NONOBSTRUCTIVE IMPACT DAMPING APPLICATIONS FOR CRYOGENIC ENVIRONMENTS

H. V. Panossian

Rockwell International/Rocketdyne Division
Canoga Park, California

Abstract

Viscoelastic materials cannot be utilized for vibration damping applications in cryogenic and severe pressure and flow environments. Such environments exist in many rocket engines; it is a challenging task to design for optimal structural damping in such systems. Impact damping techniques essentially work on the basis of momentum exchange via the energy dissipated by collisions of the impacting material with the vibrating mechanical structural. This method can be effectively utilized in rocket engines when used in such a way that it does not obstruct this flow.

Extensive impact damping experimentation was carried out in Rocketdyne's Engineering Development Laboratory on the Space Shuttle Main Engine (SSME) liquid oxygen (LOX) inlet splitter vanes. These splitter vanes often experience very high amplitude and high frequency (around 4000 Hz) vibrations, and during some post-hot-fire test inspections, cracks have been identified on their vane/shell interface, internally. In an effort to reduce the overall mentioned vibration levels of these vanes, holes were made through one of the abovementioned vanes and were filled with different metallic and nonmetallic materials at different levels; vibrations were induced by an impact hammer and a high frequency/high amplitude electromechanical shaker and responses were measured under different fill levels and with different materials filling the holes. The overall grms vibration levels were reduced drastically with the holes filled at 3/4 level. This paper will report on the findings of these experiments, will analyze the results, and will make recommendations for the application of such unobstructive methods for damping structures in harsh environments.

Work reported herein was sponsored by NASA/Marshall Space Flight Center under Contract NAS8-40000.

Introduction

In cryogenic and severe pressure and flow environments, and even in high temperatures, vibration damping is a challenging problem, to say the least. Viscoelastic materials have found widespread applications in moderate to normal environments under ambient temperatures and pressures. However, very little (if anything) has been done in the areas of cryogenic damping.

The abovementioned harsh environment exists in many parts of rocket engines, and this is often coupled with high-amplitude vibrations that can potentially be catastrophic. Thus, it is desirable to design some form of structural damping into such systems in order to be able to damp out the anomalous vibrations. Design changes are often effective;[1] however, sometimes simpler solutions can be more appropriate since it is not always possible to implement design modification without resorting to drastic measures.

The effectiveness of damping treatments is related to the extent of vibration energy being converted into some other form of energy. In the case of viscoelastic materials, some of the vibration energy is dissipated in the form of heat, while in impact damping applications, this energy is transformed into kinetic energy via the motion of the impacting particles, and eventually into heat through friction.[2] The main reason for damping treatments is to reduce vibration amplitudes and thus avoid structural failures. There are normally two main sources of structural vibration failures: fatigue failure that is related to stress level when parts fail due to increased dynamic stress,[3] and displacement of the structural parts that fail when it exceeds a particular threshold.[4]

In an effort to find an alternate option (alternate to the now implemented and successful vane modification--see Ref. 1) to fix the anomalous vibrations of the liquid oxygen (LOX) inlet splitter vanes of the Space Shuttle Main Engine (SSME), a study was initiated that was directed toward utilizing the impact damping methodology with a new approach. The idea was to make holes through the length of the vanes (from top to bottom) and fill these holes with different materials and study their effects on the vibration of the vanes. The vibrations were induced by a high-frequency/high-amplitude electromechanical exciter (Wilcoxon D125L) and an impact hammer for low-frequency response. Measurements of acceleration were recorded from five accelerometers equidistantly located along the midspan of the right vane (right as one looks down through the LOX inlet right-side-up) and at the driving point (Fig. 1). Moreover, mode shapes were derived from a 25-point grid of accelerometers located equally spaced on the surface of the vanes (5 x 5). The damping ratios for each mode were generated and compared with the damping ratios under each material damping. A band-limited flat random excitation between 3000 and 6000 Hz was used to excite the tee at the bottom of the vanes, on the shell between the two leading edges of the vanes.

