Conference Proceedings of the Society for Experimental Mechanics Series

Matt Allen
Sheyda Davaria
R. Benjamin Davis *Editors*

Special Topics in Structural Dynamics & Experimental Techniques, Volume 5

Proceedings of the 40th IMAC, A Conference and Exposition on Structural Dynamics 2022

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Conference Proceedings of the Society for Experimental Mechanics Series

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Preface: SEM 2022 IMAC XL – Volume 5

Special Topics in Structural Dynamics & Experimental Techniques represents one of nine volumes of technical papers presented at the 40th IMAC, a conference and exposition on structural dynamics, organized by the Society for Experimental Mechanics, and held February 7–10, 2022. The full proceedings also include volumes on nonlinear structures and systems; dynamics of civil structures; model validation and uncertainty quantification; dynamic substructures; rotating machinery, optical methods, and scanning LDV methods; sensors and instrumentation, aircraft/aerospace, and dynamic environments testing; topics in modal analysis and parameter identification; and data science in engineering.

Each collection presents early findings from experimental and computational investigations on an important area within structural dynamics. *Special Topics in Structural Dynamics & Experimental Techniques* represents papers highlighting new advances and enabling technologies for experimental techniques, finite element techniques, system identification, and additive manufacturing.

The organizers would like to thank the authors, presenters, session organizers, and session chairs for their participation in this track.

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Contents

Chapter 1
Multi-Cellular Damping for Composite Material Applications

Beckett Andersen, Luke Hardy, Matthew Borrowman, and Matthew Snyder

Abstract Future lightweight aircraft will increasingly rely on advances in lightweight, strong, highly damped, multifunctional composites. Increased damping capacity of these materials will grow in demand to ensure safe operations across adverse dynamic conditions. Traditional composite materials cannot provide this capability primarily due to a mismatch in the strength and stiffness between the fibers and hosting matrix. The purpose of this project is to design, fabricate, and test a damping material conceived as a cellular system, incorporating a periodic arrangement of tunable, non-linear, spider web-like absorbers. This novel approach proposes to produce a cellular material system incorporating an array of vibration absorbers to damp out structural-scale vibrations at the micro-scale level. The benefits include enhanced damping capacity with no weight penalty and tunability to maximize the kinetic energy transfer as required for the structure of interest. For this project, the USAFA team partnered with a team of researchers in Rome, Italy to create a macro-scale variant of a proposed carbon nanotube absorber system as a proof of concept. The team modeled, tuned, printed, and tested a structural-scale printed model of the repeating cellular system and showed an increase in damping ratio based on the tuned properties of the resonating structure.

Keywords Multifunctional · Honeycomb · Damping · Additive manufacturing · Modal testing

1.1 Introduction

Reinforced fiber composite materials offer several advantages to traditional isotropic materials particularly for applications requiring high, or tailored, strength properties and low weight. However, mechanical resonance can shorten the life of a composite as these vibrations may exacerbate existing damage in the matrix leading to failure. Multifunctional composites represent a class of composite materials that may provide structural composited with enhanced properties [1]. One particular area of focus has been metamaterials with higher damping ratios [2]. In addition, carbon nanotube (CNT) composites have shown promise in providing a way to increase the strength of the composite while allowing energy to dissipate [3]. A proposed way of increasing the life of composite, is to produce a cellular material system incorporating an array of vibration absorbers which damp out structural-scale vibrations at the micro-scale level. Figure 1.1 [4] shows the proposed structure.

In this case, electro-spun CNT wires connect the walls of a repeated cellular structure to a central absorber mass. The mass, wires and cellular structure are all tuned to produce a resonant response on par, but out-of-phase, with the global modes of the plate-like structure. This results in a decreased structural response. The following paper describes the design and evaluation of a macro-scale variant, produced as a proof of concept. In this case, the team additively manufactured a tuned, repeated honeycomb cellular structure with small cantilever beams protruding from one wall of each cell. The dimensions of the cellular structure, cantilever beam, and tip mass applied to the beam were optimized to move the cantilever beam fundamental frequency close to the first global mode of the plate-like structure. By the time of presentation, the response

