Research on sound absorption characteristics of Alberich anechoic coatings in debonding states

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Abstract. Viscoelastic structures with periodic cavity arrangement occupy an important position in acoustic stealth. Most studies focus on the absorption at low frequency, under large pressure and in a wide frequency band, however, the sound absorption properties of the anechoic coating in debonding states are seldom studied. The acoustic response of the composite structure is calculated by the FEM, and the incident wave and the reflected wave are separated based on the plane wave propagation principle. The sound absorption coefficient of the model can be solved with the pressure data of transmission wave, incident wave and reflected wave. Based on the finite element method, the absorption characteristics of anechoic coating in debonding states have been studied. Firstly, the FEM model is verified by comparing the solution of uniform non-cavity coatings with the corresponding analytical solution. The results indicate that the problem of acoustic pressure field can be simulated well by the symmetry condition and the absorbing boundary. Then, the Alberich anechoic coating models in different debonding ratio states and in different cavity water filling states are established by FEM, and then the corresponding absorption characteristics are calculated and analyzed. The results show that the effects of debonding on absorption characteristics are small when the cavities of coatings are filled with water, however the effects are much more when the cavities of coatings are filled with air. For the case of cavities filled with air, the main frequency band of sound absorption moves to low frequency with the debonding ratio increasing. When the frequency is very high, there are few impacts on the sound absorption coefficient no matter whether the packing medium is water or air, no matter whether the coating is debonding or not.

1 Introduction

The application of anechoic coatings on the surface of the underwater craft is a way to effectively improve the acoustical stealth performance, which has attracted the interest of many scholars. In the beginning, the anechoic coating is generally composed of rubber material with a uniform layer[1]. Later, people developed a new anechoic coating with a cavity gradually in order to improve sound absorbing performance in the low frequency band. The shape of the cavity is various, including spherical cavity, horn cavity, cylindrical cavity, combined cavity, etc. There are different acoustic characteristics for each type of different cavities. Generally speaking, there are two main methods for the research of anechoic coatings, one is based on the analytical method of wave propagation in viscoelastic materials[2,3]. This method is very effective for mechanism research, but mainly applied to two-dimensional models or three-dimensional simple structures; another one is numerical calculation method of finite element[4-8], which is convenient for the complex structures because there is no limitation on the shape or structure of the cavity.

The sound absorption mechanism of anechoic coatings has been extensively studied by many scholars,

but it is noteworthy that when the coating is mounting on the surface of the hull, it may shed off partially or all because of poor adhesion or even the failure of the adhesive. There are few studies on the change of acoustic performance when the coatings are in debonding states. In this paper, the Alberich type anechoic coatings are studied on the effect of shedding problem by the model of steel plate composite structure placed in water.

2 Theoretical background

2.1 Sound field fluid-structure interaction

The fluid finite element equation is:

$$[M^p]\{\ddot{p}\} + [K^p]\{p\} + \rho_0[R]\{\ddot{\delta}\} = \{\Phi\} \quad (1)$$

Where $[M^p]$ is the overall mass matrix integrated by the unit mass matrix, $[K^p]$ is the integrated overall stiffness matrix, $[R]$ is the overall coupling matrix, ρ_0 is the density of the fluid, $\{p\}$ is the nodal sound pressure vector in the fluid region, $\{\ddot{\delta}\}$ is the second-order derivative of the node displacement vector in the structure region, and $\{\Phi\}$ is the node load matrix.

The structural finite element equation is:

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$$[M^s]\{\delta\} + [K^s]\{\delta\} - [R]^T\{p\} = \{F^m\} \quad (2)$$

Where $[M^s]$ is the overall mass matrix of the structure, $[K^s]$ is the overall stiffness matrix of the structure, $\{\delta\}$ is the displacement vector matrix of the structural region, and $\{F^m\}$ is the equivalent node load matrix of the mechanical excitation of the structure.

Then the fluid-solid coupling equation can be written as:

$$\begin{bmatrix} [K^p] - [C_\phi] - \omega^2[M^p] & -\rho_0\omega^2[R]^T \\ -[R]^T & [K^s] - \omega^2[M^s] \end{bmatrix} \begin{Bmatrix} \{p\} \\ \{\delta\} \end{Bmatrix} = \begin{Bmatrix} \{F^m\} \\ \{C_0\} \end{Bmatrix} \quad (3)$$

