Study on the underwater acoustic performance of CFRP laminate modified by PZT particle

Hongming Zhang¹, Xin Li²,* and Mingqian Yang¹

¹Department of Civil Engineering, Harbin Institute of Technology, Weihai, China
²Library, Harbin Institute of Technology, Weihai, China

*Corresponding author e-mail: zhmbelief@163.com

Abstract. A carbon fiber-reinforced plastic (CFRP) laminate modified by lead-zirconate-titanate (PZT) particles was fabricated in this study. The simulation on underwater acoustic radiation of the modified laminate was carried out by fluid-solid coupled finite element method and acoustic direct boundary element method. Furthermore, the underwater acoustic radiation of the composite laminate modified by PZT particle was studied by the underwater experiment performed over a range of frequency (20~1500Hz) and angle (0~180 degree). The results show that the maximum underwater radiated sound power of CFRP laminate obviously reduced by the PZT particles interlayer doping method and the radiation peaks moved to high frequency, which was beneficial to attenuate underwater noise caused by CFRP composite structure.

1. Introduction

Carbon fiber-reinforced polymer (CFRP) composites have the characteristics such as high specific strength, high specific modulus, fatigue resistance and corrosion resistance, therefore CFRP has been widely used as engineering material in many industrial fields. Recently, the application of CFRP on the unmanned underwater vehicles [1], pressure hull [2] and propeller [3] in the underwater environment has been widely investigated by the researchers. Due to the requirements on light-weight and low-noise, CFRP composites have promising application in the marine structure.

However, Young et al. [4] investigated the hydroelastic vibration characteristic of CFRP composite marine blades, and the results show that the low-order natural frequency of the composite blade in wet mode was obviously lower than that of metal blade. Lin et al. [5] suggested that added mass caused by underwater inertia had a significant effect on the composite material structure in wet mode, which results in strengthen low frequency noise and weaken noise stealth performance of CFRP marine structures.

At present, many methods have been proposed to reduce the vibration noise by material techniques. The piezoelectric damping composite is a new type of damping material, which is based on the principle of piezoelectric passive shunt mechanism. The piezoelectric damping composites have obvious advantages over traditional viscoelastic damping materials such as high material stiffness, little dependence of temperature and adjustable damping according to vibration frequency. Zhang et al. studied the acoustic performance of one kind of piezoelectric composite and the results show that the acoustic absorption coefficient increased with an increase of lead-zirconate-titanate (PZT) content and the average acoustic absorption coefficient reached 0.32 [6]. Tanimoto et al. indicated that the damping of CFRP laminate could increase by interlayer modification with piezoelectric composites according to
the testing results [7]. However, so far, there are few published reports on the underwater acoustic performance of CFRP structures modified by piezoelectric composites.

In this work, the CFRP laminate modified by interlayer doping PZT particle was prepared. Based on the fluid-solid coupled finite element method and acoustic direct boundary element method, the simulation on underwater acoustic radiation of the modified laminate was carried out and the underwater acoustic radiation of the composite laminate owning piezoelectric damping was studied by the underwater experiments. On the whole, this work is beneficial to estimate the underwater acoustic performance of CFRP laminate modified by PZT particle.

2. Material and experimental procedure

In this work, the PZT-5H powder (provided by Yu Hai company) were grinded by high-speed ball mill. By the ball-milling, the average diameter of PZT powder was approximately 3 µm. The silane coupling agent (KH550) was used to treat the surface of PZT particle to increase the connectivity with polymer matrix. The treated PZT powders were mixed with acetone and epoxy resin, and the volume fracture of PZT powder was 30% in the mixture. After heating and stirring for 3 hours at 50 °C, triethylene tetramine as the curing agent for the mixture was added into the mixture. And then the mixture was evenly brushed onto the both sides of T700 carbon fiber composite prepreg (provided by Guang Wei company) by hand-lay method. The laying sequence of the modified CFRP laminate was [0°/90°/0°]s. The thickness of the laminate without modification was 1.2 mm and the thickness of the laminate modified by PZT particl was 1.35 mm. The microstructure of the CFRP laminate modified by PZT particle is shown in Fig. 1.

