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Vibration transmission characteristics of composite laminate joints based on power flow

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Abstract: [**Objectives**] In order to investigate the influence of joints in composite laminates on the vibrati on transfer characteristics of structures, this study uses finite element method (FEM) for power flow and a related visualization technique. [**Methods**] First, a method that describes plate vibration by power flow in solid elements is proven to be feasible, then transmission efficiency of power flow is introduced and to calculate it, a method in finite element model is proposed and verified with reference to the admittance power flow method. Finally, two joint simulations of embedded joints and screw joints are obtained, as well as the curve for transmission efficiency of power flow and the typical vector diagram of power flow. [**Results**] The results show significant differences in vibration transmission and transmission efficiency of power flow between the two models. [**Conclusions**] The FEM for power flow can directly reflect the transmission path of vibration energy for a connected structure, which can provide useful references for the design of composite structures.

Key words: composite laminates; connecting structures; power flow; vibration transmission; finite element method

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0 Introduction

With the continuous improvement in the level of manufacturing technology and properties of composite materials, composite structural components have been widely used in aerospace, automotive, marine and other engineering fields. However, the corresponding structural connection problems have come along with them. The influence of the connection method of composite members on the overall vibration transmission of a structure is significant. However, the existing research was mostly focused on the basic mechanical properties such as structural strength and stiffness, with the objectives of improving the structural load-bearing capacity and structural stability and reducing the weight [1-3]. It lacks the research on the targeted dynamic properties. At the same time, in practical engineering applications, the connection of composite members usually involves the composite connection of materials with different properties, such as the composite connection of steel/composite structures [4]. Their structural forms are usually more complex [5]. The structural vibration transmission cannot be accurately described by simple theoretical models. Therefore, it is necessary to conduct separate detailed studies for different connection forms.

Currently, most of the studies on the vibration transmission characteristics of connection structures focus on the transmission of structural vibration waves, such as the analysis of conversion of vibration waves in L-shaped and T-shaped connection structures [6-7]. This theoretical analysis

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is more applicable to the connection structures with simple structural forms and single material properties, and is relatively complex [8] because more influencing factors need to be considered if experimental studies are conducted. The finite element method (FEM) for power flow can analyze complex structural forms and different characteristic materials, and is therefore suitable for studying the connection of composite structures. The finite element power flow method is a combination of the finite element method and the structural sound intensity theory, which was first proposed by Noiseux [9] in 1970. This theory was derived from the sound intensity theory in acoustics. On this basis, Gavrić et al. [10] derived the calculation formula for structural sound intensity of plate and shell units based on the finite element method, and drew the diagram for structural sound intensity vector of simply supported flat plates, which greatly promoted the application of FEM for power flow. Zhu et al. [11] proposed a structural sound intensity expression for the finite element solid unit and compared it with the calculated results of the shell units. This verified the validity of the results and extended the application of FEM for power flow. The FEM for power flow has been widely used with the development of commercial finite element software because it can intuitively determine the structural vibration energy distribution and transmission paths [12-15]. However, most studies were still limited to simple structures or structures where local details were neglected, thus not facilitating the detailed analysis of the variability of structural vibration transmission.

In this paper, the vibration transmission characteristics of composite laminate joints are analyzed based on FEM for power flow. Firstly, the solid unit models of two types of composite laminate connection structures (namely, embedded connection and screw connection) are built. The power flow data of the models are calculated. The visualized diagrams for power flow vector are given. Then, the evaluation index for transmission efficiency of power flow will be introduced. The curves for transmission efficiency of power flow of the two connection structures and their characteristics of vibration transmission in different frequency bands will be compared and analyzed, which will be used to provide reference for the subsequent design of composite structures.

1 Theory for finite element power flow

1.1 Structural sound intensity method

Vibration is transmitted in various wave forms in a structure. The vibration energy carried by the waves will show different transmission characteristics. By analogy with the sound intensity theory in aerodynamics, structural intensity (SI) can be used to describe the vibration energy flow in an elastic medium, including the magnitude and direction of energy transmission. The transient structural sound intensity $I_m(t)$ is defined as [10]

$$I_m(t) = -\sigma_{mn}(t)v_n(t) \tag{1}$$

where $\sigma_{mn}(t)$ and $v_n(t)$ are the stress component and velocity component, respectively, where m, n = 1, 2, 3 and they denote three different directions of the components.

