Use of Microcellular Foam Materials in Constrained Layer Damping Treatments

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SUMMARY

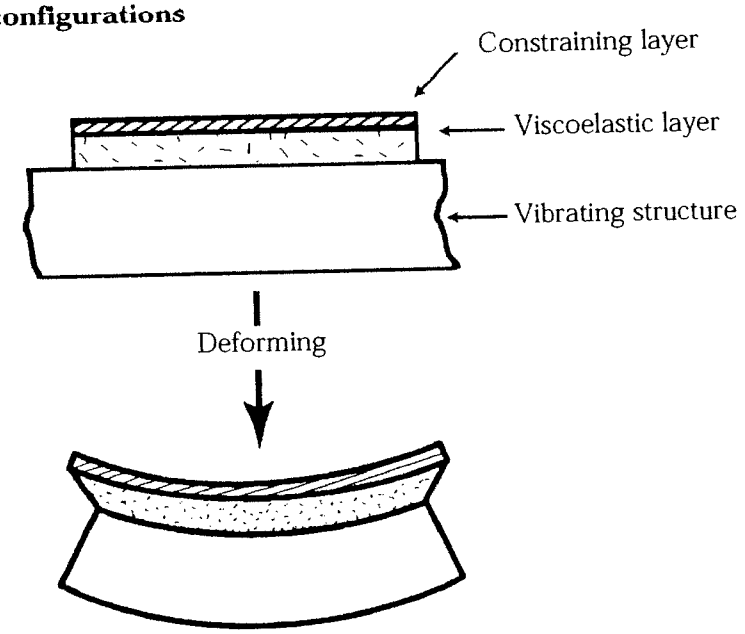
Constrained layer damping (CLD) treatment is a widely used surface damping treatment for vibration and noise control. In this paper, two feasibility studies were conducted using microcellular foam in CLD applications. The first study explores the feasibility of using modified polyethylene teraphthalate (PETG) microcellular foam as a damping material. Two foam configurations were tested: uncompressed (regular) and compressed foam. The second feasibility study evaluated damping performance of CLD with microcellular foam as a standoff layer. Results of the feasibility studies show that the loss factor of PETG foam with densities from 42 kg/m^3 to 240 kg/m^3 is in the range of 2% to 8%. In addition, there is no significant difference in loss factor between the uncompressed and compressed foams. Also, use of microcellular foam as standoff layer can reduce vibration amplitude up to 80% with only a 2% to 3% weight penalty.

1. INTRODUCTION

Constrained layer damping (CLD) treatment is a widely used surface damping treatment for controlling vibration and noise. These thin and lightweight damping treatments have been proven to be inexpensive and effective in a variety of environments. In the computer hardware industry, these damping treatments reduce vibration in head slider suspension systems, top covers and circuit board dampers, and are being considered as new substrate materials of disk media for high speed disk drives. In the aerospace industry, these treatments provide significant damping in commercial airplane fuselages and wing skins, satellite instrumentation platforms, and satellite fuselages. In the automotive industry, they reduce vibrations in disk and drum brake pads and reduce acoustical noise in passenger compartments.

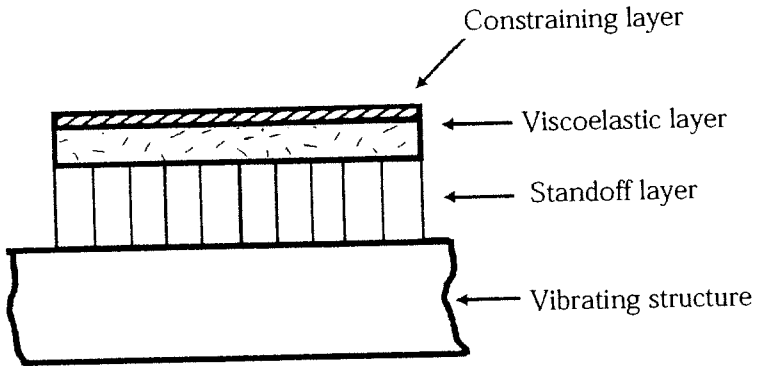
In general, CLD treatments consist of a viscoelastic damping layer sandwiched between the vibrating structure and a constraining layer as

Figure 1(a) CLD configurations



Note: viscoelastic layer deforms in shear direction

Figure 1(b) Standoff CLD configurations



illustrated in Figure 1(a). The constraining layer causes the viscoelastic damping layer to deform in shear dissipating mechanical energy. Examples of commercially available viscoelastic materials include ISD 112 (3M) and DYAD 606 (Soundcoat). To enhance damping performance, a standoff layer is often introduced to further increase the shear deformation of the viscoelastic layer; see Figure 1(b).

