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EDDY CURRENT-BASED VIBRATION DAMPING FOR AEROSPACE STRUCTURES

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ABSTRACT

A need exists for enhancing the passive damping present in proposed aerospace structures. A research program is underway to assess the feasibility of exploiting the retarding force experienced by conductors moving in the presence of a magnetic field, to provide passive damping of space-deployed structures. The characteristics of this approach are strikingly suitable for space applications: non-outgassing, relatively insensitive to temperature, noncontacting (no stiction or wear), linear, radiation tolerant, highly reliable. An eddy current-based damper could be used as the damping element in a tuned inertial reaction device (passive vibration absorber, proof mass actuator, etc.) or, alternatively, as part of a static broad-band damper. For a static damper, a flexure-based mechanism would amplify the vibratory motion of the truss member, ensuring sufficient motion of the conductor to develop adequate power dissipation. Preliminary calculations have shown that substantial modal damping ratios can be achieved at minimal weight. SatCon is undertaking an analytical, experimental and design-oriented program to assess the weight, performance, cost and reliability of this novel approach to vibration damping of space structures.

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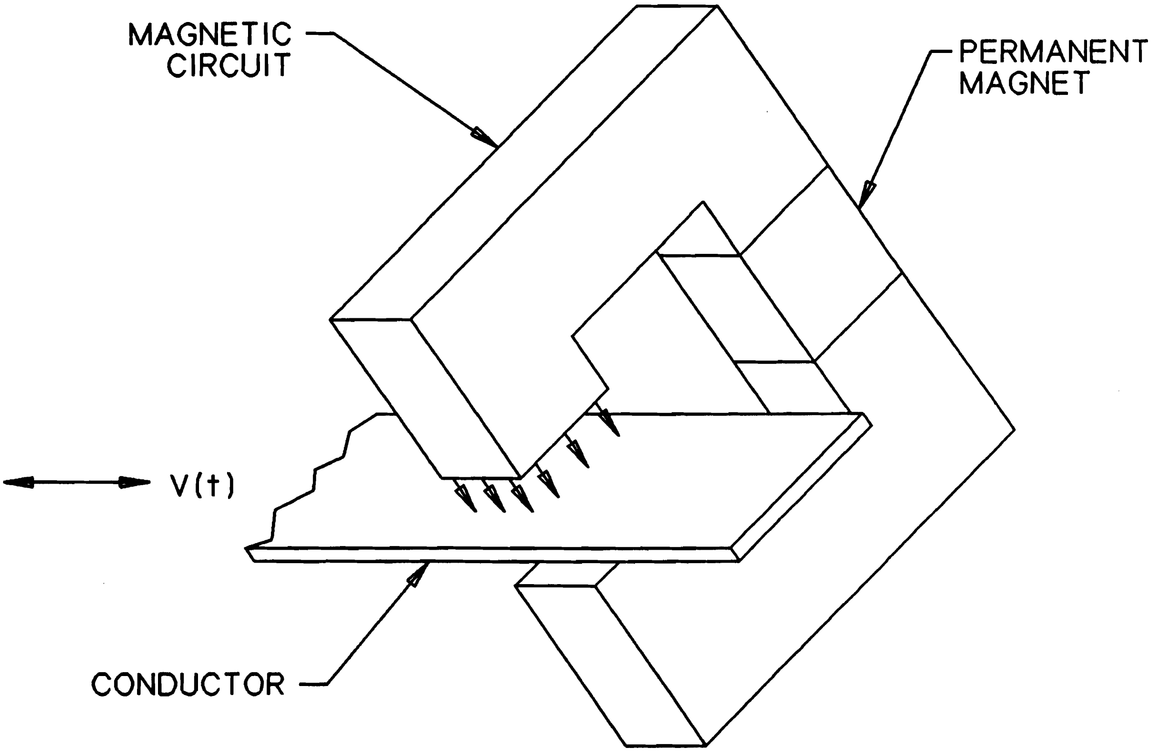
What is basic idea?



- oField can be produced by a permanent magnet
- oConductor experiences a viscous drag force
- oCurrents induced in moving conductor dissipate vibrational energy

It is well known that a conductor moving within a magnetic field will experience a drag force. As the conductor moves, eddy currents are induced which interact with the field present so as to resist the motion. The net result is that vibrational energy is converted to heat (produced by the dissipative losses of the caused by the eddy currents in the conductor).