Regarding the steady-state excitation, the structural sound intensity $I_m(\omega)$ in the frequency domain is defined as

$$I_m(\omega) = -1/2\mathrm{Re}(\widetilde{\sigma}_{mn}(\omega)\cdot\widetilde{v}_n^*(\omega)) \tag{2}$$

where ω is a circular frequency; Re is a real part; $\widetilde{\sigma}_{mn}(\omega)$ and $\widetilde{v}_n(\omega)$ are the Fourier transformed complex forms of the stress component and velocity component, respectively; $\widetilde{v}_n^*(\omega)$ is the conjugate of the velocity component in the complex form. From Eq. (2), it can be seen that the structural sound intensity can be regarded as the density of power flow.

1.2 Finite element power flow

From Eq. (1) and Eq. (2), it can be seen that the structural sound intensity is compounded by the structural stress and velocity vectors. The stress and velocity vectors can be output based on commercial finite element software. However, the structural sound intensity needs further data processing. The finite element method can discrete the structure into several units for calculation. The stress data and velocity data in the finite element software are also expressed in the form of units or nodes. Therefore, the finite element unit can be used as the basic unit when the structural sound intensity is calculated.

The structural sound intensity can be regarded as the power flow through the unit cross-sectional area. By integrating a certain cross-section of the structure, the transmitted power through the cross-section can be obtained. The finite element unit can be divided into a thin shell unit and a body unit, where the power flow per unit width through the thin shell unit is [10]

$$\begin{cases} I_x = -(\omega/2) \cdot \mathrm{Im}(N_x u^* + N_{xy} v^* + Q_x w^* + M_x \theta_y{}^* - M_{xy} \theta_x{}^*) \\ I_y = -(\omega/2) \cdot \mathrm{Im}(N_y u^* + N_{yx} v^* + Q_y w^* + M_y \theta_x{}^* - M_{yx} \theta_y{}^*) \end{cases} \tag{3}$$

where I_x and I_y denote the structural sound intensities in x and y directions, respectively; Im is the imaginary part; N_x, N_{xy}=N_{yx}, N_y are all film forces; Q_x and Q_y are shear forces; M_y and M_x are both bending moments; M_{xy}=M_{yx} are torsional moments; u^*, v^*, w^* are conjugate terms for translational displacements; $\theta_x{}^*$ and $\theta_y{}^*$ are conjugate terms for rotational displacements.

With regard to the body unit, the power flow through the unit area is [11]

$$\begin{cases} I_x = -(\omega/2) \cdot \mathrm{Im}(\sigma_x u^* + \tau_{xy} v^* + \tau_{xz} w^*) \\ I_y = -(\omega/2) \cdot \mathrm{Im}(\tau_{yx} u^* + \sigma_y v^* + \tau_{yz} w^*) \\ I_z = -(\omega/2) \cdot \mathrm{Im}(\tau_{zx} u^* + \tau_{zy} v^* + \sigma_z w^*) \end{cases} \tag{4}$$

where I_z is the structural sound intensity in z-direction; σ and τ are the positive and tangential stresses, respectively, where the subscripts x, y, z denote three directions of the components.

1.3 Transmission efficiency of power flow

The traditional evaluation indexes of structural vibration transmission include force transmission rate, insertion loss, and vibration level drop, while the transmission efficiency α_{p} of power flowis an evaluation criterion based on the energy transmission viewpoint [16], which is defined and expressed as follows:

$$\alpha_{\mathrm{p}} = 100\% \times P_{\mathrm{out}} / P_{\mathrm{in}} \tag{5}$$

where P_{in} and P_{out} are the input power and transmission power of the system, respectively. For the T-shaped connection discussed in this paper, P_{in} and P_{out} are the input power brought by external excitation on one side of the T-shaped connection and the transferred power of vibration energy transferred to the other side, respectively, and are

$$P_{\mathrm{in}} = -\omega/2 \cdot \mathrm{Re}\left(\sum_{j=1}^{n} F_{\mathrm{in}_j} \cdot \widetilde{U}^*_{\mathrm{in}_j}\right) \tag{6}$$

