

Recent Achievements in Vibration Isolation Systems for Space Launch and On-Orbit Applications

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RECENT ACHIEVEMENTS IN VIBRATION ISOLATION SYSTEMS FOR SPACE LAUNCH AND ON-ORBIT APPLICATIONS

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ABSTRACT

This paper presents successful recent applications of several vibration mitigation technologies to space and launch systems. These technologies include: whole-spacecraft vibration isolation and shock protection during launch, an innovative fluid-free magnetic isolation system for the Hubble Space Telescope servicing mission, precision isolation and pointing platforms for on-orbit applications, and pneumatic isolation technology for 0-g ground test systems.

INTRODUCTION

Increasing performance and reducing cost are major considerations affecting the design of current and future satellite systems. This design process is currently greatly affected by the vibration environment experienced during qualification, launch, and operation. In the qualification and launch phase, this vibration environment is responsible for a significant number of satellite failures. Even when the spacecraft can be designed to successfully withstand these loads, substantial mass must be added to the satellite for launch survivability. This greatly increases launch costs and reduces mass margin that could be used to launch additional payload. For these reasons, several approaches have recently been examined for reducing the effect of launch vibration and shock on satellite systems.

At the other end of the spectrum, on-orbit vibrations induced from various spacecraft disturbances can have a substantial negative effect on the performance of sensitive payloads that require precise pointing. While much less severe than launch vibration, these vibrations can drive up the cost of precision spacecraft, due to the need for low-vibration components and increased demands placed on the sensors themselves. One approach to achieving increased performance for such systems at potentially lower cost is to provide vibration isolation and suppression capabilities at the interfaces between the satellite and either the sensitive payload or the vibration generating component. Recently, several active/passive hybrid devices have been built that offer excellent performance, even at relatively low frequency (e.g. 1-2 Hz).

This paper describes some of the recent achievements for mitigation of the vibration environment for both launch and on-orbit operation. These ground and flight demonstrations are now making it possible to consider these previously immature technologies in the design and launch of current and future satellite systems.

WHOLE-SPACECRAFT LAUNCH VIBRATION/SHOCK ISOLATION

SoftRide Passive Isolation Systems

Launch dynamics are a major design driver in structural design of spacecraft. In many cases, launch survival is often a more difficult design problem than is ensuring operational performance in orbit. Either the dynamic launch loads on the spacecraft must be reduced or the spacecraft structure must be stiffened. Stiffening the structure adds weight, but reducing the dynamic loads on the spacecraft by whole-spacecraft vibration isolation can allow lighter weight systems, greatly reduce the risk that the spacecraft and its instruments will be damaged from vibration during their ascent into orbit, and allow more fragile equipment to be included in missions. As the severe launch environment also accounts for much of the expense of designing, qualifying, and testing spacecraft components, significant cost can also be saved if loads are reduced.

Other auxiliary approaches exist such as passive damping or local isolation of specific components. While often effective, these are spacecraft-specific and invariably add to the time and cost of development. An alternative approach is to isolate the complete spacecraft from the launch vehicle. By substantially changing the dynamic properties of the combined spacecraft/launch vehicle system, a whole-spacecraft vibration isolation system becomes a mechanical filter that reduces spacecraft damaging launch loads.

Typical vibration isolation systems work by connecting the isolated structure (payload) to the base structure (launch vehicle) by means of a resilient mount or mounts. The resilient mounts have low relative stiffness as compared to the base and payload, and some degree of structural damping. The stiffness of the resilient mounts is tuned so that the frequency of vibration of the supported payload on the resilient mounts is a specified value (isolation frequency). Damping in the resilient mounts reduces the amplitude of response of the payload at the isolation frequency when the system is under external excitation. The resilient mounts must allow relative motion between the vibrating base structure and the payload at the isolation frequency, which is referred to as the isolator stroke.

Because the spacecraft is a major structural component of the launch vehicle/spacecraft dynamic system, variations in the isolation frequencies greatly effect the dynamics of the entire system, not just the payload. Any unpredicted changes in the dynamics could have an adverse effect on the control system of the launch vehicle and cause instability and thereby loss of the mission. Therefore, the stiffness

properties of the isolation system must be relatively constant for the duration of the flight. This requires a linear isolation system under all load cases, including preloads from $-2g$'s to $+6g$'s accelerations of the launch vehicle. This eliminates using an elastomeric material (i.e., rubber mounts) as the stiffness component of the isolation system. Owners of spacecraft, which costs tens to hundreds of millions of dollars or more, demand a metallic connection between the spacecraft and the launch vehicle. This connection, the SoftRide system described in this paper, must provide a fail-safe connection that withstands the deflections due to the sum of the dynamic and quasi-static acceleration loads during launch. The system must also be as non-intrusive as possible (i.e. minimal height and weight).