Description of Tests

The vibration and modal tests of the baseline tee were carried out first, and data was recorded and processed in the form of frequency response functions (FRFs), power spectral densities (PSDs), mode shapes, and damping ratios. Then, four 1-mm-diameter holes were made by EDM through the vanes (Fig. 1). These holes were first filled and tested with 7-, 11-, and 23-mil steel balls at 1/2-, 3/4-, and 7/8-full levels. It was determined that the 3/4-full level was the best among the three levels tested. Then zirconium oxide (ceramics) balls of 10-mil diameter were introduced in the holes and tested for vibration levels with virtually the same amplitude and vibration conditions applied. Similar tests were carried out with nickel powder and tungsten powder.

All the tests were performed according to the rules of modal/vibration testing. Namely, the tee was suspended by flexible rubber bands to simulate a free-free condition and the shaker was bolted on a fixture with the moving tip (with a load cell (PCB) attached to it) glued on the bottom of the tee (Fig. 2). The driving point response was kept at 13.7 grms, and the vane responses at different locations along the midspan ranged from 20 grms all the way to 154.6 grms at the leading edge midpoint of the right vane.

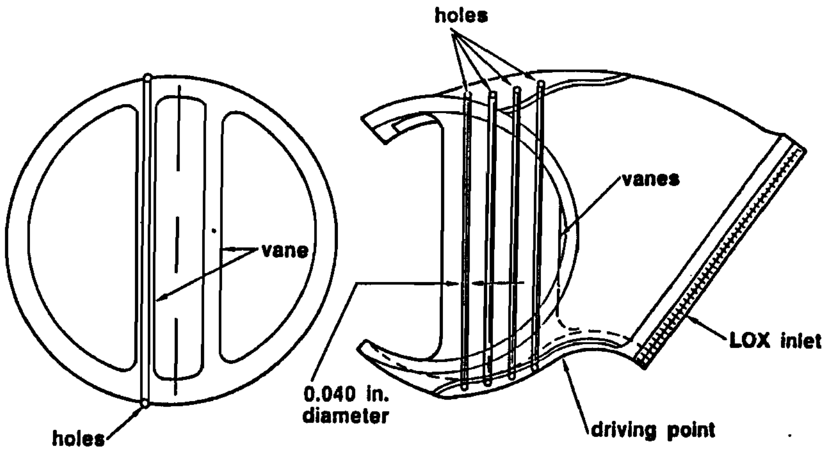


Fig. 1. LOX Inlet Tee

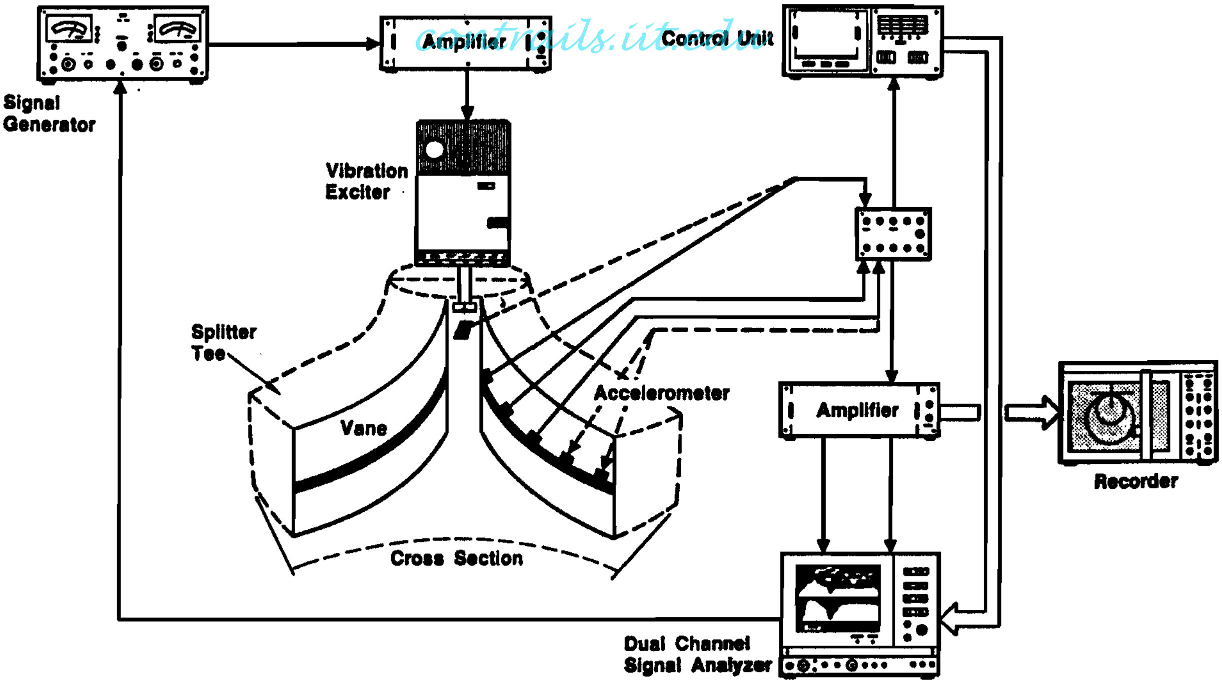


Fig. 2. Measurements of Modal/Vibration Tests

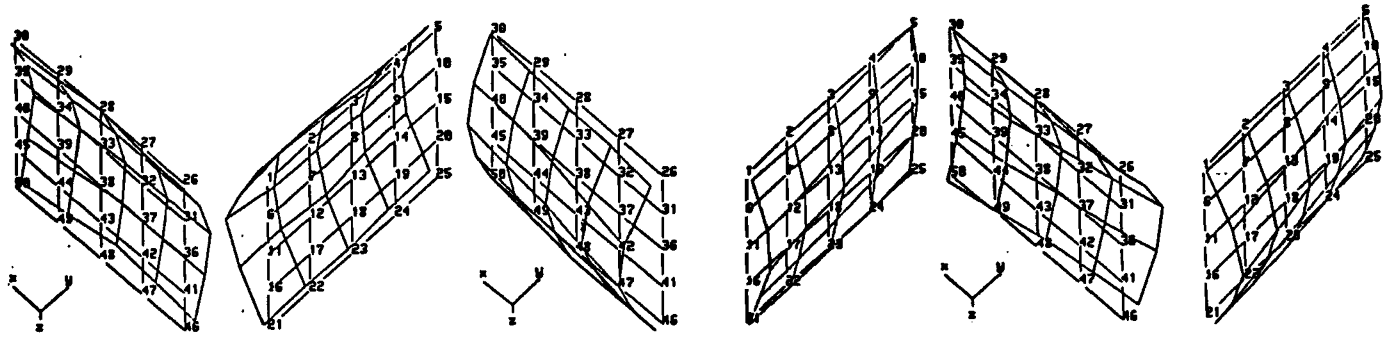
Test Results

Two main types of data were generated in the present tests. Namely, modal data: mode shapes and damping ratios at various frequencies and vibration (accelerance) levels of various modes at different material conditions.

Vane Mode Shapes and Damping Ratios (Baseline)

The vibration mode shapes of the vanes were generated from a 25-point grid acceleration measurements on each vane. These mode shapes are plotted on separate plots (Fig. 3). As the summed FRF indicates (Fig. 4), there are about 10 modes between 3000 and 6000 Hz. Moreover, there are only a couple of modes below 3000 Hz. The dominant modes are above 4200 Hz and are torsional modes, especially the dominant modes at 4740 Hz (the probable 4-kHz mode under LOX loading--see Ref. 1) is the strongest. The less dominant modes below 4200 are bending modes (Fig. 3).

The damping ratios of these modes were quite low (Table 1). They ranged from 0.076% for a strong symmetrical torsional mode at 4748 Hz to 0.20% for a mode at 5239 Hz.