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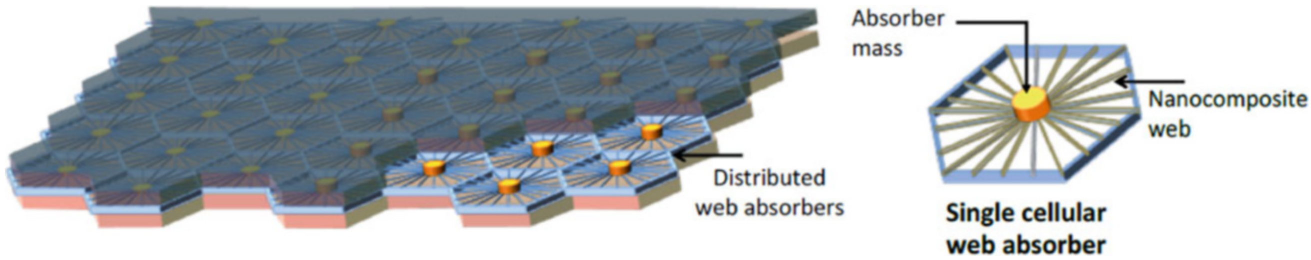
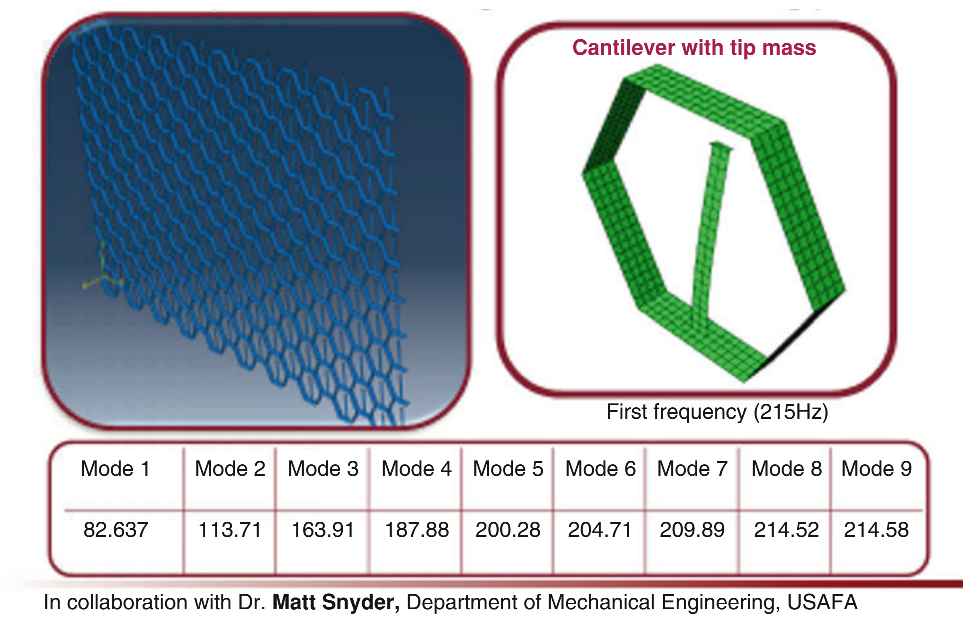


Fig. 1.1 Cellular metamaterial with spider web-like absorbers



Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6	Mode 7	Mode 8	Mode 9
82.637	113.71	163.91	187.88	200.28	204.71	209.89	214.52	214.58

Fig. 1.2 Macro-scale honeycomb structure with cantilevered beam resonators

of the beams to excitation will be captured using both a laser vibrometer and small accelerometers and the damping ratio calculated. These results will be discussed in the presentation.

1.2 Background

To prove the spider web-like damping concept, the authors created a macro-scale variant of the structure, Fig. 1.2. The addition of a matrix embedded cellular honeycomb structure with resonating beams may provide a method to maintain the strength of the composite while providing enhanced damping capability [5]. The unit cell design includes a repeating hexagonal cellular structure, honeycomb, with a cantilever beam protruding from a cell wall to the center of the unit. A tailorable point mass is fixed to the end of the beam to tune the dynamic response of the structure.