$$P_{\mathrm{out}} = -\omega/2 \cdot \mathrm{Re}\left(\sum_{j=1}^{n} F_{\mathrm{out}_j} \cdot \widetilde{U}^*{}_{\mathrm{out}_j}\right) \tag{7}$$

where F_{in_j} is the generalized excitation force, where the subscript j indicates the component direction; F_{out_j} is the generalized internal force; $\widetilde{U}^*_{\mathrm{in}_j}$ and $\widetilde{U}^*{}_{\mathrm{out}_j}$ are the generalized displacements of the excitation side and the transmission side, respectively.

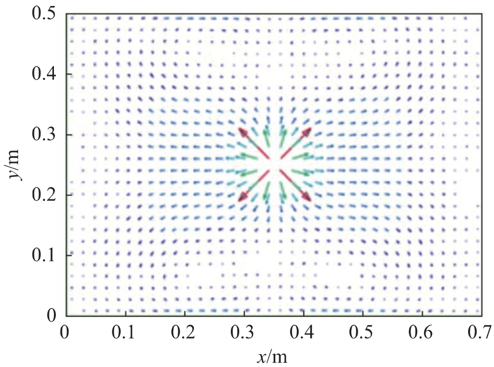
2 Validation for power flow theory

2.1 Visualization verification for power flow

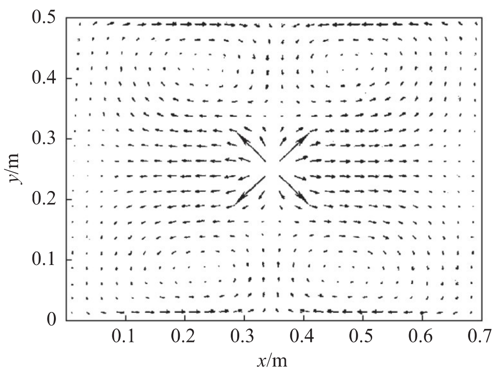
In this paper, the finite element software ABAQUS will be used as a tool for steady-state excitation response calculation. The secondary development of Python language will be used to process the calculation results, so as to obtain the power flow data of the structure and visualize the vector diagram of power flow. In the study of the vibration transmission characteristics of composite laminate connection, solid units are used to build a model in this paper due to the complexity of the details of the joint structure. Therefore, it is necessary to verify whether solid unit modeling can accurately describe the transmission of vibration power flow of the plate and shell. According to Ref. [11], one rectangular plate model with two short sides having simple supports and two long sides having freedom is established. The geometric parameters of this rectangular plate model are 700 mm×500 mm×10 mm. The material parameters are density ρ =2.1×10^{-6} kg/mm^3, elasticity modulus E =7.0×10^7 kPa, Poisson's ratio ν =0.3, and structural damping η =0.005, respec-tively. A unit excitation force perpendicular to a normal plane is applied at the position of the center of the plate (350 mm, 250 mm). The grid unit is a C3D20R unit. The thickness direction of a plate is divided into three layers of grid units. The power flow data are calculated with the middle layer of the grid as the representative. The power flow vector diagram of the rectangular plate under single frequency excitation at 480 Hz is shown in Fig. 1(a). By comparing the vector diagram of Ref. [11] (Fig. 1(b)), it can be seen that the two are consistent. Therefore, the validity of this paper to calculate the power flow of the plate and shell with solid units is verified.

2.2 Verification for transmission efficiency of power flow

Since the finite element power flow represents the power flow through a unit width or a unit area on a finite element unit, and the calculation for the transmission efficiency of power flow of a structure requires the total transmission power flow through a certain cross section of a structure, the integral calculation of the cross section is required. Here, the calculation results by the admittance power



(a) Calculation results of solid unit plate



(b) Calculation results of Ref. [11]

Fig. 1 Comparison for the vector diagram of power flow

flow method in Ref. [2] are used to further verify the validity for calculation of the trans-mission efficiency of power flow. The L-shaped coupling plate model shown in Fig. 2 is established, which consists of two 1 000 mm×500 mm×6.35 mm rectangular plates coupled together with material parameters: density ρ =2.71×10^{-6} kg/mm^3, elasticity modulus E =7.2 ×10^7 kPa, Poisson's ratio ν=0.33, and structural damping η = 0.01, respectively. The coupling side is free and the other sides are simply supported. A unit load perpendicular to a normal plane is applied to one side of the L-shaped plate. The transmission power flow transferred to the other side is calculated. Finally, the transmission efficiency of power flow is calculated.

