Design and Dynamic Performance Analysis of Tunable Lattice-Based Vibration Energy Dissipation Structures

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Abstract This research aims to explore the working principle, performance characteristics, and application scope of a performance-adjustable vibration reduction and energy dissipation structure through design and experimentation. Through this research, we hope to address the problems of traditional passive energy dissipation devices, improve the efficiency and accuracy of vibration control, and contribute to the development of the field of vibration control. The study focuses on comparing the influence of boundary conditions and structural parameters on the dynamic characteristics of pyramid-shaped and hourglass-shaped lattice-filled structures, and investigating the superior vibration reduction and isolation performance of both structures at the same relative density.

Keywords Finite element analysis, ABAQUS simulation, vibration reduction and energy dissipation structure, hourglass-shaped point

1 Introduction

Vibration is a common physical phenomenon in our daily lives. However, when the energy of vibration exceeds a certain limit, it can become a destructive force. Therefore, how to effectively control vibration and reduce its negative impacts has become an urgent problem to be solved. Against this backdrop, adjustable vibration damping and energy dissipation structures have been invented. To prevent structural failure, damping balls are added to absorb the energy generated by forced vibrations, thereby reducing structural vibration. Mechanical structures can be equipped with energy dissipation devices to effectively control vibration. However, in the development of this technology, it still faces many problems. Friction dampers have a single damping force and a small adjustment range, making it difficult to meet the needs of different working conditions. At the same time, most dampers are passively controlled and cannot effectively utilize vibration source signals for control, thus limiting the improvement of their vibration reduction effect. With the help of our teachers and graduate students, we embarked on this major research project.

2 Research Objective and Significance of the study

This study experimentally investigates the performance of damping spheres that achieve optimal vibration reduction at different vibration frequencies. A corresponding surface is fitted using machine learning on a large model. The goal is to design and manufacture a performance-adjustable vibration reduction and energy dissipation structure, and to conduct simulations and experiments. A cylindrical structure experiences forced vibration under stress. To prevent structural failure, damping spheres are added to absorb the energy generated by the forced vibration, thereby reducing structural vibration. Through simulation and experiments, the mapping relationship between structural parameters and performance is fitted, enabling performance-adjustable design.

This study explores the working principle, performance characteristics, and application scope of a performance-adjustable vibration damping and energy dissipation structure through design and experimentation. We hope that this research will address the problems of traditional passive energy dissipation devices, improve the efficiency and accuracy of vibration control, and contribute to the development of the field of vibration control.

3 Project expected outcomes and innovative points

3.1 Expected Results

(1) A complete simulation-experiment analysis process was established;

(2) A response surface model of "frequency-damping pa-

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rameters-vibration reduction effect" was constructed;
(3) Experimental verification under multiple sets of damping sphere parameters was completed;

3.2 Innovation

(1) Structure-Performance Co-design: Combining vibration-damping structures with sensors, dynamic control of structural parameters is achieved through data-driven methods, enhancing the system's adaptability to different operating conditions.
(2) Multi-parameter Coupled Modeling: Introducing neural network methods, a three-dimensional response surface of "frequency-damping sphere parameters-vibration reduction effect" is constructed, overcoming the limitations of traditional linear fitting.
(3) Simulation-Experiment Closed-Loop Optimization: Experimental data is used to feed back into the simulation model, forming a two-way optimization mechanism of "simulation guiding experiment—experiment verifying simulation," improving model accuracy and engineering applicability.
(4) Structural Form Innovation: Referring to the design concept of lattice-filled structures, a novel vibration-damping structural form is proposed, enhancing the structure's stability and energy dissipation capacity.

4 Project Description

This project addresses the common vibration problem in engineering structures by designing and researching a performance-adjustable vibration reduction and energy dissipation structure. The structure uses damping spheres as the core energy dissipation element, and by changing parameters such as the material, diameter, and number of damping spheres, the vibration response under different frequency excitations can be actively controlled. Combining finite element simulation and experimental verification, the project systematically explored the mapping relationship between structural parameters and vibration reduction performance, and introduced a neural network algorithm to construct a "frequency-damping parameter-vibration reduction effect" response surface, thus initially realizing the adjustable design of vibration reduction performance.

