Analysis of Vibration Energy Transfer in Composite Lattice Structures

Ming Zhuo Yang, A Li Tian*

School of Naval Architecture & Ocean Engineering, Jiangsu University of Science and Technology, Zhenjiang, Jiangsu, 212100, China

*545831848@qq.com

Abstract: Exploring the vibration transmission law in structures is an important method to realize vibration reduction and damping. Composite sandwich structures not only possess certain mechanical properties but also offer the advantage of lightweight construction. In this study, based on the composite coupled lattice sandwich structure, the energy transfer at different frequencies is visualized by vibration power flow. We utilize the finite element power flow method to calculate power flow at excitation and response points. We employ the finite element power flow method to calculate the power flow at excitation and response points. By integrating COMSOL Multiphysics and MATLAB, we generate power flow vector diagrams and cloud plots and observe the vibration energy transfer process in the time domain state. The results show that the vibration energy transfer path of the composite sandwich structure becomes complicated with the increase of frequency, and the energy distribution is mainly concentrated at the coupling, demonstrating an excellent vibration attenuation effect.

Keywords: Sandwich structure; Vibration; Energy transfer; Power flow

1 Introduction

Vibration and noise quality are important technical indicators to measure the performance of ships, and controlling vibration not only reduces the hazards to equipment but also effectively improves noise pollution. In recent years, sandwich panels in the field of ships highlighted the advantages of lightweight, the widely used lattice configuration core taking into account the good specific strength and stiffness, with excellent mechanical properties. The vibration of sandwich structure essentially reflects the propagation of energy, and understanding the law of energy distribution and flow under external excitation can provide a new analytical perspective for studying structural dynamics, which has become a worthwhile direction of investigation[1].

Vibration energy visualization can be characterized by power flow, through force and velocity to evaluate the energy transmitted by a vibrating system. The power flow method combined with different dynamics methods to form different theoretical approaches[2], among which the finite element power flow method (PFFEM) based on

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structural sound intensity theory is more widely used because of its ease of calculation[3,4]. Wang Y H et al.[5,6]took energy flow for perspective, through (PFFEM) revealed the energy transmission behaviors and the manipulation of power flow by the ABH. Considering that the composite structure has good mechanical properties, many scholars have investigated the vibration power flow characteristics. Zhu L F et al.[7]have designed a cracked beam made of functionally graded materials (FGMs), and analyzed the vibrational power flow. Xue X et al.[8] investigated the vibrational characteristics of a sandwich cylindrical shell structure with an elastic-porous metal-rubber core in the thermal environment by the power flow method. Zhu C D et al.[9-11] considered simple harmonic excitation, and investigated the power flow characteristics and energy transfer of variable stiffness laminated composites. Cai Y N et al.[12]visualized the vibration energy of glass fiber-reinforced plastic sandwich panels and discussed the contribution of shear, torsion, and bending components. Wu D J et al.[13]starting from the connection nodes in composite laminates, carried out the analysis of the vibration transfer. Currently, the vibration power flow about composite structures are homogeneous laminates, and there is a lack of exploration of the lattice core. In addition, the current study only analyses the power flow characteristics in the frequency domain environment, if combined with analysis in the time domain state, which will make the power flow performance clearer and more comprehensive.

This paper takes the composite lattice sandwich structure as the research object and studies the vibration energy propagation from the perspective of the frequency domain and time domain. Based on the concept of structural sound intensity, establishing a finite element power flow calculation process for visualization of vibration energy transfer. The data are extracted by finite element analysis through COMSOL, and MATLAB post-processing draws the power flow vector diagram and power flow cloud diagram under frequency response. Discussing the vibration energy distribution law and the intrinsic influence connection and analysing the transient vibration power flow transfer characteristics at different moments, verify the good vibration damping effect of the composite lattice sandwich structure through the vibration power flow evaluation.

