NON-OBSTRUCTIVE PARTICLE DAMPING TESTS ON ALUMINUM BEAMS

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ABSTRACT

Presented in this paper is a novel passive vibration damping technique referred to as "Non-Obstructive Particle Damping (NOPD)." The NOPD technique consists of making small diameter holes (or cavities) at appropriate locations inside the main load path of a vibrating structure and filling these holes to appropriate levels with particles that yield the maximum damping effectiveness for the desired mode (or modes). Metallic or nonmetallic particles in powder, spherical, or liquid form (or mixtures) with different densities, viscosities, and adhesive or cohesive characteristics can be used.

Two 24- by 3- by 3/4-in. aluminum beams were used and thirteen 2-mm diameter, equidistant cross-holes (along the width) in one, and seven 2-mm diameter, equidistant longitudinal holes (along the length) in the other, were drilled. These holes were partially filled with tungsten and zirconium oxide powder and steel (spherical) particles and the beams were tested under different conditions. Modal tests under free-free and clamped conditions indicated an increase in damping ratios from 0.02% without particles to about 10% with tungsten. Moreover, damping of specific modes by placing particles at various locations of high kinetic or strain energies were also carried out with remarkable effects. This paper will discuss the test results and will evaluate various methods of damping estimation.

INTRODUCTION

Damping in vibrating structures is described with various terms: loss factor, quality factor, reverberation time, etc. The interconnections between these various descriptions are discussed in Reference 1. One of the major concerns in vibration control problems is the response prediction of a structure excited by an external force. The reason for this concern is the difficulty in accurately determining the damping factor required for response prediction in analyses. Several different techniques are utilized for damping measurements that entail vibration decay rate, "one-half power point" at resonances, and steady-state input and stored energy measurements, among others. All of these methods involve the generation of frequency response functions (FRFs) and some curve fitting techniques that require knowledge of input amplitude and corresponding vibration measurements at various locations of a structure. Fraction of critical damping (the minimum viscous damping required in a vibrating structure for it to return to its initial position without oscillations) is the most common measure used to express the response characteristics of a structure, referred to as damping ratio.

The NOPD technique entails making small holes (or cavities) at analytically determined (and, when possible, experimentally verified) locations inside the main load path of a vibrating structure in appropriate areas and filling these holes to proper levels with such particles as to yield maximum damping effectiveness. A specific vibration mode, or

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several modes, can be addressed in a given structure. Powders, spherical, metallic, nonmetallic, or liquid (or even mixtures) with different densities, viscosities, and adhesive or cohesive characteristics can be used.[2,3]

This new approach has a great deal of potential applications under cryogenic, high-temperature, high-flow, or high-pressure environments. It does not affect the mass or the performance of the structure (on the contrary, it often reduces it). The only drawback, when applied to an existing structure, is the creation of stress concentrations when making the holes. However, this concern can be greatly reduced by making the size of the holes small compared to the material thickness and by using less destructive manufacturing techniques. In addition, the particles can be embedded inside a structure as a part of the manufacturing process, thus avoiding the previously mentioned negative effects.[4]

NOPD involves the potential of energy absorption or dissipation via friction, momentum exchange between the moving particles and the vibrating walls, heat, and viscous and shear deformations. It offers benefits in vibration reduction of rotating machinery, lasers, rotorcraft, aircraft, spacecraft, automotive, and civil structures, among others, through the decreasing of structural fatigue and associated savings in cost or extension of system life cycles.

MODAL SURVEY TESTS

Experimental modal survey tests were carried out in the Rocketdyne Engineering Development Laboratory (EDL) on two 24- by 3- by 3/4-in. aluminum beams under free-free conditions, and various modal and vibration data were generated. Acceleration measurements were taken on five equidistant points on each beam. One of the beams had seven 2-mm diameter holes along the length, and the other had thirteen 2-mm diameter holes along the width. The holes were filled with various particles and tested for damping effectiveness.

The tests were performed by suspending each beam from two rubber bands and exciting it, via an impact hammer and an electromechanical exciter with load cells at their tips, near one of its ends (Fig. 1). Five acceleration measurements were taken at equidistant points on the beam with the two accelerometers placed at the opposite corners of both ends. Frequency response functions (FRFs), power spectral densities (PSDs), time histories, and other appropriate data were evaluated to study the damping ratios, mode shapes, and frequencies.

