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Resistor-damped electromechanical lever blocks

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ABSTRACT

The paper presents an innovative technical solution which provides a combined damping and isolation interface with the appropriate transmissibility characteristics between a vibrating base and a sensitive payload, typically an optical terminal/telescope. The novelty of the solution is primarily found in the implementation of uncoupling and magnification of the incurred vibrations by means of flexures combined with the implementation of energy dissipation by means of a linear electro-magnetic actuator to constitute a passive integrated resistor-damped electromechanic lever block.

By means of frictionless flexible lever systems, the amplitude of the payload vibrations is adapted to the optimal range of the actuator with a magnification by a factor ranging typically between 10 and 30. Passive viscous damping is obtained by simply short-circuiting the electro-magnetic motor and can be adapted by setting the impedance of the shorting connection. The desired stiffness is provided by the passive springs of the elastic motor suspension and by the stiffness of the lever flexure blades. The mobile mass of the motors also provide a reaction mass which, like damping and stiffness, is amplified by the square of the lever factor.

A theoretical model of resistor-damped electromechanical lever blocks has been established. A particular property is it the good attenuation of excited vibrations only over a set frequency range. Above this range the interface properties rejoin the ones of a rigid connection. This performance makes this type of isolators particularly suitable for integration into multi-layer vibration control systems where sensitive equipment is protected by a mix of passive and active damping/isolation devices acting optimally at different frequency ranges.

Experiments performed with a dummy load (80 Kg) representative of a satellite based optical terminal demonstrated the efficiency of the system in protecting the payload by passive damping for vibration excitations of amplitude up to 0.15 mm and frequency up to about 120 Hz achieving an attenuation of the eigenmodes of the load structure by more than 20 dB.

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. The current element is called Mechanical Elastic element for Damping and Isolation (MEDI) and was developed as a damper/isolator capable to attenuate 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.

The resistor-damped electromechanical lever block has also 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.

2. THE *MEDI* PRINCIPLE

The MEDI is essentially a flexible structure which uncouples, transmits and amplifies the relative motion between its two external interfaces to electromagnetic actuators which when short-circuited act as damping systems.

The uncoupling of degrees of freedom (DOF) as well as the displacement amplification and transmission are implemented by frictionless mechanisms based on flexure blades integrated into monolithic structures (CSEM's FLEXTEC technology, see ref. 1). Levers and transmission members are obtained by slots, cut in a flat plate, perpendicular to the plane of the plate.

The basic design principle is illustrated in Figure 1. The lever is realized as a monolithic structure out of a flat plate, with in addition the ability to uncouple the five DOFs of the B attachment point as required.

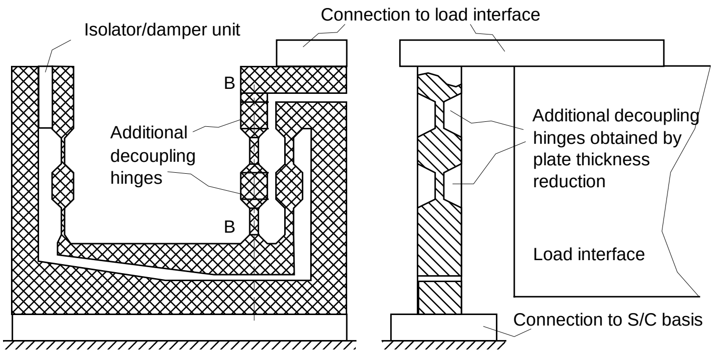


Figure 1 MEDI Principle for a single DOF.

The isolator damper is an electromagnetic linear actuator. Viscous damping is obtained by simply short-circuiting the electro-magnetic motor and can be adapted by setting the impedance of the shorting connection. The desired stiffness at the interface is provided by the passive springs of the elastic motor suspension and by the stiffness of the lever flexure blades. The mobile mass of the motors also provide 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 is controlled by six independent degrees of freedom, which may be conveniently defined by one-dimensional translations of six attachment points B_1 to B_6 (Figure 2-A) or by two-dimensional translations of three attachment points B_1 to B_3 (Figure 2-B). The latter configuration was retained for the MEDI.