4.1 Vibration Reduction and Isolation Principle of Lattice-Infill Structures

Lattice-fill structures can achieve vibration reduction and isolation effects through multiple means, including absorbing vibration energy, isolating vibration sources, and adjusting frequency response:
1) Absorbing Vibration Energy: Lattice-fill structures absorb and dissipate input vibration energy through the bending, torsion, and compression of their internal lattice-like truss structure, thus achieving vibration reduction;
2) Isolating Vibration Sources: Lattice-fill structures can act as vibration isolation layers, effectively blocking the transmission of vibration from one part to another, achieving vibration isolation;
3) Adjusting Frequency Response: Lattice-fill structures can be designed with specific natural frequencies, which can be used to absorb or avoid responses at specific vibration frequencies.

4.2 Modes and Natural Frequencies

Modal identification is a modern method for studying the dynamic characteristics of structures, focusing on free vibration analysis. This method has been widely used in the field of engineering vibration. A mode represents the inherent vibrational characteristics of a structure; each mode has a unique mode shape, natural frequency, and damping ratio. For a multi-degree-of-freedom dynamic system with n degrees of freedom, its equations of motion can be expressed as a matrix-form second-order differential equation:
[M]{ x} [C]{x} [K]x F(t)
Where [M] is an n×n mass matrix, representing the distribution of mass in each degree of freedom of the system; [C] is an n×n damping matrix, describing the damping characteristics of the system; [K] is an n×n stiffness matrix, representing the stiffness (or elasticity) characteristics of the system; x is a vector containing the displacements of all degrees of freedom; F(t) is the vector of external forces, which can vary with time. The natural frequency is the frequency of natural vibration of a dynamic system when no external force is applied. Therefore, the natural frequency of the system can be determined by solving the dynamic response when F(t) = 0. For undamped or classically damped systems (where the damping matrix is proportional to the mass and stiffness matrices), by introducing the assumed solution: x(t) = fe iwt, the equation can be transformed into an eigenvalue problem: ([K]-w 2[M])F = 0.
This is the characteristic equation, where ω is the system's natural frequency and Φ is the corresponding mode shape vector. The solution to the eigenvalue equation includes a series of eigenvalues and corresponding eigenvectors. Each eigenvalue corresponds to the square of a natural frequency, while the eigenvector corresponds to the corresponding mode shape. Solving the equation yields the system's natural frequencies as follows:
Resonance occurs when the excitation frequency is equal to or close to the natural frequency. Actual structures have multiple degrees of freedom and therefore multiple natural frequencies. The fundamental frequency corresponds to the first-order natural frequency, while the dominant frequency corresponds to the natural frequency at which the vibration energy is at its maximum. In structural dynamics and vibration analysis, the natural frequencies determine how the system responds to various external excitations.

When a structure vibrates, it is usually the result of a linear superposition of several simple harmonic vibrations at different frequencies.

4.3 Finite Element Analysis Steps Based on ABAQUS

This study uses ABAQUS finite element simulation software to perform modal analysis and steady-state response analysis on a lattice-filled structure. The general process of modal analysis and harmonic response analysis using ABAQUS mainly consists of three modules: preprocessing (ABAQUS/CAE), analysis and calculation (ABAQUS/Standard), and post-processing (ABAQUS/Viewer). The specific operation process is as follows:

1) Create/Import models: Use the geometric modeling tools provided in ABAQUS to create or directly. Import external CAD files created using other modeling software, such as SolidWorks;

2) Set material properties: Commonly used properties include: Young's modulus, Poisson's ratio, etc. For modal analysis, the density of the material must also be assigned. It should be noted that in modal analysis, we can only use linear elements and linear materials. Modal analysis does not consider the nonlinear characteristics of the material;

