Research on the optimization design method of the stiffness of the composite sandwich panel

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Abstract. Based on the optimization design of sonar fairing shell plate, aiming at the contradiction between sound transmission and stiffness design of composite shell plate, a scheme of carbon fiber-reinforced buoyancy core sandwich shell plate is proposed. The sound transmission performance and stiffness characteristics of shell plate are studied respectively. Through theoretical analysis and finite element simulation, the stiffness change law of sandwich plate meeting the sound transmission performance is discussed, and the sound transmission clamp is obtained. The stiffness optimization design method of laminates is presented, and the accuracy of the method is verified by an example.

1. Introduction

Sonar dome is an important platform to ensure the normal operation of sonar platform and give full play to the potential of sonar observation. On the one hand, the sonar fairing should ensure the normal detection of sonar as much as possible, that is, the fairing must have good sound transmission performance; on the other hand, the fairing should also bear the impact of hydrodynamic load and its fluctuating pressure, platform equipment vibration and hull vibration transmission during the service process. Among them, the contradiction between the stiffness characteristics and acoustic characteristics of the dome has long restricted the development of the structural design technology of the dome. Although the composite materials have the advantages of high specific strength and modulus, good sound transmission performance and strong aging resistance to the marine environment, and since the 1950s, the composite FRP shroud has been used, but the contradiction between the stiffness characteristics and acoustic characteristics of the shroud structure is still not well solved.

For the structure of the shroud, the effective way to improve the rigidity of the shell plate is to adopt composite sandwich structure, and the composite material has good sound transmission performance in the range of medium and low frequency. Therefore, the key to improve the sound transmission performance of the composite sandwich shell plate is to select the core material with good sound transmission performance. On the premise of the existing high permeability core material, in order to achieve the best rigidity of the shell plate on the premise of ensuring the sound transmission performance of the shroud structure, it has become another factor that puzzles the designers of the shroud. At present, for the optimization of the stiffness of composite sandwich plates, the research in this field is relatively mature at home and abroad [1]–[6]. However, for the research on the acoustic performance of composite sandwich panels, at present, the problems of sound absorption and sound insulation of shell panels are mostly involved, and the optimization of sound transmission performance is seldom considered. Among
them, kurtze et al. [7] first started the research on the transmission loss of sandwich panels, and considered three forms of dynamic state to determine the acoustic behavior of ideal sandwich panels. In reference [8]-[9], the influence of the natural frequency of sandwich panel on the sound transmission characteristics is studied, and the core stiffness is optimized. Dym and Lang [10]-[11] determined the influence of orthotropic sandwich stiffness, panel thickness and material characteristics on the transmission loss through parameter study. Taking the average transmission loss of frequency as the objective function and the panel density as the constraint condition, the transmission loss characteristics were optimized by the constraint optimization method. Narayanan and shanbhag [12] have studied the transmission loss of infinite sandwich plates, which shows that the transmission loss is more sensitive to the change of shear parameters of the core layer. However, there is little research on the coupling effect of sound transmission and stiffness design on sandwich panels. Although the above literature has studied the stiffness and sound transmission performance of composite sandwich structure, there is still no optimal solution for the structural stiffness under the condition of ensuring the sound transmission performance of composite shell plate.

In this paper, based on the research and development of sonar fairing, the stiffness optimization design method of the composite sandwich panel is studied. The carbon fiber reinforced composite material is selected as the surface layer of the sandwich panel, and the high permeable buoyancy core material is selected as the intermediate core material. This material not only has the advantages of low density and good sound permeability, but also has high modulus and shear strength, which can be applied to the guide well Flow hood sandwich shell plate. As the basic material system of the shroud shell, the above two materials are used to study the optimization design method of the structural rigidity and sound transmission performance of the shell.

