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Microgravity Vibration Control and Civil Applications

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Abstract

Controlling vibration of structures is essential for both space structures as well as terrestrial structures. Due to the ambient acceleration levels anticipated for the International Space Station, active vibration isolation is required to provide a quiescent acceleration environment for many science experiments. An overview is given of systems developed and flight tested in orbit for microgravity vibration isolation. Technology developed for vibration control of flexible space structures may also be applied to control of terrestrial structures such as buildings and bridges subject to wind loading or earthquake excitation. Recent developments in modern robust control for flexible space structures are shown to provide good structural vibration control while maintaining robustness to model uncertainties. Results of a mixed H_2/H_∞ control design are provided for a benchmark problem in earthquake engineering for building structural control.

Introduction

In space as well as on ground, the need exists for controlling structural vibrations. Due to high launch costs, space structures are designed to minimize mass, leading to lightly damped, flexible structures. In many cases, structural flexibility impacts mission objectives. Such was the case with the pointing control of the Hubble

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Space Telescope. The Hubble Space Telescope maintains very precise pointing with a stringent requirement of 0.007 arcseconds RMS (root-mean-square) pointing accuracy. In the initial configuration, a thermally driven vibration of the solar panels induced jitter that affected pointing performance to the extent that the control system had to be redesigned to provide sufficient damping of the detrimental flexible modes [Sharkey, *et. al.*, 1992].

Likewise, the International Space Station will be a flexible space structure subject to vibration disturbances. Since the International Space Station is being developed as a laboratory for scientific inquiry in extremely low gravity (called "microgravity" or µg), it is imperative to provide a low-level acceleration environment on the station. However, due to factors such as crew motion and mechanical devices such as pumps, fans, motors, the Space Station acceleration environment will be anything but quiescent. Figure 1 illustrates the anticipated RMS acceleration levels on the Space Station as a function of frequency. Also shown is the tolerable level of acceleration as specified by the µg science community.

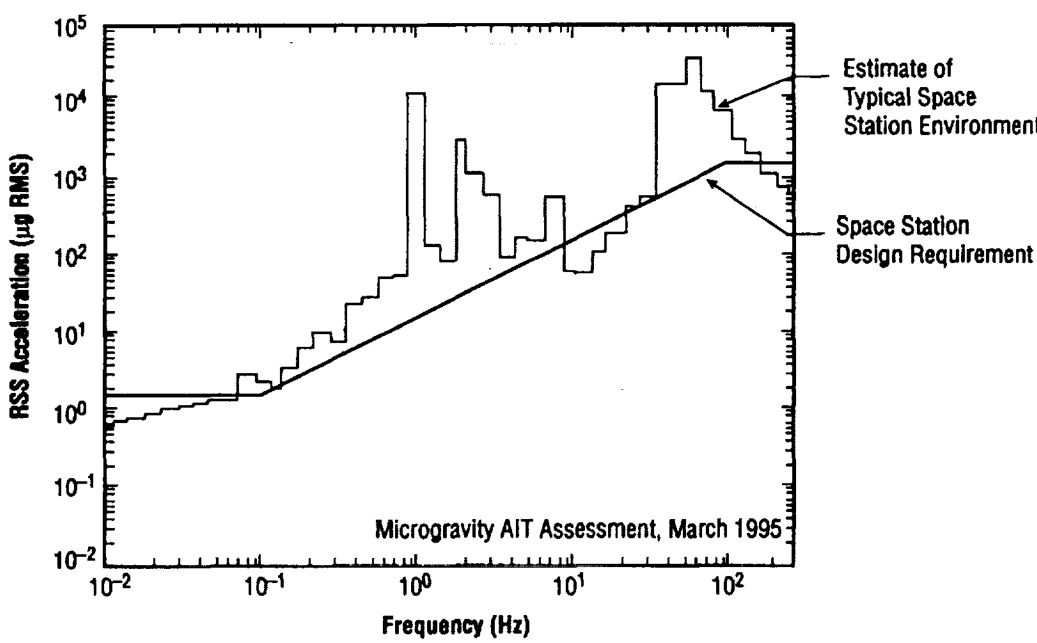

Figure 1: Microgravity Acceleration Environment of International Space Station

Clearly the need exists to reduce the acceleration environment to an acceptable level. Whereas the Hubble Space Telescope used active control to mitigate the effect of structural vibrations on pointing performance, the Space Station will not use active control for suppression of structural vibrations. Instead, active vibration isolation systems will be used to isolate acceleration sensitive experiments from the structural vibrations of the Space Station.

