Passive Vibration Damping with Noncohesive Granular Materials

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Abstract

Dynamical systems comprised of noncohesive solid particles offer a promising approach for passive vibration damping as an alternative where viscous or viscoelastic materials become ineffective at high or low temperatures or in a hostile environment. We are employing a vibrating bar apparatus to understand damping mechanisms in such systems and to identify important parameters for use in the design of efficient methods for controlling damaging vibrations in high speed aircraft and Large Space Structures. In systems involving solid particles rubbing and colliding with each other, loss of mechanical energy can be substantial but the mechanisms are complex and not fully understood. The material parameters we have been studying include grain size and shape, intrinsic grain density, packing density, and friction coefficient. Measurements on a variety of noncohesive granular materials show that damping is both frequency and amplitude dependent which indicates the combined effects of frictional and viscous-like damping mechanisms. Considerable mechanical energy loss results from friction by particle sliding, rolling and by transfer of inertia at collisions between the grains. Relatively low packing densities and fine grain size seem to be favorable properties for maximizing vibration energy losses, at least for the materials examined and in the frequency range, strain amplitudes and vibration modes employed. Microstructures which enhance internal surface area and resistance to compaction are favorable properties for promoting high mechanical energy loss. A full understanding of the mechanisms may provide the data necessary for designing and manufacturing damping materials tailored for use in applications where conventional viscoelastic materials are ineffective.

Introduction

Potentially destructive vibrations often take place in aerospace structures and components. Vibration induced cracks occur in the aircraft affecting structural elements, aircraft skin and antennas. When aircraft operate at very low temperatures conventional damping materials based on viscous or viscoelastic mechanisms are transformed from their rubbery or transitional state into their glassy state where they lose their effectiveness. Serious cracks have been known to develop in aerospace components operating at high temperatures and hostile environments. Vibration problems are also anticipated in advanced launch systems and are pervasive in many other industrial applications. The use of noncohesive granular materials as a damping medium offers a promising approach for damping vibrations in situations where conventional materials cannot be used.

The objectives of this work are to a) understand damping mechanisms in oscillating particles set in motion by a vibrating structure, b) identify critical parameters needed for design of effective damping systems, and c) acquire the knowledge necessary for recognizing potential applications and limitations of this technique.

This work is based on two studies performed independently at the Rockwell Science Center (1-3) and Rocketdyne divisions (4). We learned from previous studies on elastic wave attenuation in rocks with a wide range of cohesiveness that damping increases substantially with the increase in crack density and inversely with the strength of bonding at grain interfaces. The presence of even small amounts of water adsorbed on silicate grains causes considerable weakening of the interface bond and dramatically increases the damping factor (1/Q). Damping mechanisms in semi-consolidated materials were found to be complex, involving both internal friction and viscoelastic-like effects. In noncohesive materials with solid particles rubbing on and colliding with each other, loss of mechanical energy can be substantial; but the effects of various parameters on damping are complex and often work in opposite directions. This paper reports progress toward understanding the effects of some microstructural parameters on damping in relation to frequency and strain amplitude.

Measurements and Techniques

This study draws upon damping measurement techniques and research experience developed over the last ten years at Rockwell Science Center to characterize the dynamic mechanical properties of aerospace and geophysical materials. Figure 1 shows a schematic of a vibrating bar apparatus and measurement system we currently use for making damping and modulus measurements on composite materials. A Hewlett-Packard computer is used to control the experiment and is programmed to allow the selection of input voltage and frequency range parameters and for measurements at high temperatures and controlled environment. The system tracks and digitizes the resonance peaks, and calculates the loss factor 1/Q from the width of the resonance curve measured at 1/ 2 of the maximum amplitude and is given by

$$1/Q = \omega_2 - \omega_1 / \omega_r$$

where Q is the quality factor, ω_r is the resonant frequency in forced vibration, and ω_1, ω_2 are the frequencies at which the amplitude of the vibration has fallen to 1/2 of the maximum value.