On expendable launch vehicles, spacecraft are attached to the launch vehicle at their base either at discrete points or by a band clamp. If the attachment stiffness is made soft in the axial or thrust axis, then we refer to that type of isolation system as an axial system. Axial systems can provide isolation in the axial and two rocking directions and therefore can isolate against both axial and bending modes of the launch vehicle. If the attachment stiffness is made soft in the in-plane directions at the attachment points, then that type of isolation system will be referred to as a lateral or shear isolator. Whole-spacecraft vibration isolation systems may also be a combination of these.

Under a number of contracts from the Air Force Research Laboratory, Space Vehicles Directorate, CSA Engineering has been working on the concept of whole-spacecraft vibration isolation systems (hereinafter referred as the SoftRide system) since 1993. A number of design and performance analyses were performed on a variety of liquid-fueled and solid-fueled launch vehicles, all of which showed great promise. However, it was not until the launch of the GFO spacecraft on Orbital Science's Taurus launch vehicle in February 1998 did an isolation system designed to vibration-isolate the complete spacecraft actually fly. To date, five successful flights of the SoftRide system have been completed.

Two types of passive whole-spacecraft vibration isolation systems have been flown. These are (1) a patented uniaxial damped flexure system called SoftRide UniFlex, and (2) a patented multi-axis damped flexure system called SoftRide MultiFlex. These systems are intended to attenuate low-frequency launch vibration loads from about 40 Hz

and higher. The following sections describe the isolation systems and present flight telemetry data.

The SoftRide UniFlex whole-spacecraft vibration isolation system is intended to reduce dynamic launch loads that are predominantly axial (thrust-direction) in nature. The stiffness and damping of the isolators are sized to mission-specific requirements for reduction of these dynamic loads. This system consists of a set of damped flexure elements that connect the spacecraft to the launch vehicle. Figure 1 shows a UniFlex isolator. This consists of a titanium flexure and a constrained layer damping treatment. The metallic load path of this isolator allows a strong, predictable, stable connection between the spacecraft and the launch vehicle. The damping treatment provides sufficient damping to control resonant



Figure 1: SoftRide Uniflex Isolator

amplification of loads. The typical application of this isolation system is to replace each bolt at a field joint with a UniFlex isolator element, as shown in Figure 2. The typical location for the isolation system is just aft of the spacecraft separation system.

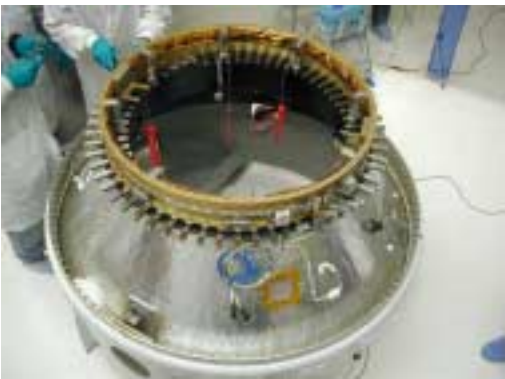


Figure 2 SoftRide UniFlex installation

The patented SoftRide MultiFlex whole-spacecraft vibration isolation system is intended to reduce dynamic launch loads that are both axial (thrust-direction) and lateral in nature. The stiffness and damping of the isolators are sized to mission-specific

requirements for reduction of these dynamic loads. Similar to UniFlex, this system consists of a set of damped flexure elements that connect the spacecraft to the launch vehicle. Figure 3 shows a MultiFlex isolator. This consists of a pair of UniFlex isolators separated from one another by a central post. The axial isolation is achieved by virtue of the UniFlex isolators in series with one another. The lateral isolation is achieved by the shearing of the assembly with bending occurring in the flexures. The typical application of this isolation system is to replace each bolt at a field joint with a MultiFlex isolator element, as shown in Figure 4.



Figure 3: SoftRide Multiflex Isolator



Figure 4: SoftRide Multiflex Isolator

There is significant flight heritage for whole-spacecraft vibration isolation. These systems have, to date, flown on five separate missions. Flight telemetry data indicating the flight performance of the isolation systems is available from four of the five missions and will be presented in the following sections.

Taurus 2 / GFO Mission

The first flight of a SoftRide Uniflex system occurred in February 1998 and successfully isolated the Geosat Follow-On (GFO) spacecraft on Orbital Science's Taurus launch vehicle. The GFO spacecraft interface was instrumented with six accelerometers that measured axial and lateral vibration during the flight. A single accelerometer was mounted in the flight direction just forward or on the soft side of the isolation system. The remaining spacecraft interface accelerometers were mounted aft or on the hard side of the isolation system. The accelerometers were sampled at 4000 samples per second with 8 bit resolution. Variable capacitance accelerometers were used which measured both the steady state and transient acceleration.