The approach shown in the figure is the simplest rendition of an eddy current-based damper. A totally passive damper can be made by letting a thin conducting strip move within the field of a permanent magnet. Alternative schemes employing superconducting field magnets or electromagnets can be envisioned. A superconducting magnet would offer extremely high flux densities and the elimination of return iron. Application of electromagnets would permit the field to be actively controlled, which would allow control of the damper characteristics.

What are the benefits of eddy current–based damping?

Applications ----→ BENEFITS:	Space	Cryogenics	Precise Positioning	Commercial Vibration Isolation
LINEAR	△			△
INSENSITIVE TO TEMP.	△	△		
NON-OUTGASSING	△			
NON-CONTACTING		△	△	
NO WEAR/FATIGUE	△			
HIGH RELIABILITY	△			
TEMPORAL STABILITY	△		△	
EASY ADD-ON	△			

SatCon is particularly excited about eddy current-based damping because of its extraordinary collection of attributes.

Its linearity under most operating conditions is attractive because of the resulting analytical simplicity and the avoidance of exciting higher modes of vibration.

Perhaps its most significant attribute is its relative insensitivity to temperature. The performance of other damping schemes involving hydraulics or viscoelastic materials is extremely sensitive to temperature. There is some sensitivity of an eddy current-based damper, due to the change in conductivity of metals with temperature. The change in conductivity, however, is relatively benign and can be tailored by the proper choice of the conducting metal and its purity. This insensitivity and tolerance to a wide temperature range is particularly beneficial for vibration damping in space or orbital applications, which experience wide temperature swings, and for cryogenic applications.

The eddy current-based damper is comprised of metals. Consequently, it will not outgas in a space vacuum.

Amongst the attributes of the eddy current damper are its noncontacting nature, and its low wear and high reliability. These attributes spring form the fact that there is no contact between the moving and stationary portions of the device. They are particularly beneficial to cryogenic, precise positioning and space applications. The noncontacting character is significant for cryogenic application, since it prevents the introduction of additional conduction paths. Applications which require precise positioning of components (such as optics) benefit since the phenomena of stiction and position hysteresis are eliminated. Finally, vibration damping applications in space benefit from the high reliability and long life offered by the eddy current-based damper.

There is no reason for the characteristics of the damper to change with time. This offers benefits for long duration space applications and precise positioning applications.

Finally, it should be added that an eddy current damper could be conveniently added to an existing structure which requires supplemental damping.

Eddy Current-Based Dampers have been used for Cryogenic Applications

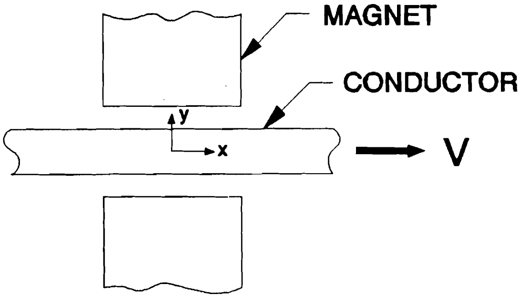
- Good conductivity at cryogenic temperatures beneficial
- Alternatives such as squeeze film dampers, viscoelastic material dampers or coulomb friction dampers not practical
- Stanford Gravity Wave Experiment
- Vibration control in cryogenic turbomachinery

Eddy current-based dampers have been used in a few specialized vibration damping applications. The most important are cryogenic applications such as the Stanford Gravity Wave Experiment, where cryogenic temperatures are required to reduce Brownian motion to an acceptable level. In its latest rendition the damping scheme is inside the cryogenics and, hence, is required to work at cryogenic temperatures. Consequently, an eddy current-based damping scheme is employed in which vapor-cooled superconductors carry the induced eddy currents out of the dewar to be dissipated in a location where the resulting heat is tolerable. The eddy current damper is particularly appropriate for this application since it does not produce heat in the cryogenics, it provides damping at cryogenic temperatures and it does not introduce substantial heat conduction paths. Some research has been performed by Robert E. Cunningham at the NASA Lewis Research Center regarding the use of eddy current damping for vibration control in cryogenic turbomachinery[1]. At cryogenic temperatures common techniques employing squeeze film dampers, viscoelastic material dampers or coulomb dampers are not feasible, whereas eddy current-based dampers exhibit improved performance. Other applications have included damping of wind tunnel models and Foucault pendulum damping[2].

[1] R. E. Cunningham, "Passive Eddy-Current Damping as a Means of Vibration Control in Cryogenic Turbomachinery," NASA Lewis Research Center, NASA Technical Paper 2562, 1986.

[2] G. Mastner, et al, "Foucault Pendulum with Eddy-Current Damping of the Elliptical Motion," Review of Scientific Instruments, Vol. 55, No. 10, October 1984.