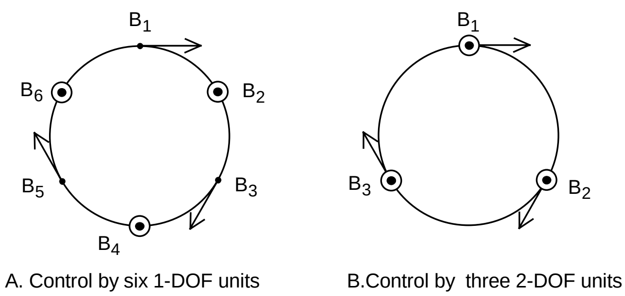


Figure 2 Typical configurations for 6-DOF load position definition

The MEDI unit is therefore designed as an interface component having suitable stiffness and damping properties along 2 DOFs while being essentially uncoupled along the other 4 DOFs. Three such elements suitably located and linked constitute therefore an almost perfect isostatic mount.

3. DESCRIPTION OF THE *MEDI* COMPONENT

The MEDI unit is illustrated in Figure 3. Essentially it consists of an assembly of the following main components:

- A main monolithic flexure structure performing the amplification function for both "working" DOFs and the uncoupling of the other four DOFs. Also both external interfaces (i.e. the load interface and the base interface) are attached to this component.
- The actuator monolithic elastic suspensions, which are in fact four identical flexure guiding elements fixed on both sides of the main structure.
- Two electromagnetic linear actuators, each including a stator element, a permanent magnet linear rotor, and a L-shaped support element. The baseline actuator model is the MLZ1 motor manufactured by the Swiss Company ETEL. The key parameters with respect to the electromagnetic damping characteristics is the motor constant: $K_p = 6\ N/\sqrt{W}$, the square of which gives the viscous damping constant of the actuator.

The overall volume of the MEDI can be contained in an oblong box envelope about 20x12x5 cm, which makes it a nice compact element, easy to assemble, mount and fit into existing hardware.

A first prototype of the 2-DOF damping mechanism had been manufactured and successfully tested in 1995. Some key characteristics of MEDI are patented. The final phase of the project, completed in 1997, comprised various design improvements of this MEDI unit.

Figure 3 Photograph of the MEDI

4. THEORETICAL MODEL

Figure 4 shows a simplified diagram for the single DOF interfacing of an actuator including a mobile mass m_{act}, a spring k_{act} and actuator force F_{act}, with a block to actuator lever displacement ratio g. Depending on whether $g > 1$ or $g < 1$, the block relative displacement $x_2 - x_1$ is magnified or reduced with respect to the relative actuator displacement $x_{act} - x_1$.

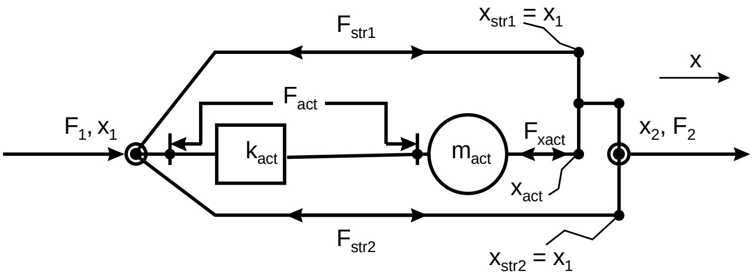


Figure 4 One-dimensional model of the lever block

With the notations of Figure 4, the system equations can be expressed as follows:

$$F_1 - F_{act} + k_{act} \cdot \left(x_{act} - \Delta x - x_1\right) - \Sigma F_{str} = 0,$$
$$F_{act} - k_{act} \cdot \left(x_{act} - \Delta x - x_1\right) - F_{xact} = m_{act} \cdot \ddot{x}_{act} = -\omega^2 \cdot m_{act} \cdot x_{act}$$
$$\Sigma\, F_{str} = \left[g_1 \cdot \left(g_2 - 1\right) + \left(g_1 - 1\right)\right] \cdot F_2 = \left[g - 1\right] \cdot F_2,$$
$$F_{xact} = -g \cdot F_2.$$