Figure 5: Taurus Launch Vehicle

An overplot of the time history of the response, during the first stage burn, from accelerometers mounted on the hard side (below isolators or on the launch vehicle side) and (above isolators or on the satellite side) of the isolation system is shown in Figure 6. The reduction due to the spacecraft isolation system is readily apparent by comparing the two time histories. The isolation system significantly reduces the vibration level to the payload by 50% for all load events.

It is of great interest to examine the performance of the SoftRide isolation system in the frequency domain. This allows inspection of the broadband attenuation characteristics of the SoftRide system. The dynamic system made up of the launch vehicle and spacecraft is non-stationary due to continual propellant depletion and stage separations. Also, the highly transient nature of most launch load events precludes digital signal processing of the flight data averaged over the entire launch window. Therefore, the frequency content of the transient flight data is best observed by creating waterfall PSD plots. These plots show the PSDs of 2-second windows of transient data, overlapped by 1 second, and stacked up next to each other.

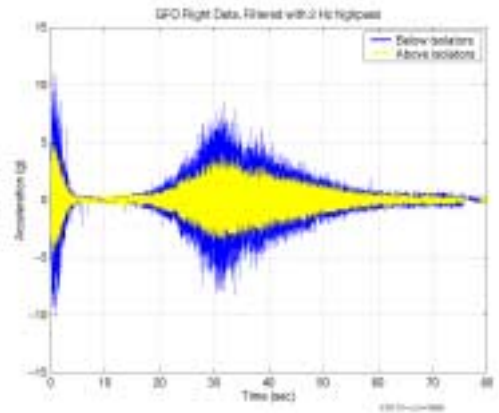


Figure 6 GFO flight data – below and above isolators

Figure 7 shows the waterfall plot for the axial acceleration below the isolators from the GFO flight. Similarly, Figure 8 shows the axial acceleration above the isolators from the GFO flight. Note that the sample rate of 4000 Hz only allows data to be examined up to 2000 Hz. Examination of these plots shows that the SoftRide system provided significant reductions in the acceleration levels across the broadband spectrum. It is believed that for this data, which was acquired during first-stage burn, the high frequency content (800 Hz to 1500 Hz) is caused by structure-borne acoustic energy.

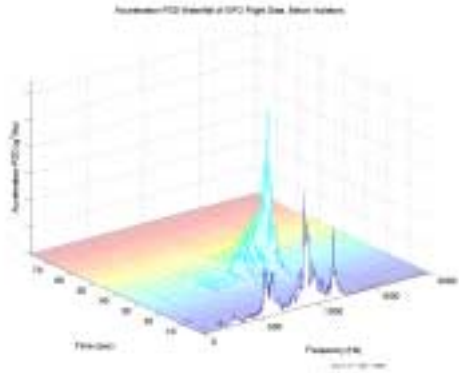


Figure 7 Waterfall PSD of GFO data - below isolators

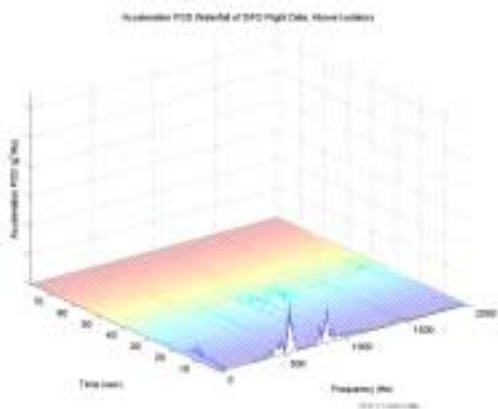


Figure 8 Waterfall PSD of GFO data - above isolators

Taurus 3 / STEX Mission

The Taurus/STEX SoftRide isolation system was very similar to that of GFO but was more aggressively designed for this mission. The STEX spacecraft was heavier than the GFO and therefore the isolation system was larger. With one successful flight of this system, the program offices allowed a slightly more aggressive design (lower in frequency) to be flown. Finite element models of the LV and spacecraft were obtained and full coupled-loads analyses were performed to design the isolation system. All of the same types of tests that were performed on the Taurus/GFO isolation system were performed on the Taurus/STEX system with the exception of a system test.

For the Taurus/STEX mission, data from two accelerometers, again one below and one above the isolators, was obtained. An overplot of this data is shown in Figure 9 (this data has been high-pass filtered to eliminate the quasi-static accelerations). This data shows a factor of five reduction in the broadband acceleration levels above the isolators.