In designing CLD treatments, there are several factors to consider. First, an effective CLD standoff layer material must be relative stiff in shear and flexible in bending. In addition, the standoff layer must also be lightweight in order to minimize the weight penalty of the CLD treatment. The ideal material for the damping layer must provide efficient energy

dissipation under cyclic shear deformation. This needs to be the case for a wide range of temperatures since it is not uncommon for a CLD treated structure to be exposed to a varying thermal environment during its operational cycle. This requirement is difficult to fulfil since most viscoelastic materials have their highest loss factor in a limited temperature range close to the glass transition temperature. Even though the damping layer is significantly thinner than the standoff layer it is still usually important to also minimize the density of the damping material. Finally, it is important to consider the strength of the adhesion between the layers in order to avoid delamination of the CLD.

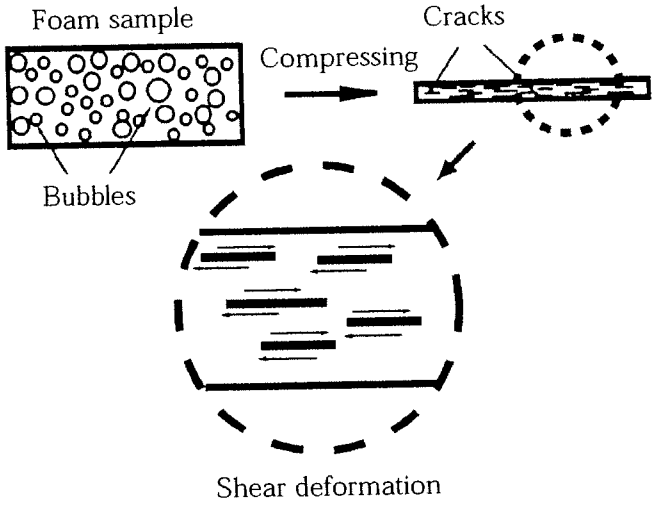
Microcellular foams commonly refer to closed-cell thermoplastic foams that have bubble diameters in the range of 5 to 50 micrometers and bubble densities exceeding 10^8 bubbles per cubic centimetre. Such foams have been created in a number of polymers such as polystyrene, polyvinyl chloride, polycarbonate, polyethylene teraphthalate, etc.[1-5]. These foams were originally developed to reduce the amount of polymer used in applications where the full strength and other mechanical properties of solid polymers are not needed. Recently, microcellular foams have generated a broader interest due to their superior mechanical properties compared with conventional foams with cells that are an order of magnitude larger. A brief overview of these materials can be found in reference 6. Because the foam material consists of a large number of bubbles, the density of the foam becomes relatively low. In this regard, microcellular foams present many desirable features for CLD treatments. For example, it is light-weighted so it can be used in CLD as a damping or standoff layer without incurring high weight penalty. The internal foam structure might be engineered to create different degrees of damping.

This paper investigates the feasibility of using microcellular foam in CLD applications. PETG microcellular foam is used as testing specimen in this paper. The first part of the feasibility study investigates the use of microcellular foam as a damping layer in CLD while the second part investigates the feasibility of using microcellular foam as standoff layer.

2. USE OF MICROCELLULAR FOAM AS DAMPING LAYER

Both uncompressed and compressed foams were tested in this study (Figure 2). The reason for testing compressed foam was that we wanted to investigate the effect of large thickness deformation on the loss factor of the foam. The hypothesis that we wanted to explore was that the loss factor could be increased by collapsing the foam bubbles into what best can be described as many small cracks. When the compressed foam layer

Figure 2 The assumptions of compressed foam



would undergo shear deformation, as in CLD, the surface of the bubbles would slide against each other and dissipate vibration energy through friction at the crack interfaces. This hypothetical mechanism would yield a compressed foam with a significantly higher damping than the uncompressed foam.

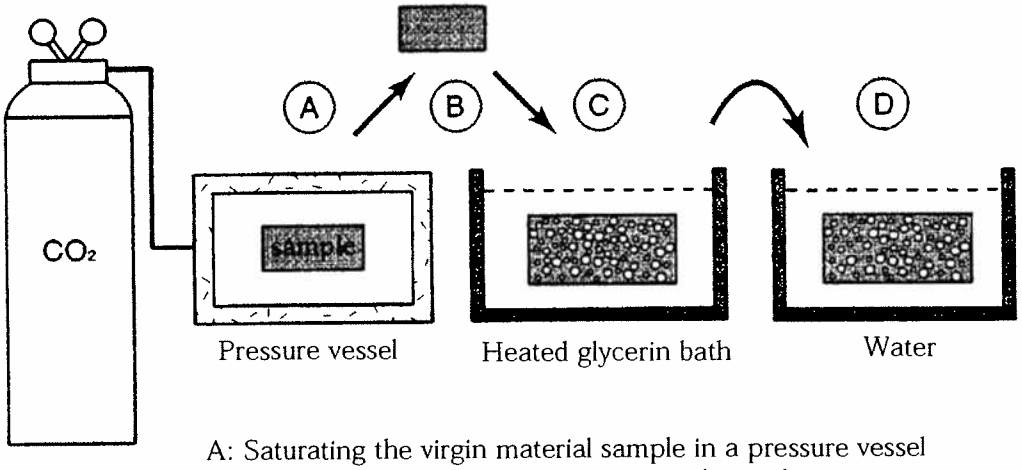
To evaluate damping performance, shear storage modulus and loss factor of the foams were measured following ASTM standard E756-80[8]. Foams with different densities and thickness were evaluated.

