Electromechanical lever blocks for active vibration isolation

Lorenzo Zago* and Pierre Genequand

CSEM, Swiss Center for Electronics and Microtechnology
Jacquet-Droz 1, CH-2007 Neuchâtel, Switzerland

ABSTRACT

This paper is a follow-up of a presentation at the Smart Structures Symposium of 1998. There we described an innovative technical solution which provides a combined passive damping and isolation interface with the appropriate transmissibility characteristics between a vibrating base and a sensitive payload, typically an optical terminal/telescope.

The particularity of the solution is primarily found in the implementation of energy dissipation by means linear electro-magnetic linear motors leveraged by means of flexure elements, to constitute an integrated resistor-damped electromechanic lever block, which we called MEDI (Mechanical Elastic element for Damping and Isolation). Passive viscous damping with attenuation of the order of -20 dB at 50 Hz with respect to a hard fixation, is obtained by simply short-circuiting the electro-magnetic motor.

The study and test program presented here extends the application of MEDIs to active vibration reduction systems. The study, contracted by the European Space Agency, aimed at investigating the possibility of using the MEDI as an active isolator for scientific experiments in the International Space Station.

By controlling the current in the electromagnetic motor in closed loop with the signal from specially designed force sensor (with extremely low noise), we achieved attenuation of the order of -15 dB at 1 Hz, -30 dB at 10 Hz, -50 dB at 30 Hz, with the isolation slope starting as low as 0.1 Hz.

1. INTRODUCTION

Modern spacecraft platforms are complex systems which include a number of vibration generating components, such as inertia wheels, various motors, pumps and, in the case of an inhabited space station, human activity. These vibrations can be of concern for many instruments and payloads. Typical examples are laser beam communication systems which must maintain a tracking accuracy better than 0.2 arcsec on the sky, and experimental equipment in biology and material science designed for extremely low microgravity levels.

An innovative technical solution has been developed at CSEM in form of a passive resistor-damped electromechanical lever block which provides a combined isolation and damping with appropriate transmissibility characteristics at the location of isostatic mounts between the spacecraft platform and the equipment. This element is called Mechanical Elastic element for Damping and Isolation (MEDI) and was originally developed as a damper/isolator capable of attenuating passively vibrations ranging from about 5 Hz up to about 120 Hz, with amplitudes up to about 0.15 mm.

The novelty of the solution is primarily found in the implementation of uncoupling and magnification of the incurred vibrations by means of flexures. Viscous damping is provided by short-circuiting a linear electromagnetic motor, in which the mobile magnet is guided by a flexural parallelogram.

The resistor-damped electromechanical lever block has various advantages with respect to competing concepts. For instance being all metallic its performance is essentially insensitive to temperature and aging. In comparison with piezo-based system it has a larger inherent strength, which makes it in particular suitable for spaceborne systems which must sustain the launch loads.

* Correspondence: email: lorenzo.zago@csem.ch; www: http://www.csem.ch

In passive mode, obtained by short-circuiting the linear electromagnetic motor, the MEDI element provides typically an attenuation up to 20 dB between 5 and 100 Hz for a load of 50 Kg [1].

In 1998 a new project was started, called AMVR (Active MEDI Vibration Reduction). It aims at improving the performance of the MEDI by active control of the motor in closed loop with sensor signals located on payload. The target is an isolation capability staring as low as 0.1 Hz, a further amplitude attenuation to about -50 dB from a few 10 Hz onwards, in order to achieve a vibration reduction performance comparable to that of current developments for active isolation systems, such as ARIS [3] and MIM-2 [4], both targeted to the biology and material science experiment payloads which will be installed on the International Space Station (ISS).

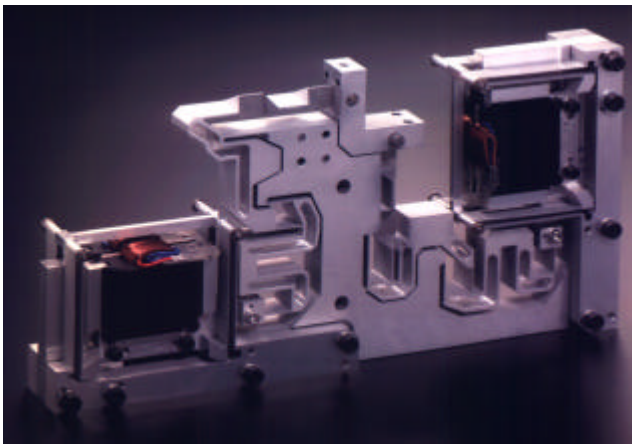

Figure 1 Two degrees of freedom interface element for isostatic mounts (MEDI)

2. THE *MEDI* FOR PASSIVE AND ACTIVE DAMPING

The MEDI lever block is essentially a flexible structure which uncouples, transmits and amplifies the relative motion between its both external interfaces (excited base and load) to electromagnetic actuators.