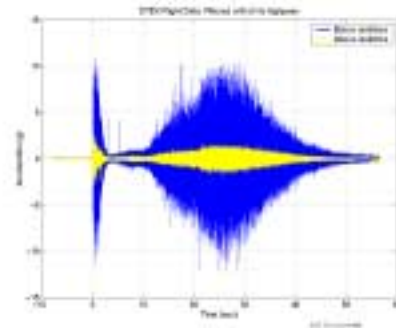


Figure 9 STEX flight data - below and above isolators

Waterfall PSD plots of this data are shown in Figure 10 and Figure 11. The high frequency accelerations below the isolators may be due to structural-borne acoustic energy. The SoftRide system has greatly reduced the structural-borne acoustic vibration on the spacecraft.

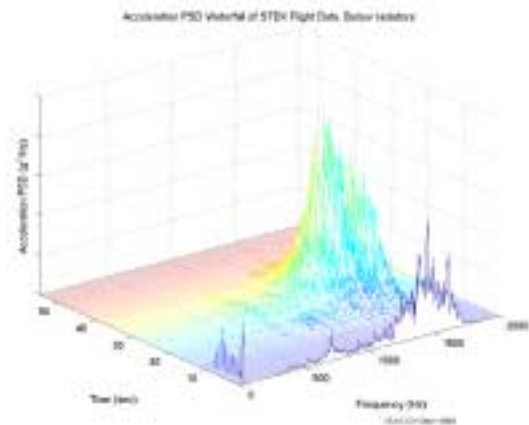


Figure 10 Waterfall PSD of STEX data - below isolators

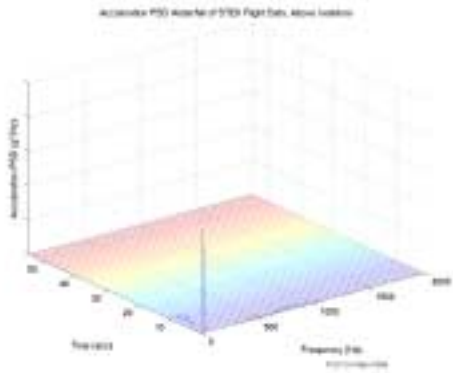


Figure 11 Waterfall PSD of STEX data - above isolators

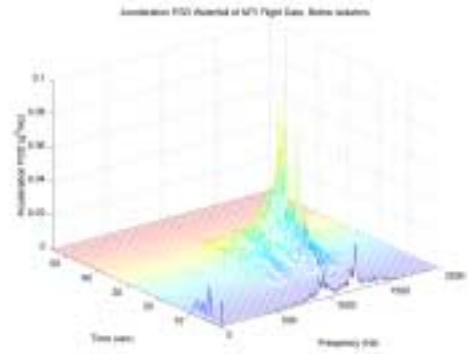


Figure 13 Waterfall PSD of MTI axial data - below isolators

Taurus 5 / MTI

For the Taurus/MTI mission, flight telemetry data was obtained below and above the isolators in both the axial *and* the radial directions. The instrumentation and data processing were done similarly to the GFO and STEX missions. Transient data and waterfall PSD plots for the axial direction are shown in Figure 12 through Figure 14. Similarly, transient data and waterfall PSD plots for the radial direction are shown in Figure 15 through Figure 17. Note that the UniFlex isolation system not only provides attenuation in the axial direction, but also provides significant reduction in dynamic responses in the radial direction.

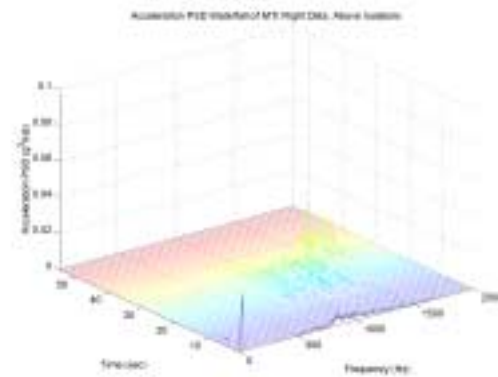


Figure 14 Waterfall PSD of MTI axial data - above isolators]