2.1 Preparing the Foam Samples

Figure 3 illustrates the basic manufacturing steps for PETG microcellular foam in a batch process. First, the PETG virgin polymer is saturated with non-reactive gas such as carbon dioxide in a pressure vessel at a relatively high pressure. After the virgin material has become saturated with gas, it is removed from the pressure vessel and then heated up in a glycerin bath at the foaming temperature for a length of time to cause bubbles to nucleate and grow. Finally, the foam is allowed to cool down in the room temperature water. By controlling the manufacturing parameters such as the saturating pressure, saturating time, foaming temperature, and foaming time in this four-stage process, foam with different densities and bubble sizes can be produced[7].

Table 1 shows the manufacturing parameters and density of the foam samples. Six PETG foams were manufactured. The foam density ranges from 40 kg/m^3 to 240 kg/m^3. In particular, two foams samples F_2 and

Figure 3 Manufacturing process for PETG microcellular foam



A: Saturating the virgin material sample in a pressure vessel
B: Desorbing the saturated virgin material sample in air
C: Foaming the sample in heated glycerin
D: Cooling down the sample in room temperature water

F_3 were deliberately made with the same density but different thickness. The thicker foam F_3 was later compressed. A Tetrahedron hot-press machine with controllable compression variables such as load, temperature, and time was used to compress the foam. Motivated by fundamental physics principles, such as glass transition temperature and gas diffusion, a cyclic temperature compression method was developed to manufacture compressing foam samples. In this method, the foam was first compressed at a temperature of 117°F for an hour to mechanically collapse the bubbles. Then the temperature was increased to 190°F that is slightly

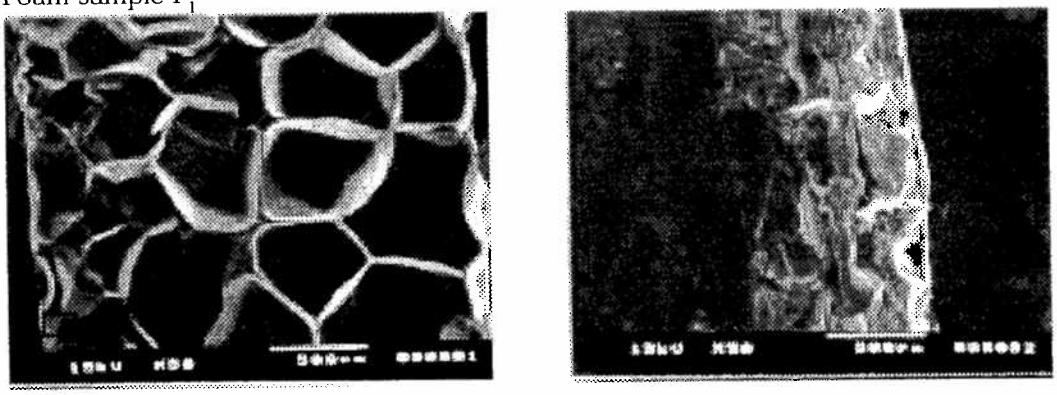
Table 1 Manufacturing parameters for foam sample and their configurations

Foam No.	Virgin material thickness (mm)	Manufacturing parameters				Final thickness (mm)	Final density (Kg/m^3)
		Saturating pressure (psi)	Saturating time (hour)	Foaming temp. (° F)	Foaming time (sec)		
F_1	0.76	600	48	200	25	1.53	200
F_2	5.08	600	22	255	60	1.7	42
F_3	1.01	600	96	255	60	3.2	45
F_4	0.76	400	48	220	60	2	100
F_5	0.76	500	48	210	30	1.7	150
F_6	0.76	700	48	200	15	1.5	240