In these experiments the forced vibrating bar apparatus was used to measure the damping factor Q^{-1} of a three-layer rectangular bar geometry. The composite bar consists of two identical constraining copper bars rigidly mounted on the vibrating bar device and separated by a space in which the test damping material is placed. The metal bars are 10 cm long, 2.5 cm wide and 0.06 cm thick and are separated by a spacing of 0.6 cm. The geometry is that of a damping layer sandwiched between two constraining metal layers Figure 2. The damping test material is contained in a tailored bag of thin mylar film placed between the two metal bars. The mylar bag had a small effect on damping of the composite bar and this was taken into consideration when making comparisons between measurements made with and without the damping layer.

The theoretical basis of damping in multi-layer beams was discussed by Ross, Ungar, and Kerwin (5). A method for determining the damping properties in various multi-layer geometries is described by Nashif et al (6), and in ASTM Standard Method E756-83 (7).

Figures 3-7 illustrate the effects of some microstructural parameters on damping (1/Q) of the composite bar system using a variety of damping materials. The measurements were made on the fundamental mode in a free-free end-loaded geometry in flexure. A rotor with calibrated weights rigidly clamped to the ends of the specimen provided a means for varying the resonance frequency. A full description of this technique was given by Papadakis (8).

Figure 3 is a plot of 1/Q four damping materials representing a range of packing densities. Diatomaceous earth (DE) with the lowest density shows superior damping compared to the high density nickel particles (Ni). The 1 micron zirconia (ZR) also shows excellent damping. The four points, collectively labeled GL, represent crushed glass beads with different packing densities. In this case, however, the observed differences in damping may not be totally attributable to packing density alone since we are dealing with different materials of different intrinsic and microstructural properties. The effect of packing density on damping is more uniquely illustrated in Figure 4 in which damping was measured as a function of resonant frequency using the same material (1 micron zirconia) at two different packing densities.

The lower packing density (D= 0.68 g/cc) curve shows higher values of 1/Q and a stronger frequency dependence than the curve of the higher packing density (D=1.27 g/cc).

In the family of curves shown in Figure 5 the resonance frequency is plotted against grain size fractions of crushed glass at five different input voltages (vibration amplitude). The shift of resonance to lower frequencies observed with the decrease in grain size and increased input voltage indictes reduced stiffness. The rapid change in slope of the 40 Volt curve suggests that the material my be showing thixotropic behavior at high strain rates. Figure 6 shows strain amplitude dependence of 1/Q for the 1-micron zirconia. Figure 7 shows the same grain size and input voltage parameters of Figure 5 plotted versus 1/Q.

Damping Mechanisms in Granular Materials

Energy dissipation mechanisms in granular materials are complex and involve both intrinsic material properties (elasticity and friction coefficient) as well as the microscopic mechanical properties involving frictional sliding and collision of particles. Microstructural properties largely determine whether energy loss by friction or collision is the dominant mechanism. The loss of mechanical energy in systems damped by noncohesive particles can be substantial, and the effects of various parameters are complex and often work in opposite directions.

Figure 8 illustrates dynamic interactions between oscillating particles set in motion by two constraining bars vibrating in flexure. Although quantitative analysis and modeling of the processes involved are difficult, some insights have emerged from numerical studies (9) describing rheological behavior of geological materials (e.g., soils) and from studies of grain flow and transport processes (10,11).

When friction is the dominant mechanism cohesionless particles support overall shear stresses through frictional contacts. The overall shear resistance decreases with decreasing interparticular friction. When grains are at their maximum (hexagonal) packing they attain high resistance to deformation and show little or no loss of mechanical energy. In moderately compacted materials large forces are carried by chains of particles that are more or less aligned in the direction of maximum compressive stress. Stiff columns thus behave like a pin-jointed structure that dissipates little or no energy. Adjacent to these are areas of relatively high damping caused by particle rotation and frictional sliding (12,13).

Energy dissipation caused by friction is a complex function of many variables including a) the number of contacts per unit volume which is dependent on grain size and and coordination number (packing density), b) normal stresses at points of contacts, which is also a function of packing density, c) the shear stress at the sliding interface, and d) the effective friction coefficient which is a function of the intrinsic friction coefficient of the material (usually measured on two smooth surfaces) modified by the presence of asperities (grain shape).