The 13 equidistant 2-mm diameter holes drilled across the width of the first aluminum beam were partially filled (about 75%) with tungsten powder, zirconium oxide powder, and steel shots (0.011 in. diameter). The beam was excited with a shaker (with flat random inputs between 10 to 1,600 Hz) and an impact hammer (both applied to one of the corners of the beam) from the opposite side of the accelerometer. The FRFs were generated under empty and filled conditions and overlayed for each of the first four vibration modes (Fig. 2). The first plot is that of the first bending mode at about 273 Hz when empty; the second at 749 Hz is the second bending mode; the third at about 1,145 Hz is the first torsional mode; and the last one at 1,455 Hz is the third bending mode. The overall FRF up to 1,600 Hz is shown in Fig. 3.

All of the seven 2-mm diameter longitudinal holes were filled with tungsten and zirconium oxide powder, and steel shots separately, and tested under (about) 90% full. Moreover, the beam was also tested with empty holes, and the FRFs were compared by overlaying the peaks of each of the first four vibration modes under a free-free test

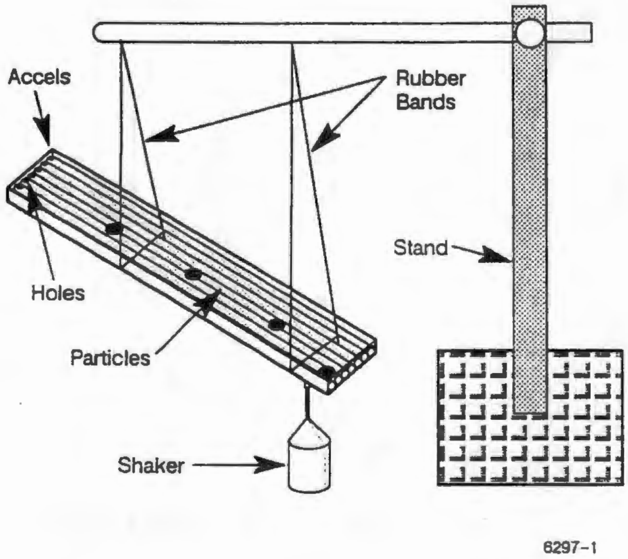

Figure 1. Free-free beam tests in air

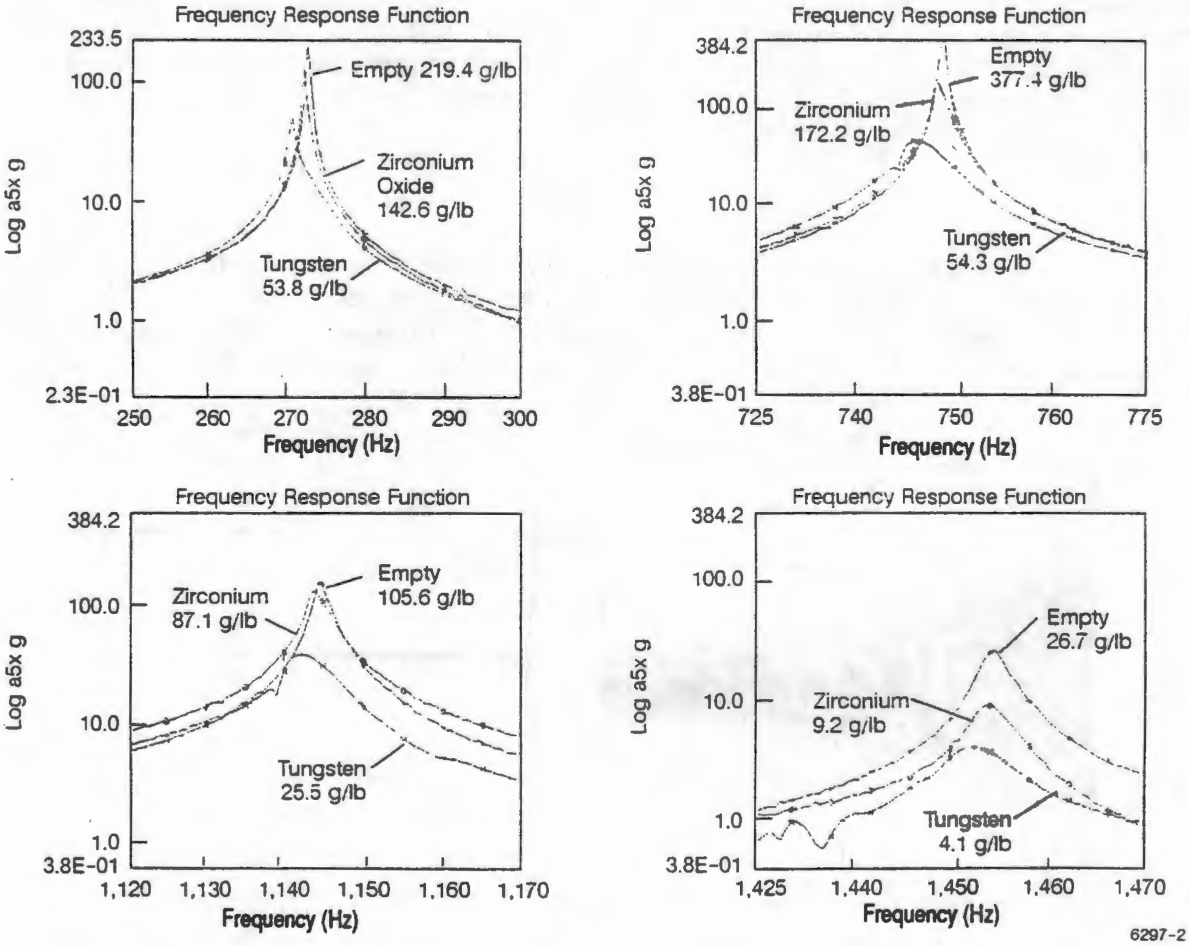

Figure 2. Free-free cross-holed beam vibration FRFs in air

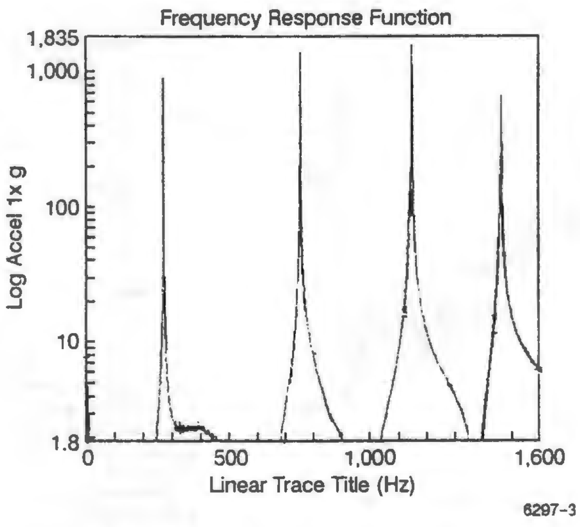

Figure 3. FRF of empty cross-holed beam free-free in air

condition with flat random (shaker) and hammer input excitations. The dramatic decay rate provided by the presence of tungsten powder (see Fig. 4) caused some difficulty in calculating the damping values and various approaches were used to derive the damping ratios for each mode. The overlays of each mode, both empty and filled with different particles, are shown in Fig. 5. The first mode decreased in amplitude from 911.7 g/lb down to 14.9 g/lb by more than a factor of 61.

DISCUSSION

Table 1 summarizes the damping ratios estimated under various damping particle treatments and with different estimation techniques. In all cases, it is apparent that damping effectiveness with such a minute particle amount is dramatic. The total mass of the aluminum beam was 5.4 lb, while the total mass of the heaviest particles used (tungsten)