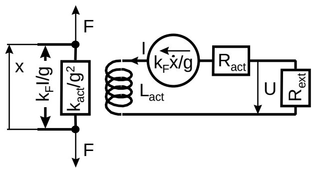
where g is the displacement ratio:

$$g = \frac{x_2 - x_1}{x_2 - x_{act}}$$

The system of can be algebraically solved, using $d^2x/dt^2 = -\omega^2 x$. This gives:

$$F_1 = -\frac{k_{act}}{g^2} \cdot \left(x_2 - x_1\right) + \frac{F_{act}}{g} - \frac{(g-1)}{g^2} \cdot \omega^2 \cdot m_{act} \cdot \left(x_2 + (g-1) \cdot x_1\right),$$
$$F_2 = +\frac{k_{act}}{g^2} \cdot \left(x_2 - x_1\right) - \frac{F_{act}}{g} - \frac{1}{g^2} \cdot \omega^2 \cdot m_{act} \cdot \left(x_2 + (g-1) \cdot x_1\right).$$

The functioning of the close-circuited electromagnetic actuator which provides the damping of the MEDI is shown in the diagram below.



The balance relationships are:

$$F = \frac{k_{act}}{g^2} \cdot x - \frac{k_F}{g} \cdot I$$
$$U = \left(R_{act} + j\omega L_{act}\right) \cdot I + \frac{j\omega k_F}{g} \cdot x$$
$$U = -R_{ext} \cdot I$$

where:

k_{act} is the stiffness of the mobile stage

m_{act} is the mass of the mobile stage

$K_F = K_P * \sqrt{R_{act}}$ is the thrust constant

R_{act} is the resistance of the actuator

L_{act} is the inductance of the actuator

R_{ext} is the resistance of the external circuit

The solution of these equations allows to compute the damping factor η:

$$\eta = \frac{\omega k_F^2 \left(R_{act} + R_{ext}\right)}{k_{act} \cdot \left[\left(R_{act} + R_{ext}\right)^2 + \omega^2 \cdot \left(L_{act}^2 + k_F^2 \cdot L_{act} / k_{act}\right)\right]}.$$

It can be shown that η can be smoothly adjusted by varying the external resistor (see Figure 5).

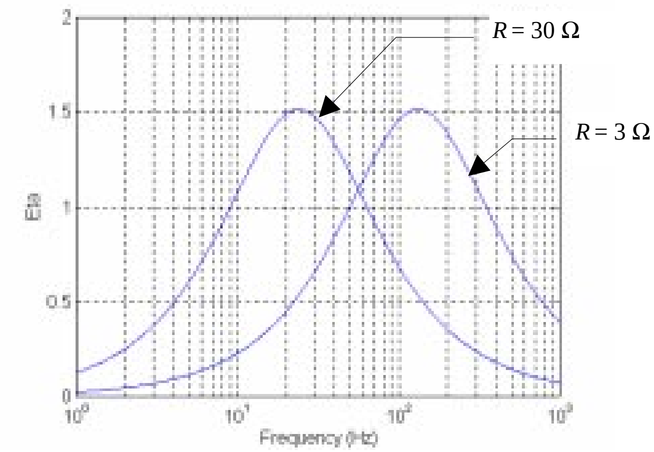
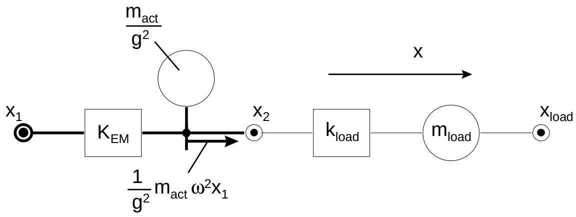


Figure 5 Damping factor η of the EM-resistor for different circuit resistance values, computed with example data

The basic theoretical models described above can be combined to evaluate the performance of an electromagnetic level block interfacing an excited base to an elastic load structure. This is schematically represented here below, where the K_{EM} block represents the complex stiffness properties of the an electromagnetic level block:



In Figure 6, various frequency responses of the load pointer X_{Load} are compared. This comparison gives indications of the isolation and damping performances of the electromagnetic lever block in passive mode:

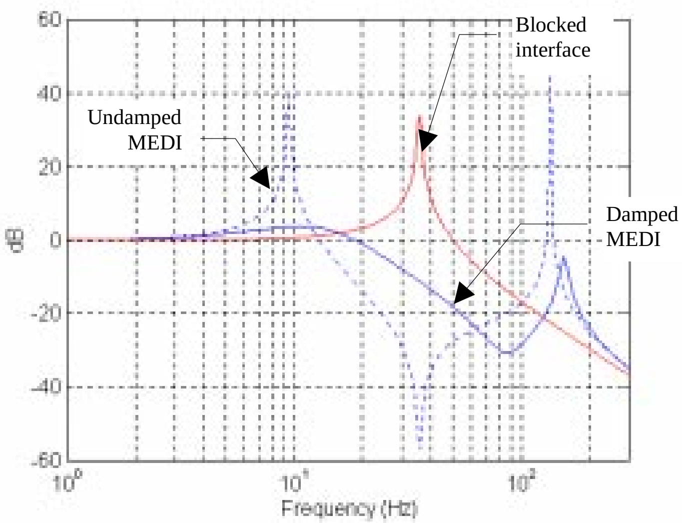


Figure 6 Response of the load/spring/EM block-resistor system

The reference curve shows the resonance of the load mass on its spring is found by assuming a large stiffness, corresponding to the *blocked* state of the interface.

The second curve is the response with open circuit (isolation but no damping). The resonance peak is split into two secondary peaks, corresponding to the modes of the masses and springs of the system. The third curve is a damped response with the actuator connected to the dissipating resistor.

Compared with the blocked curve, both the MEDI curves show a frequency range between the two peaks where a significant isolation effect of the interface can be observed. As the force necessary to accelerate the equivalent mass attached to the intermediate point x_2 increases with the frequency and as the transmission by the equivalent spring of the interface is proportional to the amplitude of the base excitation x_1, the isolation ratio increases at first above the lower resonance. Above the second resonance, the inertial cross coupling is definitely the main contributor to the x_2 motion, which then follows the base displacement without attenuation.

To conclude, the lever block interface in passive mode makes it possible to lower the resonance frequency and to efficiently damp the amplitude of the main load peak. A secondary peak appears at a higher frequency, depending on the lever ratio g and on the lowest achievable mass of the actuator. The second peak can be partially damped. Between the two peaks, isolation takes place.

5. EXPERIMENTAL MEASUREMENTS

The objective of the measurements was the evaluation of the damping and isolation characteristics of the isostatic mount system constituted by three MEDI units.

The idea and rationale for the proposed test set-up was to make a 80 Kg load representative of the SILEX (Semiconductor laser Inter-satellite Link EXperiment) optical terminal for laser communication developed by the European Space Agency.

The test structure (Figure 7) is mounted on the granite table away from nodal lines for the first plate mode, in order to be able to excite the structure continuously over the frequency range of interest (0 - 150 Hz). The excitation is provided by an electrodynamic shaker which is acting at one corner of the granite table, along the vertical direction.

The quantities evaluated are the frequency response function (FRF) measurements between the interface table level and the line-of-sight oscillations of the test structure.

Two tests were performed, one with the MEDI interface, one with rigid connections across the MEDI elements. In order to compensate the effect of the weight of the test structure, which would normally squeeze the vertical actuators to their limit stroke, a controlled constant voltage was fed into them in order to levitate the structure and reposition the mobile parts of the vertical actuator at the middle of their nominal stroke. It was thereby noted how the isostatic mount constituted by three MEDI units allows also a very accurate static positioning along all six DOFS of the load structure, thanks to the reduction factor between the actuator and the MEDI top interface.

Figure 8 presents a plot of the frequency response of the angular line-of-sight displacement at the payload (optical terminal) for both cases of a rigid (dashed line) and 6-DoF MEDI interface (full line).

These results demonstrate that the MEDI interface efficiently protects the payload by passive damping and isolation for excitations up to a frequency of about 120 Hz. The test demonstrated in particular that the critical modes of the main bracket below 60 Hz are all damped and their transmissibility is reduced by at least one order of magnitude. The same also applies to the higher range mode at 110 Hz. Above 120 Hz, the response with the MEDI interface joins the one of a rigid connection as predicted by the theory.