In more loosely compacted material the grains lose energy both by friction and collision. The latter mechanism becomes more dominant at low packing densities. In the collision dominant regime viscous-like damping results from losses during momentum transfer (14). In this case particle inertia and frequency of collisions are major contributors to energy loss. At high packing density the particle velocity, inertia and number of collisions are reduced due to the increased stiffness and resistance to deformation.

Figure 9 illustrates a rheological model of particle interactions in a system where both elastic and viscous normal forces and tangential frictional forces simultaneously take place (15). The model (16) for granular flow which is based in part on the early work of Bagnold (14) on shearing of solid spheres dispersed in a Newtonian fluid. The model considers the total stress as the sum of two parts,

$$\sigma_{total} = \underbrace{\sigma(C)_{Coulomb}}_{\text{rate-independent dry friction part}} + \underbrace{\lambda(C)\rho D^2 (dU/dy)^2}_{\text{rate-dependent viscous part}}$$

where C is the solids fraction,
dU/dy is the rate of shear strain,
λ is the linear grain concentration coefficient, defined as the ratio grain diameter/mean free dispersion distance,
$\lambda = 1/(C_o/C)^{1/2} - 1$ where C_o is the maximum possible static volume concentration,
ρ is mass density of particle material,
D is mean particle diameter.

Noncohesive granular materials are not Newtonian fluids and their flow models cannot quantitatively describe the complex movements of oscillating particles. However, the relationships described above provide some insights of the mechanisms involved.

The term $\lambda(C)$ relates to the packing density; the strain shear rate (dU/dy) is equivalent to frequency. The role of grain diameter D is more complex because it enters into the viscous part and also in the friction part of the total energy dissipated. Fine grained particles have higher surface area per unit mass and therefore produce higher levels of grain to grain friction than the coarse grained particles. The role of the intrinsic grain density ρ in relation to vibration modes is also unclear and must be investigated by further studies.

With these qualifications in mind, the granular flow model is qualitatively synergistic with energy dissipation in oscillating particles. In both processes the rate-independent, strain dependent part of damping can be ascribed to dry Coulomb friction and the 'viscous' contribution results from momentum transfer during collisions between particles. At high values of solids fraction (high compaction) and low shear rates the rate-independent term is dominant, whereas at low packing densities and high shear rates the collisional transfer term prevails.

This is qualitatively consistent with our data whereby high levels of damping are associated with low packing densities. The observed behavior of strain amplitude dependence together with frequency dependence of damping (1/Q) indicates that both frictional and viscous-like processes are involved. Diatomaceous earth, the most effective damping material found so far in this study, possesses several of the favorable microstructural properties discussed above. It consists of siliceous skeletal remains of marine microorganisms (diatoms).In addition to fine grain size with high internal surface area, diatomaceous earth has high resistance to compaction. These properties are favorable for high damping and the excellent filtration properties for which this material is very well known.

Summary and Conclusions

Laboratory studies on a variety of noncohesive granular materials show that damping is both frequency and amplitude dependent which indicates the combined effects of frictional and viscous-like damping mechanisms. Considerable mechanical energy loss results from friction by particle sliding, rolling and by transfer of inertia at collisions between the grains. Relatively low packing densities and fine grain size seem to be favorable properties for maximizing vibration energy losses, at least for the materials examined and in the frequency range, strain amplitudes and vibration modes employed. Microstructures which enhance internal surface area and resistance to compaction are favorable properties for promoting high mechanical energy loss. The effects of other paramters such as intrinsic grain density, grain shape, and the presence of very small amounts of adsorbed fluids need to be further investigated. Quantitative modeling of the complex mechanisms involved is a challenging task necessary for optimizing design of damping materials tailored for specific vibration problems. Full understanding of these mechanisms will also be useful in developing internally damped alloys and composite materials.