3) Create sections and assign corresponding sections to each component;

4) Define the assembly: In this process, the entire lattice filling structure needs to be built through the unit array;

5) Set the analysis step type: Modal analysis requires defining a frequency extraction analysis step of the linear perturbation analysis step. ABAQUS finite element software provides a variety of frequency extraction solvers, including: Block Lanczos, subspace, AMS, etc. We use the Lanczos solver. In this article, in order to solve the steady-state response, we use the modal superposition method, so the analysis step of the harmonic response analysis needs to be created after the modal analysis step;

6) Define field output and historical output: Select the target response point in the model to create a set, and select the physical quantities of interest in the field output, such as displacement, velocity, acceleration, etc. The output requirements can change between each analysis step;

7) Apply boundary conditions and loads: Because the vibration is assumed to be free vibration in the modal analysis step, there is no need to apply any load, and external loads will be ignored. In the modal superposition analysis, a simple harmonic excitation load needs to be applied, and the boundary conditions must be applied in the Initial analysis step;

8) Apply interaction relationships: ABAQUS/CAE will not automatically identify the mechanical contact relationships between components or various areas in the assembly. Therefore, when describing the contact relationship between two surfaces in an assembly, the type of interaction between them needs to be clearly specified;

9) Meshing: For the panel and the lattice-filled core layer of the lattice-filled structure, the two components need to be meshed separately;

10) Create an analysis job and submit it to ABAQUS/Standard for analysis and solution;

11) Visualization: Extract the required analysis results and make relevant evaluations on the results to guide practical applications in engineering and scientific research.

Among them, 1-9 is the pre-processing module, 10 is the analysis and calculation module, and 11 is the post-processing module.

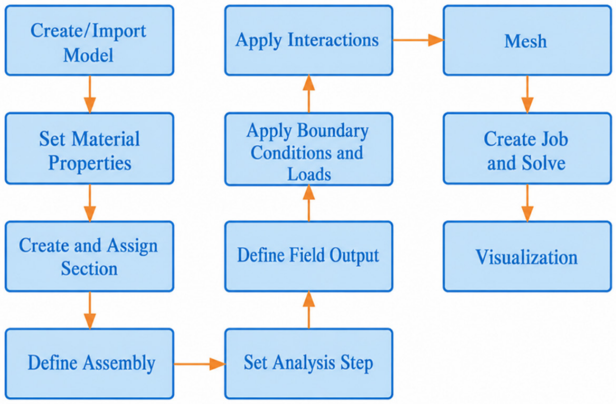

Figure 1. ABAQUS Finite Element Analysis Flowchart

4.4 Factors Affecting the Dynamic Characteristics of Lattice-Filled Structures

The degree of constraint on the structure was increased by continuously increasing the number of clamping edges to explore the influence of boundary conditions on the modes of the two structures. Modal analysis was performed on the pyramid structure and the hourglass structure under four boundary conditions: CFFF, CCFF, CCCF, and CCCC. The results are shown in Figure 2 and Figure 3. It is evident that boundary conditions have a significant impact on structural vibration. When boundary conditions differ, the mode shapes and natural frequencies of the two types of lattice-filled sandwich panels vary considerably, with the natural frequencies increasing significantly as the constraint level increases. This is because increased constraints affect the stiffness distribution of the structure, increasing the overall stiffness and consequently the natural frequencies. Under classical boundary conditions, the number of peaks and troughs in the mode shapes of the lattice-filled sandwich beams corresponds one-to-one with the modal order of the structure; that is, one mode shape corresponds to one peak or trough. Furthermore, we can observe distinctly symmetrical mode shapes, such as the second and third modes of both structures under CCCC boundary conditions, with corresponding natural frequencies of 7499 Hz, 7499.2 Hz and 6930.1 Hz, 6930.2 Hz, respectively—very similar. This is because the structural symmetry and boundary condition symmetry of the 5×5 square equal-density lattice-filled sandwich panel model