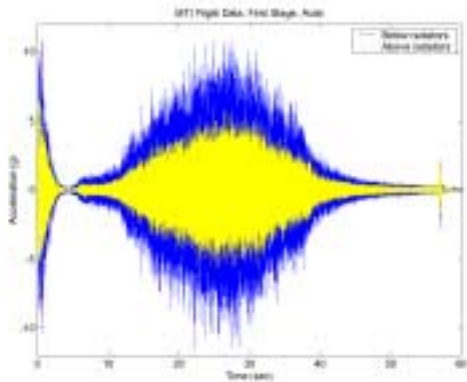


Figure 12 MTI axial flight data - below and above isolators

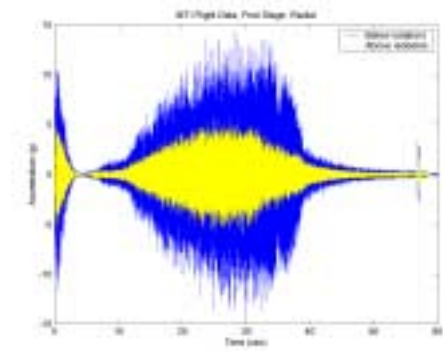


Figure 15 MTI radial flight data - below and above isolators

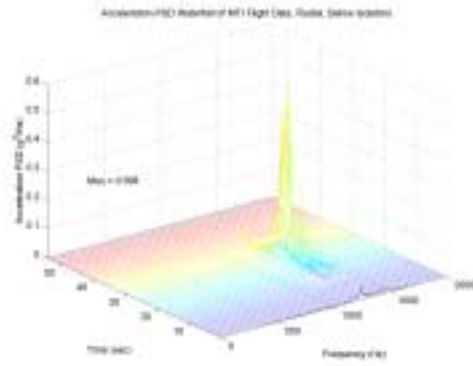


Figure 16 Waterfall PSD of MTI radial data - below isolators

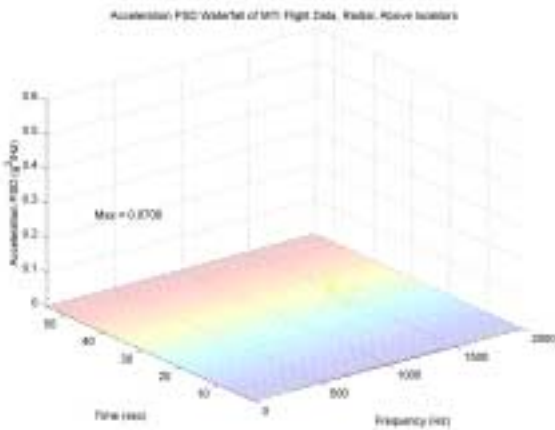


Figure 17 Waterfall PSD of MTI radial data - above isolators

Minotaur 1 / JAWSAT

The U.S. Air Force funded a significant data acquisition system on the Minotaur launch vehicle for the purpose of assessing the performance of the SoftRide vibration isolation system. A total of 18 accelerometers were flown for measuring accelerations on both the “hard” side (launch vehicle side) and “soft” side (spacecraft side) of the isolation system. These accelerometers were arranged into 6 triaxial sets: three triaxial sets on the hard side and three triaxial sets on the soft side. Flight data was examined and the trends



Figure 18: Minotaur LV

observed agreed very well with the predictions of coupled loads analyses. An example of some SoftRide acceleration flight data from the JAWSAT mission is shown in Figure 19. The quasi-static acceleration measurements have not been filtered out of this data. Note that excellent vibration isolation was achieved in both the axial (thrust) and the lateral directions.

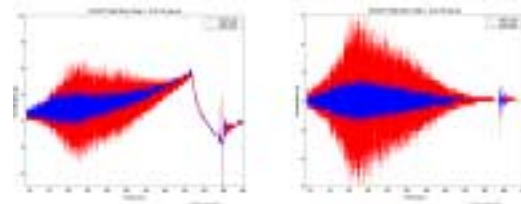


Figure 19 Typical SoftRide flight data Minotaur 1

Data showing the fairing separation shock event from the Minotaur/JAWSAT flight is shown in Figure 20. The flight accelerometers were not shock accelerometers and therefore some clipping of the high-level “hard side” shocks has occurred. However, the isolated “soft side” shows greatly reduced shock inputs to the base of the spacecraft.

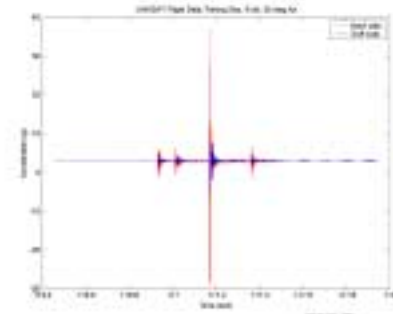


Figure 20 Fairing separation shock flight data showing SoftRide attenuation

Whole-Spacecraft Shock Isolation Systems

Whole-spacecraft shock isolation systems are currently under development for the purpose of attenuating shock inputs from the launch vehicle to the spacecraft. The major source of these shock inputs is typically fairing separation shock, dual payload attach fitting (DPAF) separation shock, stage ignitions, and stage shutdowns. While UniFlex and MultiFlex vibration isolation systems are tailored to mission-specific requirements for low frequency isolation, the shock isolation system is planned to be more of an “off-the-shelf” component. It is envisioned that, for each class of launch vehicle, the shock isolator will be a “one size fits all” or “two-sizes fit all” type of system for the purpose of

attenuating launch dynamic loads from frequencies of about 200 Hz and higher. A prototype patented shock isolator is shown in Figure 21.