Acknowledgements

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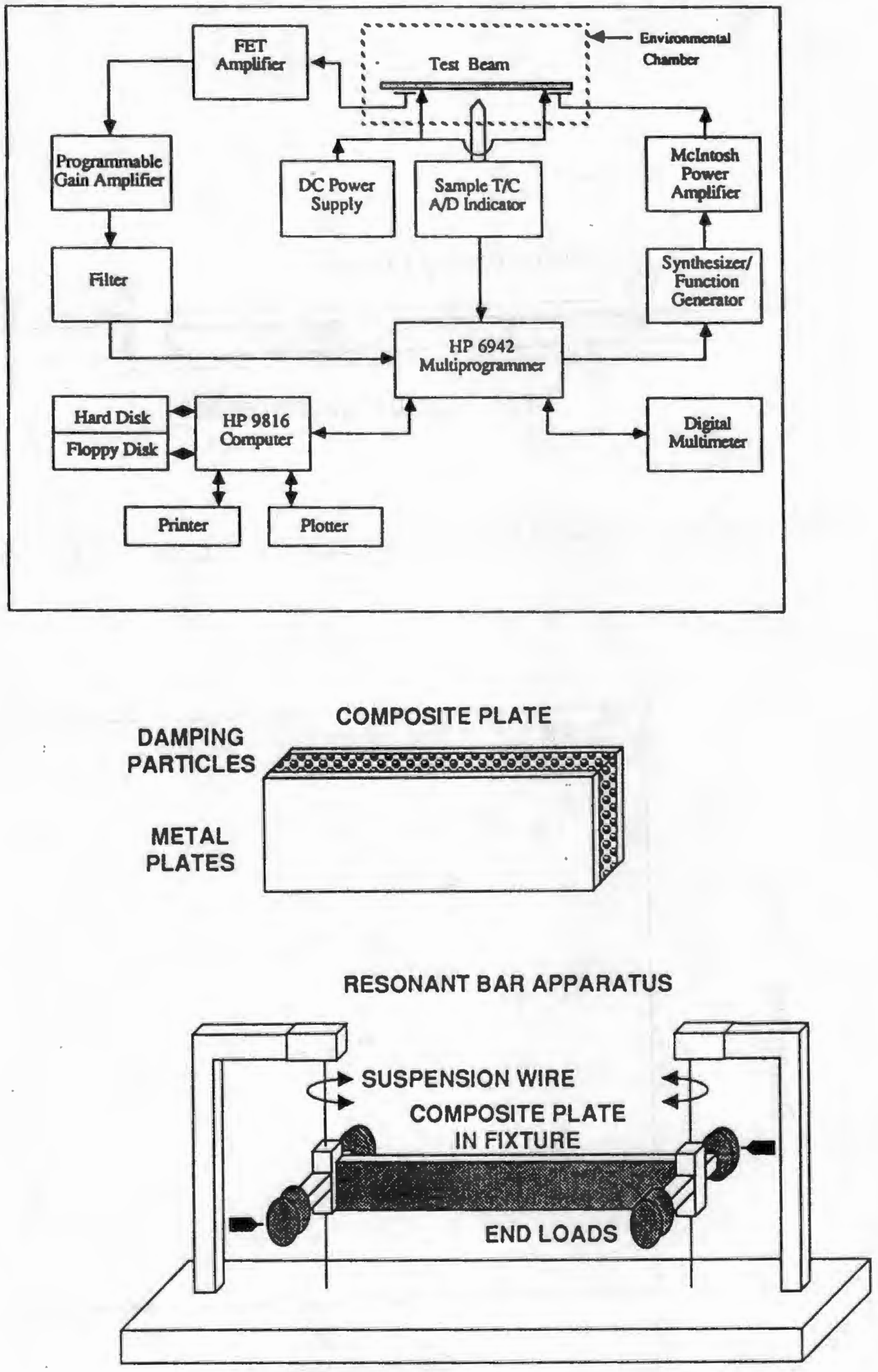


Figure 1- Vibrating Bar Apparatus and Measurement System Schematic

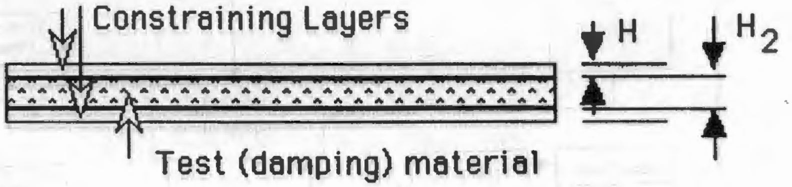


Figure 2. Three-Layer Geometry of Composite Test Bar.