This paper is organized as follows. First, background information is presented on science operations in microgravity. Next, the microgravity vibration isolation problem is given with descriptions of various vibration isolation systems which have been developed for reducing disturbances. Attention is then directed to application of vibration control technologies to terrestrial applications with a description of new developments in robust control theory. Finally, results are given of a robust control design for a benchmark problem in building control during an earthquake.

Science in Microgravity

Many scientific endeavors require controlled conditions that cannot be obtained in ground-based laboratories. For science that requires a low gravity environment, a variety of options exist depending on the duration of the low forces needed. Researchers may use drop towers (couple of seconds), low-gravity aircraft such as the NASA Learjet or KC-135 Reduced Gravity Aircraft (tens of seconds), sounding rockets (several minutes), or orbital vehicles such as the space shuttle and International Space Station (ISS) (hours or days). In addition to the varying duration of low gravity with these options, the magnitude and spectral content of accelerations and resources available to the user differ.

A key function of the ISS is to provide a world-class capability for research in the biological, chemical, and physical sciences that require a microgravity acceleration environment. NASA's Microgravity Science Research Program sponsors research in the areas of biotechnology, combustion science, fluid physics, fundamental physics, and materials science [Delombard, *et. al.*, 1997]. The NASA Microgravity Biotechnology Program addresses research to identify and understand protein structure, protein crystal growth, and cell/tissue culturing leading to developments in the medical, pharmaceutical, and agricultural industries. The NASA Microgravity Combustion Science Program focuses on understanding combustion processes such as ignition, propagation, and extinction of various flames in low-gravity to enhance fire safety in space and on earth. Research on fluid dynamics and transport phenomena in the presence of low gravity is conducted as a part of the NASA

Microgravity Fluid Physics Science Program. Other science disciplines are benefited as well from fluid physics research in that an understanding of gravity-dependent fluid phenomena that affect experimental observations is sought, leading to better design of space-based facilities that rely on fluid processes. The NASA Microgravity Fundamental Physics Science Program provides opportunities to test fundamental scientific theories that require low gravity or cryogenic temperatures. Research in areas such as transient and equilibrium critical phenomena, condensed matter physics, relativistic physics, and atomic physics is conducted under this program. A better understanding of materials processes that might lead to improvements in production methods and materials is sought under The NASA Microgravity Materials Science Program.

Each of these distinct disciplines, as well as specific investigations within each discipline, vary in sensitivity to the magnitude, direction, and transient and/or spectral nature of the acceleration environment. Recognizing that the tolerable levels of acceleration vary greatly among experiments, a generalized, composite representation of the desired acceleration environment for the space station has been developed as shown in Figure 1. Although this plot of acceleration versus frequency is used for deriving requirements for both the science user community and vehicle (ISS) designers, it is at best a broad generalization of the effects of accelerations on science experiments. Requirements are also determined from a specification of acceptable levels of transient impulsive disturbances. Note that these requirements are specified for monochromatic harmonic accelerations in one axis and the effect of simultaneous excitations in multiple axes at multiple frequencies is not explicitly addressed (nor is it well-understood at this point).

Microgravity Vibration Isolation

In light of the anticipation that the acceleration environment of the ISS will exceed the acceptable level for microgravity science research, two options for remediation exist. Both options involve active isolation because passive methods are ineffective due to the low frequencies of interest and constrained volume of the payloads. However, hybrid passive/active isolation approaches are useful in many instances. The first option is to isolate the primary disturbance sources which will reduce the acceleration levels experienced by the experiments. The ubiquity of disturbance sources and the difficulty of predicting the effect of these transmitted disturbances locally at the experiment renders this option technically and economically infeasible. The preferred option is to provide isolation at the experiment and ISS has adopted this philosophy. The following section highlights various systems developed for isolating payloads from disturbances.