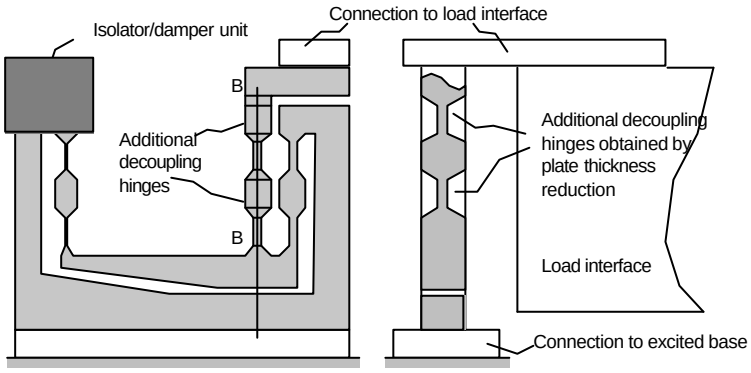

Figure 2 MEDI principle for a single degree of freedom.

The basic design principle is illustrated in Figure 2 above. The uncoupling of degrees of freedom (DoF) as well as the displacement amplification and transmission are implemented by flexure blades machined into monolithic structures (CSEM's FLEXTEC technology [2]).

The isolator damper unit is an electromagnetic linear actuator in which the mobile magnet is guided by a flexural double parallelogram. Viscous damping is obtained by simply short-circuiting the electromagnetic motor and can be tuned by setting the impedance of the shorting connection. The desired stiffness at the interface is provided by the passive springs of the magnet guiding flexure and by the stiffness of the lever flexure blades. The magnet mass also provides a reaction mass which, like damping and stiffness, is amplified by the square of the lever factor.

As for any solid in space, the position of the load interface can be controlled by six independent degrees of freedom. As a single MEDI (Figure 1) handles 2 degrees of freedom, three units suitably located and linked constitute therefore an almost perfect isostatic mount (Figure 3)

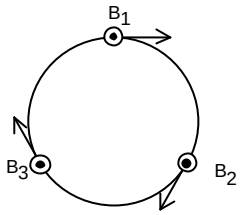

Figure 3 MEDI configurations for 6-DOF load position definition

3. ACTIVE VIBRATION REDUCTION

A description of the theory underlying the MEDI lever block and its properties as a passive damper is found in ref.1. To extend the application of MEDIs to active vibration reduction, the electromagnetic linear motors are driven in current closed loop with some payload sensor input.

The following signals are considered for the closed loop operation:

- Load absolute acceleration $s^2 x_L$.
- Load absolute velocity $s\,x_L$: feedback with this signal appears required in order to achieve attenuation at very low frequencies.
- Payload- base differential velocity. This is actually the mode used to obtain viscous passive damping, by implementing a "passive closed loop" in which the gain equals the motor thrust constant K_F . This damping effect can also be tuned actively by setting a different gain.
- Payload- base differential position. This signal may be required at very low frequencies to prevent long-term motion between the load and the base.

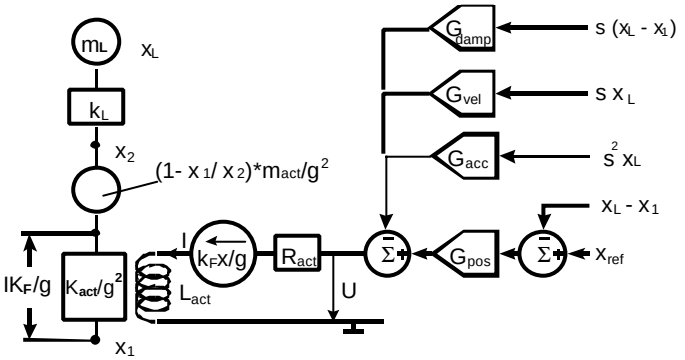

Figure 4 General schematic for active control of an 1-DoF MEDI

The gains G_{acc} and G_{vel} are foremost in importance for the active control of the MEDI. Their general expressions were defined as:

$$G_{acc} = G_v \frac{\left(1+\frac{s}{2pf_{a1}}\right)}{\left(1+\frac{s}{2pf_{a2}}\right)^3} \qquad G_{vel} = G_v \frac{\left(\frac{s}{2pf_{f_{v0}}}\right)\left(1+\frac{s}{2pf_{v1}}\right)}{\left(1+\frac{s}{2pf_{v0}}\right)\left(1+\frac{s}{2pf_{v2}}\right)^3}$$

where
$G_{v,a}$ are respectively constant gain values,
$f_{v0,v1,v2}$ are respectively low-suppress, lead and low-pass cut-off filter frequencies.
$f_{a1,a2}$ are respectively lead and low-pass filter frequencies.

4. SOFTWARE SIMULATOR

One of the project aims was the development of a comprehensive software simulator for active and passive vibration isolation with an integrated structural model of the platform, the MEDI elements, and the isolated equipment. The MEDI software simulator in particular allows us to study all scaling and similarity issues with MEDIs of different design characteristics and perform an optimum sizing for the eventual 6-DoF microgravity payload case.

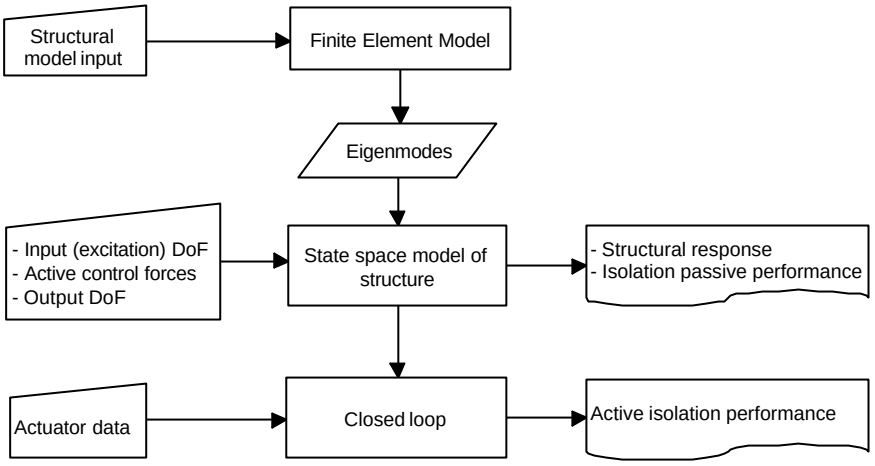

Figure 5 Flow-chart of AMVR simulation model

The software, implemented in MATLAB, comprises the various modules:

- Finite element model of the overall set-up. This is implemented by functions available in dedicated MATLAB toolboxes (CalFem and SDT): available element types are beams, plates and lumped masses.
- Special finite element model of the MEDI.
- In/ouput definition: degrees-of-freedom for base excitation, load vibration/motion, internal forces for active control.
- Formulation of a standard LTI (state space) model suitable for use in the MATLAB V.5 Control Toolbox.
- Parameterization of actuator properties
- Evaluation of closed loop performances

The key to a reliable model of a MEDI-isolated structure is a compact but accurate representation of all the MEDI properties: stiffness along the in-plane DoFs, residual stiffness in the out-of-plane DoFs, lever factor, motor force application.