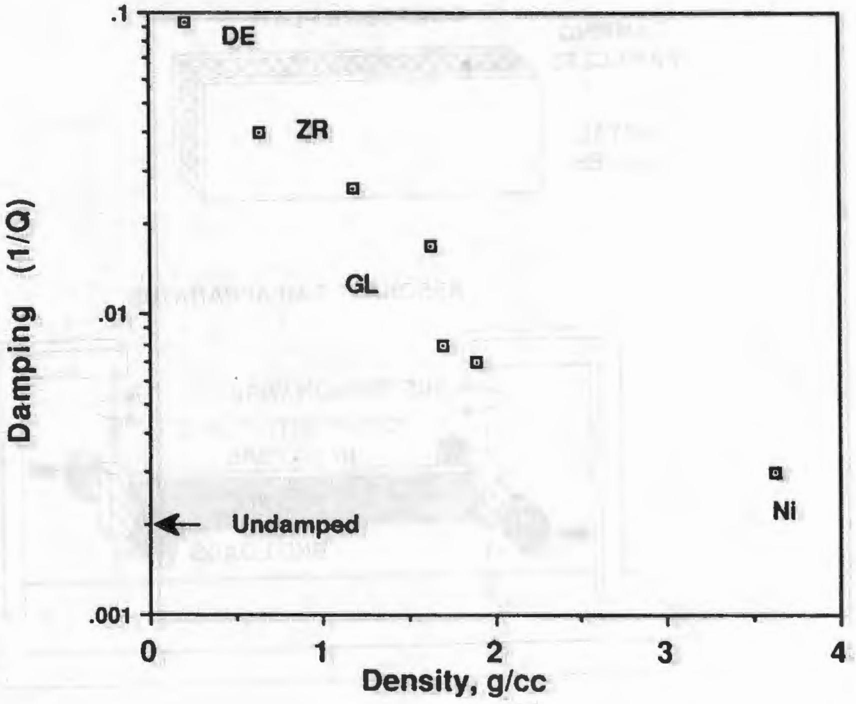


Figure 3. Damping versus Packing Density- DE: Diatom.Earth, ZR: 1-micron zirconia, GL: glass (4 points), Ni: Nickel.

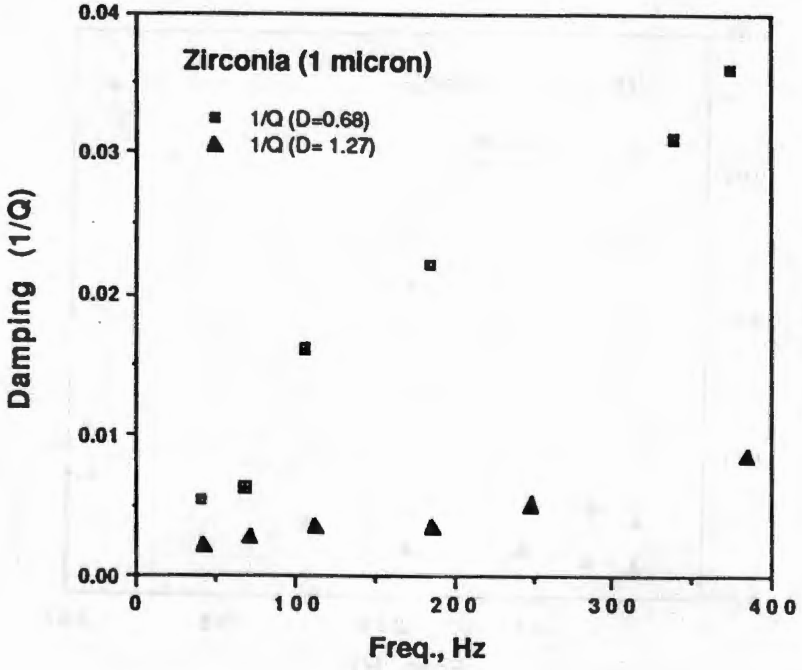


Figure 4. Frequency and Packing Density Dependence of 1/Q.