2 Research Methodology

2.1 Structural Sound Intensity Theory

In 1970, Noiseux[14]introduced the theory of acoustic intensity in aeroacoustics to continuum medium mechanics, taking into account the internal forces and plasmonic response of the structure, which kicked off the theory of structural acoustic intensity. The PFFEM based on this theory was proposed by Nefake[15]in 1989, which can characterize the energy flow of complex structures by post-processing intuitively and analyzing the data obtained from finite elements distinctly.

The instantaneous structural sound intensity in a certain time domain is a time-dependent vector equal to the power flow of the vibrating structure per unit area, which is expressed as:

$$i_n(t) = -\sigma_{nl}(t) v_l(t) \tag{1}$$

where $\sigma_{nl}(t)$、 $v_l(t)$ is the stress component and velocity component in the direction at the time.

The energy flow through the structure is obtained by averaging the instantaneous sound intensity over time:

$$I_n = \langle i_n(t) \rangle = \frac{1}{T} \int_0^T i_n(\tau) \mathrm{d}\tau \tag{2}$$

The structural sound intensity formula in the time domain is Fourier transformed to obtain an expression for the sound intensity in the frequency domain:

$$I_i(\omega) = -1/2 \cdot \mathrm{Re}(\tilde{\sigma}_{ij}(\omega) \tilde{v}_j^*(\omega)) \tag{3}$$

Where ω is natural frequency; $\tilde{\sigma}_{nl}(\omega)$、 $\tilde{v}_l(\omega)$ is the complex form of stress and velocity components after Fourier transformation; $*$ is taking the complex conjugate; Re is taking the real part.

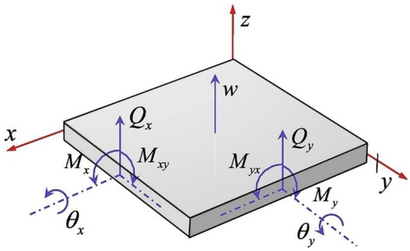


Fig. 1. Schematic diagram of force, moment, angle, and displacement of plate and shell unit

According to equation (3), the structural sound intensity is compounded by the structural stress and velocity vectors. The idea of the finite element power flow method (PFFEM) is to discretize the structure into several units for calculation, and the stress and velocity data are expressed in the form of units or nodes. The internal forces as well as the displacements of the plate and shell cells are shown in figure 1.

The strength of the structure is expressed in the form of a net energy flow per unit width, which lies in a plane tangent to the midplane of the structure. The displacement at any point in the structure can be expressed in terms of translational and angular displacements of the midplane, so the unit width power flow can be expressed as:

$$\begin{aligned} I_x &= -(\omega/2) \cdot \mathrm{Im}(N_x u^* + N_{xy} v^* + Q_x w^* + M_x \theta_y^* - M_{xy} \theta_x^*) \\ I_y &= -(\omega/2) \cdot \mathrm{Im}(N_y u^* + N_{yx} v^* + Q_y w^* + M_y \theta_x^* - M_{yx} \theta_y^*) \end{aligned} \tag{4}$$

A vector map of structural sound intensity is modeled, with the start of the vector representing the spatial coordinates of the structural sound intensity in the structure, the endpoint representing the direction of the vector, and the length representing the amplitude of the structural sound intensity at a given point.

$$|I| = \sqrt{I_x^2 + I_y^2 + I_z^2} \tag{5}$$

The traditional evaluation indexes of vibration transfer include force transfer rate, insertion loss, vibration level drop, etc. While the power flow transfer rate is an evaluation criterion based on the viewpoint of energy transfer, and the steady-state time-averaged input power injected into the plate during an excitation cycle is first derived via mechanical impedance theory[16]:

$$P_{\text{in}} = \omega / 2 \cdot \text{Re}(\sum_{j=1}^{n} F_{\text{in}_j} \cdot \tilde{V}^*_{\text{in}_j}) \tag{6}$$

Where $F_{in}(w)$ is the amplitude of the excitation force; $V^*_{in}(w)$ is the complex number of velocity conjugates at the point of excitation of the receiving system.