Free vibration method was used to obtain the damping loss factor of the modified CFRP laminate according to the ASTM E756 and the mechanical properties of the laminates was tested by the electronic universal testing machine (Instron 4505) according to the ASTM D628 and ASTM D5379. Underwater vibration acoustic radiation testing was conducted in the acoustic test pool with the depth of 4m. The specimens of CFRP laminate with diameters of 200mm×200mm were fixed on the rigid mount in which the vibration exciter was installed. In the experiment, the vibrator sank into water at the depth of 1.8m and the testing was performed over a range of exciting frequency (20~1500Hz) and angle (0~180 degree). The underwater vibration acoustic signal of the specimen was collected by hydrophone and treated as the value of sound pressure which reflects the degree of underwater noise radiation.
3. Numerical simulation method

Because the influence of additional mass caused by water on the structural dynamic’s behaviour, the fluid-solid coupled finite element method is used to solve the coupled equation with sound pressure equation and structural dynamics equation, which can be represented as follows:

\[
[K_{FSI}] \{ \delta \} + [C_{FSI}] \{ \dot{\delta} \} + [M_{FSI}] \{ \ddot{\delta} \} = \{ F \}
\] (1)

Where \([K_{FSI}]\) is stiffness matrix of fluid-solid coupling dynamics equation, \([C_{FSI}]\) is damping matrix of fluid-solid coupling dynamic equation, \([M_{FSI}]\) is mass matrix of fluid-solid coupling dynamic equation, \(\delta\) is generalized displacement and \(F\) is generalized force.

In the basis of the solution of fluid-solid coupling dynamic equation, the calculated displacement is converted into the velocity which is used as boundary condition in the solution of Helmholtz acoustic equation given by Eq. (2):

\[
\nabla^2 p(r, \omega) + k^2 p(r, \omega) = q(r)
\] (2)

Where \(r\) is source point distance, \(\omega\) is angular frequency, \(k\) is wave number, \(p\) is sound pressure and \(q\) is harmonic excitation.

The acoustic direct boundary element method is chosen to calculate the sound pressure, due to the high calculation speed and reliable outcomes.

In this study, the fluid-solid coupled finite element analysis of the CFRP laminates in underwater environment was conducted on the commercial finite element software ANSYS. The finite element model is shown as Fig. 2 and the boundary condition was quadrilateral fixed support. SOLID46 element was selected to mesh structural model and the number of composite solid element was 400. Meanwhile, FLUID30 element was selected to mesh the flow field model and the number of flow element was 35900. In addition, 482 structural contact element was defined on the surface of the solid model. The material properties of the unidirectional CFRP laminates are given in the Table 1 according to the testing results of material property and it can be found that the mechanical properties of CFRP laminates were not affected too much for the modification by interlayer doping PZT particle.

| Table 1. Mechanical properties of the mechanical properties of CFRP laminates |
|-----------------------------|----------------------------|-------------------|-----------------|-----------------|-----------------|-----------------|---------------- |
| E1  (GPa) | E2  (GPa) | E3  (GPa) | G12 (GPa) | G13 (GPa) | G23 (GPa) | Poisson ration | Damping loss factor |
| Unmodified CFRP laminate | 135.3 | 9.4 | 9.4 | 4.2 | 4.2 | 4.2 | 0.28 | 0.005 |
| Modified CFRP laminate | 138.5 | 10.1 | 10.1 | 4.6 | 4.6 | 4.6 | 0.28 | 0.018 |

Based on the model and calculated displacement results of the fluid-solid coupled finite element analysis, the acoustic direct boundary element analysis was carried out by the acoustic module of LMS Virtual.Lab software. The flow field was encircled by CFRP laminate and rigid boundary in the model and the boundary element grid was meshed on the surface of the closed boundary. The number of the boundary element was 1536.

