Damping And Vibrations Experiment (DAVE): On-Orbit Performance of a CubeSat Particle Damper

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ABSTRACT

The Damping And Vibrations Experiment (DAVE) is a 1U CubeSat designed to study the performance of particle damping technology in the space environment. Particle dampers rely on the free movement and collision of particles and, as such, are influenced significantly by gravitational effects on Earth. Damper performance was characterized using a single degree of freedom cantilever beam experiment. Beams were equipped with particle dampers and then excited to produce a response at various input amplitudes and frequencies. The on-orbit response of the system was compared to a theoretical model of particle damping as well as ground and ZERO-G flight test data in order to ascertain the degree of non-linearity of the system.

Background

Particle damping is a robust method for vibration suppression that relies on the free movement and collision of particles within a confined cavity. On Earth, the motion of these particles is strongly influenced by gravitational acceleration, making the system's orientation with respect to gravity an important parameter. In space, however, gravitational effects are much less significant and, as such, the performance of particle damping technology under these conditions is not well understood. In order to characterize these systems in the space environment, the Damping And Vibrations Experiment (DAVE) was constructed. DAVE is a 1U CubeSat equipped with a single-degree-of-freedom cantilever beam experiment. The experiment consists of three identical beams that are equipped with hollow tip masses at the end. The beams are excited by piezoelectric actuators and their response is recorded by sensors mounted directly under each tip mass. Two of the tip masses are filled with damping material while one is left empty as a control. In 2009, DAVE participated in NASA's Reduced Gravity Flight aboard the Zero Gravity Corporation's ZERO-G flight. The test provided valuable flight data of simulated microgravity, however, various anomalies reduced the significance of the results. Since launch in September of 2018, various on-orbit experiments have been conducted to characterize the

performance of the damper. Similar experiments conducted on the ground as well as on the ZERO-G flight provide a baseline for on-orbit testing.

Theory

Simonian et. al[1] showed that the equation of motion for a particle damper system with total particle mass m_p, structural mass m_p, center-of-mass particle motion x_p, proportional loss factor η, viscous damping coefficient c, structural stiffness k, and structural motion y can be written as:

$$\left(m_s + m_p\right)\frac{d^2 y}{dt^2} + \left(\frac{dm_p}{dx_p}\frac{dy}{dt} + \frac{\eta}{2} + c\right)\frac{dy}{dt} + ky = 0 \quad (1)$$

Assuming the structural mass is much greater than the particle damper mass, the damping term proportional to the peak beam velocity $\frac{dy}{dt}$ can then be written[1] as:

$$\Xi = \alpha\frac{dy}{dt} + \beta = 2(\xi_c\omega_c - \xi_d\omega_d) \quad (2)$$

Here, α is the damping loss factor proportional to the squared velocity, β is the damping loss factor proportional to velocity, ω_c is the center frequency of the control (no particles) beam for a given peak, and ω_d is the center frequency of the damped beam for a given peak. The control and damped damping ratios ξ_c and ξ_d with frequency resonance full width

at half maximum Δf, resonant frequency f_0, and quality factor Q can be calculated as:

$$\xi = \frac{1}{2Q} = \frac{\Delta f}{2f_0} \qquad (3)$$

By measuring the damping ratio and peak frequency for a given resonance peak of the particle-damped beam alongside the same parameters for an undamped control beam with the same structure, Ξ can be easily calculated for a given experimental run. By obtaining values of Ξ across many beam driving amplitudes, α and β can be calculated via linear regression if the maximum velocity $\frac{dy}{dt}$ is known. Approximating the short-term motion of the beam as a simple harmonic oscillator, the maximum tip velocity and acceleration for oscillation amplitude A and angular frequency ω are given as:

$$\left(\frac{dy}{dt}\right)_{max} = A\omega \qquad (4)$$

$$\left(\frac{d^2y}{dt^2}\right)_{max} = A\omega^2 \qquad (5)$$

If the peak acceleration is known for a given frequency, the peak velocity can then be calculated using equation (4). By subsequent linear regression, the performance characteristics and linearity of the damped system can be obtained.

The type and quantity of damping particles used in a cavity, in addition to the cavity's physical dimensions, directly affects the performance parameters (α and β) of a system. As such, measuring these parameters allow for a geometry-specific characterization of a given system.