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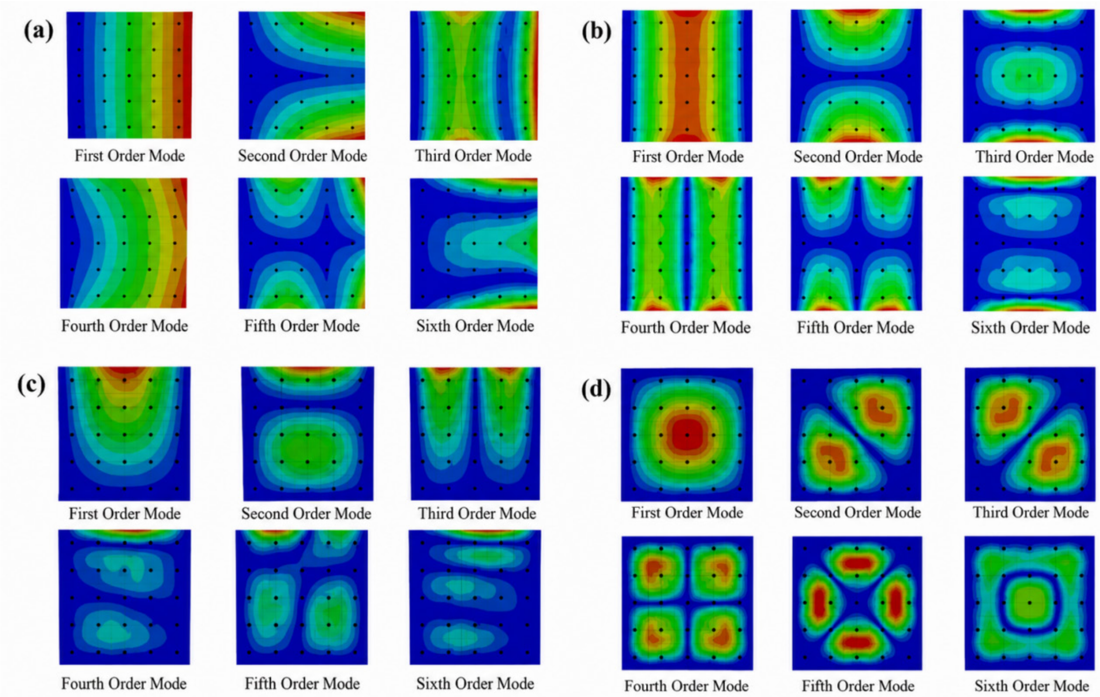