The property whereby the MEDI electromagnetic lever blocks provide a good attenuation of eigenmodes between a set frequency range can be particularly interesting. This performance makes the MEDI system particularly suitable for integration into multi-layer vibration control systems where sensitive equipment are protected by a mix of passive and active damping/isolation devices acting optimally at different frequency ranges.

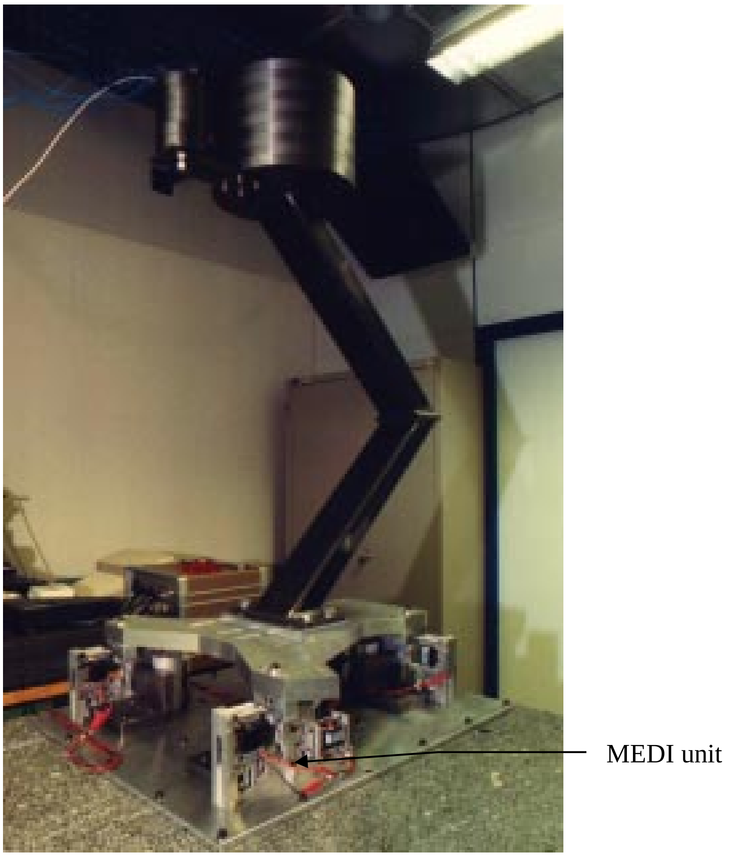


Figure 7 Test set-up. Note the three MEDI elements and the dummy payload representing an optical terminal.

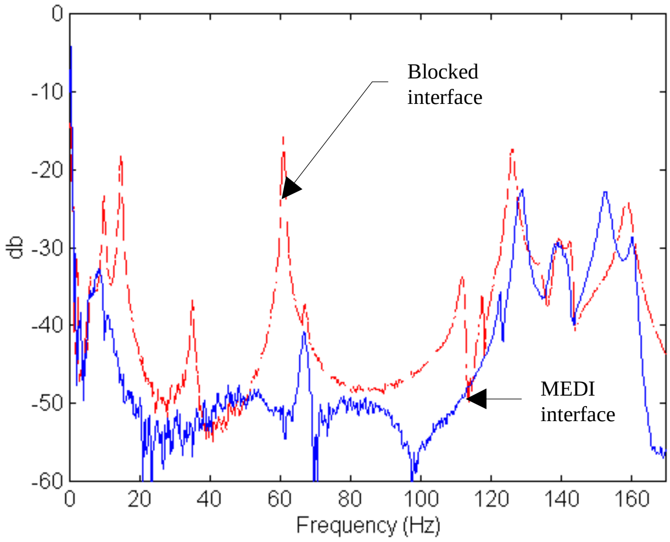


Figure 8 Frequency response of the line-of-sight angular displacement at the payload (optical terminal) for both cases of a rigid (dashed line) and MEDI interface (full line).

6. ACKNOWLEDGEMENT

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7. REFERENCES

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