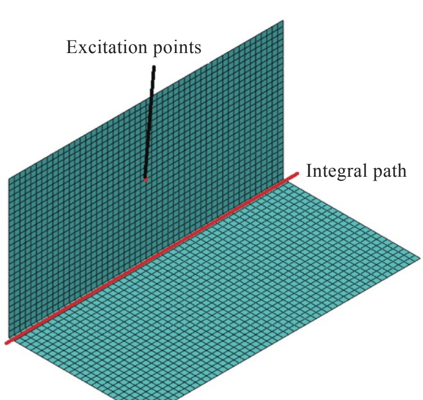


Fig. 2 Finite element model of L-shaped plate

In the finite element calculation model, it can be considered that the vibration energy at the excitation point shall pass through the coupling edge when it is transferred to the lower side of the L-shaped plate. Therefore, the transmission power can be obtained by integrating the power flow along a coupling edge. Firstly, the power flow along the integration path and connected with the coupling edge is calculated by Eq. (3), multiplied by the unit width and then summed to obtain the power flow transferred to the lower side of the L-shaped plate. Then, according to Eq. (6), the external excitation force is multiplied with the excitation point displacement to calculate the input power flow. Finally, the transmission efficiency of power flow is calculated by Eq. (5). The comparison between the finite element power flow and the admittance power flow in Ref. [17] is shown in Fig. 3. This shows that the overall consistence between the two is good, thus proving the effectiveness of the method in this paper. However, there are some differences between the peak values of the two calculations. The peak value of the finite element calculation in this paper is lower because of the theoretical difference between the structural damping considered in this paper and the damping of the complex stiffness assumed in Ref. [17].

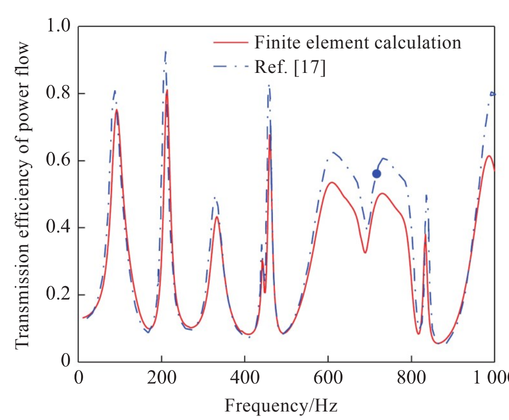
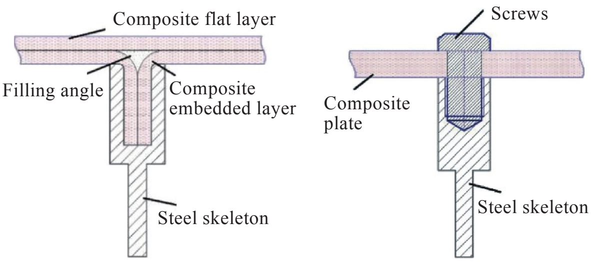


Fig. 3 Comparison for transmission efficiency of power flow

3 Example of connection of composite laminates

3.1 Numerical model

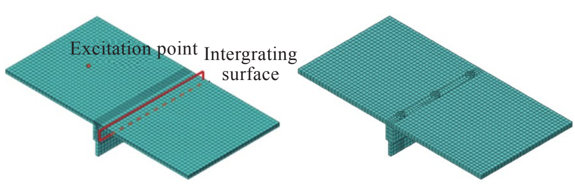
In this section, the vibration transmission of the connection of two composite laminates is analyzed, one of which is embedded connection and the other of which is screw connection. The section diagram of the connecting structure is shown in Fig. 4.