Figure 2. Modes of pyramid structure under different boundary conditions

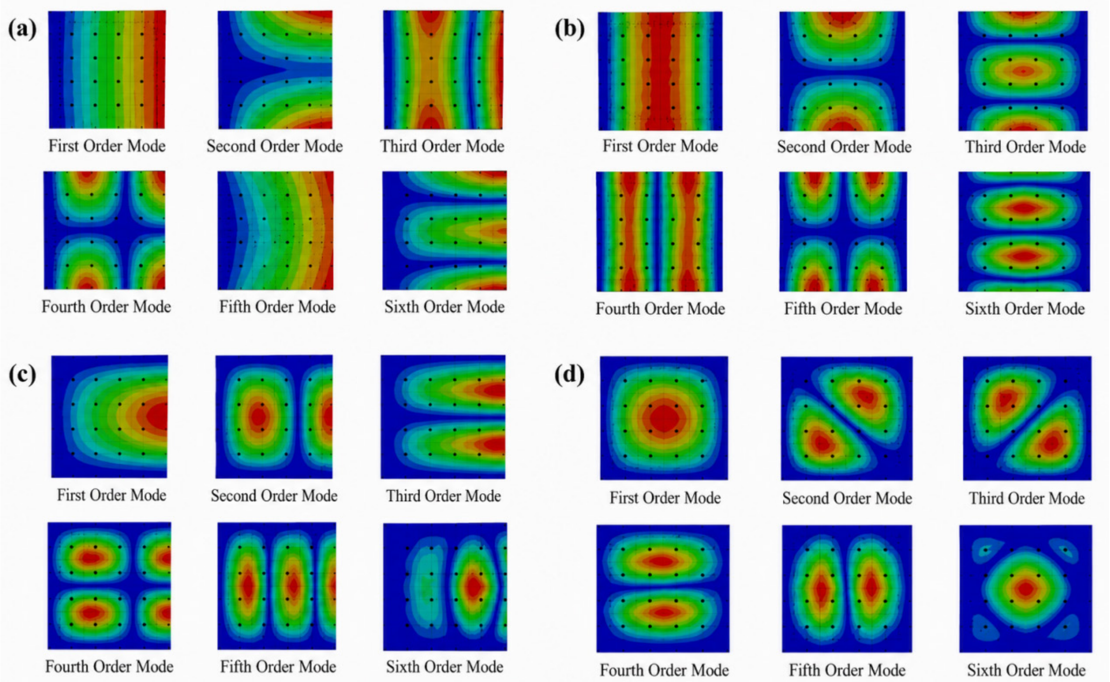

Figure 3. Modes of hourglass structure under different boundary conditions

analyzed in this section lead to modal symmetry. At the same time, since isotropic materials are used in this paper, the natural frequencies of the symmetrical vibration modes are relatively similar.

The natural frequencies of the pyramid structure, hourglass structure, and solid plate structure under the same boundary conditions are plotted on the same graph for comparative analysis (see Figure 4).

As shown in Figure 4, under the same boundary conditions, the natural frequencies of the pyramid-shaped and hourglass-shaped lattice-filled sandwich panels exhibit very similar trends, with the natural frequency of the pyramid structure being slightly higher than that of the hourglass structure. This may be because the hourglass structure is weaker in the middle compared to the pyramid structure, leading to greater stress concentration at the center and a reduction in overall structural stiffness, thus resulting in a lower natural frequency for the hourglass-shaped lattice-filled sandwich panel. Compared to solid panels, under the single-sided clamping (CFFF)