Experimental Design

In order to put this theoretical model of particle damping to the test, a single-degree-of-freedom cantilever beam system was constructed. The spacecraft is equipped with three identical beams that have hollow tip masses mounted at one end. The

Particle Selection

Since particle dampers rely on the interaction between particles to produce the desired attenuation, particle selection is a critical parameter for damper performance. Particle size, shape, and material

beams are driven by piezoelectric actuators mounted at the base of the beams, and their response is recorded by sensors mounted directly under the tip mass.
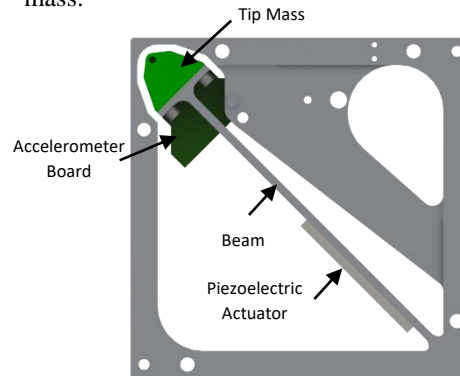

Figure 1: Cross-sectional view of cantilever beam.

Beam Design

As shown in Figure 1, each beam is fully integrated into the structure and is machined out of a single piece of 6061-T6 alloy in order to remove any parasitic damping caused by mechanical joints, as it would complicate the characterization of the particle damper. In addition, the beams were designed to have essentially a single degree of freedom, simplifying analysis. This was accomplished by making the length of the beams much larger than their height and making the height of the beams much larger than their width (L>>H>>W). Table 1 summarizes the approximate geometry of the beam.

Beam Geometry		
Length (mm)	*Width (mm)*	*Height (mm)*
107.70	2.41	12.70
Material: 6061-T6 Aluminum		

Table 1: Approximate beam geometry (mm).

With the geometry of the beam established, a particle damping system was then designed to attenuate vibrations in the beam.

selection are all ways that the characteristics of a damper can be modified.

By varying particle size for a given mass of damping material, the number of particles available for interactions decreases. This increases the

momentum of the individual particles significantly, however, the distribution of particle velocities becomes less uniform. On the other hand, as particle size decreases, individual particles lose momentum and begin behaving more like a fluid.

Particle geometry plays an important role in the collision between particles. For particles with spherical symmetry, the orientation of the particle during collision has no effect on the outgoing trajectory of the particle. Conversely, particles with limited symmetry experience orientation dependent collisions, where the geometry at the collision interface differs significantly from collision to collision.

Following research conducted at Northrup Grumman on particle damping technology, powder with a mesh size of -85 +325 (diameters ranging from 175-44 µm) was selected as the damping material for the experiment.[1] The powder was selected due to significant ground testing that showed good correlation to the theoretical particle damping model detailed in Equations 1 and 2. In addition, particles with small diameters tend to have roughly uniform geometries; making collisions less orientation dependent.

Cavity Geometry

Another important characteristic of a particle damper is its cavity. The particle cavity plays an important role in both constraining the damping material as well as being a catalyst for the momentum transfer between the beam and the individual damping particles; attenuating vibrations in the beam.

The first major design parameter for a particle damping cavity is its fill ratio. The fill ratio describes how much of the cavity volume is occupied by damping material. This is an important parameter for particle damping systems, as if the cavity is completely filled (fill ratio of 100%), particles are

unable to move, and no damping occurs. On the other hand, a small fill ratio (~5%) grants the particles nearly unconstrained motion in the cavity causing collisions to become infrequent and, as such, damping is minimal. Thus, a balance must be met between the number of particles available for interaction and the amount of space available for each particle to move before colliding with the walls of the container or another particle. Ideal fill ratios are dependent on many factors such as cavity geometry, particle size, and particle shape. Testing done at Northrup Grumman suggested that for powder with particle size ranging from about 175-44 µm, a fill ratio of between 90 to 95% produces the best results.[1]

The second parameter for cavity design is the cavity geometry. Since the cavity walls facilitate the exchange of momentum between the damping material and the cantilever beam, the geometry of the cavity can influence the efficiency of such transfer. As DAVE is not equipped with an attitude control system, the walls of the container were made as uniform as possible, while not constraining machinability. Thus, a simple cubic design with radiused corners was chosen.
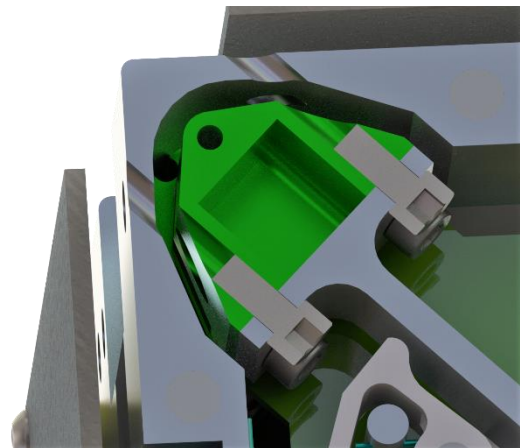

Figure 2: Cross section of damping cavity (0.742 cm³).