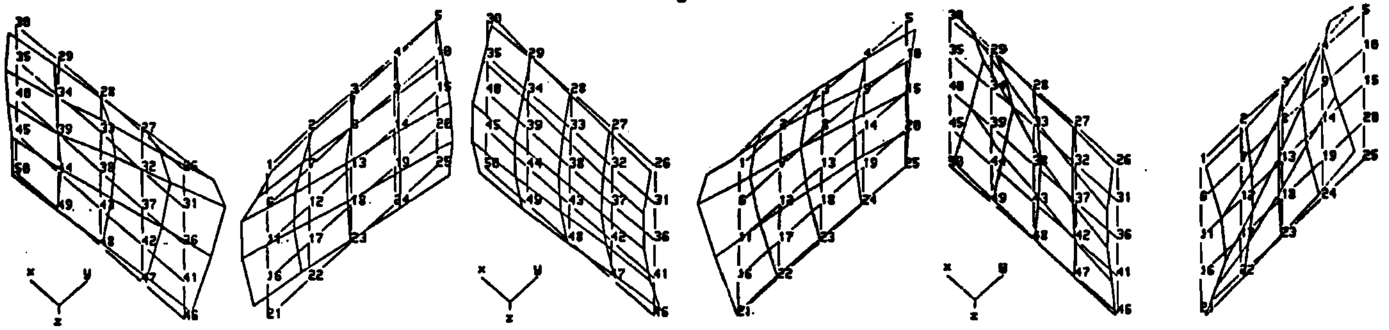


SYMM. BENDING, F = 3533 Hz

SYMM. BENDING, F = 3810 Hz

OPPOSITE BENDING, F = 4065 Hz

Fig. 3

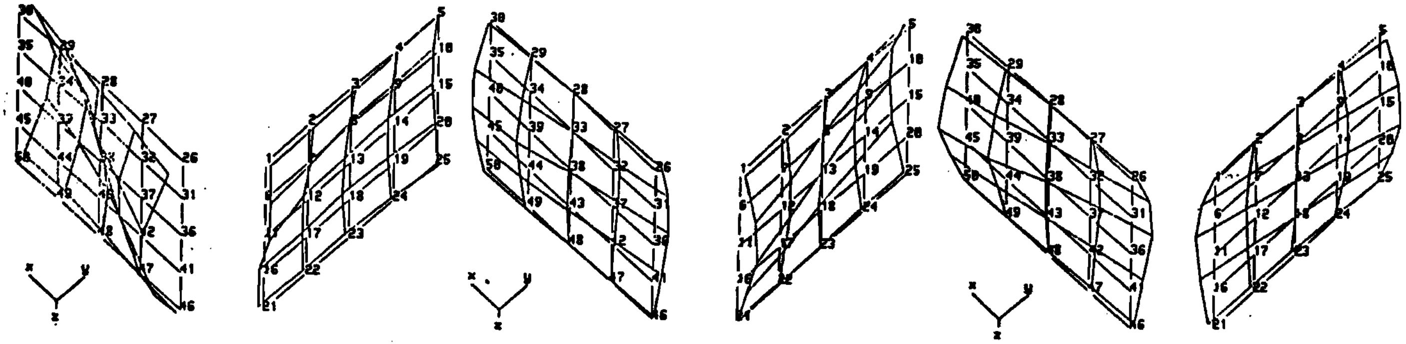


SYMM. BENDING, F = 4265 Hz

RIGHT TWISTING, F = 4320 Hz

SYMM. TWISTING, F = 4736 Hz

Fig. 3

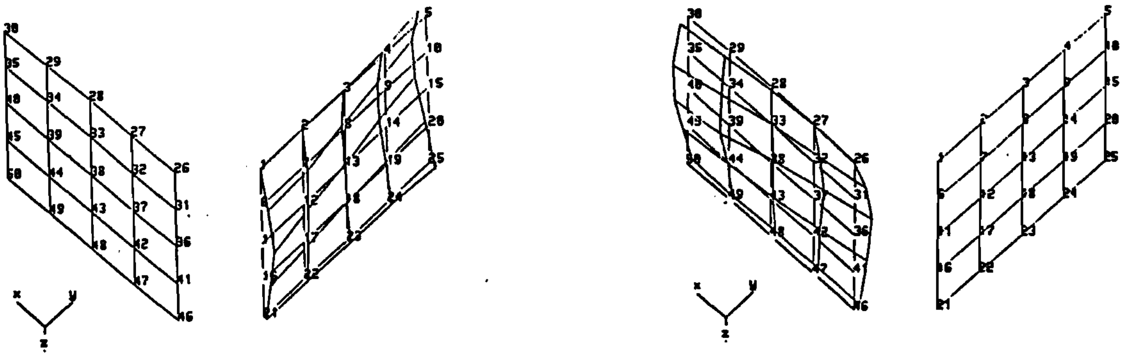


LEFT TWISTING, F = 4763 Hz

OPPOSITE TWISTING, F = 5011 Hz

SYMM. TWISTING, F = 5224 Hz

Fig. 3



RIGHT TWISTING, F = 5595 Hz

LEFT TWISTING, F = 5605 Hz

Fig. 3. Vane Mode Shapes

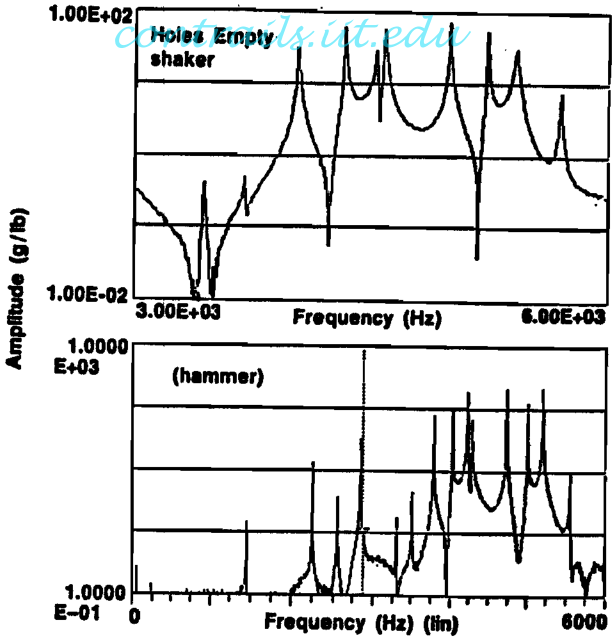


Fig. 4. Vane FRF

Vibration (Accelerance) Amplitudes Under Different Materials

Eight of the 10 modes above 3000 Hz were isolated and the accelerance amplitudes and damping ratios for each material fill (at 3/4-full level) were recorded (Table 1). The results of damping performance with such a little amount of mass added (the mass of steel taken out was about 1 gram and the amount of the heaviest material (tungsten) added was also 1 gram) is really surprising. The amplitude reduction with tungsten seemed to be the greatest in general. Thus, for the torsional mode at 5021 Hz, the damping ratio was 0.0006 and the amplitude was 52.8 g/lb when empty, and it changed to 0.0035 and 9.5 g/lb (Fig. 5), respectively, a factor of greater than 5. See Table 1 for details. A sample of three modes is presented in Fig. 5 through 7.