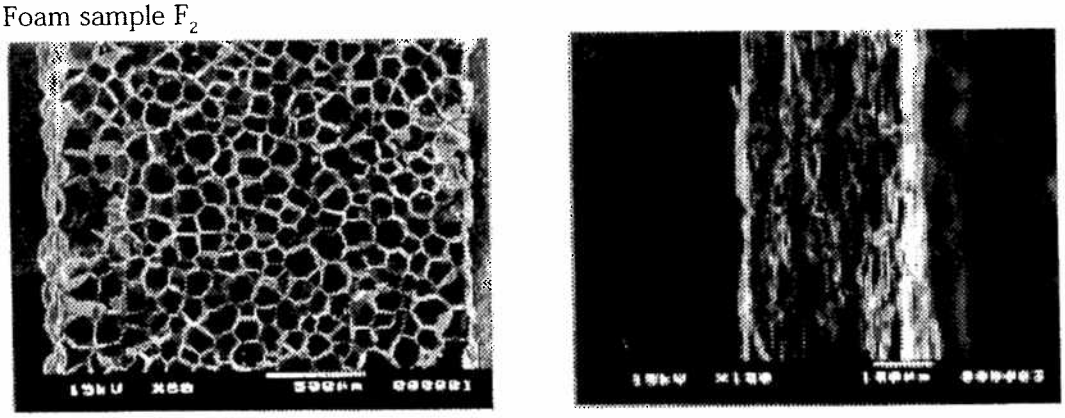
above the glass transition temperature to anneal and allow the gas in the bubbles to diffuse into the foam matrix materials. Finally, the foam was compressed for an hour at 117°F to further the compression of the collapsed walls. The compression load remains at 20 psi throughout the process. Figure 4 shows the microstructure of the foam before and after the compression. Most bubbles in the foam were collapsed.

Figure 4 Microstructure of uncompressed and compressed foam sample F_1 and F_2

Foam sample F_1



Foam sample F_2



2.2 Experimental Setup

Following ASTM standard E756-98[8], the specimen was constructed by sandwiching a layer of foam sample between two identical base beams as shown in Figure 5. The base beams were made of aluminium and were integrally machined with a root as indicated. The dimensions and configurations of the specimen are shown in Table 2. An aluminium spacer whose thickness is identical to that of the foam sample was sandwiched between the root sections in order for the foam materials to deform in pure shear. The foam was glued to the base beam using high

Figure 5 Configurations of the specimen

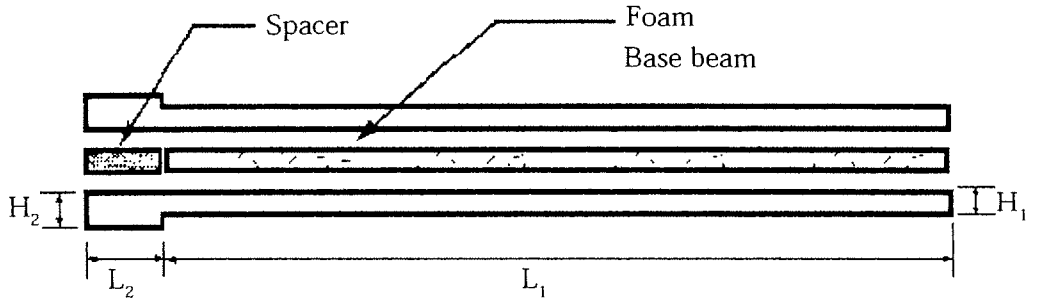


Table 2 Configurations of the specimen				
Specimen	Materials	Length (mm)	Thickness (mm)	Width (mm)
Root	Aluminium	$L_2 = 33.5$	$H_2 = 4$	10
Base beam	Aluminium	$L_1 = 220$	$H_1 = 2$	10
Spacer	Aluminium	33.5	Varying	10
Foam	PETG foam	220	Varying	10

strength cyanoacrylatester. Since the thickness of the adhesive was very small (around 5 μm), the damping effect from the adhesive could be ignored.

Figure 6 shows the setup of our measurement system that was designed according to ASTM standard E756-98. The specimen was cantilevered at its base to a shaker. A signal generator powered the shaker with Gaussian broadband noise. An accelerometer was mounted at the base beam's cantilevered end to measure the excitation level. A non-contact laser vibrometer was used to measure the response of the specimen's free end. Both the laser vibrometer and the accelerometer were connected to a spectrum analyzer for the computation of the frequency response function (FRF). The ambient temperature was maintained at room temperature. The first seven modes (0-5 kHz) were observed and recorded for the FRFs. In order to obtain high resolution of the FRFs, each mode was zoomed and averaged 20 times. Finally, the resonant frequency and half-power bandwidth of each mode were extracted from the FRFs to compute the dynamic complex shear modulus and loss factor of the foam through the formulation developed by Ross, Ungar, and Kerwin[9].

2.3 Results and Discussions

Several major results can be summarized from the test data. First, shear modulus and loss factor of PETG foams with the same density are independent of the foam thickness. Figure 7 show the test results of PETG