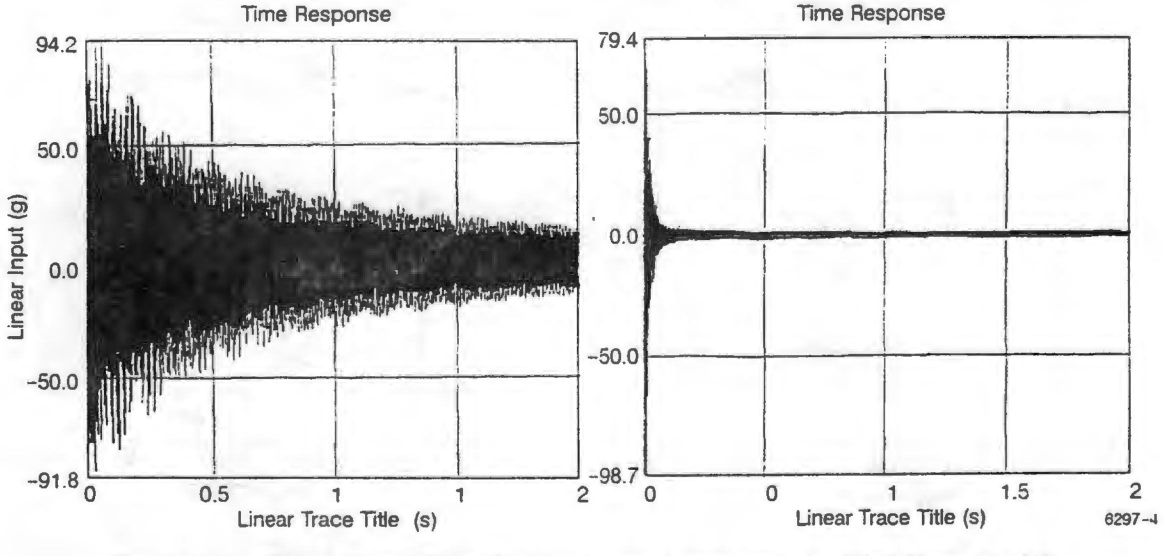

Figure 4. Time histories of aluminum beam empty (right) and with tungsten powder (right) in air

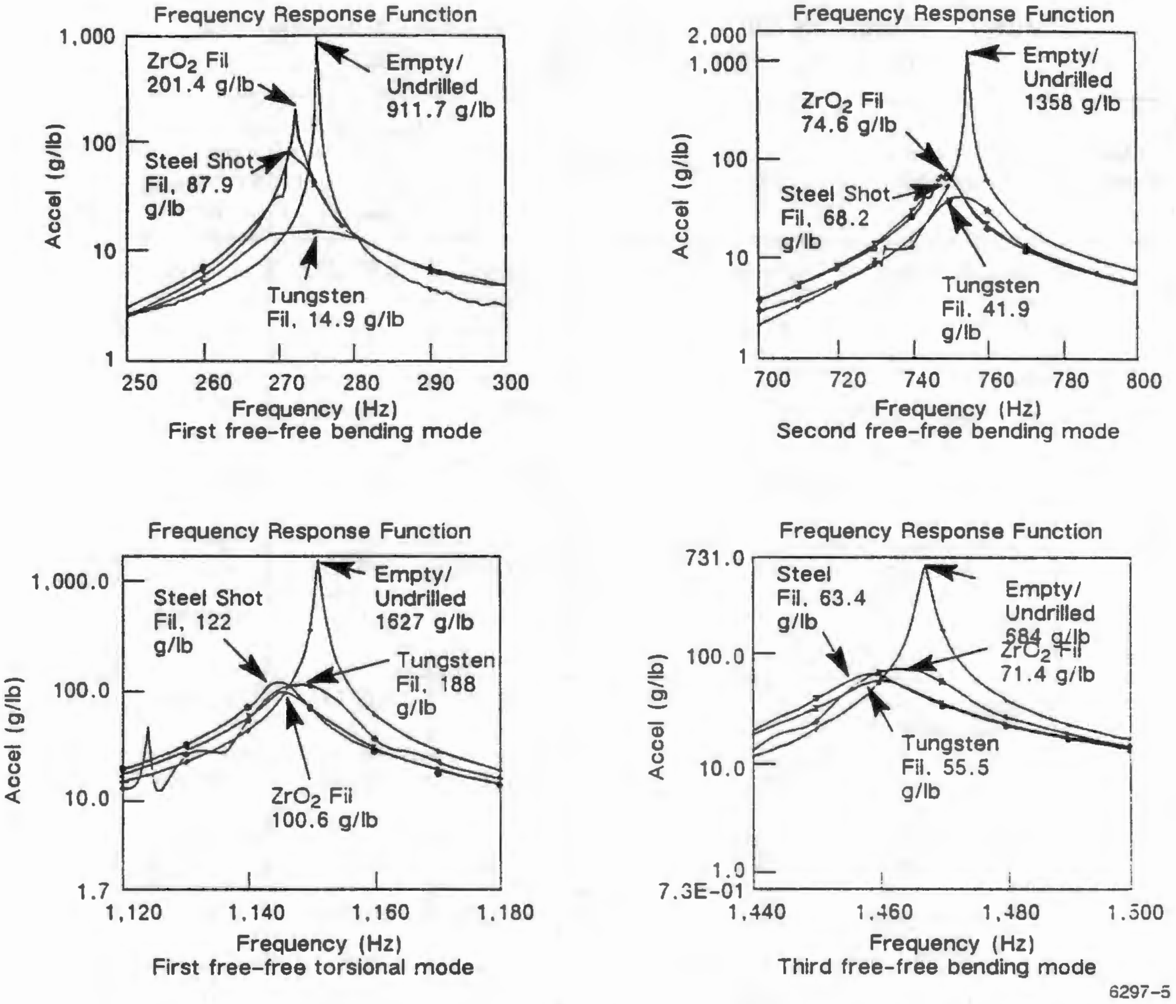

Figure 5. FRF overlays of first four free-free in air vibration modes of longitudinal-holed beam with different particles