Vibration Isolation Systems

Much work has been done during the past several years toward the development of active isolation systems for μg payloads. The NASA Lewis Research Center (LeRC) conducted an Advanced Technology Development Project in Vibration Isolation Technology from 1987 through 1992 which sponsored in-house technology and funded numerous contractor studies and hardware development [Lubomski, *et. al.*, 1994]. A six degree-of-freedom (DOF) laboratory testbed was developed to evaluate concepts and control strategies which led to an aircraft testbed system that was successfully tested on the NASA LeRC Learjet. Based on two decades of experience in active suspension systems, the Honeywell Corporation (formerly Sperry) developed the first isolation system for space shuttle flight applications called the Fluids Experiment Apparatus Magnetic Isolation System (FEAMIS) to support Rockwell's Fluid Experiment Apparatus (FEA) [Allen, *et. al.*, 1986]. However, FEAMIS was never flown. McDonnell Douglas Aerospace Corporation (MDAC) developed a 6-DOF active isolation system using piezoelectric polymer film actuators [Edberg, *et. al.*, 1993]. In early 1995, MSFC joined with MDAC to develop a vibration isolation system called STABLE. [Edberg, *et. al.*, 1996]. STABLE utilized non-contact electromagnetic actuators developed for a helicopter imaging system. The STABLE flight experiment on STS-73 was the first successful μg vibration isolation system to be flown in space. The Canadian Space Agency has developed a system called the Microgravity Vibration Isolation Mount (MIM) which began operation aboard the Russian MIR space station during 1996 and was flight tested on the space shuttle flight STS-85 in August, 1997. The Active Rack Isolation System (ARIS) developed by The Boeing Corporation provides isolation to an entire rack. ARIS uses voice coil actuators with pushrods to attenuate disturbances transmitted through the utility umbilicals to the isolated rack. Based on the large mass and low stiffness of the umbilicals and actuator flexures, ARIS relies on passive attenuation in frequencies above the five Hz range. ARIS was flight tested on STS-79 in September 1996 [Bushnell, 1996]. An isolation system was developed by the European Space Agency, also called the Microgravity Isolation Mount (MGIM), and tested in the laboratory to support Space Station research [Owen, *et. al.*, 1993]. Satcon Corporation developed a ground test version of a 6-DOF vibration isolation system as did

Applied Technology Associates, Inc. with a 3-DOF system. With the exception of the MDAC piezoelectric polymer film actuator and the ARIS system, each of the systems previously described above non-contacting electromagnetic actuators to isolate an individual experiment.

Terrestrial Application of Advanced Technology for Vibration Control

Much like the need to control vibrations in space structures, many terrestrial applications of structural quieting exist. Traditional methods for mitigating vibrations of structures include adding structural mass to stiffen the structure. However, the cost of launching payloads to orbit renders this option unfeasible for flexible space structures. Instead, active control must be used to mitigate vibrations of flexible space structures. Active control may be thought of as a means to effectively stiffen a structure (such as with position feedback) or effectively increase its structural mass (such as with acceleration feedback). Force producing devices (actuators) may be used to actively cancel disturbance forces applied to a structure. However, in many cases adding structural mass may not be sufficient for ground structures either. In those cases, technologies that have been developed for space application can be fruitfully applied to the problem of controlling vibrations in civil structures such as buildings, bridges, and towers.

Both space and terrestrial applications of vibration control have many common issues. In both cases, the design objective is to mitigate the motion of a flexible structure in response to the motion of a "base" in order to protect a "payload" (i.e. people, sensitive equipment, or the structure itself). Efficient usage of resources such as power is essential. Reliable, fault-tolerant components such as power systems, electronics, processors, sensors, actuators, and data systems are critical in both applications. From the control design perspective, the need is to accommodate the excitation uncertainties while being robust with respect to structural dynamic uncertainties. Although some minor distinctions exist, the same control theory applies to both application. For example, with space applications the objective is to minimize inertial acceleration while for terrestrial structures the objective is to minimize relative displacements and/or accelerations. Also, low force level electromagnetic actuators are desirable for space usage whereas ground applications require high force actuators such as hydraulic mass-driver systems or tendon/electrical motor systems.

Concepts for active and hybrid active/passive control of structures have been explored for many years with recent attention given to the application of robust control theory. Robust control is concerned with maintaining stability and performance with uncertainty in the dynamical system. Uncertainties are basically the discrepancies between the mathematical model of the plant to be controlled and the actual plant. Uncertainties may include neglected dynamics, nonlinearities, and unknown or poorly known parameters such as mass, stiffness, and damping. Exogenous inputs or disturbances may also be considered uncertainties. For microgravity vibration isolation, these exogenous inputs include sensor noise, forces applied directly to the isolated platform and base motion transmitted through flexible umbilical connections. For an actively controlled building, seismic activity, wind gusts and sensor noise are examples of exogenous disturbances. Because robust controllers can tolerate uncertainties, control of structural vibration such as microgravity science payloads or the seismic response of a building are ideal applications.