How is an eddy current–based damper analyzed?



Field Problem for Eddy Current–Based Damper

- Complete 2–D model

$$\frac{1}{\mu\sigma}\left(\frac{\partial^2 B_y}{\partial x^2}+\frac{\partial^2 B_y}{\partial y^2}\right)=\frac{\partial B_y}{\partial t}+V\,\frac{\partial B_y}{\partial x}$$

Includes skin effect, end effects and nonlinearity.

- For many operating conditions and design parameters, a simple model may be used

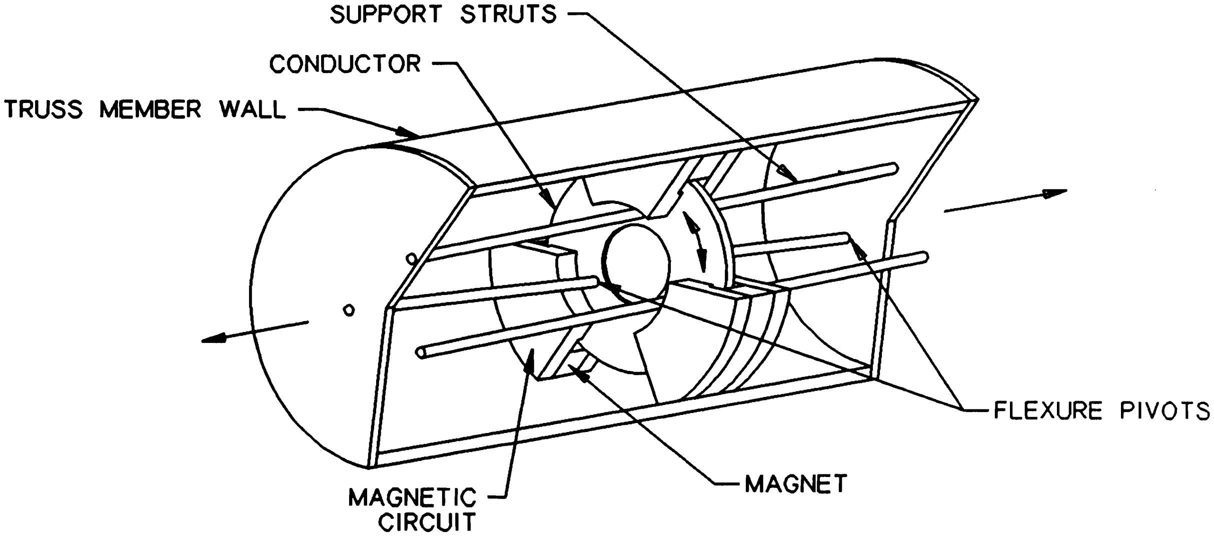
$J_z = \sigma V B_y$

$F_x = -\sigma V B_y^2 \bullet (\mathrm{Vol})_{cond}$ (Lorentz force)

$b = \sigma B_y^2 \bullet (\mathrm{Vol})_{cond}$

The field equations can be combined to yield a two-dimensional partial differential equation for the flux density for a conductor moving in a magnetic field. This is a challenging analytical problem, due to the nonlinearity caused by the variation of the vibrational velocity, V. In many situations the field produced by the eddy currents is small compared to the imposed field. Under these circumstances the drag force is proportional to the velocity, the conductivity and the square of the flux density.