The volume of the cubic cavity was selected by considering the fill ratio as well as the required damper mass. In testing, it was determined that the mass of the Tungsten particles should be equal to roughly 10% to 15% of the effective mass of the first mode of the beam and mass system.[1] The resulting volume was calculated by:

$$V_{Cavity} = \frac{m_{req}}{\rho_{Particles}\ \rho_{Pack}\ \rho_{Fill}} \qquad (6)$$

where m_{req} is the required damper mass, $\rho_{Particles}$ is the bulk density of the particles, ρ_{Pack} is the packing ratio of the damping material, and ρ_{Fill} is the cavity fill ratio. The bulk density of a material describes how dense a substance is; including any air pockets that may exist between the individual particles as they are stacked. For example, given two particles with different geometry, each made of the same material ($\rho > \rho_{air}$), the one with the higher bulk density can be packed more tightly than the one with the smaller bulk density. The packing ratio, ρ_{Pack}, relates the bulk density to the true density of the material. For Tungsten particles ranging in size from 175-44 μm, a packing ratio of 55% can be assumed. That is, 55% of the volume occupied by the Tungsten particles is material, while the remaining 45% is filled with voids (air pockets). Using this information, the required volume of the cavity was calculated to be 0.742 cm^3.

Piezoelectric Actuator

In order to simulate a vibrational load, piezoelectric elements were adhered to the side of the beams. Piezoelectric materials are materials that deform when a voltage is applied across them. By applying a strong signal across the piezoelectric, the piezoelectric deforms and displaces the beam about its equilibrium position; causing an excitation in the beam. The displacement of the beam is proportional to the voltage applied across the piezoelectric; allowing the input amplitude to be varied by changing the input potential. A rectangular PZT5A3 ceramic plated piezoelectric actuator was selected to drive the beams with dimensions of 1.75"x0.50"x0.10". Although the piezoelectric elements provide a simple and precise method for excitation, mounted to the sides of the beams, the elements complicate the simplified beam design, as additional stiffness is provided on portions of the beam. This was corrected though repeated simulation until the optimal beam response was achieved[3]. In addition, the piezoelectric elements require a high voltage input to cause any significant beam displacement. As such, the spacecraft is equipped with a high voltage amplifier that can output up to 740V_{pp}.[2]

Sensor Selection

Once a beam is excited, its response must be recorded in order to characterize the effects of the damper. To do this, an in-house sensor module was developed at Cal Poly San Luis Obispo to seamlessly integrate with the tip mass. The sensor module consists of an accelerometer and supporting circuitry to measure the peak acceleration of the beam under a wide range of frequency conditions. The sensor is also designed to monitor the input amplitude provided by the piezo electric actuator and the phase of the signals. The sensor system is described in detail in Reference 1.

Data & Analysis

Data collection consisted of UHF uplink and downlink from DAVE at 437.15 MHz. To initiate an experiment, DAVE first receives an experiment command from an Earth station. The experiment command contains important parameters such as input amplitude and frequency range as well as time delays for the experiment to be carried out. By modulating these input parameters, experiments across various input amplitudes and frequency ranges can be carried out.