Figure 6 Measurement system

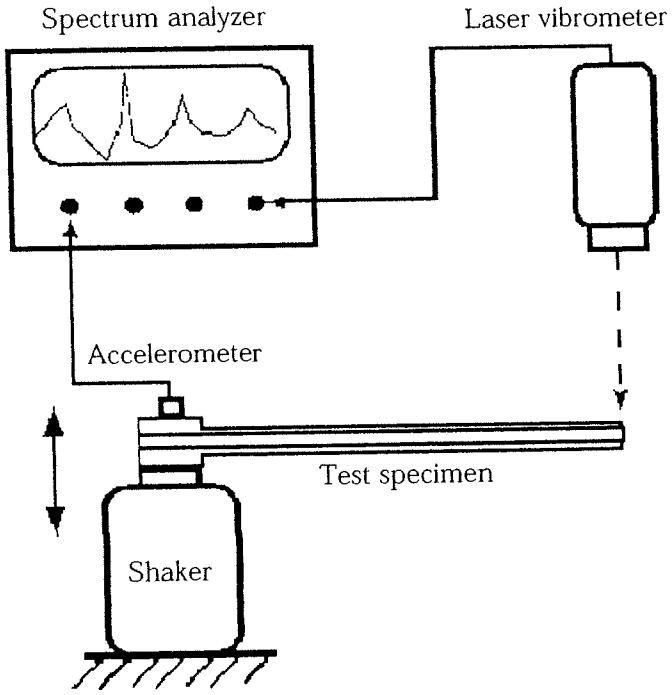
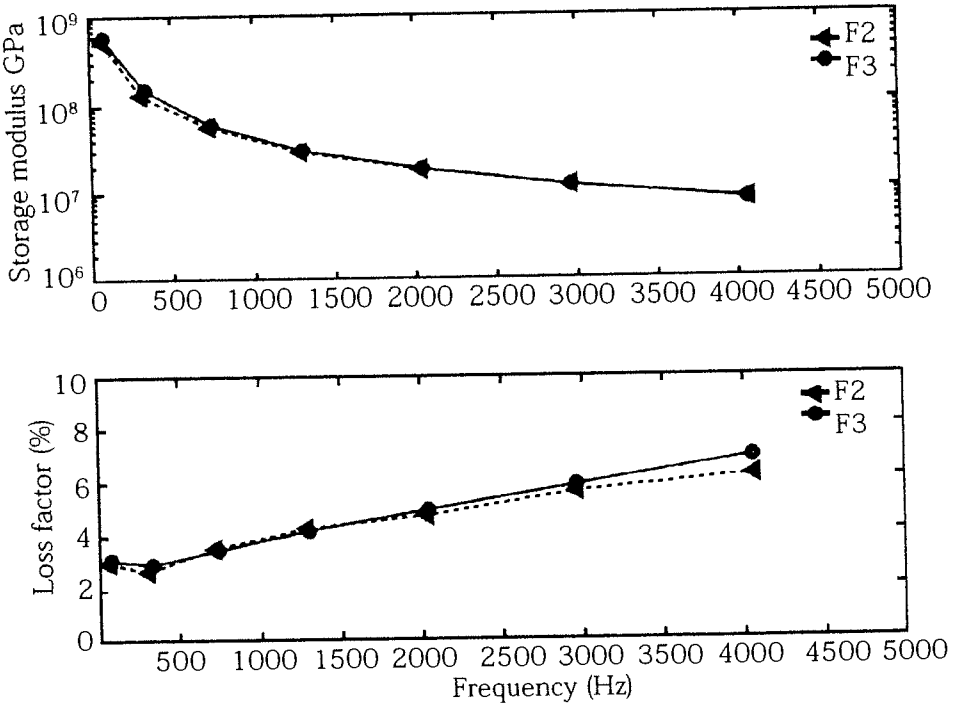


Figure 7 Shear modulus and loss factor of F_2 and F_3



foam with thickness of 1.62 mm (foam F_2) and 3.24 mm (foam F_3). Note that F_2 and F_3 have very similar density (see Table 1). Both foams present almost identical loss factor and shear modulus up to 4000 Hz.

Second, loss factor is independent of foam density. Figure 8 shows the shear storage modulus and loss factor of five PETG foams with different densities (foams F_2, F_4, F_5, and F_6). As expected, microcellular foams with higher density have larger shear modulus. However, the range of the loss factor value varies from 2% to 8% and does not seem to have a direct relationship to foam density.

Third, loss factor cannot be increased by compressing the foams. The shear modulus and loss factor of uncompressed, compressed and partially compressed foam for PETG foam (foam F_2) are illustrated in Figure 9. The compression thickness ratio (CTR) is 75% for the fully compressed foam and 40% for the partially compressed foam. Note that compression reduces the shear modulus and the loss factor of the PETG foam. The larger the compression, the smaller the shear modulus and loss factor. Similar results were also obtained for other PETG foams (foam F_5). The lower shear modulus of the compressed foam might result from squeezed and damaged cells (see Figure 4). The lower loss factor may result from the fact that significant friction cannot be induced during the shear deformation without applying a normal preload to the compressed foam.