2. Study on sound transmission performance of sandwich pane

2.1. Material acoustic tube test and result analysis

In order to master the sound transmission performance of sandwich panel material, T700 and buoyancy core material sound tube test pieces are made in this paper. The test work is entrusted to the national defense science and technology industry underwater sound level I measuring station. The test standard is GB/T14369-2011 measurement method for insertion loss, echo reduction and absorption coefficient of acoustic and underwater sound material samples. Then, based on the insertion loss value of each material obtained from the acoustic tube test, according to the calculation formula of sound insulation loss (1), the value of the sound transmission coefficient $t_l$ [13] is inversely deduced, and the specific results are shown in the table below.

$$TL = 10 \log n_l = 10 \log \frac{1}{t_l} (dB)$$

Table 1. Transmission coefficient of carbon fiber materials with different thickness in different frequency bands

| $f/KHz$ | 12mm | 12.5mm | 13mm | 13.5mm | 14mm | 14.5mm | 15mm | 15.5mm | 16mm |
|-------|------|-------|------|-------|------|-------|------|-------|------|
| 1     | 0.998 | 0.998 | 0.998 | 0.998 | 0.998 | 0.998 | 0.998 | 0.998 | 0.998 |
| 2     | 0.993 | 0.993 | 0.993 | 0.993 | 0.993 | 0.993 | 0.993 | 0.993 | 0.991 |
| 3     | 0.989 | 0.989 | 0.986 | 0.984 | 0.984 | 0.984 | 0.984 | 0.984 | 0.982 |
| 4     | 0.982 | 0.979 | 0.979 | 0.977 | 0.975 | 0.975 | 0.975 | 0.973 | 0.971 |
| 5     | 0.973 | 0.971 | 0.968 | 0.966 | 0.964 | 0.962 | 0.959 | 0.957 | 0.955 |
| 6     | 0.962 | 0.959 | 0.957 | 0.953 | 0.951 | 0.946 | 0.944 | 0.940 | 0.938 |
| 7     | 0.951 | 0.946 | 0.942 | 0.940 | 0.935 | 0.931 | 0.927 | 0.923 | 0.918 |
| 8     | 0.938 | 0.933 | 0.927 | 0.923 | 0.918 | 0.914 | 0.908 | 0.904 | 0.897 |

It can be seen from table 1 that when the thickness of carbon fiber material is fixed, the change of its sound transmission coefficient with the frequency is basically linear. According to the average value of
the carbon fiber transmission coefficient, the relationship between the sound transmission coefficient and the thickness of carbon fiber can be fitted to be \( y = -0.0038x + 1.022 \). Similarly, according to the test data of buoyancy core material sound tube, the relationship between the sound transmission coefficient and the thickness of buoyancy material can be analogically deduced to be \( y = -0.00065x + 0.999 \). Because the data of 18mm thick material fluctuated greatly, the data of 20mm thick material was brought into the formula validation, and it was found that the analogy formula met the requirements.

### Table 2. Test data of buoyant material acoustic tube

| t/mm | 1 KHz | 2 KHz | 3 KHz | 4 KHz | 5 KHz | 6 KHz | average value |
|------|-------|-------|-------|-------|-------|-------|---------------|
| 18   | 0.99  | 0.99  | 0.96  | 0.92  | 0.85  | 0.77  | 0.913         |
| 20   | 0.99  | 0.99  | 0.99  | 0.99  | 0.98  | 0.98  | 0.987         |

It can be seen from the data in table 1-2 that although the sound transmission performance of carbon fiber material is slightly worse than that of buoyant material, its modulus is large, and its contribution to the bending rigidity of shell plate is obvious as the surface material; the sound transmission performance of buoyant material is good, and its modulus is high, and its density is small, so it is an excellent material as the core material. The test data of the material acoustic tube confirmed the feasibility of the sandwich panel scheme in this paper. At the same time, it can be seen that the thickness of the surface layer of the sandwich panel is an important variable affecting the stiffness and sound transmission performance.

2.2. Sound transmission model of sandwich panel

The objective function is defined as the sound transmission coefficient \( S \), and the variable is the surface thickness \( x \) and the core material thickness \( y \). According to section 1.1, the sound transmission coefficient per unit thickness of each material is shown in Table 3.