1.3 Analysis

This particular study involved design, analysis and testing of the hexagonal cellular structure where each cell was sized at 1 inch. Initial analysis included modeling of the resonator to determine ideal geometric and material properties modeling a single unit cell. The first test results were different from the predicted values. The team reasoned that the results were different because the bulk material properties were different from the post printed material properties. To find the corrected material properties, dog bone testing was completed along a wide range of infill percentages. The team decided that the

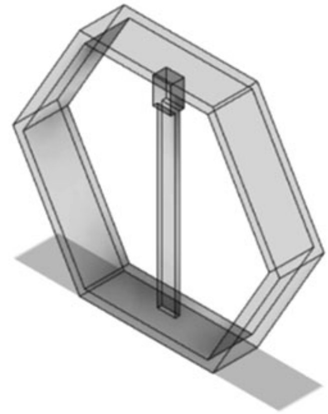


Fig. 1.3 Honeycomb structure with cantilever resonator

Table 1.1 Initial testing model response data

Test number	1	2	3	4	Average	Std dev
Peak 1 (Hz)	121	121	121	121	121	0
Peak 2 (Hz)	234	235	234	234	234	0.34

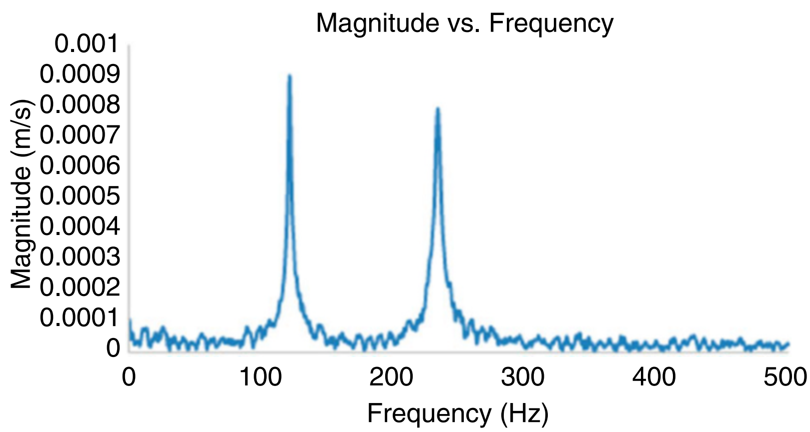


Fig. 1.4 Frequency response graph of the 6-inch cantilever beam

material properties changed the least when the plastic was printed with an infill of 100%. The 3D printer that as used to print the models used ASA as the printing material. Based off of the bulk material properties, the predicted value for the first cantilever mode was 150 Hz. This single cell is shown in Fig. 1.3. After performing this computational investigation, the team additively manufactured the proposed concepts to test them using accelerometers and a laser vibrometer to characterize the response.

The team clamped one edge of the unit cell and measured the response of an enlarged cantilever beam, measuring 1 × .5 × 6 inches, due to excitation by an impact hammer. The first two frequencies are shown in Table 1.1 and Fig. 1.4 and show a typical response.

The first natural frequency occurred at 121 Hz for all four tests. The second peak that coincides with the second natural frequency of the beam was determined to be 234 Hz. The fundamental frequency of the beam is given by Eq. (1.1). Using the bulk material properties, the team calculated the fundamental frequency to be 123 Hz. The difference between the two is accounted for in the variation of bulk to as-printed material properties and the team tuned the printed modulus of elasticity from 2.05 GPa to 2.0 GPa to match the experimental results.

$$\omega = 3.51602\sqrt{\frac{\mathrm{EI}}{\rho \mathrm{Al}^4}} \tag{1.1}$$

With the corrected property values for the materials, testing was once again resumed on creating and predicting the response of an $m \times n$ unit cell matrix. The model was then extended to 8×10-unit cells matrix, each measuring 30 millimeters wide. For this analysis, the team used the FEA capabilities organic to Fusion 360. When the model without