The output power flow dissipated or transferred by the system through the damping unit to the other side of the connected neighboring structure is:

$$P_{\text{out}} = \omega / 2 \cdot \text{Re}(\sum_{j=1}^{n} F_{\text{out}_j} \cdot \tilde{V}^*_{\text{out}_j}) \tag{7}$$

Where $F_{out}(w)$ is the complex amplitude of the damping force or response side, and $V^*_{out}(w)$ is the complex number of velocity conjugates at the output position.

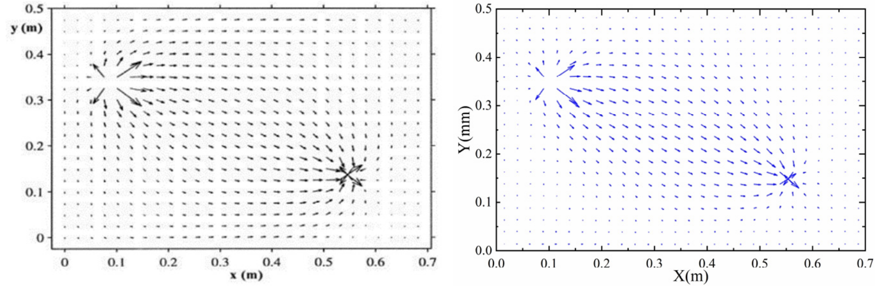
The power flow transfer rate is expressed as:

$$\alpha_{\text{p}} = 100\% \times P_{\text{out}} / P_{\text{in}} \tag{8}$$

2.2 Simulation Analysis and Verification

The finite element power flow method is used to obtain the data of displacement and internal force through COMSOL Multiphysics, and vector diagrams are drawn based on the structural sound intensity formula. To verify the accuracy of the calculation method, the rectangular aluminum plate in literature[15]is used as an example, the length of the aluminum plate is 0.707m, the width is 0.5m, the thickness is 3mm; the density is 2100kg/m^3, the Young's modulus is 70Gpa, and the Poisson's ratio is 0.3. The boundary conditions of the structure are short side simply supported, long side free, and the effect of structural damping is ignored. A simple harmonic excitation force with an amplitude of 1N and 14Hz is applied at coordinates (0.101m, 0.35m), and a damping coefficient of 2000Ns/m is attached to the dampers at coordinates (0.555m, 0.15m), and a comparison of the power flow calculation results is shown in figure 2.

The results show that the energy flows out from the excitation point and has the largest input power flow at the excitation, which is effectively pooled and absorbed at the damper through the energy flow. A comparison of the two power flow vectors is found to be in good agreement with the trend, which clearly describes the vibration energy transfer path and verifies that the finite element power flow visualization method used in this paper is correct and feasible.



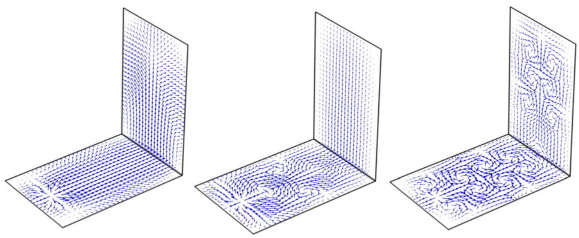
(a) Methodology of the literature (b) Methodology of this article

Fig. 2. Verification of structural sound intensity calculation

3 Structural Vibration Power Flow Analysis

3.1 Coupling Plate Structure

Consider the influence of simple plate coupling boundary on the structure power flow, the L-type plate for modal analysis, according to the first two orders of the intrinsic frequency selected close to the excitation frequency of 125Hz、235Hz、435Hz different frequencies corresponding to the vibration of the power flow transfer distribution as shown in figure 3. As the excitation frequency increases, the power flow transfer in the structure becomes more and more complex. The vibration in the plate and shell structure includes transverse vibration and in-plane longitudinal vibration, and the coupling structure makes the stress wave in the structure reflect and scatter when encountering the impedance mutation or the waveform transformation, and achieves a certain vibration isolation effect.