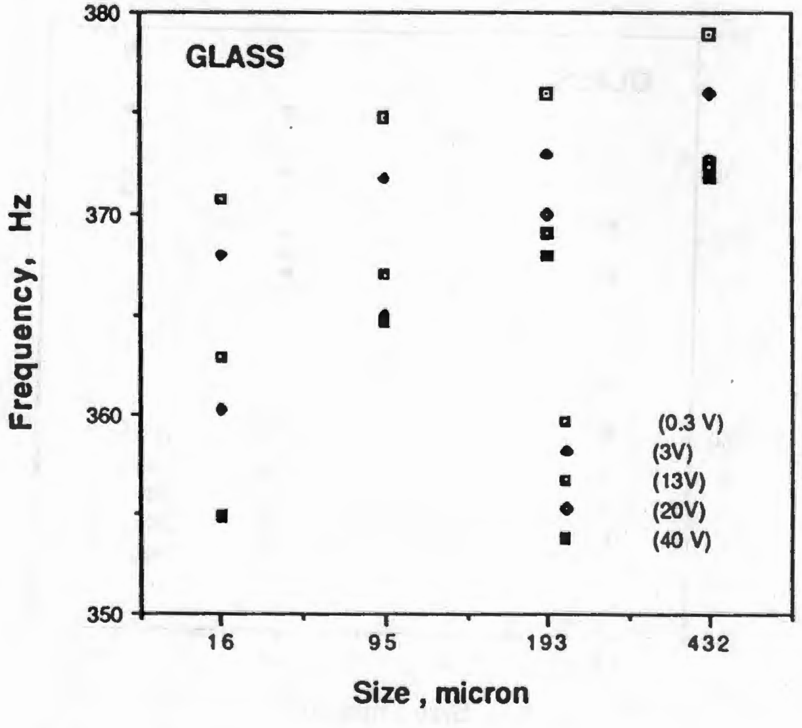
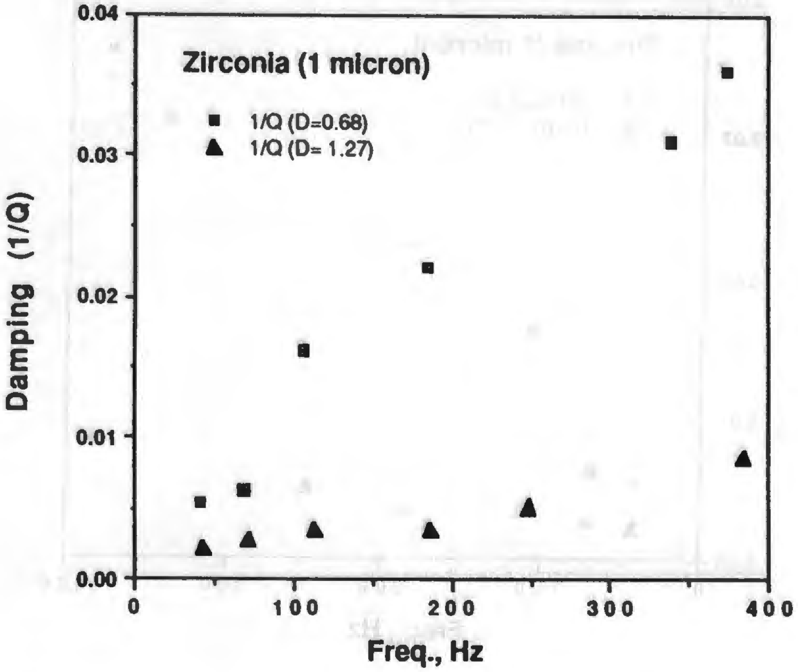


Figure 5. Frequency, Grain Size and Amplitude Dependence.



