Exploring Structural Dynamics — Technical Paper

Exploring Structural Dynamics

Design and Application of Vibration Suppression

Excessive vibration can be detrimental to the structural integrity of structures or can adversely affect the performance of instruments such as telescopes or antennas. One field in Structural Dynamics is the design and application of systems that reduce the amplitude and duration of vibration. There are two types of vibration suppression systems: passive and active. Passive means that the damping is inherent in the material or physical characteristics of the system. Active damping mechanisms require measurement of response and feedback control to reduce the vibration of the structure. If the problem can be solved passively, it will probably be less expensive and complex than active methods. If active methods are required, well-designed passive methods can greatly ease the burden of active systems.

Overview of Effects of Damping

Damping is the dissipation of energy in a system such that the amplitude and duration of response of the system is reduced. When excited, a lightly damped structure will exhibit large responses at its resonant or natural frequencies. Addition of damping can reduce the resonant response as shown in a frequency response curve (Figure 1) and shorten the duration of response as shown in a time history plot (Figure 2).

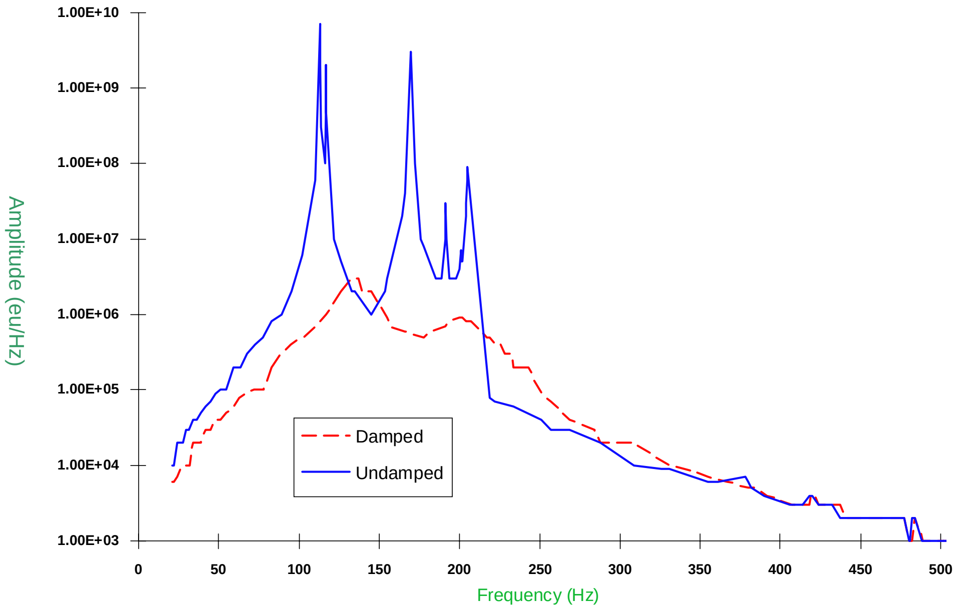

Figure 1 Frequency Response Curves Showing Reduction of Resonant Responses

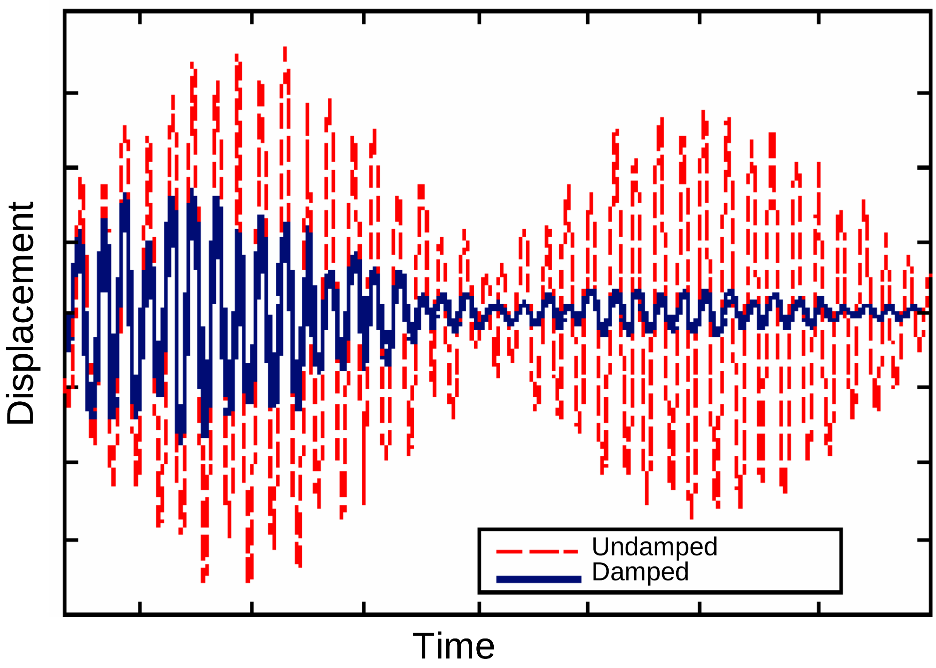

Figure 2 Time History Plot Showing Reduction of Response Duration

Some Definitions

Amplification Factor (Q) - The amount of mechanical gain of a structure when excited at a resonant frequency. The ratio of the amplitude of the steady state solution (amplitude at resonance) to the static deflection for the same force F. The amplification factor is a function of the system damping. For a damping ratio ζ=0 (no damping) the amplification factor is infinite, for ζ=1 (critically damped) there is no amplification. Quality or amplification factor can be expressed as $Q = {}^{1}\!/_{\eta} = {}^{1}\!/_{2\zeta}$.

Critical Damping - The smallest amount of damping required to return a system to its equilibrium condition without oscillating. Critical damping factor can be expressed as $C_{cr} = 2m\omega_n = 2\sqrt{km} = {}^{2k}\!/_{\omega_n}$ where m is mass, k is stiffness, and ω_n is the natural frequency.

