Study on Vibration and Acoustic Radiation Characteristics of Composite Material Superstructures of Underwater Vehicles

Cong Gao¹, Xichun Huang²*, Guobing Huang² and Huiling Dai¹

¹College of Shipbuilding Engineering, Harbin Engineering University, Harbin, 150001, PR China
²China Ship Development and Design Center, Wuhan, 430064, China
E-mail: conggao@hrbeu.edu.cn

Abstract. Composite materials have been widely used in underwater ships for advantages of high specific strength, excellent acoustic performance and well designability. As an important indicator to measure combat effectiveness and vitality of underwater ships, structural radiation noise is the main target of acoustic detection weapons and the main factor that interferes with sonars. Underwater vibration and acoustic radiation characteristics of superstructure using composite sandwich panels directly affects the acoustic performance of underwater vehicles and the comfort and safety of personnel, therefore, research on vibration and acoustic radiation characteristics of underwater vehicle superstructure with composite material has important theoretical value and engineering prospect.

1. Introduction
Superstructure structure is an important part of a underwater vehicle. When composite material is applied to superstructure of the underwater vehicle, vibration and acoustic radiation performance of the structure are changed relative to traditional steel material. At present, composite material superstructure use sandwich panel structures, which are mainly composed of two thin layers of fiber skin and a relatively low density core material in middle. Composite sandwich panels that have been widely used have simple structures and mature preparation process[1]. At the same time, their mechanical properties are relatively simple, various dynamic and static mechanical properties have been extensively studied, such as extrusion shear, bending deformation and fatigue damage[2]. In addition, influences of factors such as thickness of the skin layer, layup order and core material on the mechanical properties of sandwich structure are extensive[3]. Therefore, this paper takes a composite material superstructure of underwater vehicle as a research object, and carries out the analysis of underwater vibration and acoustic characteristics of the structure, aiming at providing reference for low noise design of underwater vehicle structures.
2. Theoretical basis
In this paper, a composite material superstructure is taken as a research object which size is 1.5 m × 2.0 m, and thickness of the composite sandwich panel is 50 mm. Numerical calculation model of composite superstructure is showed in Figure 1. The ratio of length of short side to the thickness of the panel is greater than 10 so the first constraint condition of the first-order shear deformation theory is satisfied; and because surface layer of the composite sandwich panel is made of FRP material, and core layer is made of foam material, elastic modulus of the two materials along thickness direction is not more than two orders of magnitude, satisfying the second constraint of the first-order shear deformation theory. Therefore, the composite material superstructure can be calculated by the first-order shear deformation theory. Compared with the boundary element method, calculation scale of acoustic-solid coupling finite element analysis method is relatively slow with the increase of the number of meshes, and its prediction accuracy is relatively high. Therefore, this paper uses the acoustic-solid coupling finite element analysis method to calculate and analyze underwater vibration and acoustic radiation characteristics of the composite superstructure.

3. Research of Vibration characteristics
3.1 Calculation function
The mean square vibration velocity is defined as:

\[ v^2 = \frac{1}{S} \iint_S |V|^2 \, ds \]  

According to the definition of vibration speed level or vibration acceleration level, vibration speed level and the vibration acceleration level can be expressed as follows:

\[ L_v = 10 \times \log \left( \frac{v}{v_0} \right) \]  
\[ L_a = 20 \times \log \left( \frac{a}{a_0} \right) \]

Where the acceleration reference value \( a_0 = 1 \times 10^{-6} \) m/s², and the speed reference value \( v_0 = 1 \times 10^{-9} \) m/s;

Vibration acceleration level or mean square vibration speed level of each frequency point is solved by energy superposition, and the total level of vibration acceleration or mean square vibration speed can be obtained:

\[ L_T = 10 \log \left( \sum_{i=1}^{n} 10^{\frac{L_i}{10}} \right) \]  

3.2 Analysis of vibration characteristics in air
Under action of vertical unit force at center of the superstructure, vibration acceleration level at the loading position in air and vibration acceleration level of shell surface of the superstructure are shown in figure 2 and figure 3.