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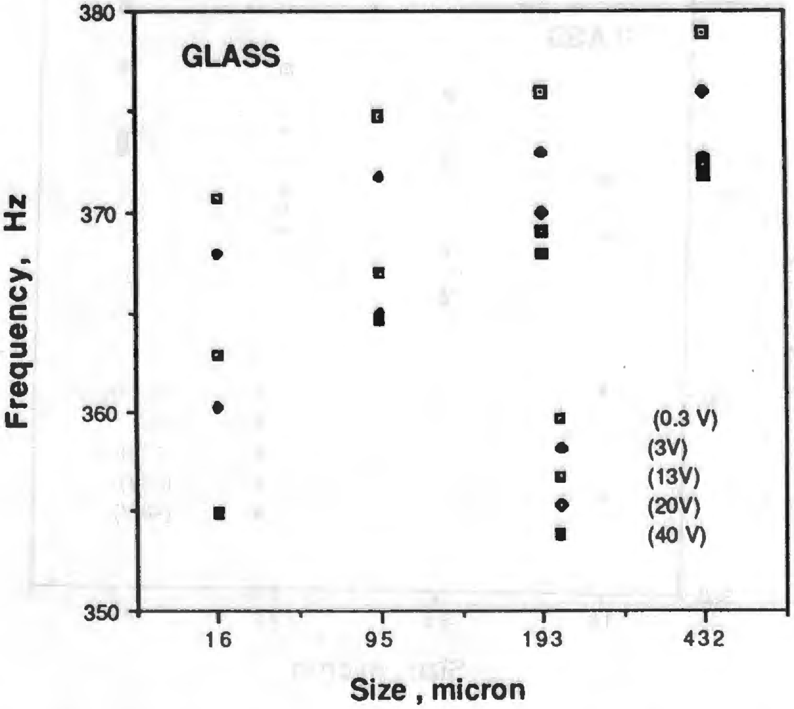

Figure 5. Frequency, Grain Size and Amplitude Dependence.

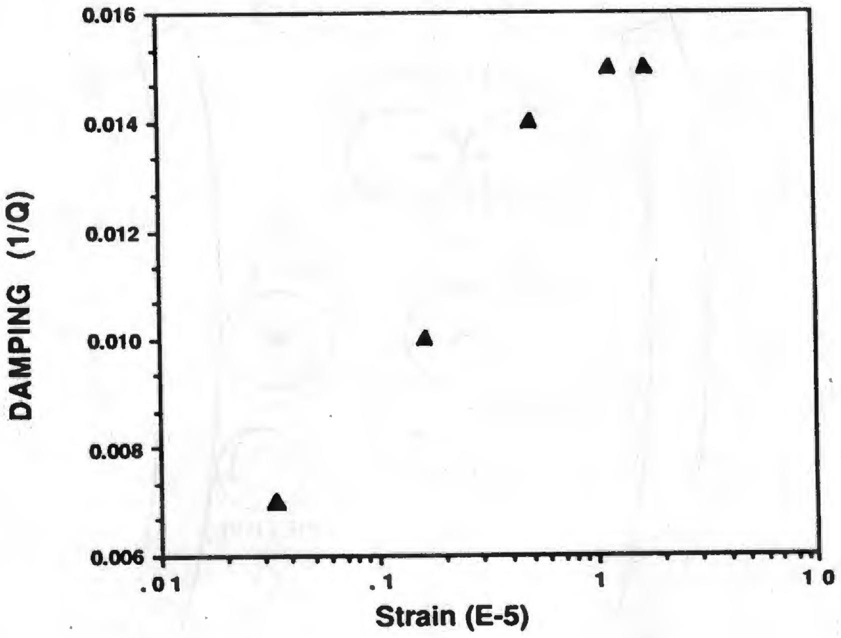

Figure 6. Damping Dependence on Strain Amplitude.