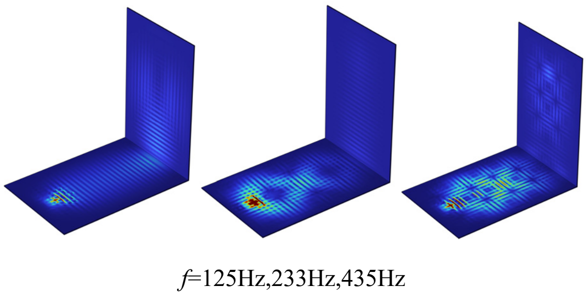


Fig. 3. Power flow transfer of L-plate

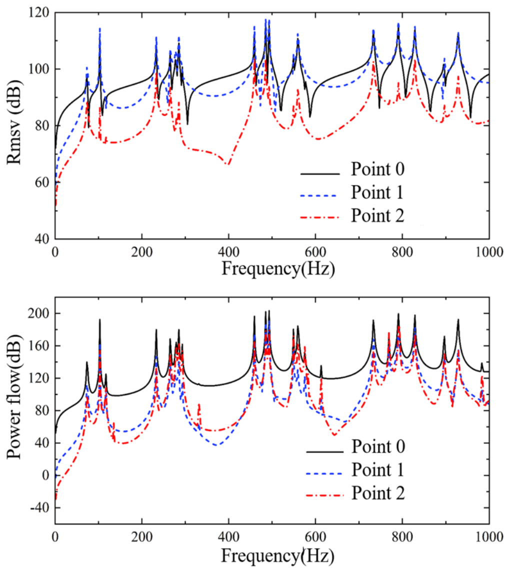


Fig. 4. Velocity response and power flow versus frequency curves for L-plate structure

Carrying out the harmonic response analysis for the L-plate, with the sweep range of 0-1000 Hz and sweep step of 2 Hz. Define the excitation position as point 0, take a response point 1 at the boundary of the coupling plate and a response point 2 at the upper side of the right panel. The velocity response and power flow versus frequency curves of the L-type plate structure are obtained as shown in figure 4. It can be found that the power flow is consistent with the trend of vibration velocity change, and there is a large response value at the intrinsic frequency. The vibration energy is higher at the boundary, and the power flow at response point 2 is very small due to the longer transfer path distance.

3.2 Composite Lattice Structure

The structural model of the complex qualified lattice is shown in figure 5, the top and bottom are thin panels with length a=600mm, width b=500mm, thickness t_1=4mm, and in the middle is the core layer of the lattice consisting of equally spaced longitudinal, transversal, or intersecting lattices, with the height h=50mm, the thickness t_2=3mm, the transversal spacing l_1=118mm, and the longitudinal spacing l_2=77mm. the panel material is structural steel, and the lattice material epoxy resin is selected, considering the structural damping, the material properties are shown in Table 1. The symmetry conditions of the panel are set with four sides solidly supported and the boundary of the lattice is free. To reveal the effect of lattice arrangement on energy flow, (b) transverse lattice structure and (c) longitudinal lattice structure in figure 5 were set up for this study.

Table 1. Structural material properties

Material	ρ(kg/m^3)	E(Gpa)	υ
steel	7800	200	0.3
resin	1180	4.35	0.368

According to the intrinsic frequency of the structure, the intrinsic frequencies of different lattice arrangements, f=221Hz, and f=287Hz, were selected as the excitation frequencies to study the effect of the frequency magnitude of the excitation force on the sound intensity characteristics of the structure. Considering that the ship machinery and equipment are the main source of the excitation environment, the contact area size is small compared with the size of the lattice structure, so the point harmonic excitation of one cycle is applied as the vibration source of the structure located in the upper panel of the structure (40mm,200mm), and the amplitude of the excitation is 10 N.