Figure 8 Shear modulus and loss factor of different foam

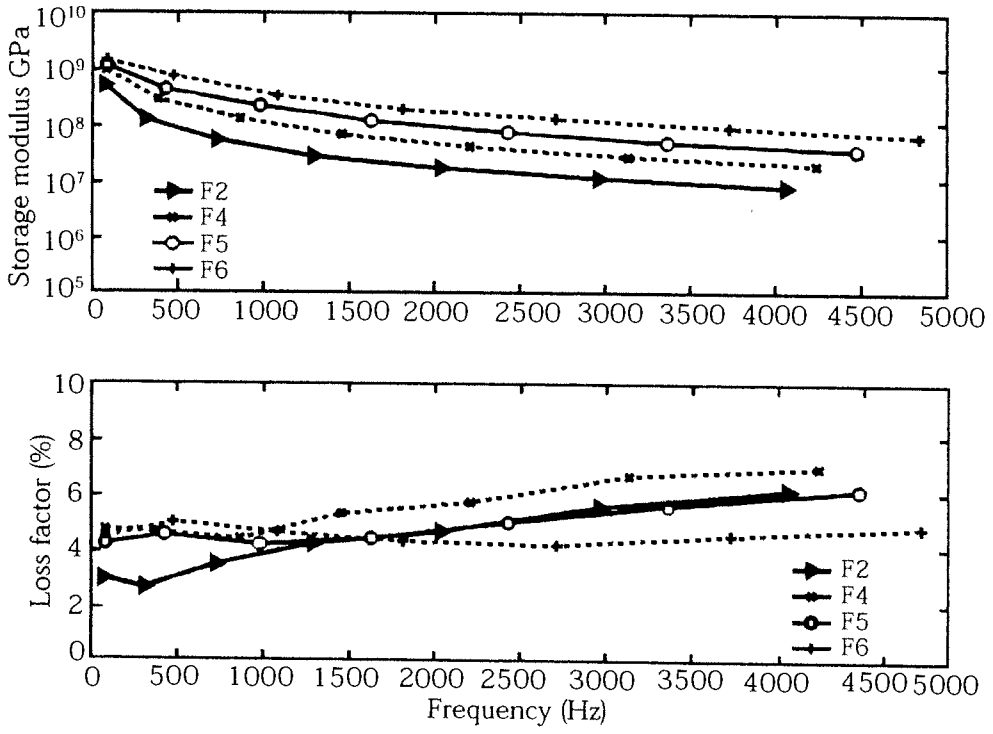
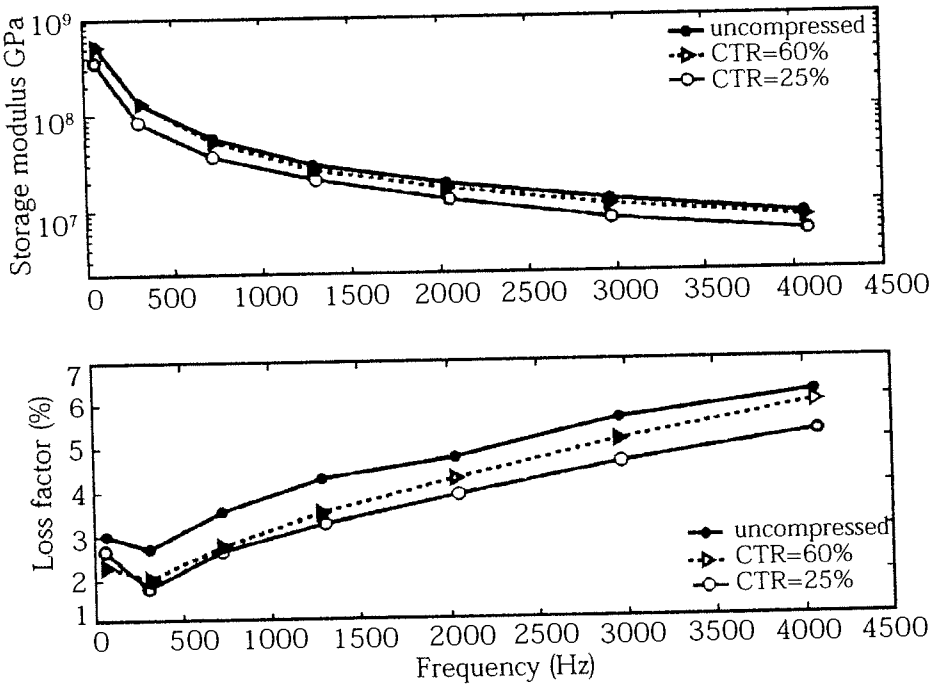


Figure 9 Shear modulus and loss factor of uncompressed and compressed F_2



3. USE OF MICROCELLULAR FOAM AS STANDOFF LAYER

Standoff CLD was first proposed by Whitter in 1959[10]. A good candidate for the standoff layer should have greater shear stiffness than that of the damping layer[11], a low bending stiffness, and a low density to minimize the weight penalty. This section investigates the feasibility of using microcellular foam as a standoff layer in CLD.