**Figure 2.** Comparison curve of Vibration acceleration level in air

Vibration acceleration of loading position of the superstructure of three materials is basically consistent with frequency. In 10Hz-400Hz frequency band, vibration acceleration response peak of the composite superstructure is significantly less than the other two materials. When the superstructure structure adopts different materials, influence of mean square vibration velocity on surface of the structure is greater. When the superstructure uses composite reinforced sandwich panels, mean square vibration velocity in 10Hz-100Hz frequency band is not much different from the other two material parameters, and after 100Hz, the vibration response is significantly lower than the other two materials.

3.3 Analysis of underwater vibration characteristics

Considering coupling between flow field and superstructure of composite material, vertical unit force is also applied at the center of the superstructure shell. Vibration acceleration at the loading position of the shell surface are shown in the figure 4.

**Figure 4.** Comparison curve of vibration acceleration level under water

Vibration acceleration at the loading position of the superstructure of three materials is basically consistent with frequency. Vibration acceleration response of the composite superstructure is significantly less than that of the other two materials, especially after 200 Hz. Acoustic material and
the superstructure of steel material have a large peak of vibration response and a concentrated distribution in frequency band of 80 Hz-120 Hz. When the superstructure uses a composite reinforced sandwich structure, response of vibration acceleration level is significantly smaller than the other two materials in 150Hz-400Hz frequency band.

4. Study on characteristics of acoustic radiation

4.1 Calculation function
Underwater radiated acoustic power and acoustic source level of the superstructure structure can reflect its acoustic characteristics as a noise source, and the two do not differ with change of measurement position. Sound intensity refers to work done by the sound wave per unit area in direction of advancement adjacent to the coal mass, and radiated acoustic power refers to average sound energy radiated outward by area $S$ perpendicular to direction of sound propagation per unit time. Therefore, the radiated acoustic power can be expressed as:

$$W = I \ast S = \frac{S}{T} \int_{0}^{T} \text{Re}(p) \text{Re}(v) \, dt$$  \hspace{1cm} (4)

The definition of acoustic power level is as follows:

$$L_w = 10 \times \log \left( \frac{w}{w_0} \right)$$  \hspace{1cm} (5)

Among them, acoustic power reference value $w_0 = 1 \times 10^{-12}$Pa.

4.2 Analysis of underwater acoustic radiation characteristics
Under action of vertical unit force at center of the shell plate, underwater acoustic radiation of the superstructure structure changes with change of material parameters. Far-field calculation results are transformed, and radiation of the superstructure of three materials can be obtained. Comparisons of acoustic radiated power level of the three materials are shown in figure 5.

![Figure 5](image)

Figure 5. Comparison curve of acoustic radiated power level

The change of material parameters has a great influence on underwater acoustic radiation of the superstructure structure. Radiation acoustic power of the superstructure of the three material parameters is basically consistent with frequency. In 10Hz-100Hz frequency band, acoustic material superstructure has a large acoustic radiation power level. When the composite building shell structure adopts composite materials, acoustic radiation power level is obviously smaller than the other two material parameters, and acoustic radiation power level of the superstructure is the largest when using steel material.
5. Conclusion

Underwater vibration and acoustic characteristics of underwater vehicle superstructure with composite material greatly improved related to traditional material.

Reference
[1] Inayathullah J, Nagarajan V A, Kumar S H 2016 Development of hybrid composite radar wave absorbing structure for stealth applications J. Bulletin of Materials Science, 39 pp 279-84.
[2] Lei H, Yao K, Wen W 2016 Experimental and numerical investigation on the crushing behavior of sandwich composite under edgewise compression loading J. Composites Part B: Engineering, 94 pp 34-44.
[3] Ahmed A, Bingjie Z, Ikbal M H 2015 Experimental Study on the Effects of Stacking Sequence on Low Velocity Impact and Quasi-Static Response of Foam Sandwich Composite Structures J. Advances in Structural Engineering, 18 pp 1789-806.

Acknowledgments
This study was funded by Major innovation projects of High Technology Ship Funds of Ministry of Industry and Information of P. R. China, Ph.D. Student Research and Innovation Fund of the Fundamental Research Funds for the Central Universities (HEUGIP201801), National key Research and Development program (2016YFC0303406), High Technology Ship Funds of Ministry of Industry and Information of P.R. China, Assembly Advanced Research Fund Of China (6140210020105), Fundamental Research Funds for the Central University (HEUCFD1515, HEUCFM170113), China Postdoctoral Science Foundation (2014M552661), National Natural Science Foundation of China (51209052).