2.2 Incident wave and reflected wave separation

When the plane wave is perpendicularly incident on the surface of the composite structure, there are both incident wave and reflected wave exist simultaneously, and another part of the wave is absorbed by the sound absorbing material as well. In fact, the sound pressure in the sound field is the superposition of the incident wave and the reflected wave. Therefore, the reflection coefficient can be obtained by a transfer function to separate the incident wave and the reflected wave. And then the sound absorption coefficient can be obtained for further calculation through the sound pressure value at the transmit end. Assuming that the coordinate of measuring point 1 is x_1 , and the sound pressure value is P_1 , the distance between measuring point 2 and measuring point 1 is S , and the sound pressure value of measuring point 2 is P_2 . then

$$\begin{pmatrix} P_1 \\ P_2 \end{pmatrix} = \begin{pmatrix} e^{jk_0x_1} & e^{-jk_0x_1} \\ e^{jk_0(x_1-s)} & e^{-jk_0(x_1-s)} \end{pmatrix} \begin{pmatrix} P_I \\ P_R \end{pmatrix} \quad (4)$$

If $B = \begin{pmatrix} P_1 \\ P_2 \end{pmatrix}$, $H = \begin{pmatrix} e^{jk_0x_1} & e^{-jk_0x_1} \\ e^{jk_0(x_1-s)} & e^{-jk_0(x_1-s)} \end{pmatrix}$, $P = \begin{pmatrix} P_I \\ P_R \end{pmatrix}$, then

$$P = H^{-1}B \quad (5)$$

Then the reflection coefficient can be obtained

$$R = \frac{P_R}{P_I} \quad (6)$$

If the sound pressure at the transmit end is P_t , then the transmission coefficient can be obtained.

$$T = \frac{P_t}{P_I} \quad (7)$$

The sound absorption coefficient can be expressed as:

$$\alpha = 1 - |R|^2 - |T|^2 \quad (8)$$

3 Numerical calculations

Since the cavity of the anechoic coating is periodically arranged, it is possible to approximate the overall characteristics by studying a periodic unit, which is widely used in current research. For the periodic unit, the infinitely large structure can be approximated by the the symmetrical boundary condition. As for the interface of the fluid interception domain, the influence of the cross-section reflected wave can be eliminated as much as

possible through the acoustic absorption layer. Finally, the physical quantity needed can be obtained by certain processing once the node pressure data affirmed.

3.1 Calculations validity verification

In this section, considering the case in which the uniform layer is laid on the backing of the steel plate and the composite structure is immersed in the infinite water area, then the frequency response curve of the reflection coefficient and the transmission coefficient under the normal incidence of the plane wave is calculated. The numerical simulation results are compared with the analytical results to verify the correctness of the finite element method. The incident angle $\theta=0^\circ$ and material parameters are selected as shown in Table 1, the units are standard unit system. A sketch is shown in Fig. 1.

Table 1 The parameters of composite model

Material Parameters	Steel	Rubber	Water	Air
Thickness (m)	0.01	0.05		
Density (kg/cm ³)	7840	1100	1000	1.205
Young Modulus (N/m ²)	2.16×E11	1.4E8×(1+0.23j)		
Poisson Ratio	0.28	0.49		
Velocity (m/s)			1500	343

Fig. 1. Diagram of computed structure
 The numerical simulation results compared with the analytical results are shown in Fig. 2.

Fig. 2. Comparison of sound absorption coefficient

From the frequency response curve in the Fig. 2 can be seen that the theoretical solution and the finite element solution are in good agreement. On one hand, the illustrated results prove the correctness of the analytical program. On the other hand, it is feasible to deal with the multi-layer composite structure even the more complex structure by the finite element method.

3.2 The calculation results for different water length

Since the sound absorption characteristics of the composite structure is placed in infinite water, it is necessary to consider the influence of water length assuming that the water length of the incident end and the transmission end are the same. The results of different truncation domain lengths are in Fig. 3.

Fig. 3. Sound absorption coefficient for different water length

It can be seen from Fig. 3 that the water domain length has few impacts on the result, and the accuracy is sufficient when the truncation domain is 6cm, so the water length of 6cm in the following calculations can be a better use in saving computing resource.

3.3 Models in debonding states

The Alberich type sound absorbing anechoic coating is a widely used structure in the research which mainly embeds a periodically distributed cylindrical air cavity in a highly damping viscoelastic material. When the sound waves incident on the material, the cavity wall resonates to achieve the purpose of noise reduction. In this section, the Alberich type anechoic coating is used as the research object to establish debonding models of different

percentage, and the influence for different shedding models on the structure sound absorption coefficient is calculated. A periodic unit contains the filler of water or air. The distribution of the cavity is arranged vertically, and the schematic is in Fig. 4.

Fig. 4. The unit cell of the structure

The number in the figure represents the shedding ratio, and the area is filled with corresponding shedding medium. For example, the number is 25%, which means the area is replaced with air or water, and the rest of the model is rubber. The results are in Fig. 5(a) and Fig. 5(b).