Damping Factor or Damping Ratio -The ratio of actual damping in a system to its critical damping: $\zeta = {}^{C}\!/_{C_{cr}}$. Figure 3 shows the decrease in response amplitude with increase in damping ratio for a single-degree-of-freedom system.

Hysteresis Damping (Hysteretic Damping, Structural Damping) - Energy losses within a structure that are caused by internal friction within the structure. These losses are independent of speed or frequency of oscillation but are proportional to the vibration amplitude squared.

Logarithmic decay – The characteristic of reduction in response as time increases for a damped, freely vibrating system. The damping ratio can be calculated from the ratio of the peak amplitudes of successive response cycles: $\zeta = \frac{1}{2\pi} \ln\left(\frac{X_i}{X_{i+1}}\right)$

Loss Factor – The loss factor indicates the degree of energy lost per vibration cycle. It can be expressed as $\eta = \frac{1}{2\pi} \frac{energy\_lost\_per\_cycle}{\max imum\_stored\_energy} = \frac{quadrature\_force}{in-phase\_force}$

Viscous Damping - Damping that is proportional to velocity. Viscous damping is used largely for system modeling since it is linear. The viscous damping ratio can be expressed as $\zeta = \frac{C}{C_{cr}} = \frac{1}{2} \frac{quadrature\_force\_at\_resonance}{in-phase\_force\_at\_resonance}$

Click here for more definitions.

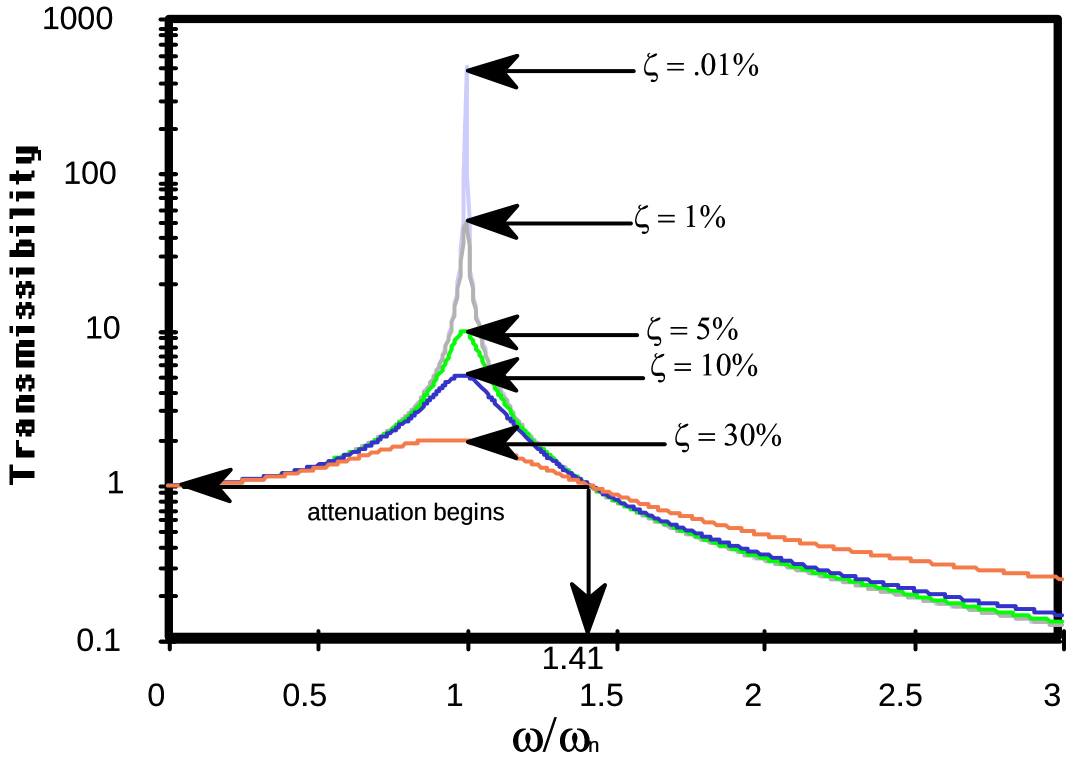

Figure 3 Transmissibility for a Single Degree-of-Freedom System for Various Critical Damping Ratios

Passive Damping Mechanisms

Systems have inherent damping as evidenced by the fact that there is no such thing as "perpetual motion." But materials or structures can have significantly different damping characteristics that can be used to an engineer's advantage (Figure 4). An empty room with hard ceilings, walls and floors is very noisy. But cover the floor with carpet, the ceiling with acoustic tiles, and the walls with fabric draperies and the room becomes very quiet. This same principal is employed in aircraft cabins to damp the noise from engines and flight. Another example of damping is the shock absorber on a car. As the card drives over a rough road or railroad track, the wheels bounce. But the passengers may not even feel a bump because the shock absorbers isolate the car body from the wheel axels. Incorporating damping into aircraft and spacecraft designs follows the same principals, but is more challenging because the designs must be lightweight and compact. The discussion below highlights damping materials used today and being developed for future use.