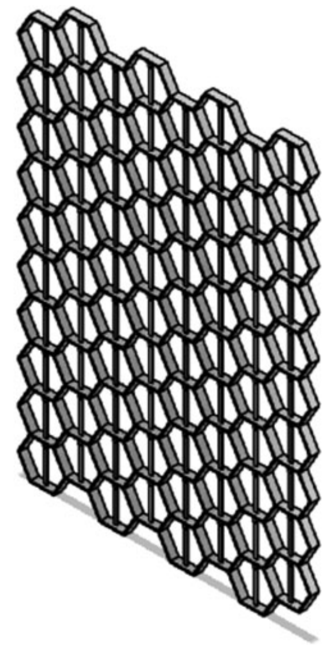


Fig. 1.5 Honeycomb structure with protruding cantilever beam

cantilever beams was run in Fusion 360, the first modal frequency was predicted to be at 112 Hz with the second frequency predicted to be at 118 Hz. When the cantilever beams were added, the frequency changed to 132 Hz and 212 Hz, for the first and second modes, respectively. The authors then tuned the cantilevers to match the matrix frequencies. This then changed the first and second frequencies to be 185 Hz and 223 Hz.

Figure 1.5 shows the honeycomb structure with protruding cantilever beams. The overall dimensions of the structure are 180 × 163 millimeters, the dimensions of the cantilever are .5 × 2 × 20 millimeters. Each cantilever beam has a tip mass with the dimensions of 1.5 × 2 × 2 millimeters.

The team is in the process of manufacturing and testing the specimens (Fig. 1.6). The team is planning on testing both a specimen that has no cantilevers, which can be seen in Fig. 1.7, and a specimen with the cantilevers. This will show the difference in between a non-damped specimen and one with damping added to the system.

The team will capture the response of both the "no cantilever" and "with cantilever" specimens to compare the experimental to predicted response.

1.4 Conclusion

Multifunctional composites show much promise to give structural composites enhanced, tuned properties dependent on application. This study showed that the addition of a hexagonal walled matrix with cantilever beams protruding from the hexagonal walls in a composite matrix led to increasing the damping ratio of the composite which will lengthen the life of a composite. Results of the experimental validation of the computational model will be complete and presented at the conference.

Acknowledgements The team would like to acknowledge the support of Prof. Walter Lacrabonara and Prof. Giulia Lanzara in assisting with modeling the honeycomb structure. In addition, Mr. Jeff Logsdon and Mr. Lonn Rodine, Applied Mechanics Laboratory, USAFA, were instrumental in assisting with the printing and testing of the structure.

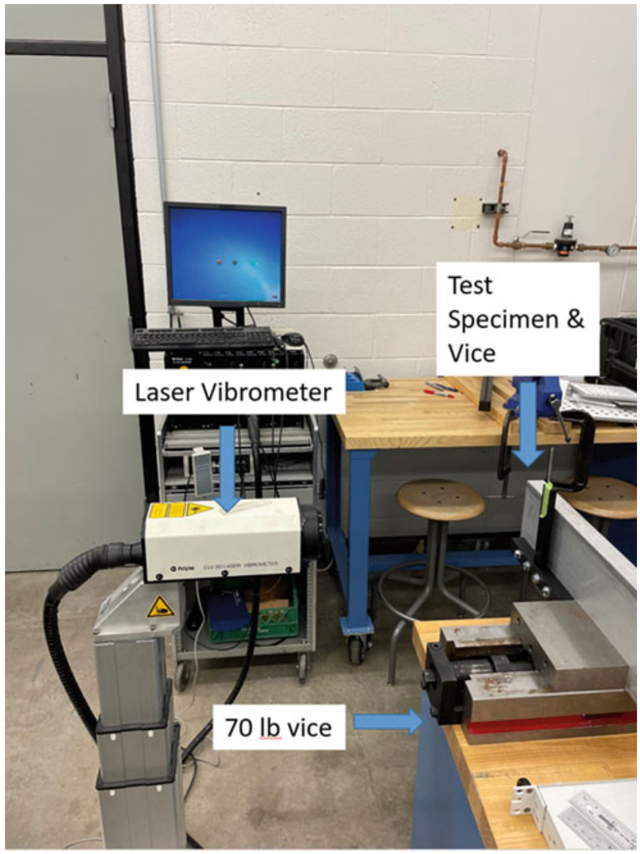


Fig. 1.6 Experimental test set up

Fig. 1.7 8 × 10 honeycomb no cantilever matrix test article