Figure 21 Shock isolator

This isolator would be placed at a field joint below the spacecraft or be fabricated as part of the payload attach fitting. Typical test data for the shock isolator is shown in Figure 22. It is envisioned that this shock isolation system will be widely used in both small and large launch vehicles once the development and test of the system is completed.

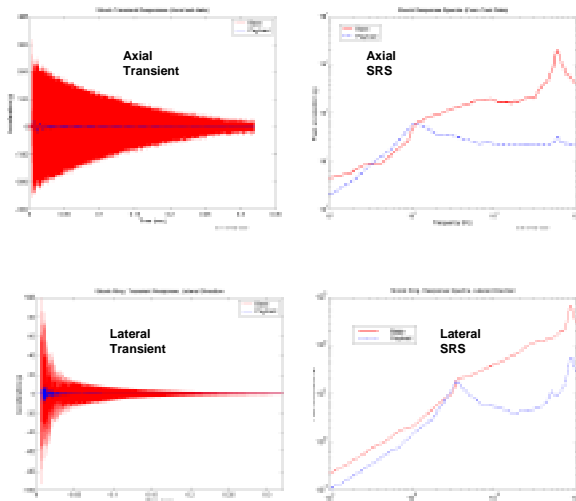


Figure 22 Transient responses and shock response spectra from test

HST Servicing Mission Isolation System

CSA conceived, designed, built, tested, and delivered a passive vibration isolation system to isolate a sensitive payload during launch aboard the Space Shuttle. The payload, called the Near-Infrared Camera/Multi-Object Spectrometer (NICMOS), flew on the February 1997 launch as part of the second servicing mission for the Hubble Space Telescope (HST). The Figure 23 shows the payload in its protective enclosure (called the ASIPE), supported by isolation system during testing at NASA Goddard.

The primary requirements on the isolation system are very long stroke (10.0 inches) and an integral damping mechanism that is highly reliable, qualified for space flight, and relatively insensitive to temperature over a range of -40 to +65°C. Of particular concern was the requirement that the damped isolation struts be absolutely free from any fluid leakage. In response to these requirements, CSA developed a fluid-free isolation strut using magnetic eddy current dampers. It is designed to meet not only the basic functional requirements of stroke, compliance, and damping, but the usual long list of reliability, space-compatibility, and quality assurance requirements expected of any critical flight hardware.



Figure 23: Reusable Magnetic Isolation System HST Servicing Mission (STS-82)

ON-ORBIT VIBRATION ISOLATION

SUITE

Spacecraft carry instruments and sensors that gather information from distant points, for example, from the Earth's surface several hundred kilometers away. Small vibrations on the spacecraft can reduce instrument effectiveness significantly. Satellites and their instruments are subject to vibration throughout their lifetimes. Improving performance during the operational lifetime of satellites and instruments is of primary interest. Although space is a much gentler vibration environment than that encountered during launch, vibration can cause problems during operation, the time over which the satellite functions on-orbit. Aside from their payloads, satellites require certain supporting equipment to carry out their missions. This may include reaction wheels to allow attitude control, solar array drives to position light gathering surfaces towards the sun, and cryogenic coolers to remove heat from instruments. The satellite may also act as host for multiple instruments, some of which may use gimbals or

scanning/articulating components to make their measurements. All of these devices and others are sources of vibration.

The major consequence of vibration is degraded performance of various satellite instruments. For example, for a satellite camera used to image objects on the ground or in the Earth's atmosphere, a small vibration on the spacecraft may result in significant image degradation. A relatively minor 10 microradian (0.00057 degree) angular vibration or jitter is equivalent to 50 m in the field of view or image at a distance of 500 km. Some, but not all jitter-induced effects can be removed with signal and image processing. Actual reduction of the jitter by more direct means is often desirable, if it can be done efficiently. This physical jitter reduction augments what is done later in signal processing.

In addition to imagers or cameras, satellites contain other vibration-sensitive components such as inter-satellite communications links. Each particular type of component is more or less susceptible to vibrations in certain bandwidths, at certain amplitudes. This includes components that are actively pointed via gimbals or other devices, whose actuators do not have the bandwidth necessary to control the higher frequency vibration.

Vibration isolation systems are one means of minimizing the jitter of sensitive instruments. This paper describes one such system, the Satellite Ultraquiet Isolation Technology Experiment (SUITE), designed and fabricated under an Air Force Phase-II Small Business Innovative Research (SBIR) contract. SUITE is a piezoelectric-based technology demonstration scheduled to fly in August 2001 on PICOSat, a microsatellite fabricated by Surrey Satellite Technology, Ltd.