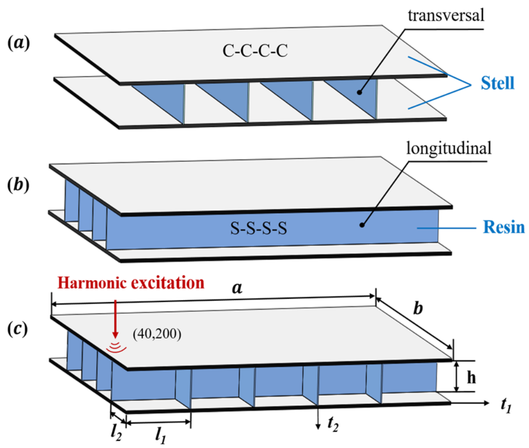
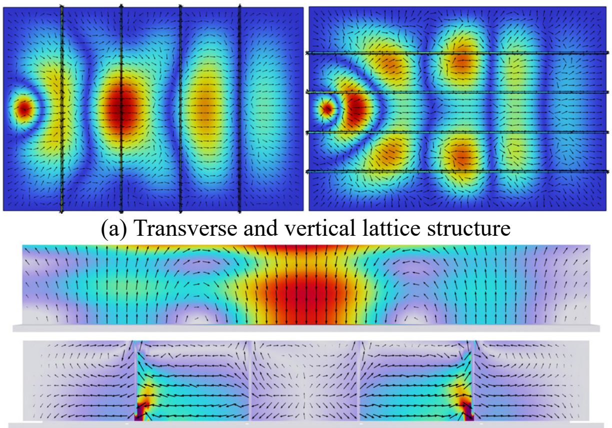


Fig. 5. Lattice structure model



(a) Transverse and vertical lattice structure

(b) First row of lattices for one-way and cross

Fig. 6. Power Flow in Lattice Structure

As shown in figure 6, the panels bear most of the in-plane compression loads, and the lattices bear most of the lateral loads and bending moments, which act as reinforcement to stabilize the panels. Under such loads and boundary conditions, the energy flow distribution of the lattice structure behaves in a complex manner. The excitation energy is divided into different regions of energy zones by the longitudinal and transverse lattice, and the location of the maximum stress moves from the top side of the reinforcing ribs to the bottom side of the reinforcing ribs. The edges of the flat plate are subjected to in-plane compressive stresses, and due to the bending of the lattice, tensile stresses are generated at the joints, resulting in an opposite change in the direction of the structural strength. The structural strength vectors at the edges of the flat plate and the lattice flanks are in the same direction and the values of structural strength at the flanks are much greater than the values of structural strength in the plate.

The curves of power flow versus frequency for different lattice structures are shown in figure 7, the peak input power flow has a strong relationship with the intrinsic frequency of the structure, which is due to the larger response caused by resonance and acts significantly in the first three orders, similar to the displacement response. The bi-directional cross-lattice structure has enhanced stiffness compared to the transverse and longitudinal structures, and its peak input power flow corresponds to frequencies shifted to the right, with low troughs, showing good suppression. The comparative results of the power flow transfer rate for different lattice settings. It can be observed that the output power flow is systematically smaller than the input power flow due to the energy separation at the excitation point and the dissipation caused by the damping of the structure, which is dominated by the resonance peak of the structure. The peak of the input power flow is not synchronized with the peak of the transfer rate, and a peak of the transfer rate also occurs at the input power flow valley. The transfer rate is very low or even close to zero in most frequency bands, with higher transfer rates in individual bands. The cross-lattice structure has a lower transfer rate and provides better vibration damping.