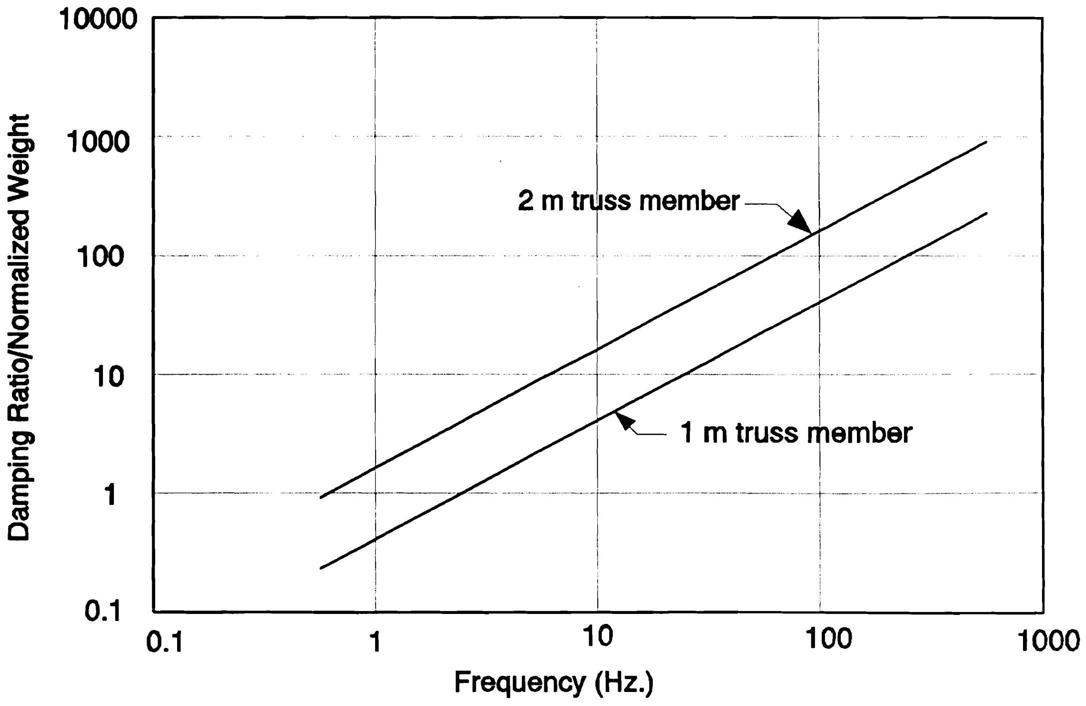
Broad Band Supplemental Damping of Space Truss Structure



- **Relatively small vibrational strains/velocities**
- **Damping is enhanced by use of flexure–based mechanism**

$$b_{eff} = m^2 b$$

One approach envisioned by SatCon for applying an eddy current-based vibration damper to individual members of a space truss structure results in a broad-band damper that would enhance damping in much the same way that a hydraulic or viscoelastic-based damper would. The fundamental difficulty with this approach is that the vibrational strains and velocities are too small to develop significant power dissipation. In order to properly match the impedance of the damper to the structure, a flexure-based mechanism such as the one shown can be employed. It should be noted that the figure is intended to clarify the concept and, consequently, is not to scale. The helical orientation of the support struts causes the conducting disc to rotate substantially when the truss member axially deforms. The large mechanical gain developed by a mechanism of this sort allows the damper to dissipate significant vibrational energy. The use of flexures avoids the difficulties of stiction, backlash and lubrication of metal surfaces in sliding contact.



The Damping Ratio (divided by normalized weight) as a Function of Vibrational Frequency

The Damping Ratios Achieved with 1 m Struts and a Broad-band Eddy Current Damper

f(Hz)	ζ (%)	W'
1	1.0	.024
1	2.5	.061
10	5.0	.012
10	10.0	.024
100	25.0	.006

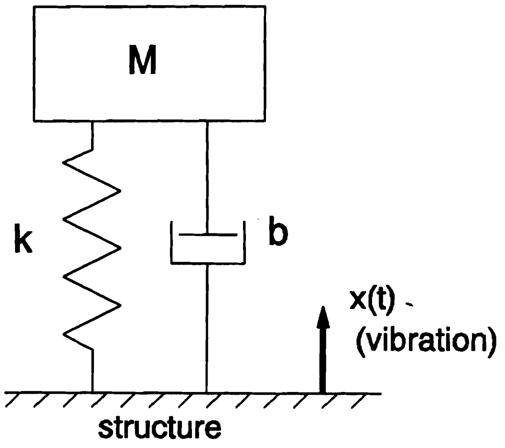
As with most engineering design, there is a tradeoff between desired characteristics. In the case of the broadband damper, there is a tradeoff between performance (i.e., damping ratio) and weight of the device. Assuming that the design shown in the figure is used, the simple model discussed above can be used to investigate this tradeoff. The plot shows the damping ratio divided by the normalized weight of the damper (weight of the damper as a fraction of the weight of the associated truss member) as a function of frequency. This calculation includes the weight of the magnetic circuit components and the conductor required and assumes that the truss member is hollow and made from graphite epoxy and that the conductor used is copper. The damping ratio is calculated as $1/4\pi$ times the ratio of the energy dissipated per cycle by the damper to the strain energy of the member at it largest axial deformation.

It is worth noting that the modal frequencies associated with the important lower modes of space-deployed truss structures are well below those of the individual truss members. Consequently, motion of an individual truss member will be predominantly static axial deformation caused by the vibrational movement of the overall structure.