3.1 Experimental Method

In these experiments, the specimen consisted of a base beam, an ISD 112 viscoelastic (0.13 mm thickness) layer, a layer of an aluminium constraining layer (0.2 mm thickness) and a PETG foam as the standoff layer as shown in Figure 1(b). Two types of foams (F_3 and F_4) with densities 42 kg/m^3 and 100 kg/m^3 were used. In addition, in order to evaluate the damping performance of partially treated standoff CLD in relationship to the weight of the treatment, different sizes of CLD treatments were applied to the centre of the base beam. Using the setup in Figure 6, FRFs of all the specimens for the first seven modes from 0 to 5k Hz were recorded. The half-power method was used to calculate the loss factor of each mode.

3.2 Results and Discussions

Figure 10 shows the comparisons of FRFs for specimens with and without standoff layer in the full CLD treatment. It can be seen that the amplitudes were reduced significantly by the presence of the standoff layer for all vibration modes. Table 3 shows that amplitude reduction for specimen

Figure 10 Comparison of FRFs of CLD and standoff CLD

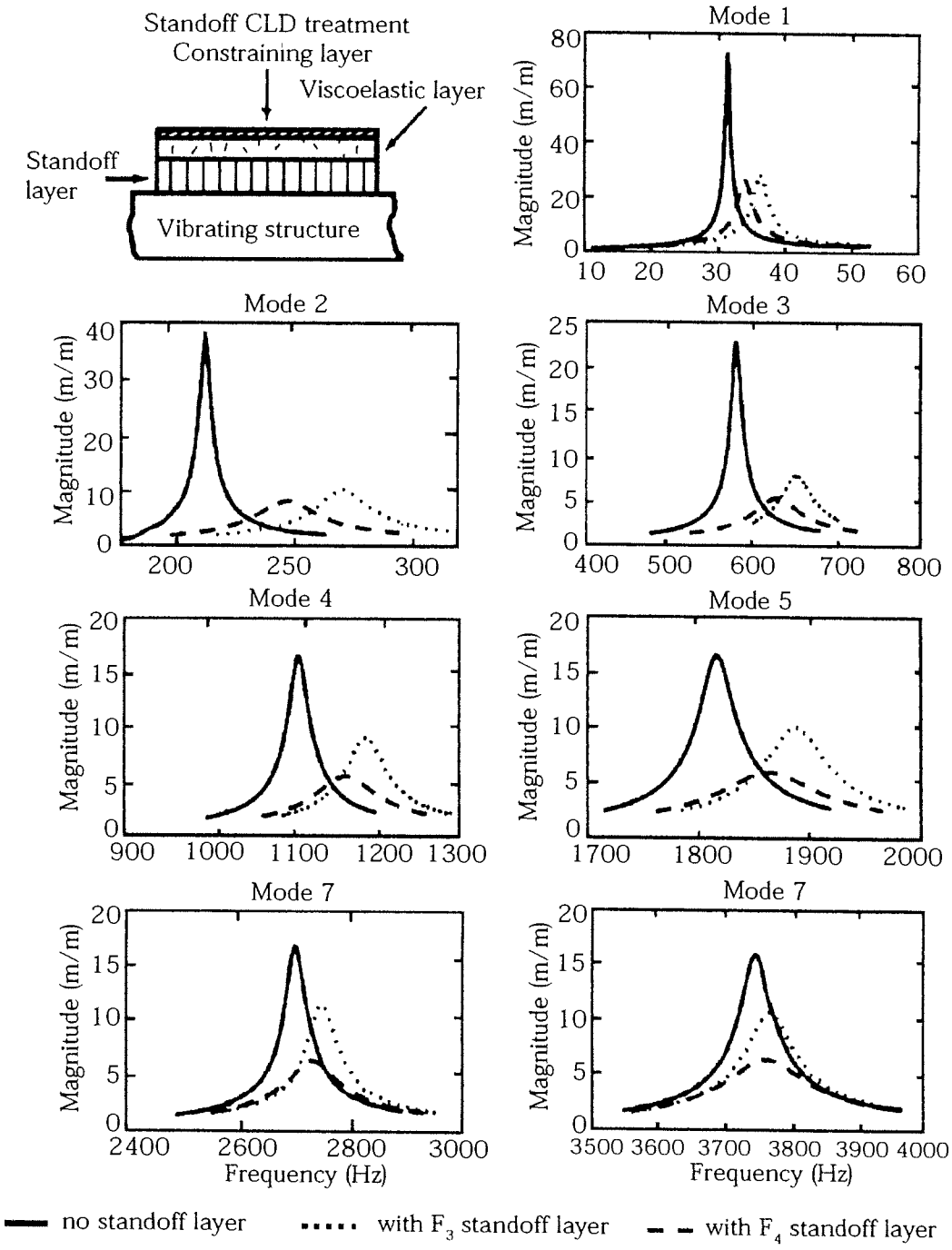


Table 3 The comparisons of FRF's amplitude of specimens with and without standoff layer

No.	Standoff materials		Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6	Mode 7	Weight penalty
A	None		71	38.19	22.67	16.42	16.42	16.51	15.7	0%
B	F3	Amplitude	27.47	10.10	7.86	9.0	9.88	11.21	10.53	2%
		Reduction	63%	74%	65%	45%	40%	32%	33%	
C	F4	Amplitude	25.54	8	5.34	5.47	5.78	6.27	6.36	3%
		Reduction	64%	79%	76%	67%	65%	62%	60%	

B with foam F_3 as the standoff layer reached 74% for the second mode with a 2% weight penalty. For the higher modes, the amplitude reduction was around 30% to 45%. The use of the thicker and denser foam F_4 (specimen C), resulted in higher damping than foam F_3 for all modes but with a 3% weight penalty.