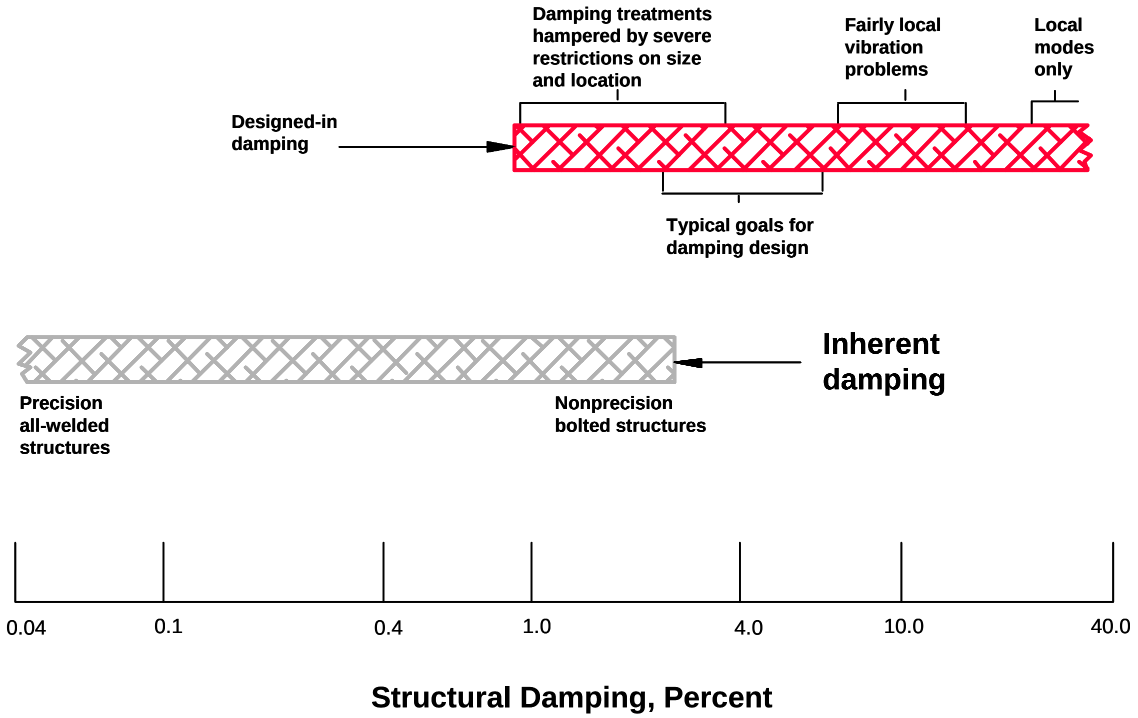

Figure 4 Passive Damping in Real Structures

Viscoelastic materials (VEM) are materials such as rubber, polymers, some adhesives, urethanes, epoxies, and enamels. Shearing of VEM dissipates vibrational energy as heat that is generated when the material is stressed by deformation. These materials have low shear modulus values (20 to 10,000 psi) but high loss factors (2 or more) as shown in Figure 5. However, the material properties are typically temperature and frequency dependent. VEM may be implemented with or without a constraint layer. Constrained-layer application (Figure 6) is one of the most effective damping treatments. Free-layer application (Figure 7) is good for extensional and bending modes, but requires high stiffness VEM.