The SUITE flight hardware, shown in Figure 24, consists of a hexapod assembly of six hybrid active/passive struts to provide vibration isolation and control of the platform in six degrees-of-freedom. Each strut contains a damped mechanical flexure to provide passive isolation above 28 Hz, with a piezoelectric stack actuator in series to provide control actuation. SUITE has been designed with the capability to be reprogrammed to implement a variety of control algorithms. A key component of the SUITE program has been to make active isolation systems more attractive by decreasing complexity and significantly lowering cost.

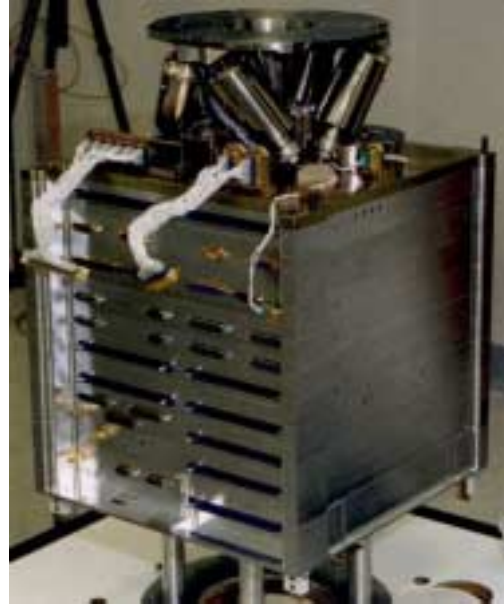


Figure 24: SUITE Isolation Platform and Control Electronics Integrated to Picosat

SUITE was designed to reduce the vibration transmitted between the spacecraft bus and the isolated payload, measured as a root mean square quantity above 5 Hz, in each of six axes by 20 dB (a factor of 10) in the presence of vibration sources located on the satellite.

The Data Control System DCS is located in a $338 \times 338 \times 32$ mm tall module tray in PICOSat and is separated from the hexapod assembly (HXA) by another double-height tray. Three cable harnesses incorporating 78 individual wires connect the DCS and HXA. The DCS is functionally a single board computer, with processors, memory, power converters, programmable logic, a communications interface, and interfaces to the analog transducers of the HXA. The DCS receives +14V power from the host spacecraft, filters it for EMI, and converts it to +5V, ± 15 V, and +100 V. Total power draw for the DCS is approximately 0.9A at 14 V. At room temperature, the full SUITE system consumes 15-16 W in data acquisition mode, 16-18W in full control mode, and up to 22.5 W if a disturbance generator is being used to shake the spacecraft.

The heart of the DCS is a Texas Instruments TMS320C31 digital signal processor (DSP). The DSP runs on a 40 MHz clock. Two field programmable gate arrays (FPGAs) interface the DSP and memory with the rest of the DCS and the HXA. A PIC 16C74 microcontroller at 16 MHz performs

several peripheral tasks, including communication with the PICOSat controller area network (CAN) bus, temperature sensor reads, and generation of PWM signals to drive the disturbance generators.

Each of the six isolation struts was designed to be identical with the others, both mechanically and electromechanically. The active-passive series architecture has been designed to decouple action of each strut from the others to allow a single input single output (SISO) control architecture. The SISO control approach is simple, requiring only a motion sensor and an actuator that can change its length within each strut. Although the SISO collocated controller is baselined within each strut, SUITE has the built-in flexibility to allow complex, fully-coupled, 12-input, 6-output control architectures. Only software and the processing power of the digital signal processor (DSP) limit the architectures.

Using the baseline controller, transmissibility was measured in the radial direction as well as the vertical (axial) direction. These results are shown in Figure 25 and Figure 26.

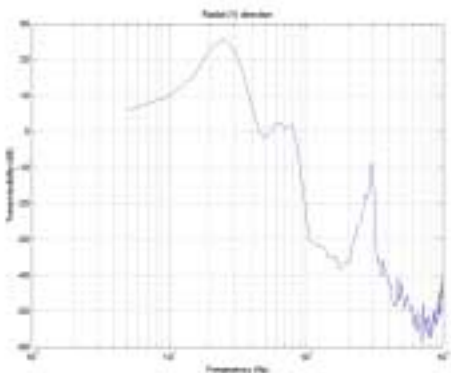


Figure 25: Measured Transmissibility in Radial Direction

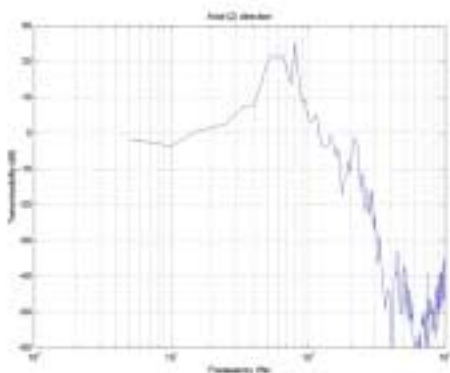


Figure 26: Measured Transmissibility in the

For reduced radial vibration transmission, the role of the active control is to reduce response in the 5 to 100 Hz range. The resonance at 300 Hz is a mode of the base plate resting on the test fixturing. The greater stiffness in the axial direction requires that the active control bandwidth extend to about 250 Hz to insure that the net transmissibility is below -20 dB.