(a) Embedded connection (b) Screw connection

Fig. 4 Section diagram of the connecting structure

The finite element models of the two connection structures are shown in Fig. 5. The panel size is 600 mm×300 mm×12 mm. The material is a resin-based glass fiber reinforced composite material. The material damping loss factor η' =0.05. The support skeleton material is steel, with the elasticity modulus E =2.06×10^8 kPa, the density ρ=7.85×10^{-6} kg/mm^3, the Poisson's ratio v=0.3, and structural damping η=0.001. The model distribution of screw connection includes three screws of ϕ16 mm with a screw spacing of 114 mm.



(a) Embedded connection (b) Screw connection

Fig. 5 Finite element model for two connection structures of composite laminates

Material properties of the composite panel are shown in Table 1, where E_1, E_2, E_3 are the elasticity moduli in different directions. μ_{12}, μ_{13}, μ_{23} are Poisson's ratios; G_{12}, G_{13}, G_{23} are shear moduli.

Table 1 Material properties of composite panel

Material properties	Value
E_1, E_2 /GPa	18.5
E_3/GPa	6
μ_{12}	0.12
μ_{13}, μ_{23}	0.3
G_{12}/GPa	3.75
G_{13}, G_{23}/GPa	6.75

In the calculation of the vibration transmission characteristics of the model, the side end surfaces of the steel skeleton are set to be rigidly fixed, while the panel is kept free around. A unit excitation is applied at the center of one side of the panel to calculate the transmission power along the integral area at the other side of the joint, where the calculated frequency band is 10−1000 Hz.

3.2 Analysis for power flow

The curves for transmission efficiency of power flow calculated by two connection methods are shown in Fig. 6. From the figure, we can see the following results:

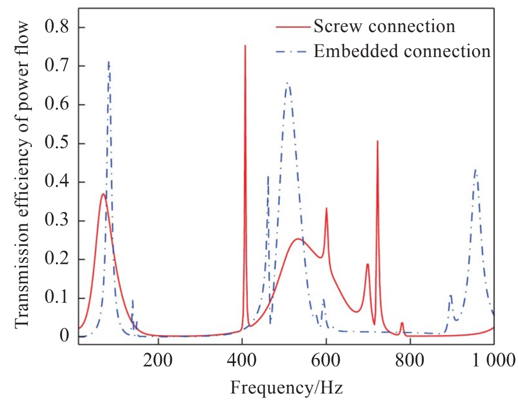
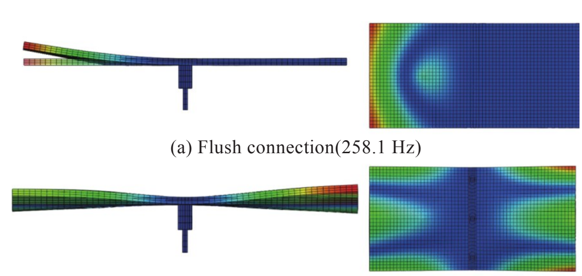


Fig. 6 Comparison for transmission efficiency of power flow

1) Whether screw connection or embedded connection, the transmission effciency is only high in some frequency bands, while the transmission effciency in other frequency bands is very low or even close to zero. For example, the power flow transmission efficiencies of the two connection methods in the 200−400 Hz frequency band in Fig. 6 are both close to zero, which is equivalent to the introduction of one forbidden zone of energy transmission at the joints. Its typical vibration pattern is shown in Fig. 7(a). The existence of this energy transmission forbidden band is not related to the specific structural form of the joints, although it is caused by the connection joints.



(a) Flush connection(258.1 Hz)

(b) Screw connection(699.8 Hz)

Fig. 7 Displacement contours of structural vibration

2) In the frequency band of 600−800 Hz, the transmission efficiency of power flow with the embedded connection has been maintained at a low level, while the transmission efficiency of power flow with the screw connection is more variable and has a local peak. Its vibration pattern is shown in Fig. 7(b). It can be seen that the displacement contour of the screw connection is bounded by a screw position, showing a clear zoning state, which

is due to the fact that the position between the screws and the position between the screw and the outer edge of the screw are involved in vibration transmission as transmission channels. Unlike the linear constraints of the embedded connection, the screw connection shows a point-like constraint characteristic, i. e., different stiffness constraints lead to the difference in transmission efficiency of power flow.