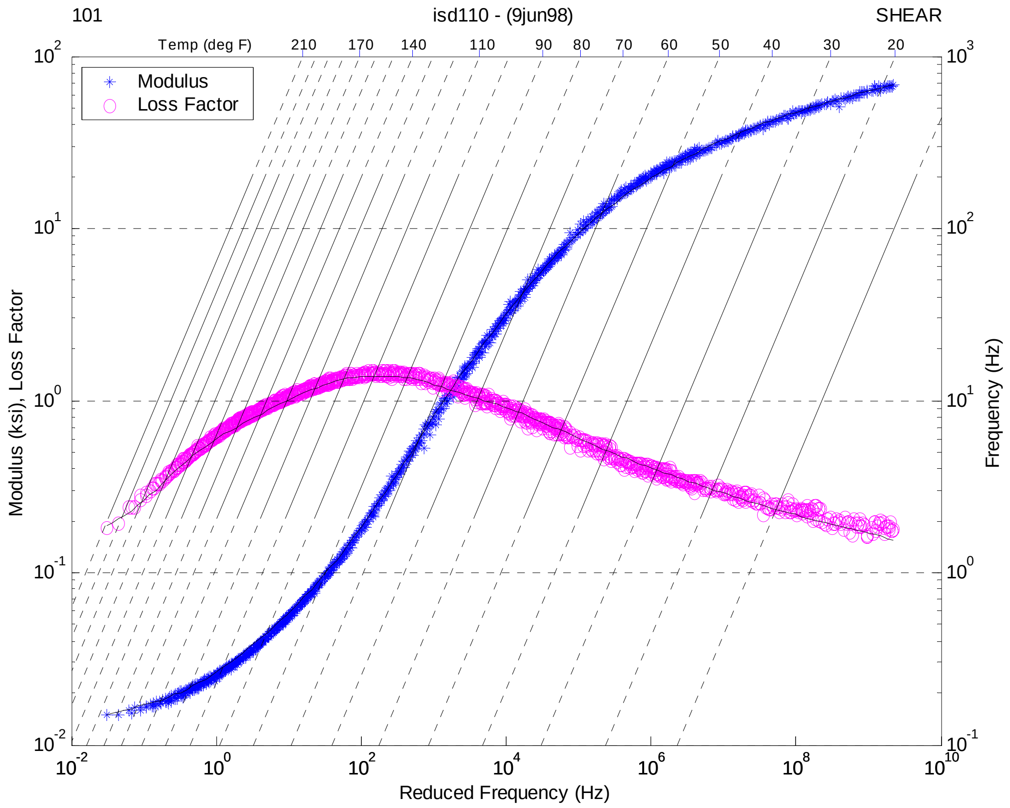

Figure 5 Example Shear Modulus and Loss Factors for VEM

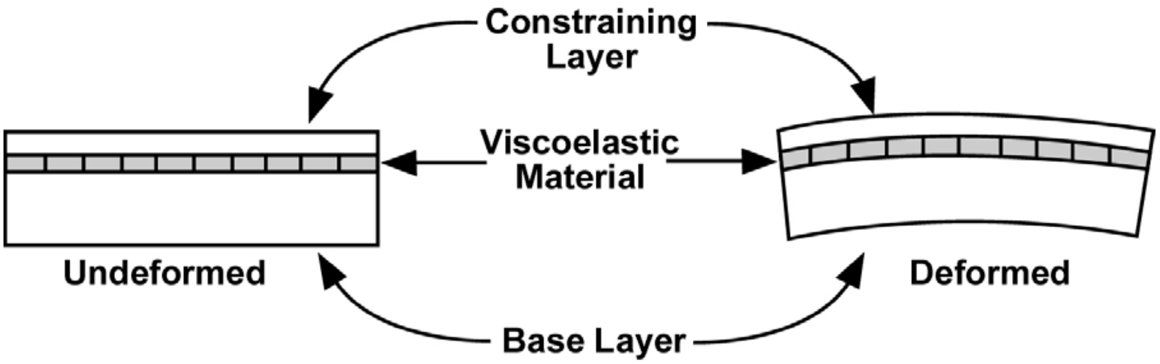

Figure 6 Constrained-Layer VEM

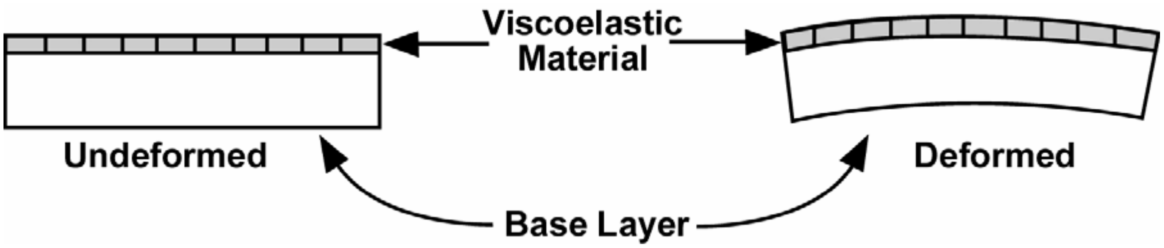

Figure 7 Free-layer VEM

Viscous fluid dampers (such as automobile shock absorbers) force fluid through a precision orifice or annulus to dissipate energy (Figure 8). The fluids are typically silicone, oil or grease, which have some sensitivity to temperature. The amount of damping is proportional to the velocity of the fluid movement.

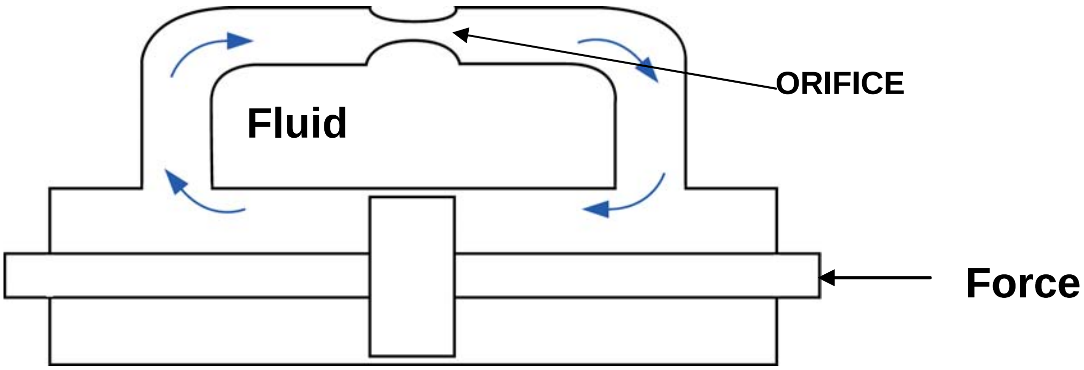

Figure 8 Viscous Fluid Schematic

Magnetic dampers operate on the principle of eddy currents in a moving conductor to dissipate energy. There are many advantages to this design including the construction is simple, uses common materials and is robust. The damper device is compact and produces a large damping constant. Properties are almost temperature invariant and have true linear viscous damping characteristics. Magnetic dampers are used in some isolators, strut dampers and tuned-mass damper applications.

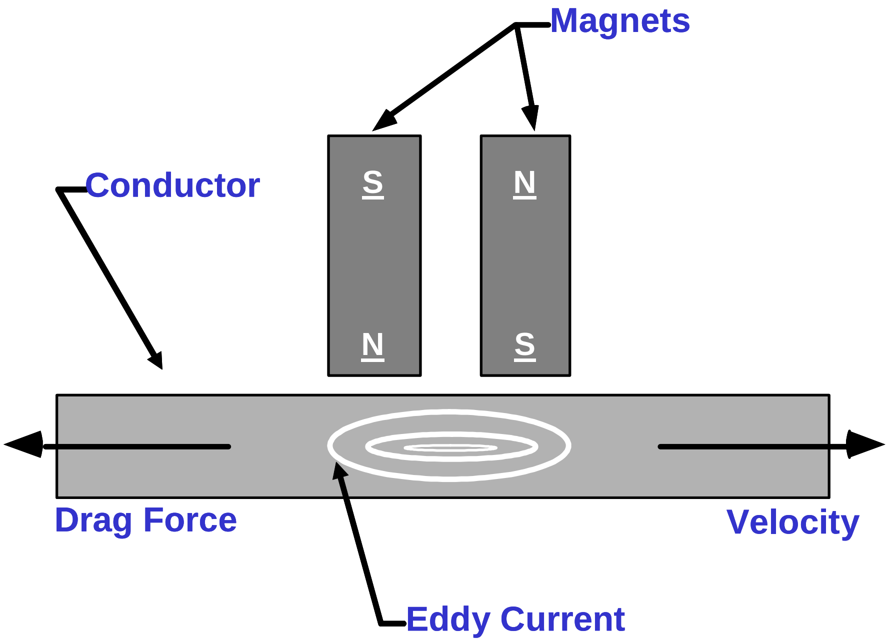

Figure 9 Magnetic Damper Schematic

Particle impact dampers dissipate energy through the friction caused by motion of particles within a closed volume and deformation of the particles themselves. The volume is partially filled with particles such as sand or plastic beads (Figure 10). Although this adds effective damping, the particles also add weight that may not be desirable. The effectiveness of particle impact dampers is difficult to analyze, so designs are usually empirically based ("educated" trial and error). The behavior is dependent on amplitude of vibration and also to the orientation of the device in an acceleration field.