Robust Control Design and Results

While robust control provides performance in the presence of uncertainties, the performance is often defined by an H_∞ norm measure, which may not be well suited to the performance objectives. In cases such as minimizing control energy, line-of-sight pointing error, or minimizing the mean-square vibration response of a structure, the H_2-norm is a better measure of performance. However, it is well known that H_2 design at high control authority levels has very poor robust stability properties. These issues are addressed in the mixed H_2/H_∞ design method. Mixed H_2/H_∞ design seeks to minimize the H_2-norm of one transfer function while satisfying an overbound constraint on the H_∞ norm of another transfer function. Using this approach allows one to design for H_2 nominal performance while maintaining the robust stability provisions of H_∞ design.

There are various design approaches for the problem of building structural control which achieve nominal performance only (H_2), robust performance (H_∞ or μ-synthesis), and nominal performance/robust stability (mixed H_2/H_∞ or mixed H_2/μ). The challenge is to achieve the highest attainable level of mean-square performance for a specified bounded set of uncertainties. For a more thorough treatment of the underlying control theory, uncertainty modeling and control design results, reference is made to [Whorton, 1997]. This reference compares these controller design techniques and applies the design approach to a benchmark problem in structural control of buildings using the three-story tendon controlled structure at the National Center for Earthquake Engineering Research [Spencer, *et. al.*, 1997].

The results of this work show that while considering nominal mean-square performance, robust stability is a necessary design consideration. Robust stability requires the closed loop system to remain stable for bounded model errors. A significant difference in performance exists between the H_2 and μ designs since the μ designs achieve a given level of output performance at a higher control cost than the H_2 designs. However, the mixed H_2/H_∞ designs effectively recover the mean-square performance of the H_2 designs while providing the same level of robust stability as the μ designs. The mixed H_2/μ design procedure provides performance comparable to H_2 design while overcoming the major shortcoming of H_2 design, namely a lack of stability robustness. An evaluation model was used with the Simulink model provided with the benchmark problem to generate time responses for the controller designs.

Conclusions

The demand for light weight structures in space presents challenges to the control designer. Light weight structures tend to be very flexible with lightly damped low frequency vibrational modes. Robust control theory has been developed to provide high performance vibration control in the presence of uncertain dynamical systems. A current application of this technology is microgravity vibration isolation for Space Shuttle and Space Station science experiments. This technology may also be fruitfully employed for terrestrial applications such as building vibration control. In particular, modern robust control provides the good mean-square performance while maintaining robustness to uncertainties in the earthquake excitation and structural dynamics of a building. This paper has presented various isolation for space application of vibration control as well as highlighting a design example for a terrestrial building control problem to demonstrate the successful transfer of space technology to terrestrial applications.

References

Allen, T. S., Havenhill, D. D., and Kral, K. D., "FEAMIS: A Magnetically Suspended Isolation System for Space-Based Materials Processing," 1986 AAS Guidance and Control Conference, Keystone, Colorado, Feb. 1-5, 1986.

Bushnell, G., "STS-79 Quick Look Report, RME-1313," Boeing Defense & Space Group, Research & Technology, Document No. SK683-62235-1, Oct. 16, 1996.

DeLombard, R., Bushnell, G., Edberg, D., Karchmer, A., and Tryggvason, B., "Microgravity Environment Countermeasures Panel Discussion," AIAA Paper No. 97-0351.

Edberg, D. L., and von Flotow, A., "Design Considerations for a Microgravity Vibration Isolation System," AIAA Paper 93-1116, Presented at the AIAA/AHS/ASEE Aerospace Design Conference, Irvine, CA, February 16-19, 1993.

Edberg, D. L., Boucher, R., Schenck, D., Nurre, G. S., Whorton, M. S., Kim, Y. and Alhorn, D., "Results of the STABLE Microgravity Vibration Isolation Flight Experiment," AAS Paper 96-071, *Guidance and Control 1996, Volume 92, Advances in the Astronautical Sciences*, Ed. By Robert D. Culp and Marvin Odefey, 1996.

Lubomski, J. F., Grodsinsky, C. M., Logsdon, K. A, Rohn, D. A., and Ramachandran, N., "Final Report-Vibration Isolation Technology (VIT) ATD Project," NASA TM 106496, March 1994.

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

Sharkey, J. P., Nurre, G. S., Beals, G. P., and Nelson, J. D., "A Chronology of the On-Orbit Pointing Control System Changes on the Hubble Space Telescope and Associated Pointing Improvements," *Proceedings of the AIAA Guidance, Navigation, and Control Conference*, Hilton Head, SC, August 1992.

Spencer, B. F. Jr., Dyke, S., and Deoskar, H., "Benchmark problems in structural control,'' *Proc. 1997 ASCE Structures Congress*, April 13-16, 1997, Portland, OR.

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