ISOLATION FOR 0-G TESTING

Another important use for isolation technology is for ground testing of spacecraft and their components in simulated zero gravity. To simulate zero-gravity, it is desirable to replicate free-free boundary conditions through the use of an extremely soft isolation system (plunge frequencies below 0.2 Hz) that allows payloads to behave dynamically as if they are in zero gravity.

Using a frictionless air piston and air-bearing carriage (shown in Figure 27) in conjunction with an external tank volume, the system achieves high payload capacity with virtually no DC stiffness. A very light mechanical spring is used to hold the payload's mean position near the center of the vertical stroke of the device. Measured frequency response for 20 and 350 lb. payloads shown in Figure 28.



Figure 27: Zero-Gravity Suspension Device

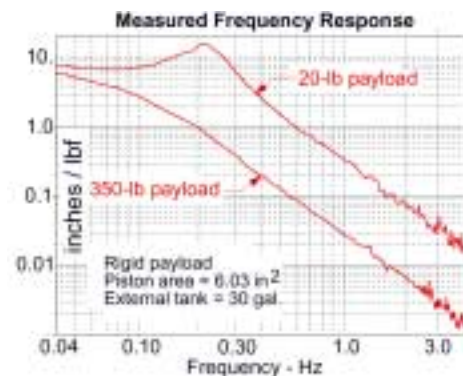


Figure 28: Measured Frequency Response for Zero-Gravity Suspension

CONCLUSION

Recent demonstrations of several vibration isolation systems make it feasible to now consider these technologies for use in operational systems. The SoftRide UniFlex and MultiFlex whole-spacecraft vibration isolation systems for all of the missions flown to date have proved to be a very effective means of reducing spacecraft responses due to the broadband structure-borne launch environment. From both the transient data and the waterfall PSD plots, it is clear that the SoftRide whole-spacecraft vibration isolation system performed very well to reduce structure-borne vibration levels transmitted to the spacecraft. The isolation system was designed specifically to reduce the effects of solid motor resonant burn in the 45 Hz to to 60 Hz frequency range, which it did very well. It should also be noted that the SoftRide vibration isolation system provided extreme reductions of shock and structure-borne acoustics at higher-frequencies. In the future, shock isolation systems will be available for use when low-frequency vibration isolation is not required. The shock isolation system has the benefit of not being a payload specific design. This should greatly reduce cost and simplify the analysis for many missions. In addition, isolation systems such as the one demonstrated in the HST servicing mission (STS-82) show that high performance systems can be designed that accommodate both launch and landing of reusable space vehicles.

Jitter reduction in sensitive spacecraft payloads is a serious concern, which is being addressed through a variety of approaches. Precision isolated platforms such as the SUITE experiment show that it is feasible to apply active and passive technology together to produce high performance robust systems for mitigating on-orbit spacecraft disturbances.

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BIOGRAPHIES

Dr. Keith Denoyer is a Senior Engineer with CSA Engineering and Manager of its Albuquerque, NM Branch Office. Prior to joining CSA in 2001, he was the Technical Advisor to the Spacecraft Component Technology Branch at AFRL's Space Vehicle Directorate. Over his government career, he has been involved in adaptive structures and spacecraft components research in activities ranging from basic research to advanced flight demonstrations. For these achievements as a civil servant, he has received several awards including the 2000 Arthur S. Flemming Award. Dr. Denoyer received his Ph.D. in Aerospace Engineering Sciences from the University of Colorado in 1996, an M.S. in Mechanical Engineering from Stanford University in 1992, and a B.S. in Mechanical Engineering from the University of Michigan in 1990.

Dr. Conor Johnson is a Principal Engineer and President of CSA Engineering. His technical expertise lies in the development, design, analyses, and application of passive vibration suppression. He was instrumental in the development of the modal strain energy method for finite element design of damping treatments, and was the recipient of the 1981 ASME Structures and Materials Award for this work. He received his Ph.D. in Engineering Mechanics from Clemson University in 1969, an M.S. in Engineering Mechanics from Clemson University in 1967 and a B.S. in Engineering Mechanics from Virginia Polytechnic Institute in 1965.