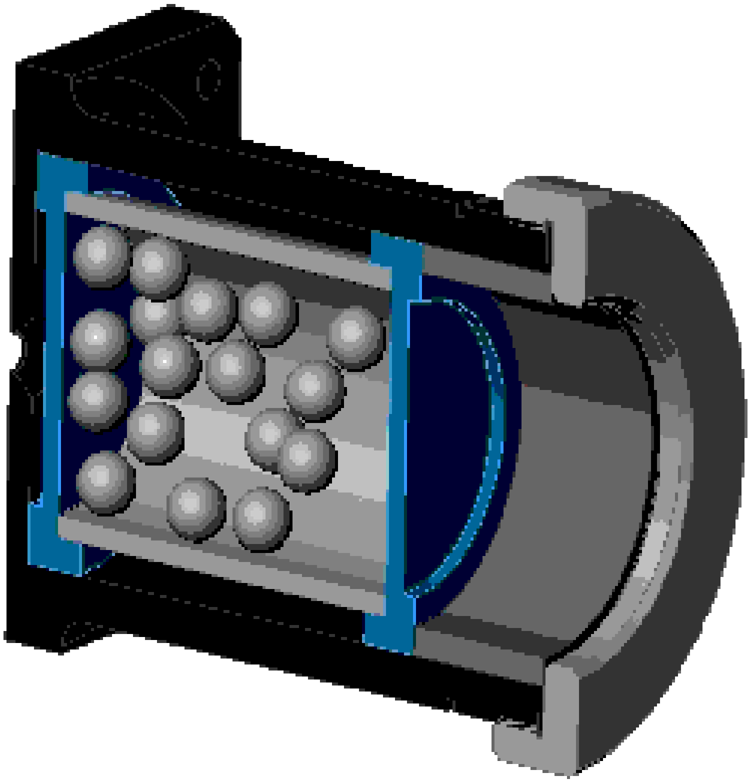

Figure 10 Particle Damper

Friction is a dissipating force caused by two surfaces rubbing together. An everyday example of a friction damper is the brake pad on an automobile. Friction dampers are useful in aerospace applications because they can tolerate vacuum and other harsh environments.

Most metals have high stiffness, but low damping or low stiffness and high damping (lead). High damping alloys have been developed that have the best of both worlds - high stiffness and damping. Magnesium alloys have comparatively high damping capacities, up to about 3 times that of cast iron and up to about 30 times that of aluminum and have a high strength-to-density ratio. The combination of high damping, good strength and low mass make magnesium alloys an excellent choice for vibration test fixtures.

“Smart materials” refer to materials that undergo controlled transformations through physical interactions. Examples are piezoelectrics, piezoceramics, magnetorheological (MR) fluids, electrorheological (ER) fluids, electrostrictive, magnetostrictives, and shape memory alloys (SMAs).

Piezoelectric and piezoceramic materials create electrical charge when mechanically stressed. Conversely, an electrical field will change the shape of the material. An oscillating electric field makes the material resonate at its natural frequency, thus adding an extra mode to the system. Buzzers inside pagers and cell phones are piezoelectric devices. The stress in the material creates heat that is dissipated. The location of high strain energy of a system mode determines optimal location of the piezoelectric device.

Magnetorheological fluids and electrorheological fluids change from a liquid to a semi-solid state when exposed to a magnetic or electric field (Figure 11).

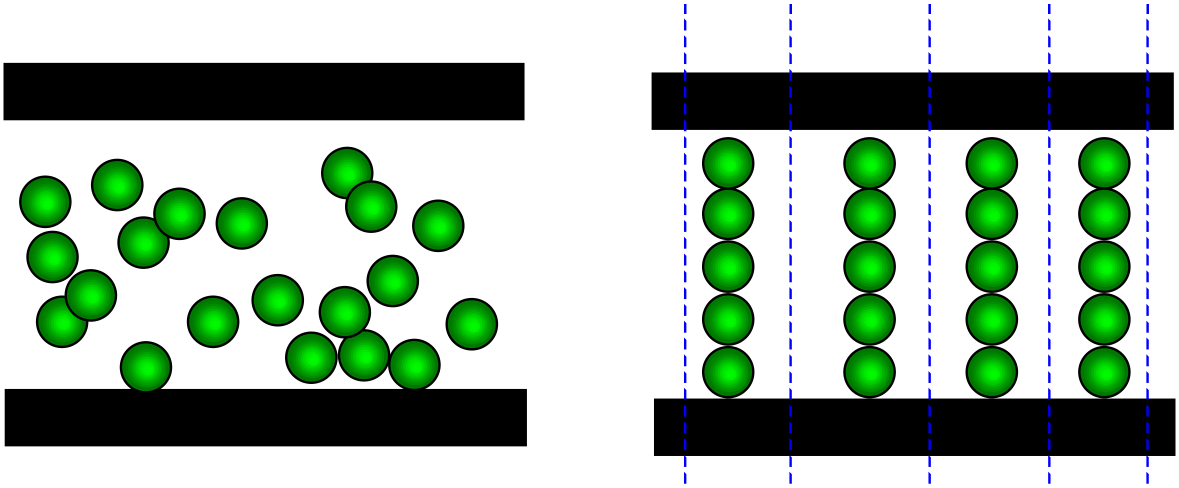

Figure 11 MR or ER Fluid Particles Become Aligned when Exposed to a Magnetic or Electric Field

Magnetostrictives and electrostrictves are materials that experience an elastic strain when subjected to a magnetic or magnetic field respectively.

Shape memory alloys (SMAs) are metals that can be severely deformed and then returned to their original shape simply by heating or cooling them.

As you have read above, there are many possible methods of adding passive damping to a structural system. Table 1 compares some of these. The engineer must decide which is best for his particular design.