(a) The packing medium of water

(b) The packing medium of air

Fig. 5. Absorption coefficient of the calculation model

It can be seen from the Fig. 5(a) that the sound absorption characteristics of the anechoic coating changes in debonding states. As for water, the first large sound

absorption peak moves toward the low frequency, and the shedding ratio increases, the bandwidth of the movement becomes more and more obvious. But there is almost no effect on the sound absorption performance after falling off in extremely low frequency. The regularity is similar to that of the water while the filler is air to some extent. The same is that after falling off the sound absorption peak near 4 kHz moves toward to the lower frequency both for air and water. However, compared to water, the movement is more noticeable at a small shedding ratio and the sound absorption coefficient increased in extremely low band when completely detached. This is mainly because when the shedding model is established, it is considered that a certain area is detached, and all the water or air is introduced into the area, which is similar to adding a cavity to the coating, therefore sound absorption peak moves to the low frequency.

From Fig. 5(b), it can be seen that when the cover layer falls off and mixes with air, and the change of the sound absorption coefficient is similar to that of the water. The sound absorption peak moves to the low frequency band, which broadens the sound absorption band to a certain extent. In fact, the introduction of the cavity improves the sound absorption performance at low frequency band. After the shedding, for air, it is equivalent to the introduction of a small cavity. The higher ratio, the better sound absorption.

By observing the cavity deformation of sound absorption coefficient in peak, it is found that the deformation of the cover layer at the corresponding frequency of the sound absorption peak is large. Fig. 6(b), Fig. 6(c), Fig. 6(d) in the cloud map are respective corresponding to the deformation at the sound absorption peak in specific frequency, and the deformation of cloud map Fig. 6(a) corresponds to the small sound absorption coefficient. At the same deformation ratio, not only the deformation magnitude is large, but also the position is concentrated at the two ends of the cover as the sound absorption coefficient in peak. The cloud map are as follows.

Fig. 6. The vibration displacement of anechoic coating which is of different shedding ratio for air

However, in particularly low frequency band, the sound absorption performance of the covering layer is almost completely lost for air. In this paper, the impedance value of water is $1.5 \times E6$, for rubber it's about $1.62 \times E6$, and the air is $4.13 \times E2$, which means that the difference between rubber and air impedance is huge, and the air layer acts as sound insulation, which means that the existence of air layer almost isolates the transmission of energy to the transmission end and the elastic strain energy of the covering layer is small, so the energy is almost completely reflected, thus the sound absorption coefficient is very small. In general, the change of sound absorption coefficient should be a gradual change for different shedding ratio, and the sudden change of curve has attracted our attention.

In order to solve this problem, the theoretical solution was first carried out. The scheme of the model and the theoretical value in completely debonding states as follow in Fig.7 and in Fig. 8.

Fig. 7. Scheme of uniform layer in completely debonding states

Fig. 8. Theoretical value of uniform layer in completely debonding states

Because the anechoic coatings completely fell off and the filling medium was air, the theoretical solution of the uniform layer was carried out. The results are shown in Fig. 8 and it is found that, for the homogeneous layer, the same problem appears at low frequency, which indicates that the numerical solution is correct.

Through the above research, the sound absorption coefficient of the covering layer is related to the deformation of the covering layer structure. The power of deformation is provided by the incident sound wave. Therefore, the elastic strain energy and the kinetic energy of the covering layer can illustrate the change of sound absorption coefficient in Fig. 9 and Fig. 10.

Fig. 9. Curve of elastic strain energy

Fig. 10. Curve of kinetic energy

In particularly low frequency band, the kinetic energy of the models in different shedding ratios did not differ significantly, but the elastic strain energy varied greatly, especially in completely debonding states, the strain energy was very small and far smaller than the other models. Therefore, the sound absorption performance of

partial shedding models is stronger than that of complete shedding model in low frequency band.

It is worth noting that at 3800 Hz and 7600 Hz, all curves have a small twist. Since all curves show tortuosity at the two frequencies, it may be independent of shedding and it's an inherent property of the structure. In order to verify this idea, the case of cavity reduction and shape change were calculated from 50Hz to 20000Hz. It was found that when the cavity size changed, the twists were still existed, but the cavity reduced, the frequency moved to high frequency band. However, when the cavity turned to a spherical shape, the twists disappeared.

4 Conclusions

- (1) Through the symmetry condition and the absorbing layer, the acoustic problem of infinite large objects in the infinite domain can be well simulated by the finite element method, and the accuracy is sufficient.
- (2) The interception length of the infinite water domain has few effects on the calculation results. The shorter water length can save calculation time and computing resources without accuracy damage.
- (3) In debonding states, the sound absorption peak moves to the low frequency, and air is more obvious than water.
- (4) For air, there is a terrible effect of sound absorption coefficient in the low frequency band when completely detached.

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