The comparison results for the input power, output power and transmission efficiency of power flow of the screw connection model are shown in Fig. 8. The input/output power has a unit of dB, and the reference power value is 1×10^{-12} W. As can be seen from Fig. 8, the output power increases with the increase of input power, while the transmission efficiency of power flow does not increase with the increase of input power. The peaks of input power and output power are not synchronized with the peak of transmission efficiency. The peak of transmission efficiency may also occur at the valley of input/output power. Therefore, when the connection structure is designed, not only the input power and output power situations are focused, or only the vibration performance on both sides of the joint is focused, but also the transmission efficiency of power flow is combined comprehensively to analyze the overall transmission of vibration energy.

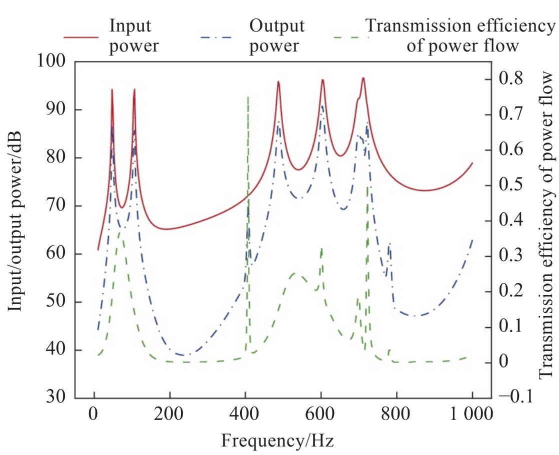


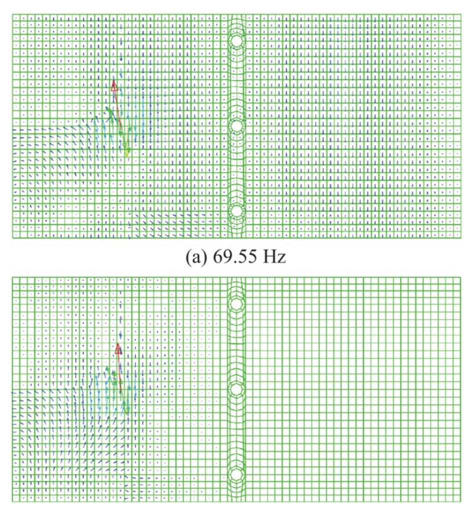
Fig. 8 Power flow analysis of screw joints

3.3 Visualized analysis of power flow

By visualizing the power flow of the composite laminates of the two models, two kinds of visualized power flow images can be obtained. One is the vector diagram for power flow, and the other is the vector diagram for uniform power flow. The vector diagram for power flow can effectively distinguish the magnitude of the power flow vector of each part, while the vector diagram for uniform power flow can distinguish the power direction to determine the power transmission path.

In this section, typical vector diagrams for power flow of two models are selected for comparison and analysis.

1) Comparison for different transmission efficiencies of power flow. Fig. 9(a) and Fig. 9(b) show the vector diagrams for power flow of the screw connection at 69.55, 193.6 Hz, respectively, and the differences are obvious. From Fig. 9(a), it can be seen that the vector length of the power flow on both sides of the joint at 69.55 Hz is approximately equal, while the power flow on the transmission side at 193.6 Hz (Fig. 9(b)) is almost negligible compared with the excitation side. This difference corresponds to the curve for the transmission efficiency of power flow (Fig. 6), which again verifies the rationality of the calculation method for power flow.



