frequency domain transfer function can be written which depicts the various possibilities of actively controlling a single degree-of-freedom system through these various inertial feedforward/feedback techniques.

$$\left| \frac{X(j\omega)}{U(j\omega)} \right| = \left[ \frac{(1 - b_{ff})^2 + (2\xi\frac{\omega}{\omega_n})^2(1 - b_{ff})^2}{(1 - (1 + a_{fb})(\frac{\omega}{\omega_n})^2)^2 + (2\xi\frac{\omega}{\omega_n})^2(1 + a_{fb})^2} \right]^{1/2} \quad (6)$$

The frequency response transfer function is the magnitude response of dynamic output over dynamic input. As depicted by equation (6), 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. [ref. 4, and 5] 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 performance requirements.

Based on a relative feedback and inertial feedforward controller design a laboratory prototype six DOF system was designed and developed 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.

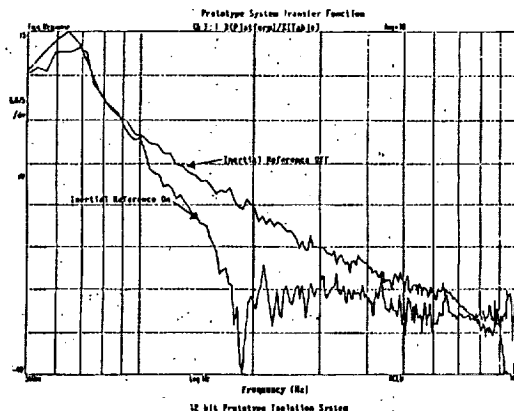


Figure 2: Prototype System Transfer Function.

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 in 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 2, the relative feedback control shows 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 systems tends to flatten out at about 26 to 33 dB where the 12 bit relative 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 2, are shown in figure 3. Figure 3 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.

### VIT Technology Demonstration: Theory, Results and Discussion

The objective of our research and development 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 course of our ATD VIT project, it was decided to attempt a hardware proof-of-concept demonstration during low gravity parabolic flight. The duration of these parabolic trajectories typically last 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 50° dive followed by a 2 to 3 g pull-up maneuver.

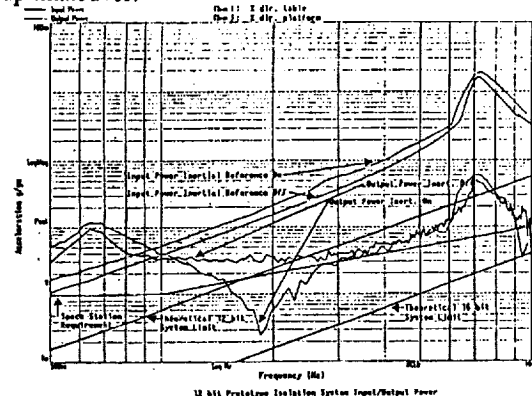


Figure 3: Prototype sys. Input/Output Power.

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 histories. A total of 18 acceleration and two gyroscopic data channels were digitized by a 14 bit converter at a speed of approximately 142 Hz per channel.

A noise floor performance measurement was taken of the 16 bit demonstration hardware. As shown in figure 4, the noise floor of the demonstration hardware with a system natural frequency set to about .5 Hz tends to follow the superimposed 16 bit theoretical resolution limit. The theoretical acceleration noise floor calculation assumes that a one bit change at the frequencies plotted will result in an acceleration on the payload. In practice, there will be random bit error and therefore, the actual noise floor should be better than predicted, but limited by the measurement sensor resolution, which for the Sunstrand QA-2000 accelerometers is on the order of  $.1\mu g/\sqrt{Hz}$ .

Figure 5 is a photograph of the active demonstration hardware integrated into a Learjet experimental rack. As shown in figure 5, the active six DOF demonstration hardware was integrated into a trunnioned testbed rack designed during the development portion of the VIT ATD project. This trunnioned support structure was designed to keep it's initial orientation during the low gravity portion of the trajectory. Therefore, during the course of the parabolic flight the payload package seemed to rotate with respect to the aircraft. This was done in order for the inertial feedforward loops not to inertially reference the payload during the aircraft's rigid body rotation of approximately 90°. Internal to this trunnioned support structure three actuation pods were mounted with the isolated payload structure housed within the volume defined by the attractive electromagnets attached to their respective actuation pods. The experimental hardware was configured to give a push-pull capability in two dimensions at three points, defined by the actuation pod locations, acting on the ferro-magnetic platform.