The loss factors of the partially treated specimen were also evaluated and the results are given in Table 4. Note that specimen B with 70% partially treated standoff CLD and specimen C with 60 % partially treated standoff CLD have equivalent loss factors of fully treated CLD beam (without standoff layer) for mode 1. In other words, by adding a very light standoff layer, we can effectively decrease the required size (and the resulting weight penalty) of the CLD treatment and still obtain the same result of vibration control as when a full CLD treatment is used. These results become important when weight is a significant consideration, such as in aerospace applications.

4. CONCLUSIONS

In this feasibility study we have evaluated the use of microcellular foam in CLD treatments. Our investigation has shown that the use of CLD standoff layer made out of microcellular foam offer good potential of weight savings and increased damping over conventional CLD treatments. It was shown that by using PETG microcellular foam as standoff layer material it was possible to reduce vibration amplitude of a cantilevered aluminium beam by 80% with only 3% weight penalty. A further increase in the performance can be expected by the use of foams that have been optimized to have high shear stiffness, low bending stiffness and low density.

We found that PETG microcellular foams with densities in a range between 42 and 240 kg/m^3 are not suitable as the damping layer material in CLD treatments. These foams were shown to have a loss factor between 2 to 8%, which is too low of a range for an efficient damping layer

Table 4 The comparisons of loss factors of specimens with partially treated standoff layer CLD

No.	Standoff materials	Treatment size (%)	Loss factor (%)							Relative weight
			Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6	Mode 7	
A	None	100	1.07	0.99	1.03	1.04	0.81	0.66	0.58	1
B	F3	100	2.73	3.74	2.73	1.83	1.31	0.96	0.89	1.02
		70	1.09	3.28	1.66	1.05	0.81	0.65	0.54	0.71
		60	0.80	2.57	1.03	0.97	0.78	0.55	0.40	0.61
C	F4	100	2.98	4.89	4.12	3.06	2.26	1.63	1.49	1.03
		70	1.23	4.29	2.31	1.48	1.16	1.01	0.93	0.72
		60	0.93	3.37	1.66	1.46	1.20	1.00	0.69	0.62
		50	0.70	3.14	1.04	1.41	1.15	0.72	0.59	0.51

material. Compression of the foams was shown to slightly decrease the loss factor.

The loss factors of microcellular foams may be high enough to contribute significantly to the damping capacity of the CLD treatment when used as a standoff layer rather than a damping layer. The standoff layer is typically an order of magnitude thicker than the damping layer, which means that in spite of the moderate loss factor of the microcellular foam standoff material it can contribute significantly to the overall damping of the CLD.

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REFERENCES

1. Handa V.P., Wong B., Zhang Z., Kumar V., Eddy S. and Khemani K., "Some Thermodynamic and Kinetic Properties of the System PETG-CO_2, and Morphological Characteristics of the CO_2-Blown PETG Foams", Polymer Engineering and Science, **39**, 1, (1999), 55-61
2. Kumar V. and Weller J.E., 1993, "A Process to Produce Microcellular PVC", International Polymer Processing, **VII**, 1, Feb. (1993), 73-80
3. Kumar V. and Weller J.E., "Production of Microcellular Polycarbonate using Carbon Dioxide for Bubble Nucleation", ASME Journal of Engineering for Industry, **116**, (1994), 413-420

4. Park C.B. and Suh N.P., Polymer Engineering and Science, **36**, (1996), 34
5. Ramesh N.S., Rasmussen D.H. and Campbell G.A., Polymer Engineering and Science, **31**, (1991), 1657
6. Kumar V., "Microcellular Polymers: Novel Materials for the 21st Century", Progress in Rubber and Plastics Technology, **9**, 1, (1993), 54-70
7. Sharon L. Eddy, "Solid-state PETG Foams", Master thesis, University of Washington, (1996)
8. American Society for Testing Materials, "Standard for Measuring Vibration Damping Properties of Materials, E756-80", ASTM (1998)
9. Ross D., Ungar E. and Kerwin E.M., "Damping of Plate Flexural Vibrations by Means of Viscoelastic Laminae", Structural Damping, Proceedings ASME Colloquium on Structural Damping, (1959), 49-88
10. Whittier J.S., "The Effect of Configurational Additions Using Viscoelastic Interfaces on the Damping of a Cantilevered Beam", WADC Technical Report 58-568, Wright Air Development Center (1959)
11. Mead D.J., Passive Vibration Control, Wiley, London, (1999), 409