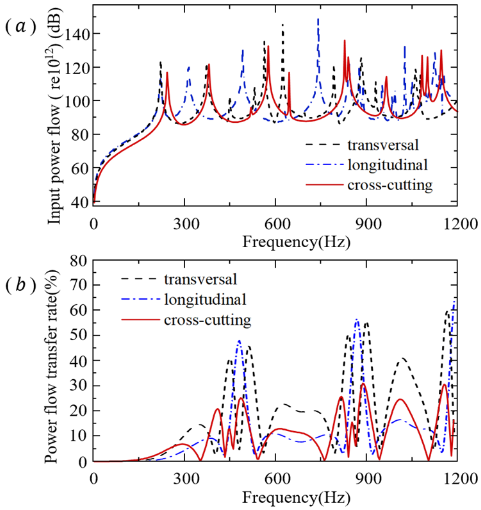


Fig. 7. Power flow for different structures

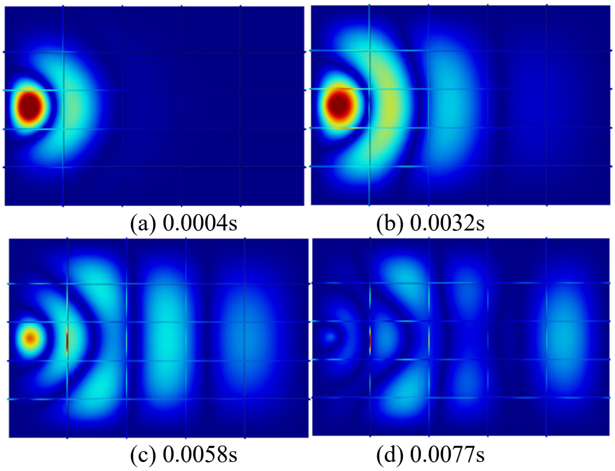


Fig. 8. Vibration power flow in the time domain

To observe the vibration energy propagation path and the damping effect of the lattice structure, the vibration power flow of the complex qualified lattice structure is represented in the time domain. The time-domain simulation with a step size of 0.0001s and calculated to 0.008s was performed, and the vibration power flow at typical moments was obtained as shown in figure 8. Observation of the power flow cloud at different moments reveals that the vibration energy flows out from the excitation point and decays continuously in the transfer path. At the moment of 0.0004s in figure 8(a), the vibration energy is concentrated at the excitation point; at the moment of 00032s in (b), the vibration wave is effectively blocked by the second row of lattice, and the energy buildup is formed by reflecting at the lattice; at the moments of (c) and (d), the dissipation of vibration energy gradually occurs, with energy being transferred from the connection between the lattice and the panel to the center of the transverse lattice, particularly near the excitation point.

4 Conclusion

Based on the composite lattice sandwich structure, investigating the vibration characteristics from the perspective of energy flow to visualize the vibration energy transfer, and the conclusions of this study are as follows:

(1) In the composite lattice sandwich structure, the presence of the lattice affects the normal transfer path and distribution of energy. The energy flows out from the excitation point and is not completely transferred to the other side, but rather a localized pooling of energy occurs, causing the structure to produce regions of high energy density.

(2) The vibration power flow is related to the frequency of the structure, and the exchange of energy flow between the lattice and the panel depends on the vibration mode that dominates in a given frequency range. The output power increases with the increase of the input power, and the transfer rate of the power flow is different due to the complexity of the transfer path caused by the lattice setup.

(3) Power flow analysis of the lattice structure can clearly and intuitively observe the location of the power flow distribution and can lay damping materials to achieve efficient vibration damping in the location where there is a large amount of energy gathered to achieve the purpose of structural light-weighting.

Since the object chosen for this study is the composite lattice structure with a uniform surface, but the vibrational power flow encounters abrupt coupling such as cross-section changes, material changes, and changes in the direction of the structural extension during the transfer process is very much worthy of consideration, and can be continued to explore the performance of the relevant power flow transfer characteristics in future work.

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