### Table 3. Sound transmission coefficient per unit thickness of each material

| Material                 | Carbon fibre | Buoyancy material |
|--------------------------|--------------|-------------------|
| Sound transmission coefficient /mm\(^{-1}\) | \(3.8 \times 10^{-3}\) | \(6.5 \times 10^{-4}\) |

If the data is brought into the expression, the expression of sound transmission performance of sandwich panel is

\[
S = 1 - (x \times 2 \times 3.8 \times 10^{-3} + y \times 6.5 \times 10^{-4})
\]  

(2)

3. Study on the bending stiffness of sandwich shell plate

3.1. Bending stiffness coefficient of sandwich panel

In this paper, the surface layer of sandwich panel is T700 unidirectional cloth with orthogonal layer, the core material is self-developed buoyancy material, the carbon fiber material with larger modulus is placed on the surface layer, the buoyancy material with excellent sound transmission performance and low density characteristics is used as the core material, and the strength, rigidity and sound transmission performance indexes are taken into account. It can be considered that sandwich panel is composed of surface orthotropic laminated panel and isotropic core material. The bending stiffness coefficient is deduced theoretically.

The surface layer of sandwich structure can be considered as laminated plate. According to the classical laminated plate theory [14], D11 in the stiffness matrix can be mainly used to measure the bending stiffness of laminated plate. Therefore, for any thickness of surface material, the stiffness expression is
\[
D_{11} = \frac{1}{3} \times (\overline{Q}_j)_k (z_k^3 - z_{k-1}^3)
\]  

(3)

Where \( (\overline{Q}_j)_k \) is the transformation stiffness coefficient of the k-th layer of single-layer plate, and \( z_k \) is the coordinate of the k-th layer of single-layer plate.

The core material of sandwich panel is homogeneous material, and the bending rigidity can be calculated directly by using the theory of mechanics of materials. At the same time, because the surface carbon fiber material is an orthogonal layer, it can be considered that the bending rigidity of material in one direction is equal to that in two directions, so the calculation formula of bending rigidity of sandwich panel can be obtained

\[
D = 2E_1I_1 + E_2I_2
\]  

(4)

Where \( E_k \) represents the modulus of elasticity of each material, \( I_k \) represents the bending moment of inertia of the surface or core material to the neutral axis of the sandwich plate.

3.2. Bending stiffness model of sandwich panel

The objective function is defined as bending stiffness \( D \), and the variables are surface thickness \( x \) and core material thickness \( y \). The stiffness model can be obtained by introducing the variables into the stiffness expression (5)

\[
D = 2E_1I_1 + E_2I_2 = E_1 \times \left( \frac{1 \times x^3}{12} + \frac{1 \times 1 \times x \times (x + y)^2}{4} \right) + E_2 \times \frac{1 \times y^3}{12}
\]  

(5)

Where \( E_k \) represents the modulus of elasticity of each material, \( I_k \) represents the bending moment of inertia of the surface or core material to the neutral axis of the sandwich plate.

3.3. Study on the stiffness variation of laminated plates based on ABAQUS simulation

On the basis of theoretical analysis, this paper uses ABAQUS software to simulate the influence of the surface and core material thickness on the stiffness. According to the background requirements of the project, a 3 m × 2 m rectangular plate grid is selected. The surface of the plate grid is carbon fiber, the core material is buoyant core material, the boundary condition of the model is fixed support, and the load condition is 10KPA uniform load. The thickness of core material shall be 8mm, 10mm, 12mm, 14mm, 16mm, 18mm and 20mm respectively, and the thickness of surface layer shall be 2, 4, 6, 8, 10, 12, 14, 16 and 18 (0.31mm for each layer), and the curve of rigidity with the thickness of surface layer under different core material thickness shall be drawn, as shown in Figure 1.

![Figure 1. Surface thickness stiffness curve of different core material thickness](image)
It can be seen from Figure 1 that when the thickness of the surface layer is fixed, with the increase of the thickness of the core material, although the rigidity of the sandwich plate model increases gradually, the influence degree of the core material thickness on the bending rigidity decreases significantly when it is 16mm; when the thickness of the core material is fixed, the rigidity of the sandwich shell plate increases gradually with the increase of the thickness of the surface layer, but the influence degree also decreases, which is mainly reflected in the thickness of each curve on the surface layer. When the thickness reaches a certain degree, there are inflection points in the surface thickness displacement curve of different core material thickness. After the inflexion point, the increase of surface thickness has a significant impact on the rigidity of the shell plate. For the plate grid taken in this paper, the rigidity optimization effect decreases significantly after the surface thickness of 2mm.