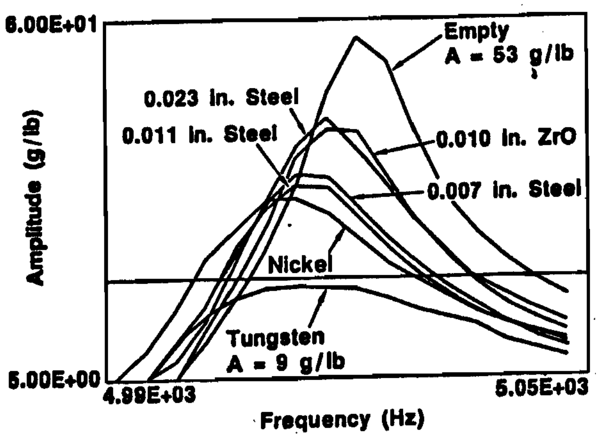


Fig. 5. Accelerance Amplitudes of a Torsional Mode at 5021 Hz Under Various Materials

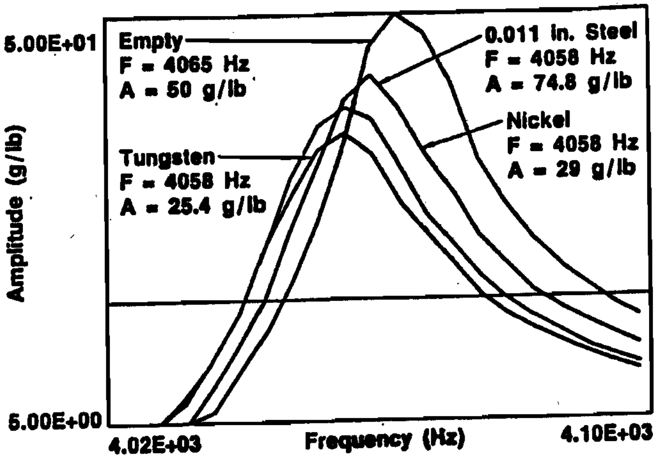


Fig. 6. Accelerance Plots to Show Damping Effects of Various Materials for a Bending Mode of the LOX Splitter Vanes

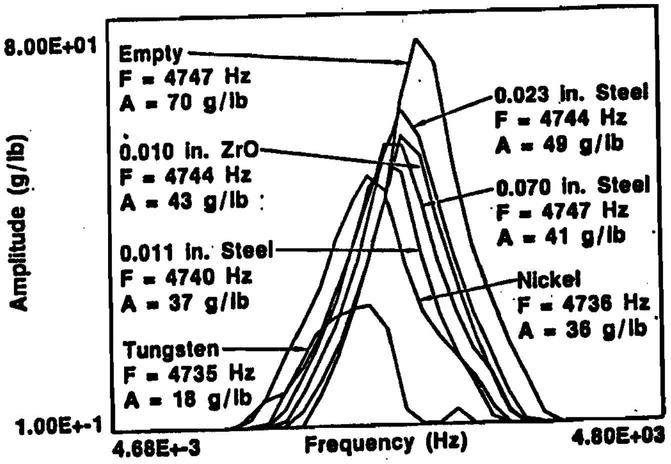


Fig. 7. Accelerance Plots to Show Damping with Various Materials for a Torsional Mode of the LOX Inlet Splitter Vane

Table 1. Amplitudes and Damping Ratios of LOX Inlet Tee Splitter Vanes Under Various Material Damping