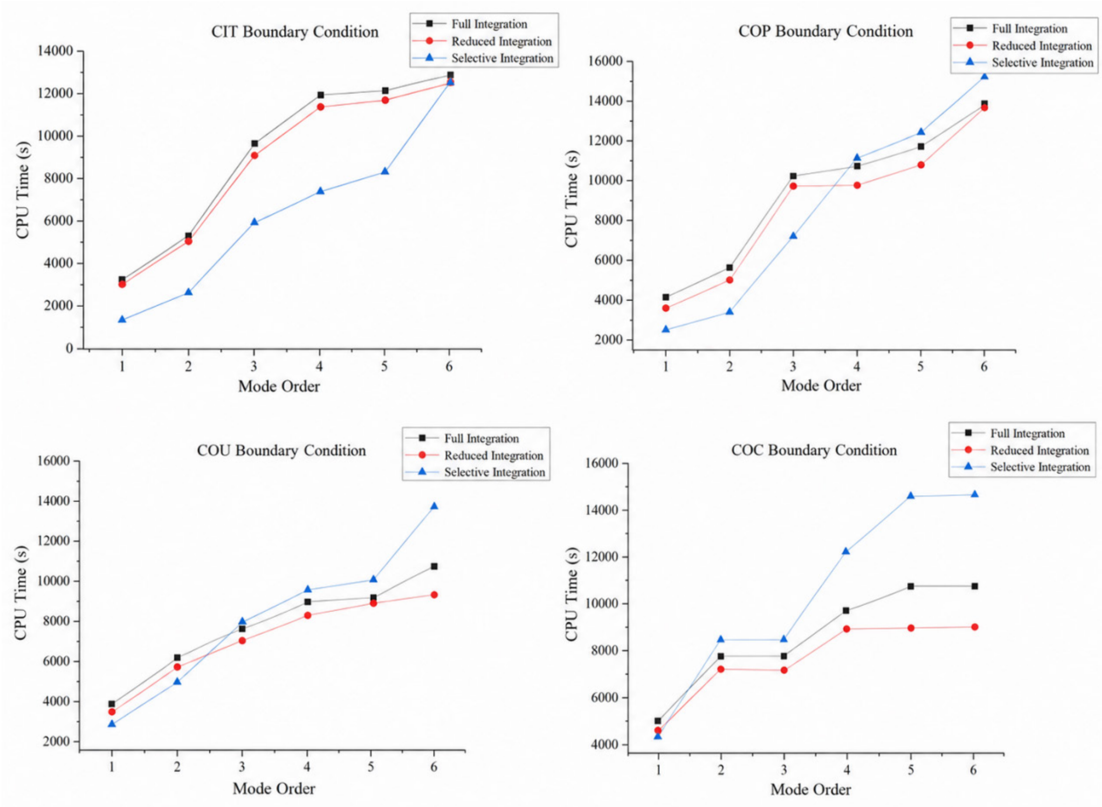

Figure 4 The natural frequencies of pyramid structures, hourglass structures, and solid plate structures under the same boundary conditions

boundary condition, all natural frequencies of both lattice-filled structures are higher than those of solid panels; under the double-sided clamping (CCFF) boundary condition, the first three natural frequencies of the lattice-filled structure are higher than those of solid panels, but the latter three are lower; under the three-sided clamping (CCCF) boundary condition, the first two natural frequencies of the lattice-filled structure are higher than those of solid panels, the third natural frequency is similar to that of solid panels, and the subsequent frequencies are lower; under the fully clamped (CCCC) boundary condition, only the fundamental frequency of the lattice-filled structure is slightly higher than that of solid panels. This may be because, under the premise of equal mass, the internal space design of the lattice-filled structure affects its energy distribution. The stiffness characteristics of the structure can be utilized more effectively in lower-order modes. In contrast, solid plates, due to the absence of internal structural discontinuities, can distribute stress and vibration energy more evenly in higher-order modes. Therefore, the natural

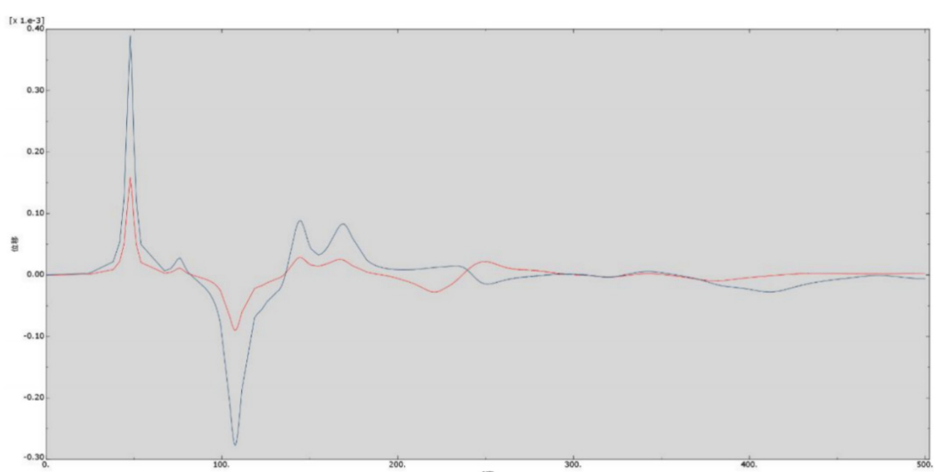

Figure 5. Displacement curves of the upper (black) and lower (red) panels at point 1 of a pyramid-structured lattice-filled sandwich panel.

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frequency of solid plates increases significantly with the increase of the mode order in higher-order modes.

4.5 Modal Analysis and Harmonic Response Analysis Results

The displacements of the upper and lower panels at observation point 1 in the harmonic response analysis were directly plotted in ABAQUS, as shown in the figure 5.