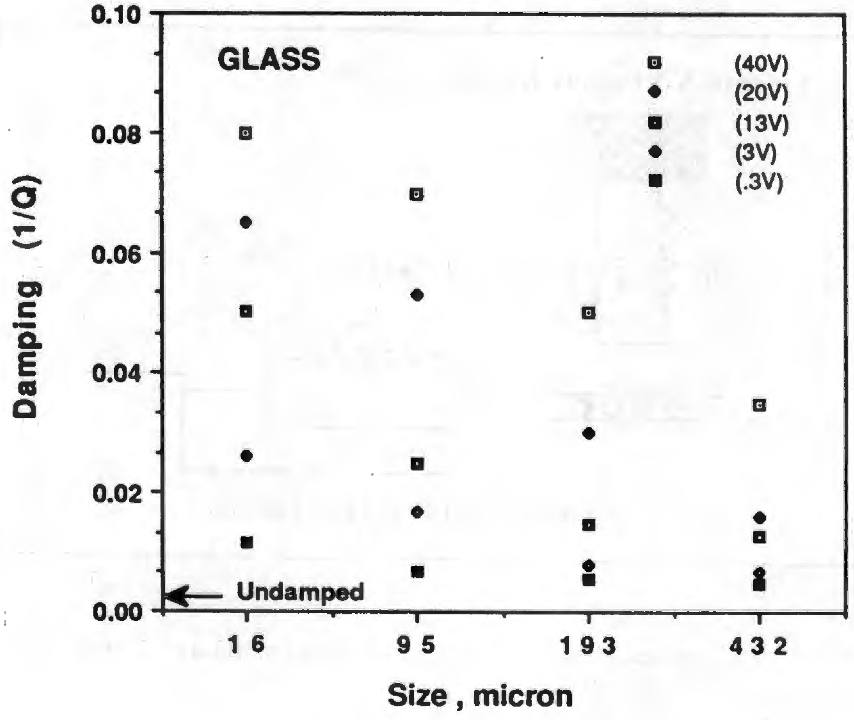

Figure 7. Damping, Grain Size and Amplitude Relations.

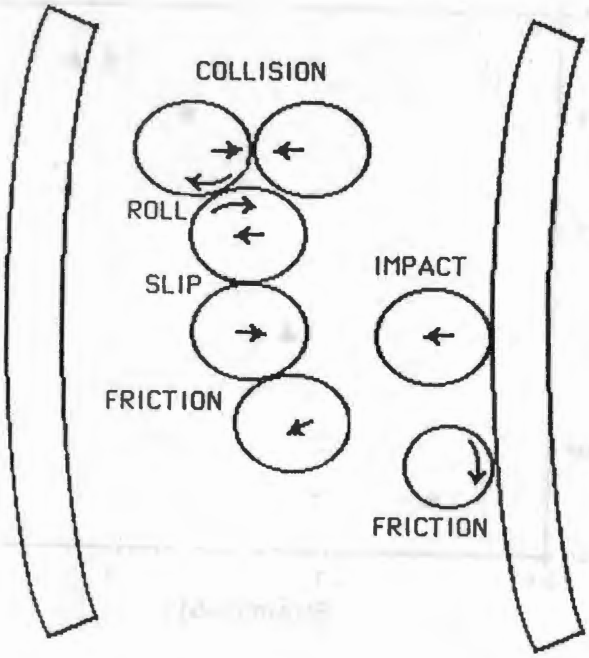

Figure 8. Energy Dissipation Mechanisms in Grains Oscillating Between Beams Vibrating in Flexure.

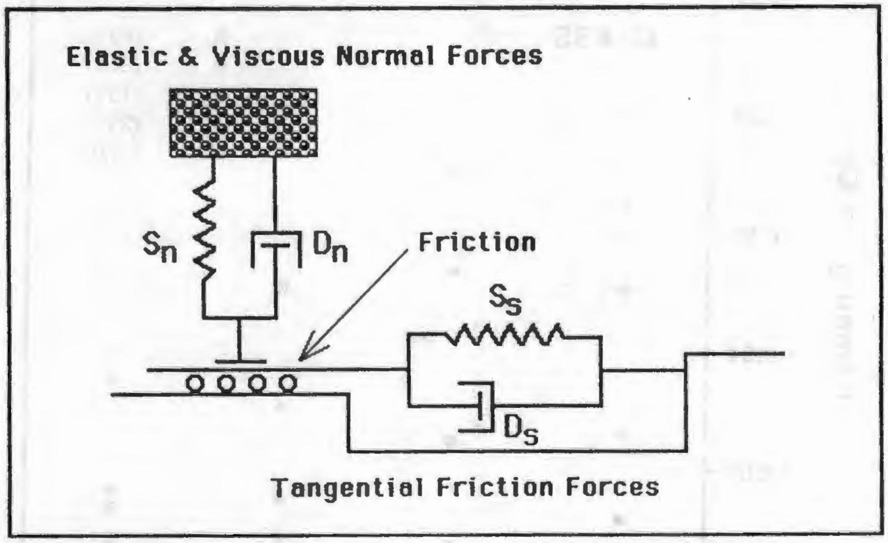

Figure 9. Rheological Model of Intergranular Contact Forces (after Walton, 1980).