was only 0.3 lb in the longitudinal-holed beam (about 5%). The damping estimates were derived by using curve fitting, one-half power point calculation, and fast Fourier transform (FFT) decay rate methods. There are discrepancies in the damping ratios, especially when particles provide high damping values (Table 1). The reason for this is the fact that all the curve fitting routines used consider structures with low damping values, thus making provisions for approximations and losing accuracy. The most reliable damping estimation technique for highly damped systems is probably the log decrement (or the FFT decay rate) for each mode. Thus, FFTs are used to generate the time history of each resonant peak in a waterfall pattern and then take the log decrement of each mode (Fig. 6). The damping ratios were calculated by the following formula:

$$\zeta = \frac{D}{8.69\omega} \tag{1}$$

where ζ is the damping ratio, D is the decay rate in dB/s, and ω is the natural frequency.

Table 1. Damping Ratios With Different Estimation Methods for Longitudinal-Holed Aluminum Beam

Mode Number	Particle/ Condition	Frequency (Hz)	Peak Amplitude (2/lb)	Damping Ratios		
				Curve Fit	One-Half Power Point	FFT Decay Rate
1	Holes empty	275.45	911.7	0.000148	0.000272	0.00046
	0.011-in. steel shots	271.7	87.9	0.00415	0.00391	0.00253
	Zirconium oxide powder	272.6	201.4	0.00154	0.00142	0.00111
	Tungsten powder	272.67	14.9	0.109	0.0912	0.0875
2	Holes empty	755.2	1,358	0.000135	0.000342	0.00090
	0.011-in. steel shots	749	68.2	0.0146	0.0156	0.00942
	Zirconium oxide powder	749.2	74.6	0.00442	0.00541	0.00365
	Tungsten powder	753.45	41.9	0.0143	0.0275	0.00998
3	Holes empty	1,151.4	1,627	0.000277	0.000344	0.000443
	0.011-in. steel shots	1,144.8	122	0.00325	0.00415	0.00311
	Zirconium oxide powder	1,145.6	100.6	0.0033	0.00536	0.00315
	Tungsten powder	1,148	188	0.0085	0.0091	0.0069

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CONCLUSIONS

Extensive modal testing on two aluminum beams (one with thirteen 2-mm diameter holes along the width and the other with seven 2-mm diameter holes along the length) provided significant data regarding the effectiveness of NOPD. Moreover, different characteristics and key parameters that influence NOPD performance were identified. The main objective of this program, to assess the applicability of NOPD at low frequencies, was achieved. Further studies are needed to evaluate the subtle influences exerted by various test conditions, materials, holes, and structural characteristics.

It is especially remarkable to achieve over 60 times vibration amplitude reduction by minute amounts of particles placed inside small cavities in a beam. The practical issues related to implementation of NOPD remain to be tackled. However, the effectiveness of NOPD over a wide range of frequencies undoubtedly opens new avenues for further research and even applications.

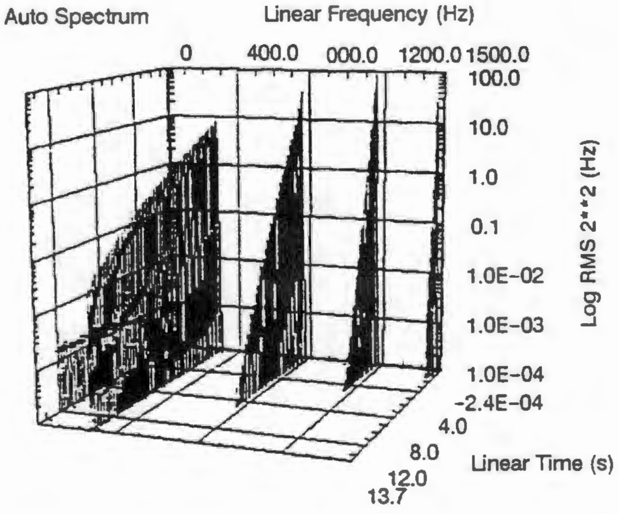

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Figure 6. FETs of free-free beam in air

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