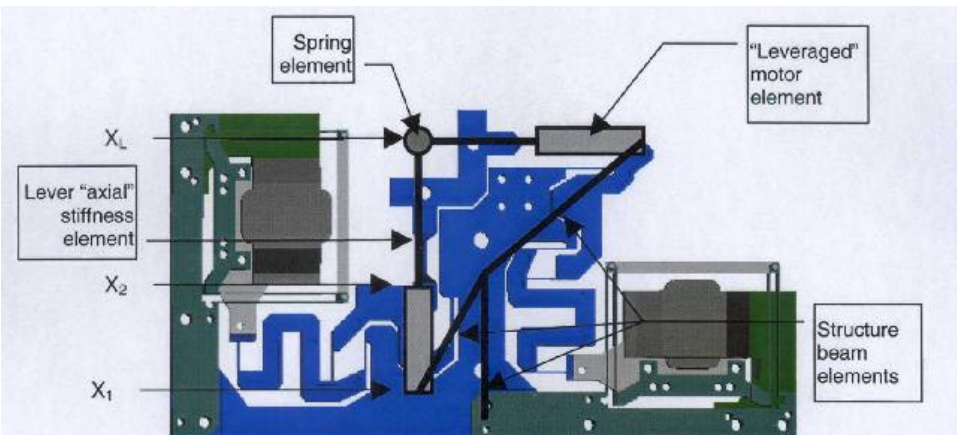

Figure 6 Special finite elements defined for the MEDI representation

5. EXPERIMENTAL MEASUREMENTS

The experimental verification of the active vibration reduction was made for one MEDI lever block acting along one degree of freedom. The main characteristics of the test setup are summarized hereafter.

- A shaker excites a base mass which is guided along the longitudinal (horizontal) excitation direction by means of knife-edge supports. Elastomeric plots damp any spurious out-of-line motion.
- The MEDI is attached to this excited base mass and provides the interface to a payload mass of 8 Kg for which vibrations must be reduced. The MEDI motor which acts along the vibration direction is driven by a KEPCO power amplifier type which provides a controlled current from the signal output by the DSpace PC-based system which performs the closed loop control.
- The payload mass is shaped such that its center of gravity passes by the line of excitation motion and is supported by specially made air-cushions. The vibration response of the of the payload mass is measured by a force sensor which measures the force transmitted by the MEDI to the payload. This force is proportional to the absolute acceleration and, in particular, will become zero if no vibrations are transmitted to the payload, as long as no other paths of force are present.
- The force sensor consists of a FOGALE capacitive sensor type which measures actually the relative displacement across the low compliance spring which is found between the active lever of the MEDI and the payload interface. This signal provides the main input to the feedback loop which performs the active vibration reduction.
- In order to measure the frequency response function of the payload mass with respect to the excited base mass, accelerometers are fixed to both masses. The response of the payload mass is also recorded by the force sensor which measures the force transmitted by the MEDI to the payload.

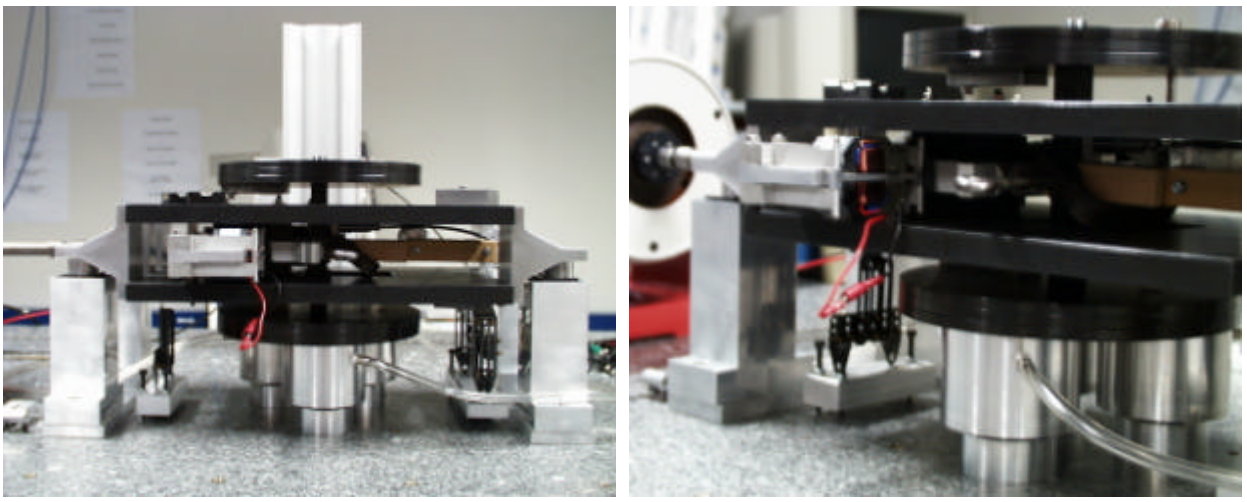

Figure 7 Photographs of the AMVR demonstrator

Some aspects of the set-up outlined above were in fact the outcome of a long experimental process in which many difficulties had to be overcome before we were able to operate and measure the desired vibration attenuation. We initially had planned that the feedback signal for the active vibration control was to come from a high sensitivity capacitive accelerometer. The envisaged accelerometer type CSEM MS 6100 has a noise PSD of about 10 $\mu g/\sqrt{Hz}$. However this level was found still excessive to provide a stable closed loop control with the performance required.