Table 1 Overview of Passive Loss Mechanisms

	VEM/Enamel	Viscous	Magnetic	Piezoelectric	Friction	Impact/Particle
Advantages	Many Different Applications	High Loss	Almost Temperature Invariant	Coupled With Active	All Metal	Temperature Invariant
Disadvantages	Temperature Sensitive	Fluid	Low Damping Force	Brittle	Needs Relative Motion Between Components	Nonlinear, Relatively Low Loss
Comments	Low Stiffness Attracts Strain Energy, High Loss	Loss Depends on Static Load-Carrying Ability	TMD is Best Application	Used in Soft Failure Mode for Active Controls	Dependent on Surface Effects	Best for Shock and High-G Loads, Main Loss Through Change in Momentum
Types of Treatments	All	Discrete, TMD	TMD and Isolators	Discrete, Free-Layer	Interface	Cavity
Temperature Sensitivity	High	Moderate	Low	Low	Low to Moderate	Low
Thermal Control	Heaters	Heaters	None	None	None	None
Loss Factor	High	High	Moderate	Moderate	Moderate	Low
Frequency Range	Wide	Moderate	Moderate	Moderate	Wide	Wide
Weight	Low	Moderate	Moderate	Moderate	Low	Low

Discrete Damping Devices

Passive damping devices incorporate discrete damping mechanisms such as tuned-mass dampers (TMD), link, strut, or shear strap dampers, and joint or interface dampers.

TMDs offer high damping for a single mode with a small weight penalty. The principal of a TMD is to choose the mass and stiffness to make the natural frequency of the TMD match the problematic, resonant mode of the structure. This "splits" the problematic mode and causes the high damping of the TMD to be effective in the two closely spaced modes as shown in Figure 12. TMD designs are compact and easily incorporated into a structural system as shown in Figure 13.

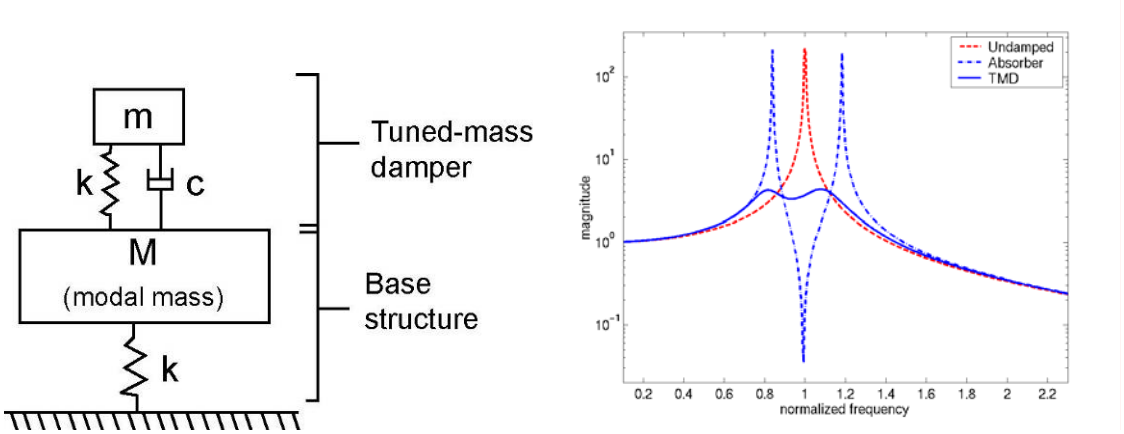

Figure 12 TMD Operating Principle

Figure 13 Magnetic and Viscous TMD (http://www.csaengineering.com)

Link, strut or shear strap dampers are useful for damping and shifting troublesome modes (Figure 14). Joint or interface dampers insert damping material, such as VEM, at the connection between two pieces of structure (Figure 15). There is a small weight penalty for either of these designs.

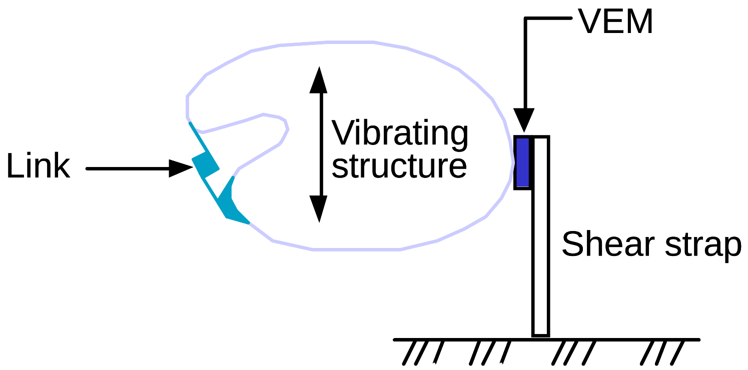

Figure 14 Link and Shear Strap Damper Schematic

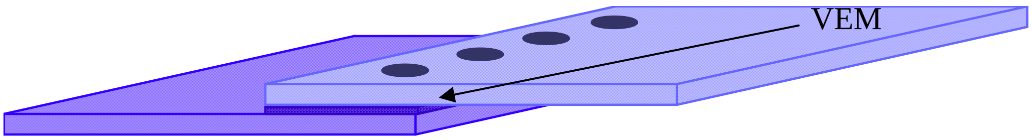

Figure 15 Joint or Interface Damper

Real-Life Examples

Successful implementation of damping can show dramatic reductions in response. Here are two examples.

The Hubble Space Telescope (HST) imaging instruments do not perform well when subjected to vibration: The images become "fuzzy" because the pointing accuracy cannot be maintained. Although the telescope body is fairly stiff, the telescope reacts to the vibrations of the very flexible solar panels. The vibrations are caused by changes in temperature as the HST orbits the earth and is in shadow or sunlight. A damper damps the movement of the arrays, thereby causing less motion of the telescope, as shown in Figures 16 and 17.