By observing the modal analysis results, we found that the natural frequency distribution of the pyramid-shaped lattice-filled sandwich panel is relatively concentrated, and many symmetrical modes appear. Under sinusoidal frequency sweep excitation, the displacement curves of the upper and lower panels at the same observation point generally show the same trend, and the displacement of the upper panel is greater than that of the lower panel. This proves that the pyramid-shaped lattice-filled sandwich panel has a certain vibration reduction and isolation capability. In the range of 0-200 Hz, the structure produces low-frequency resonance, corresponding to a large-scale deformation of the overall structure with a large amplitude and four obvious resonance peaks. After 200 Hz, the structure gradually tends to high-frequency resonance, corresponding to local deformation with a smaller amplitude. Therefore, the following section mainly focuses on further exploring the frequency range of 0~200 Hz. We extracted the displacement of the lower panel at observation points 1, 2, and 3, and used Origin to plot the frequency response curves, as shown in Figure 6.

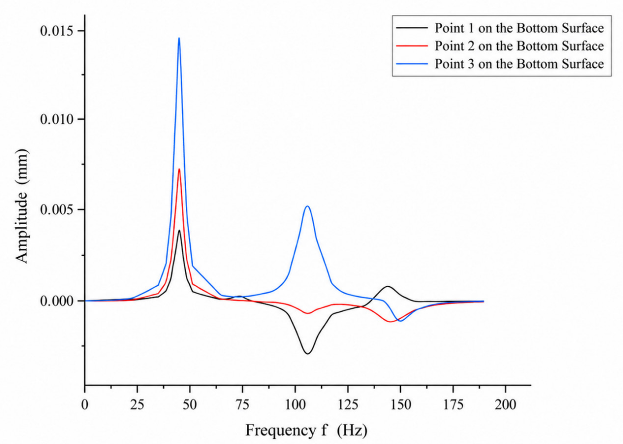

Figure 6. Frequency response curve of a pyramid lattice-filled structure under harmonic excitation

As shown in Figure 6, we can see that the three observation points on the lower panel of the pyramid-shaped lattice-filled sandwich panel exhibit obvious resonance phenomena at approximately 47 Hz, 107 Hz, and 140 Hz, which are consistent with the natural frequencies obtained from the modal analysis in Table 5.1. Observation point 3 has the largest amplitude at the first resonance peak, while observation point 1 has the smallest amplitude. This is because point 3 is the load excitation point, and point 1 is the farthest from the excitation point.

Similarly, we performed the same analysis on the hourglass structure and obtained the following results (see Figure 7).

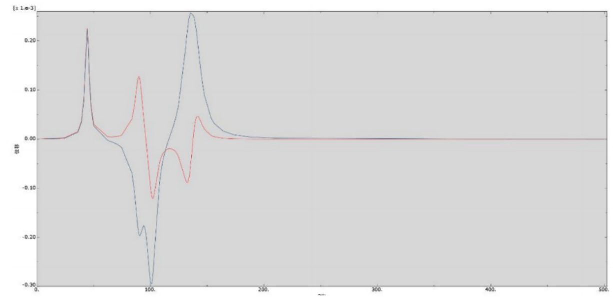

Figure 7. Displacement curves of the upper (black) and lower (red) panels at point 1 of the hourglass structure lattice-filled sandwich panel.