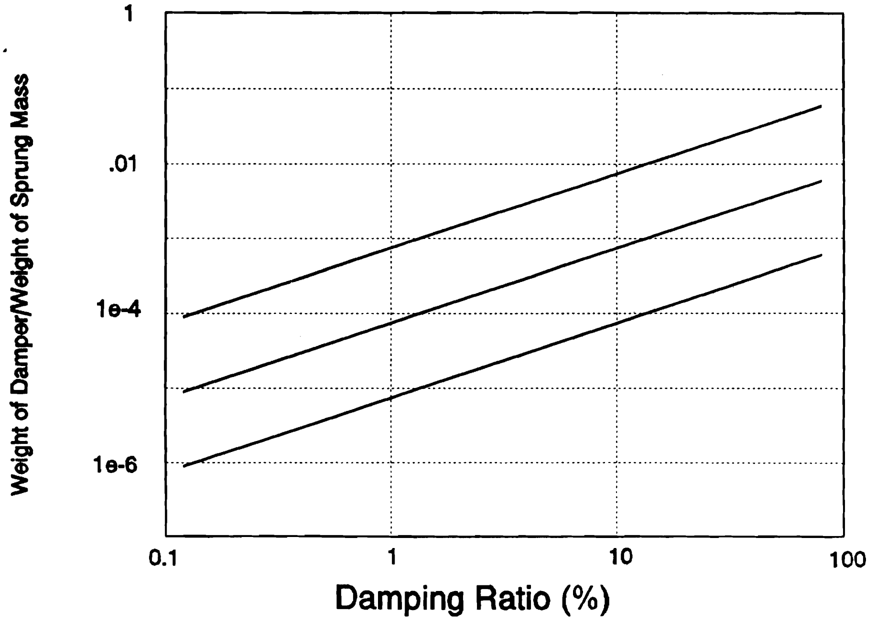
As the plot indicates, the performance improves linearly with frequency and with truss member length. The improvement with length stems from the fact that practical considerations limit the mechanical gain possible independent of truss member length. Consequently, the power dissipated per cycle varies as the square of the truss member length and strain energy only linearly with length for a given maximum truss member strain.

The table gives some typical damping ratios and normalized damper weights as a function of frequency. As the table indicates substantial damping ratios can be achieved at small weights. For example, at 10 Hz. a 5% damping ratio can be achieved with a damper which is only 1.2% of the weight of the associated truss member.

Damping Element in a Tuned Passive Vibration Absorber or Proof Mass Actuator



- Tuned to slightly below first structural mode
- Appropriately sized to structure
- Damping ratio chosen to maximize vibrational power dissipation



Another promising application of this technology is as the damping element for tuned passive vibration absorbers[3,4] or proof mass actuators. These devices are typically tuned to resonate at slightly below the first mode of the associated structure. They are appropriately sized to the structure to which they are attached, and their damping ratio is set to maximize vibrational power dissipation. Of course, in this case the device added to a structure includes energy storage (the spring and mass) as well as the damping element and, hence, the damping ratio is defined as ($1/4\pi$) times the energy dissipated per cycle of the damper divided by the maximum strain energy of the damper itself.

The plot shows the ratio of the damping element weight to the weight of the sprung mass, as a function of the damping ratio for three different resonant frequencies. The plot indicates that the eddy current-based damping element is a very small portion of the overall weight of the device and, therefore, should be seriously considered for use as the damping element in these devices.

[3] J. R. Sesak, et al, "Passive Damping Augmentation for Flexible Structures," Lockheed, First NASA/DOD CSI Technology Conference, November 18–21, 1986, pp. 475–493.

[4] D.W. Miller and E. F. Crawley, "Theoretical and Experimental Evaluation of Space–Realizable Inertial Actuation for Passive and Active Structural Control," J. Guidance Control & Dynamics, Vol. 11, No. 5, Sept–Oct 1988, pp. 449–458.

How is SatCon pursuing this approach to vibration damping?

- Theoretical understanding and modelling
  - How and when is performance influenced by skin effect, end effects and nonlinearity?
  - Create models to predict performance

- Develop promising strawmen designs for specific applications

- Experimentally evaluate prototypes

- Consideration of alternative uses
  - Noise suppression (aircraft, spacecraft)
  - Precise positioning (optics)

SatCon is pursuing development of eddy current-based structural damping through a combined analytical and experimental program. The initial efforts have been aimed at developing analytical design tools which can be used to evaluate some promising strawmen designs. In addition, SatCon shall build and evaluate some prototypes for an eddy current-based damper.

SatCon believes that this approach to vibration damping offers benefits for a wide range of applications and should, therefore, be pursued aggressively.