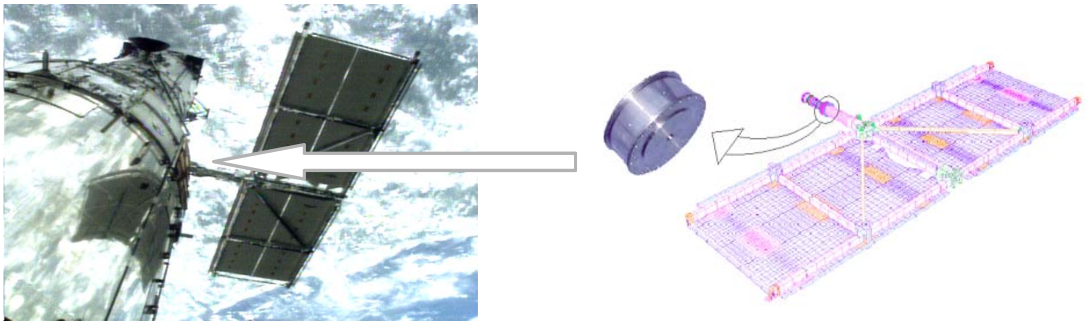

Figure 16 Damper Isolates Solar Array from the Hubble Telescope
(http://www.csaengineering.com)

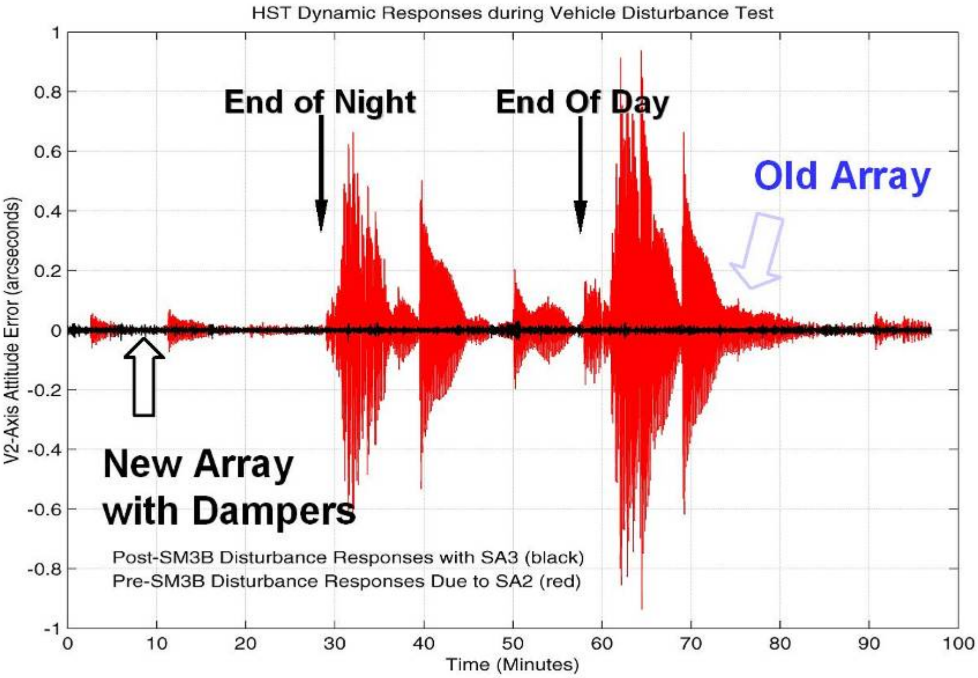

Figure 17 Effect of Dampers on Hubble Space Telescope Vibration

Isolation systems also protect fragile satellites from the rough ride during launch. One concept of an isolation system is shown in Figure 18. Measurements of acceleration above and below the isolation system (Figure 19) show that the satellite vibration levels (in yellow) are markedly reduced from those on the launch vehicle (in blue).

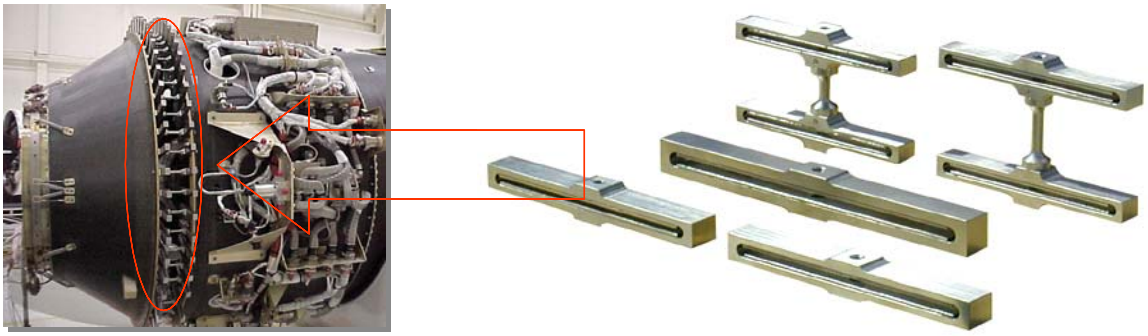

Figure 18 SoftRide™ Isolation System (http://www.csaengineering.com)