MODE FREQ., AMPLI., DAMPING REDUCTION FACTOR		EMPTY	HOLES FILLED WITH DIFFERENT MATERIALS - 3/4 FULL STEEL 23	ZIRCON OX.	STEEL 7	STEEL 11	NICKEL PDR.	TUNGSTEN PDR.	
Frequency-Hz	B	3807	3805	3805	3807	3805	3807	3804	MODE 1
Amplitude g/lb		30.2	30.5	26.3	24.5	27.0	29.3	27.5	
Damping Ratio		0.0009	0.0009	0.0009	0.001	0.0009	0.001	0.0011	
Vibration Reduction Factor		-	1	1	1.2	1	1.2	1.25	
Frequency-Hz	B	4064	4063	4061	4061	4060	4057	4056	MODE 2
Amplitude g/lb		57.5	43.4	39.8	37.3	34.9	29.0	25.2	
Damping Ratio		0.0009	0.0011	0.0012	0.0013	0.0014	0.0017	0.0016	
Reduction Factor		-	1.2	1.3	1.4	1.6	1.9	1.8	
Frequency-Hz	T	4257	4258	4256	4259	4257	4257	4258	MODE 3
Amplitude g/lb		27.6	32.6	27.1	30	30.5	20.4	25.5	
Damping Ratio		0.0015	0.0011	0.0015	0.0012	0.0012	0.0013	0.0013	
Reduction Factor		-	-1.2	1	-1.1	-1.1	1.4	1.1	
Frequency-Hz	T	4309	4308	4308	4308	4306	4306	4306	MODE 4
Amplitude g/lb		55.5	48.5	40.5	52.8	38.4	46.4	41.5	
Damping Ratio		0.0012	0.0013	0.0013	0.0013	0.0014	0.0016	0.0015	
Reduction Factor		-	1.14	1.4	1.06	1.45	1.2	1.34	
Frequency-Hz	T	4748	4744	4743	4741	4740	4737	4734	MODE 5
Amplitude g/lb		70.1	49.0	42.7	41.1	37.0	35.0	18.2	
Damping Ratio		0.0008	0.001	0.0009	0.001	0.0013	0.0017	0.0028	
Reduction Factor		-	1.4	1.64	1.7	1.9	2	3.9	
Frequency-Hz	T	5021	5017	5018	5015	5014	5010	5010	MODE 7
Amplitude g/lb		52.8	30.1	27.6	20.4	18.9	17.1	9.4	
Damping Ratio		0.0006	0.0009	0.001	0.0012	0.0015	0.0017	0.0035	
Reduction Factor		-	1.76	1.9	2.6	2.8	3.1	5.6	
Frequency-Hz	T	5239	5233	5234	5235	5232	5232	5234	MODE 6
Amplitude g/lb		29.5	26.4	26.3	20.5	22.6	32.7	30.9	
Damping Ratio		0.002	0.0028	0.0025	0.0034	0.0025	0.0016	0.0017	
Reduction Factor		-	1.12	1.12	1.44	1.31	-1.11	-1.05	
Frequency-Hz	T	5606	5604	5603	5605	5603	5593	5593	MODE 8
Amplitude g/lb		7.9	7.0	7.0	6.0	7.0	6.9	6.4	
Damping Ratio		0.001	0.0011	0.0011	0.0012	0.0011	0.001	0.001	
Reduction Factor		-	1.13	1.13	1.32	1.13	1.15	1.2	

NOTE: B = Bending mode T = Torsional mode Reduction Factor = Amplitude empty ÷ Amplitude filled

Conclusions and Recommendations

The modal and vibration tests reported herein add significantly to the knowledge base on damping characteristics of structures. The methodology presented, commonly called impact damping technology in the industry, has been used extensively in many applications. But the approach taken in these experiments--with tiny amounts of various materials added to such a small volume and producing such a tremendous effect--is novel. The potential application of such an approach to rocket engine components (like turbine blades) to laser systems, etc., is promising. Further experimentation is necessary to fully understand the mechanisms involved, the optimal fill levels necessary, and the best dimensions of holes for specific applications.

References

1. O'Connor, G. M. and J. Jones, "Flow-Induced Vibrations of the SSME LOX Inlet Tee Vanes," presented at the AIAA 24th Joint Propulsion Conference, Boston, MA, July 1988.

2. Semercigil, S. E., Popplewell, N., and Tyc, R., "Impact Damping of Random Vibrations," Journal of Sound and Vibration, Vol. 121, pp. 178-184, 1988.

3. Newland, D. E., An Introduction to Random Vibrations and Spectral Analysis, (2nd ed.) Longman, New York, 1984.

4. Aoki, S. and K. Suzuki, "Reduction of First Excursion Probability of Mechanical Systems under Earthquake Excitation by Inelastic Restoring Force-Deformation Relation," Bulletin of the Japanese Society of Mechanical Engineers, Vol. 28, No. 240, pp. 1226-1232, 1985.