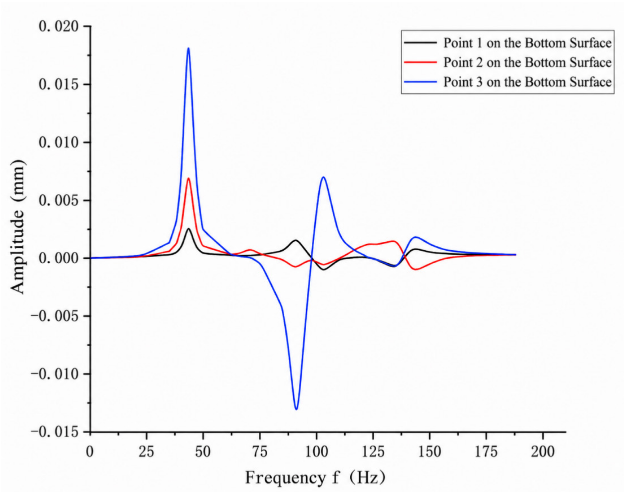

Figure 8 Frequency response curve of a pyramid lattice-filled structure under harmonic excitation

Figure 8 shows that the displacement of the upper panel at point 1 is greater than that of the lower panel, proving that the hourglass-shaped lattice-filled sandwich panel has a certain vibration reduction capability. Figure 8 also shows that the three observation points of the lower panel of the hourglass-shaped lattice-filled sandwich panel exhibit obvious resonance phenomena at approximately 45 Hz, 90 Hz, and 110 Hz, consistent with the modal analysis results. We found that the amplitude of both lattice-filled structures is largest at observation point 3 and smallest at observation point 1, meaning that the amplitude of each of the three observation points is directly related to its distance from the excitation point; the closer the distance, the larger the amplitude. At the same frequency, the positive and negative displacements at each point are due to their phase. When the structure vibrates, the wave propagates within the structure, and different points may be in different phases of the wave at the same moment, resulting in different displacement directions. Figure 9 shows the frequency response curves of the lower panels of the two structures at the same observation point for comparison (the results are shown in Figure 9).

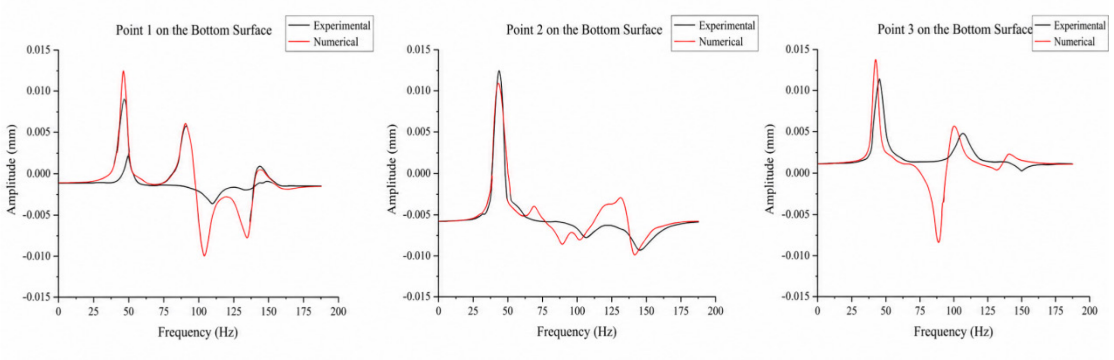

Figure 9. The frequency response curves of the two lattice structures on the lower panel at the same observation point, from left to right, are for observation points 1, 2, and 3.

5 Conclusion

This study systematically studied "performance-adjustable vibration-damping and energy-dissipating structures," completing a full closed loop from theoretical modeling and simulation analysis to experimental verification. By introducing neural networks and closed-loop optimization methods, a preliminarily adjustable mapping between structural parameters and vibration reduction performance was achieved. The project results lay a solid foundation for further development of intelligent vibration reduction systems and provide theoretical support and technical reserves for related engineering applications.

Reference

[1] Rao, S. S. (2017). Mechanical Vibrations (6th ed.). Pearson.
[2] Gibson, R. F. (2016). Principles of Composite Material Mechanics (4th ed.). CRC Press.
[3] Allen, H. G. (1969). Analysis and Design of Structural Sandwich Panels. Pergamon Press.
[4] Deshpande, V. S., Ashby, M. F., & Fleck, N. A. (2001). Foam topology: Bending versus stretching dominated architectures. Acta Materialia, 49(6), 1035–1040.