(a) 69.55 Hz

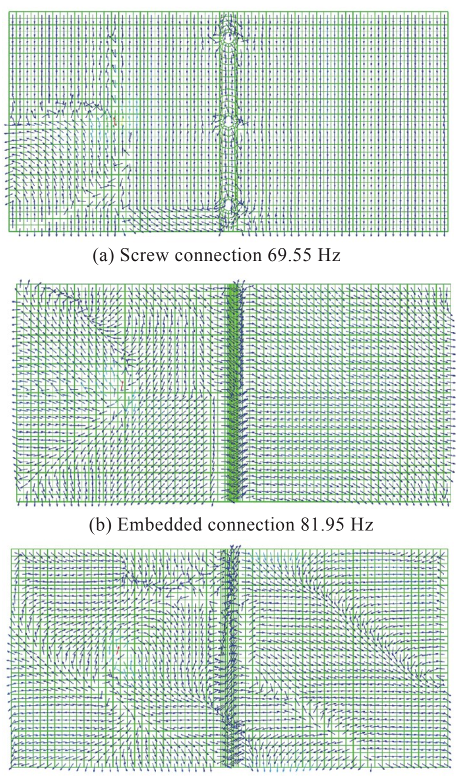
(b) 193.6 Hz

Fig. 9 Comparison for vector diagram of power flow

2) Comparison of different connection forms. Fig. 10(a) and Fig. 10(b) show the vector diagrams of uniform power flow at 69.55, 81.95 Hz for the screw connection and the embedded connection, respectively. From Fig. 10(a), it can be seen that the power flow vector at the open position is distributed around the open position, which indicates that the vibration wave transferred to the screw position is no longer continuous. Therefore, the transmission path of power flow becomes more complex, while the power flow transmission of the embedded connection is relatively uniform.

3) Comparison of low and high frequencies. Fig. 10(b) and Fig. 10(c) show the vector diagrams for the uniform power flow of the embedded

connection at 81.95, 957.82 Hz, respectively. The transmission direction of power flow in Fig.10(b) is very obvious. The transmission path is clear and evenly distributed. The intermediate joints in Fig. 10(c) have obvious bi-directional power flow transmission. Its overall transmission path is more complicated than that in Fig. 10(b), which indicates that the transmission of high-frequency vibration waves is more complicated than that in low frequency conditions. Therefore, it should be paid special attention in the design of structural connection.



(a) Screw connection 69.55 Hz

(b) Embedded connection 81.95 Hz

(c) Embedded connection 957.82 Hz

Fig. 10 Comparison for vector diagram of uniform power flow

4 Conclusion

By analyzing the vibration transmission characteristics of the composite laminate joints by the FEM for power flow, the following conclusions are obtained:

1) The method to describe the vibration transmission of plate and shell structures by the power flow of finite element solid units is feasible, which provides a basis for analyzing relatively complex composite laminate connection structures.

2) When both sides of the joints exhibit low input/low output power, there will also be high transmission efficiency of power flow. Therefore, the structural design should be paid particular attention to.

3) The vibration transmission of the two connection methods, screw connection and embedded connection, is significantly different in some frequency bands, on one hand, due to the difference in stiffness constraints, and on the other hand, due to the discontinuous structure caused by the screw connection openings. This also makes the vibration transmission path more complex.

4) The vibration transmission of the connection structure under high-frequency and low-frequency conditions is significantly different. The transmission path of low-frequency vibration is clear and uniformly distributed, while the high-frequency vibration transmission exists in power flow bi-directional transmission. Therefore, the high-frequency vibration transmission is more complex, and is the focus of attention when designing the connection structure.

It can be seen that the FEM for power flow and the related visualization technique can effectively analyze the vibration transmission characteristics of composite laminate connections and describe the vibration energy flow conveniently and intuitively, which can provide a reference for the connection design of composite structures and also lay the foundation for further in-depth analysis of vibration transmission of connection nodes with different materials, different geometric parameters and different boundary conditions.

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基于功率流的复合材料层合板连接节点振动传递特性

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摘　要：［目的］为了研究复合材料层合板连接节点的振动传递特性，提出一种采用有限元功率流法并结合功率流可视化技术的分析方法。［方法］首先，验证用有限元实体单元功率流描述板壳振动的有效性；然后，引入功率流传递率评价指标，提出有限元模型功率流传递率的计算方法，并以导纳功率流法计算结果为参照来验证其有效性；最后，建立嵌入式连接和螺钉连接这 2 种复合材料层合板的连接模型，计算其功率流传递率曲线和典型功率流矢量图。［结果］对比验证结果表明，2 种连接模型的振动传递路径和功率流传递率存在明显差异。［结论］有限元功率流法直观反映了连接结构的振动传递能力及振动能量传递路径，可为复合材料结构设计提供参考。

关键词：复合材料层合板；连接结构；功率流；振动传递；有限元法