Once an experiment command has been received by the spacecraft, it performs a frequency sweep at the given input amplitude across all three beams. Each of these beams is excited separately; preventing the excitations from contributing to each other. Then, the data is downlinked as three separate data files; one for each beam. On the ground, the data is post-processed to correct for sensor specific offsets and the data is concatenated to produce a dataset for the given input amplitude.
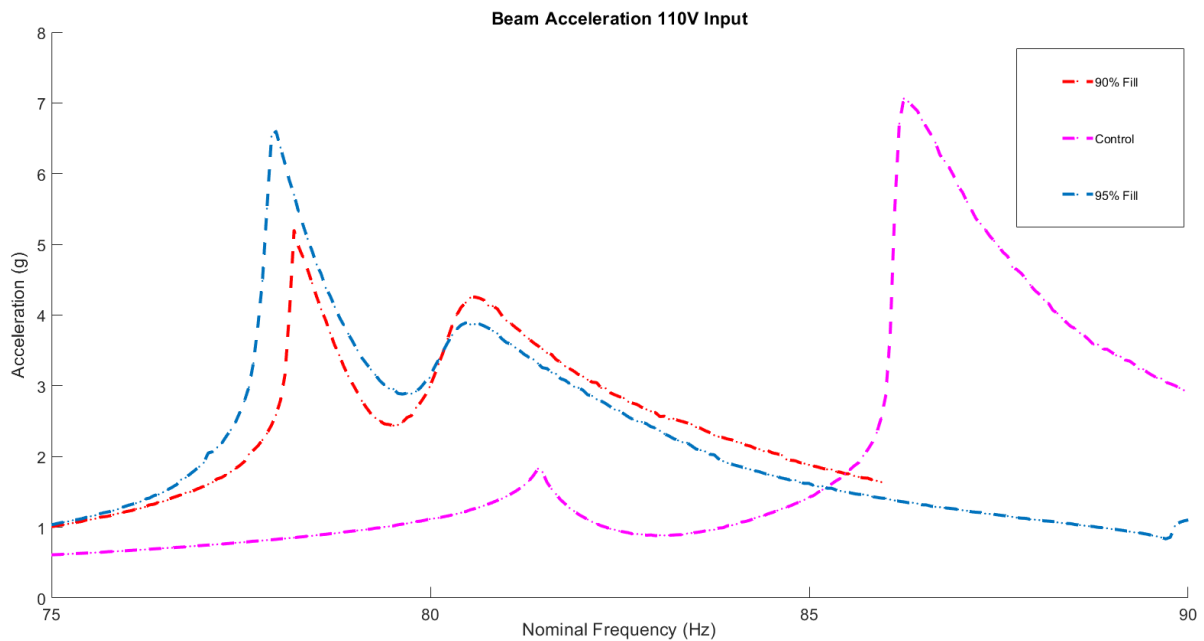
Beam Acceleration 110V Input

Figure 3: Response of beams (82 N input).

Figure 3 details the peak response of the three-beam system at an input amplitude of 110V and a frequency range of 75 Hz to 90 Hz. From the piezoelectric element's data sheet, this correlates to an excitation of 82N.[2]

Three distinct modes are visible at 78 Hz, 80.5 Hz, and 86 Hz respectively. Modes at 78 Hz and 86 Hz correspond to the natural frequency of the damped and control beams. Although these two beams have identical geometry, a shift in the natural frequency is observed due to the presence of damping material in the damped beams; giving them more mass. The mode at 80.5 Hz is most likely cause by a coupling between beams as they are driven. Although the beams are driven at different times during the experiment, it is likely that there is some coupling that occurs between the beams as one is driven; given that they are not well isolated.

Comparing the peak accelerations of the beams, both damped beams resulted in a decrease in the response at the resonant mode. The 95% fill cavity had a peak acceleration of 6.6 g while the control

had a response of 7.0 g; resulting in 5.7% attenuation. That being said, this level of attenuation in rather insignificant given the potential for coupling and differing transmissibility produced by the difference in peak response frequency. On the other hand, the 90% fill ratio cavity provided much stronger attenuation at the 82N input with a 5.2 g peak response. This correlates to 25.7% attenuation relative to the control's peak response.

This is a significant reduction in vibration levels given the small addition of mass to the system; exactly what particle damping aims to accomplish. As alluded to earlier, cavity fill ratio plays an extremely important role in determining the damping properties of the system. If the fill ratio is too large at a given input level (95% for example), little damping occurs, as the particles are too constrained to provide any significant momentum exchanges. On the other hand, too few particles in the cavity and the response will behave similar to the control. A sweet spot can be found between too little and too many particles in the cavity relative to cavity size. In this case, a 90% fill ratio seems to provide adequate spatial freedom for the particles while also maintaining a significant number of particles in the cavity. As such, the attenuation of the signal is much more dramatic.

Conclusion

Particle damping is an emerging technology for the suppression of resonant vibrational modes in structures; offering attenuation across a wide range of frequencies with the addition of little mass. These characteristics make particle dampers attractive for space-based applications, where mass constraints and high vibrational environments are present. Although attractive, this technology has seen little space-based application, as the use of new, uncharted technology presents risk to mission success.

As a technology demonstration, the Damping And Vibrations Experiment has shown that particle dampers can provide significant attenuation to vibrational modes when compared to an undamped control. It is hoped that this will provide a steppingstone for the future use of particle damping technology in space-based applications.

Finally, data acquisition is currently underway to describe the performance of the system as described by Equation 2. This information should be available in the coming months.

Works Cited

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