Therefore we experimented the use of a force sensor located between the MEDI and the payload mass. Indeed the use of a force sensor can be considered equivalent to that of an accelerometer provided that the stiffness of umbilical links is kept (also, if required, by means of a separate active system) below this axial stiffness value of the MEDI. The implemented force sensor consist of a specially made membrane-guided spring and a FOGALE capacitive relative position sensor. Thus the noise level is much less critical because the resolution depends on the stiffness of the guiding system which can be adapted as needed.

The optimal implementation of the force sensor implied a further adjustment of the MEDI compliance. The MEDI, original designed for a passive damping application [1], has a stiffness of about 500 N/mm. Therefore an add-on low stiffness spring is applied at the interface of the payload which provides the required passive isolation at low frequencies.

6. TEST RESULTS

5.1 Passive behavior

The passive behavior is characterized by the low compliance of the MEDI interface spring, which provides a resonance at about 5 Hz, followed by a steep isolation slope.

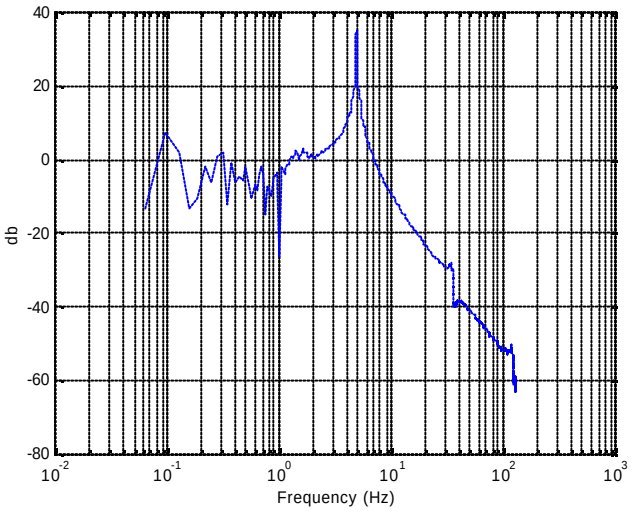

Figure 8 Response function in passive mode.

5.2 Active vibration reduction

Several measurements of the closed loop vibration response performance were recorded in which the frequency range and resolution was varied. During the tests also some parameters of the closed loop were varied slightly in search of the optimum tuning

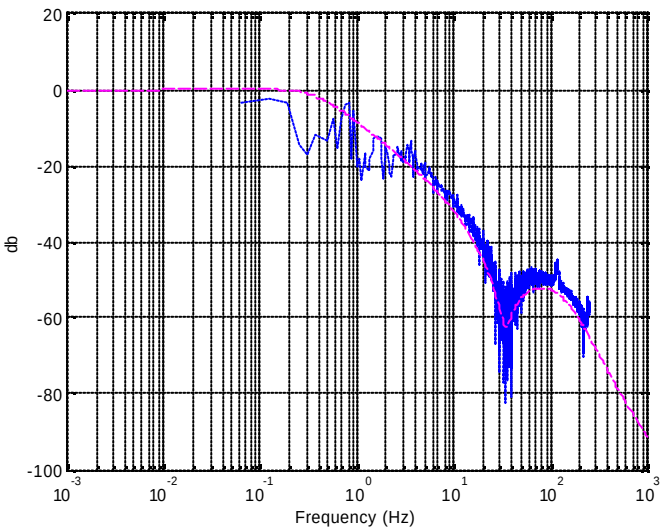

Figure 9 Comparison of closed loop response of the force sensor with the theoretical prediction by the AMVR simulator (dashed line). This test was performed with a frequency resolution of 0.05 Hz. The attenuation is already -15 dB at 1 Hz, reaches -30 dB at 10 Hz and stays at about -50 to -60 dB from 40 up to 256 Hz.