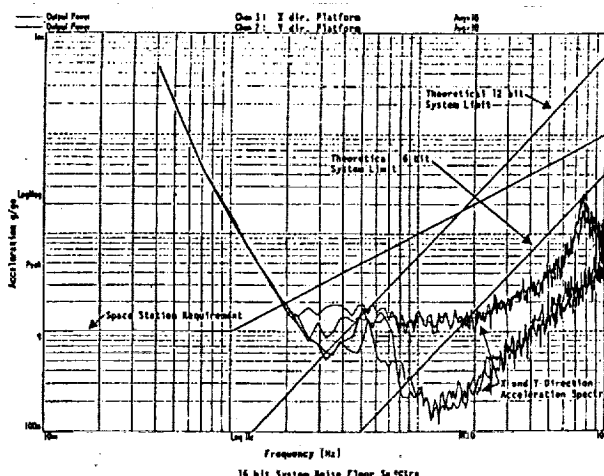


Figure 4: Demonstration Hardware Noise Floor.

This configuration gave the ability to control six rigid body DOF: three translations, and three rotations. The natural frequency of the demonstration hardware was set at about .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 6, shows the frequency response curves for two typical trajectories where the active system is under a 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. 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 .2 and .24 Hz for the relative and inertial cases, respectively. Figures 6 shows the response functions of a soft well damped system with a natural frequency of about .5 to .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, seems to have been masked in the bandwidth from 2 to 10 Hz due to directly induced vibrations from the on-board DAS equipment. Since the inertial feedforward and relative feedback control does not control on-board disturbances, the excited on-board 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 used as well as the performance limitations caused by the airborne energy seen during all parabolic 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.

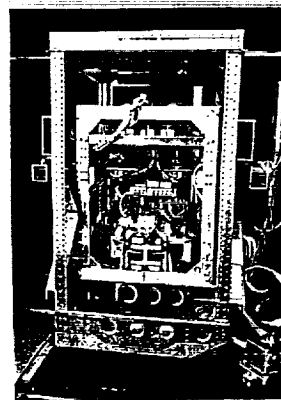


Figure 5: Active Demonstration Hardware Learjet Experiment Rack.

### Conclusions

The Vibration Isolation Technology Advanced Technology Development project was initiated in 1987 by MSAD. This project was chartered to develop and demonstrate the technology to isolate and produce a reproducible microgravity environment. During the course of the VIT ATD project two vibration isolation technology workshops were held to initially guide the project in developing the areas of expertise to achieve the desired systems and finally to conclude with the developments and findings of both the VIT ATD project and the other groups involved in this technology development. An additional outcome of the International Vibration Isolation Technology for Microgravity Science and Applications Symposia and Workshop was to give direction to future isolation needs and development work.

The VIT project was conducted in three concurrent phases. These phases were organized into technology requirements definition, technology development, and technology demonstration phases. The technology requirements phase consisted of surveying potential users as to their requirements in addition to determining the current state-of-the-art capabilities in the area of low frequency vibration isolation. The Vibration Isolation Technology workshop proceedings gave direction for the technology development and demonstration phases in order to meet the perceived requirements. In addition to these studies sensitivity analyses were made on certain classes of "microgravity" experiments and their respective susceptibility to oscillatory disturbances. The technology development phase concentrated on the control approaches for the stable isolation of a typical "microgravity" science payload and the development of a generic testbed system to demonstrate these control strategies. Once the development of the control approaches were completed the demonstration phase of the VIT ATD project was conducted to demonstrate a functional six DOF system concept in a reduced gravity environment.

Two six DOF systems were built and tested. Performance results showed the viability of using active relative and inertial control strategies in order to actively control ones acceleration environment to sub-Hertz frequencies. It is our belief that these techniques are readily applicable to the orbital environment and the application of such control strategies to lowering the control bandwidth to the .01 Hz range. The difficulty of ground based testing six DOF systems down to this frequency range is self evident however, the control bandwidth tested during the course of the VIT ATD project has validated the technology developed both in its advantages and disadvantages.

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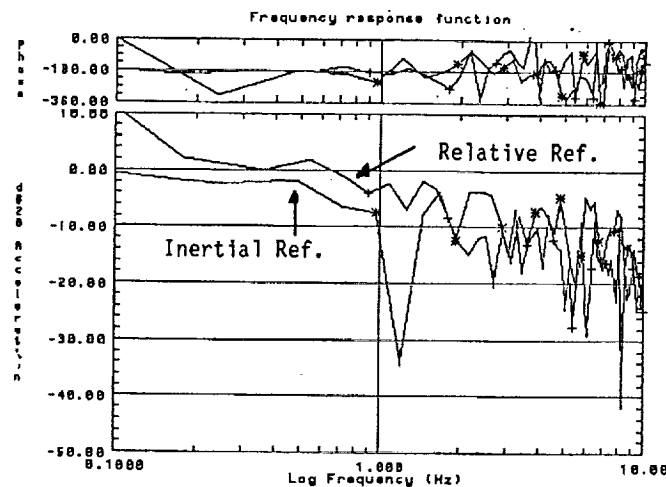


Figure 6: Frequency Response Curves for Inertial and Relative Feedforward/Feedback Control.

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