4. Research on the optimization method of the stiffness of the composite sandwich panel

4.1. Study on the stiffness variation law of acoustic performance constraints
On the basis of Section 2.3, calculate the sound transmission coefficient of sandwich plates with different core material thickness when the thickness of the surface layer changes, and draw the curve, and calculate the stiffness of sandwich plates through formula (4), to obtain the thickness stiffness curve of the surface layer of sandwich plates under the sound transmission performance constraint, as shown in Figure 2.

![Figure 2. Thickness stiffness curve of sandwich panel with acoustic performance constraint](image)

It can be seen from figure 1-2 that the bending stiffness curve of sandwich shell plate has the same change trend, which verifies the accuracy of formula (4), and the optimal interval of sandwich plate can be determined according to the sound transmission performance curve. For example, when the sound transmission coefficient is required to be no less than 0.97, under the engineering background of this paper, the sandwich shell plate with the surface layer thickness of 2.48mm can be selected as the preliminary scheme, and then the core material thickness can be determined according to the stiffness requirements degree. At the same time, the accuracy of the inflexion point of the surface thickness stiffness curve is illustrated through the comparison of figure 1-2, which can provide experience reference for the subsequent optimization design.

4.2. Stiffness design method of sandwich panel with acoustic performance constraints
According to the sound transmission performance and stiffness model established above, the stiffness optimization design scheme of sound transmission sandwich panel can be established. Assuming that the thickness of the sandwich panel is x and the thickness of the core material is y, as for the sound transmission coefficient, assuming that the test piece only reflects and refracts, without considering the sound dissipation, the paper combines the sound transmission coefficient of each material unit thickness
in Section 1.1, the sound transmission performance model of the sandwich panel in section 1.2 and the bending stiffness model in Section 2.2 to solve the problem, then this paper is a bivariate single objective optimization problem.

Constraint conditions: sound permeability $S(x, y)$, thickness $h(x, y)$;
Objective function: bending stiffness $D(x, y)$;

The results show that the bending stiffness is $D_{\text{max}}(x_i, y_i)$, the thickness of the surface layer is $x_i$, and the thickness of the core material is $y_i$.

The design flow of the sandwich panel is shown in Figure 3.

![Figure 3. Design process of sound permeable composite sandwich panel](image)

4.3. Example verification

According to the optimization model proposed in Section 3.2, taking the constraint condition $S > 0.97$, $h < 21mm$, using MATLAB programming to realize this optimization algorithm, we can get $x = 2$, $y = 17$, compared with figure 2, we can see that the optimization results are located at the inflection point of the stiffness curve, and the accuracy of the design method in this paper is verified by the calculation examples and theoretical calculations.

5. Conclusion

The main conclusions are as follows.

(1) It can be seen from the stiffness formula of sandwich panel that the bending stiffness of sandwich panel is mainly affected by the properties and thickness of the surface material. Selecting high modulus material and placing it on the surface can greatly improve the stiffness, but it will be restricted by the sound transmission performance. Therefore, this paper puts forward the optimization idea of the stiffness optimization of the sound permeable sandwich panel: according to the material system, first optimize the sound permeable performance, determine the thickness range of the surface layer and the core material, then optimize the stiffness, make the thickness of each layer close to the inflection point of the stiffness curve as much as possible, so that the optimization efficiency reaches the highest.

(2) The method proposed in this paper can be used to optimize the stiffness of composite sandwich panel for the acoustic performance constraints, and give full play to the advantages of composite material designability.
(3) In this paper, the relationship between the thickness of the material and the sound transmission coefficient is calculated by the interpolation of the test results of the acoustic tube. The accuracy needs to be further discussed. In this paper, only the research of optimization design method is completed, and it needs to be dimensionless in the follow-up research. On the basis of this method, the optimization efficiency is improved. At the same time, in this paper, the composite layer only considers orthogonal layer, and the other angle layer also needs further optimization research.

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