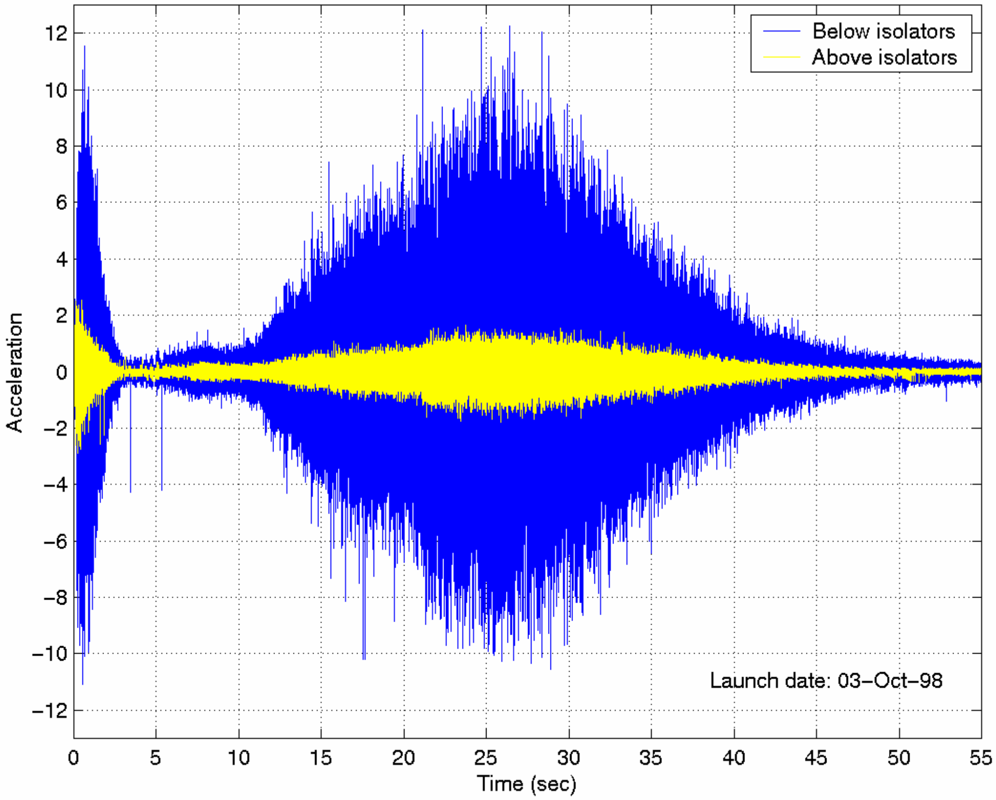

Figure 19 Effect of SoftRide™ (http://www.csaengineering.com)

Active Vibration Suppression

In special cases, active damping devices (Figure 20) are employed to reduce vibration levels. "Active" means that the response of the structure is measured and sent to a computer. The computer activates the vibration suppression system and the response of the structure is changed. A computer requires power and adds mass to the system, so benefits must be outweigh the penalties. Active systems can very effective as shown in Figure 21.

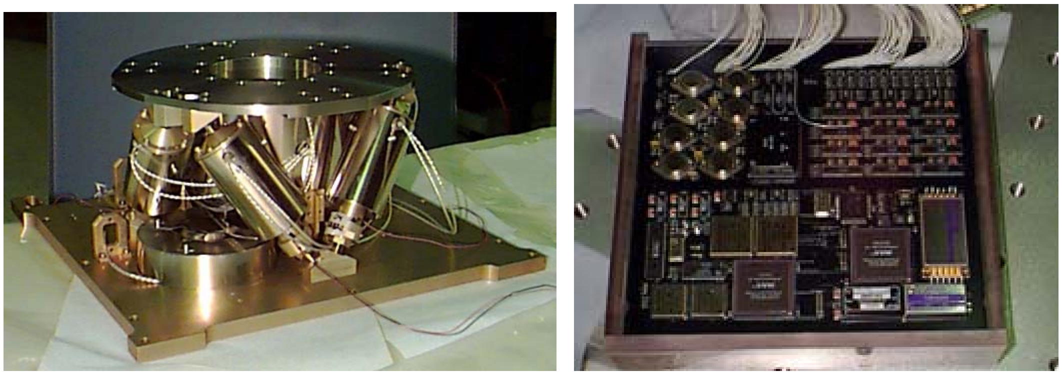

Figure 20 Satellite Ultra-quiet Isolation Technology Experiment (http://www.csaengineering.com)

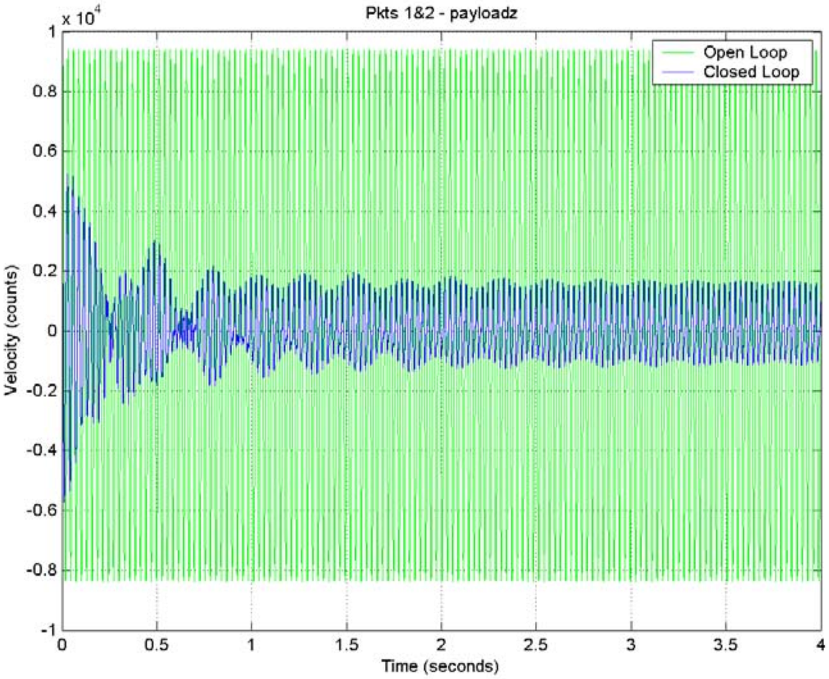

Figure 21 Vibration Reduction Due to an Active System

Design of Vibration Suppression Systems

Vibration suppression is an integrated structural and material design process. To achieve increased damping, two conditions must be met. First, significant amounts of strain energy must be directed into the damping mechanism for the modes of interest. Second, the damping mechanism must dissipate energy.

Analysis methods have been developed to design dampers and predict the performance. These methods include modal strain energy, complex Eigenvalues, frequency response analysis and transient response analysis.

In summary, damping is a very important consideration in the design of aerospace structures. Passive damping and isolation are very effective in reducing amplitude and duration of vibrations. Use of active solutions is warranted only when performance improvements offset the cost and complications. Passive designs should be integrated into all active solutions. Analysis and design tools help the engineer to choose the proper technology to fit the application.

Sources:
http://www.csaengineering.com
http://www.lord.com
http://www.cs.ualberta.ca/~database/MEMS/sma_mems/sma.html

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Vibration Suppression–Precision Motion–Noise Control

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