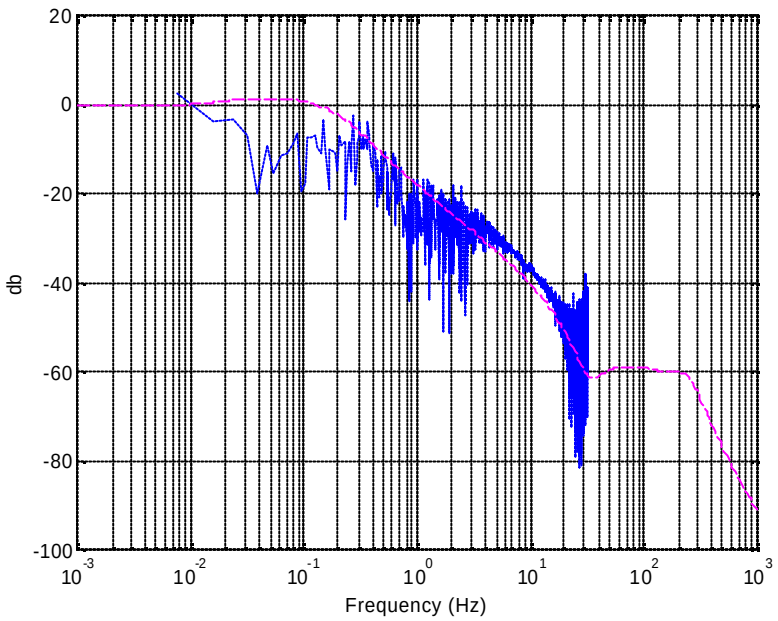

Figure 10 The low frequency effects are evaluated in this test, limited to 32 Hz but with a resolution of 0.008 Hz. The attenuation capability starts at about 0.1 Hz. In this test the loop gain was set at the largest value that appeared achievable with the current MEDI setup. Again, the comparison with the theoretical prediction by the AMVR simulator (dashed line) is quite good.

7. CONCLUSIONS

This work has demonstrated that an Active Vibration Reduction system for microgravity payloads can be made with special electromagnetic lever block actuators (called MEDI - Mechanical Elastic element for Damping and Isolation) which were originally developed [1] as components for passive damping in the frequency range 20 to 100 Hz.

A software simulator was produced which allows us to model and predict the active performance of AMVR system which can be represented by means of a finite element model.

The test of a 1-dimensional demonstrator was performed with a current MEDI element, suitably modified to provide low frequency isolation. The test setup provided 1-dimensional guiding, representative of 0-g conditions. The extremely low noise measurement of the payload mass behavior required for a stable active vibration reduction was obtained by means of a custom force sensor made of a relative displacement capacitive transducer set across a membrane guided spring. Indeed the originally planned use of commercially available accelerometers proved to be impossible due to their residual noise. This force sensor worked very well as a provider of feedback signal for the active vibration reduction and constitutes indeed a main innovative aspect demonstrated in this test program.

The vibration reduction performance of this test demonstrator may be summarized as follows:

- Lower frequency bound of 0.1 Hz
- -15 dB attenuation at 1 Hz, -30 dB at 10 Hz, -50 dB above 30 Hz up to 256 Hz

The test results confirm very well the model predictions. The achieved performance of the AMVR demonstrator is very similar to the one actually measured for other microgravity payload isolation developments such as the ARIS [3] and MIM-2 [4] systems.

ACKNOWLEDGMENTS

A number or CSEM co-workers contributed in various forms to the work presented here: we would like to name in particular Jun Zhao, Peter Spanoudakis, Michel Roulet and Ivar Kjelberg. This work was contracted by the European Space Agency: we thank in particular Rafael Bureo for the technical and managerial support on the ESA side.

REFERENCES

1. L. Zago et al., *Resistor-damped electromechanical lever blocks*, Proc. SPIE Vol. 3327, p. 370-377, Smart Structures and Materials 1998: Passive Damping and Isolation.
2. L. Zago et al., *Application of flexure structures to active and adaptive opto-mechanical mechanisms*, Proc. SPIE Vol. 2871, p. 127-135, Optical Telescopes of Today and Tomorrow.
3. G. S. Bushnell et al., *Active rack isolation system development for the International Space Station*, AAIA-97-1203, p.1500-1513.
4. B. V. Tryggvason et al., *The Microgravity Vibration Isolation Mount: development and flight test results*, IAF-97-J.2.04, 48th International Astronautic Congress, Oct 1997