4. Results and discussion

In the fluid-solid coupled finite element analysis, the central node of CFRP laminates vertically subjected to a harmonic concentrated force which was over a range of frequency (20~1500Hz). Fig. 3 shows the displacement harmonic responses simulation curves of the unmodified CFRP laminate and CFRP laminate modified by PZT particle in the vertical direction. It can be found that the frequencies
of displacement resonance peaks of the CFRP laminate modified by interlayer doping 30 vt.% PZT particle are obviously different to that of the unmodified CFRP laminate and the overall displacement resonance peaks have a higher frequency. And the maximum harmonic displacement of the CFRP laminate modified by PZT particle is lower than that of the unmodified CFRP laminate. In Fig. 4, similar tendency appears in the underwater acoustic radiation power simulating results at the point which lies directly over the laminate. It can be indicated that the vibration energy of CFRP laminate can partially convert into electric power by the interlayer doping PZT particle and the electric power further convert into Joule-heat due to the electrical conductivity and self-resistance of carbon fibre. Consequently, above power dissipation mechanism is beneficial to attenuate the radiation power of CFRP laminate modified by PZT particle. In addition, the Fig. 4 shows that the sound radiation resonance peaks of the CFRP laminate modified by PZT particle have higher frequency, which contributes to attenuate the underwater noise of CFRP composite structure, because high-frequency noise have higher attenuation velocity than low-frequency noise for underwater acoustic propagation.

Figure 3. Displacement harmonic response simulation curves of the CFRP laminates

Figure 4. Underwater acoustic radiation power simulation curves of the CFRP laminates

The underwater acoustic radiation experiment was conducted to confirm the noise reduction effect of the CFRP laminate modified by PZT particle. In the experiment, the vibration table can rotate axially, therefore the underwater acoustic pressure of the CFRP laminates can be measured at different directions in the horizontal plane by hydrophone. The sound pressure frequency response curves of the unmodified CFRP laminate and modified CFRP laminate by PZT particle over a range of exciting frequency (20~1500Hz) and angle (0~180 degree) are shown in Fig. 5(a) and (b) respectively. It can be found that the sound pressure in different directions are close to each other at the maximum sound pressure frequency. The maximum sound pressure peak occurs at relatively low frequency, where the modal shape of the CFRP laminate is simple, therefore the distribution of sound pressure is relatively uniform. On the contrary, due to the complex higher-order modal shape of the CFRP laminates in the water, the directivity of the sound pressure peaks at high frequency can be observed in the experiment.

Fig. 6 shows the sound pressure frequency response curves of the CFRP laminates at the angle of 90 degree in the horizontal plane. The maximum sound pressure value of the unmodified CFRP laminate and the CFRP laminate modified by PZT particle are 93.7 dB at and 86.6 dB, respectively. Although many interferential acoustic pressure peaks caused by testing sensitivity and pool background noise exist in the results, it is suggested that the numerical simulation can approximately predict the position and values of the sound pressure peaks by comparison with the experimental results as showed in Fig. 4. Sound pressure directivity diagram of the CFRP laminates at the maximum sound pressure frequency is shown in Fig. 7. The results show that the sound pressure value of the CFRP laminate modified by
PZT particle is lower than that of the unmodified CFRP laminate with the angle of 0~180 degree and the average sound pressure difference is about 6dB in the same direction.

![Graphs showing sound pressure response curves](image)

**Figure 5.** Sound pressure frequency response curve: (a) unmodified CFRP laminate; (b) modified CFRP laminate by PZT particle

![Graphs showing sound pressure curves and directivity diagram](image)

**Figure 6.** Sound pressure frequency response curves of the CFRP laminates at the angle of 90 degree in the horizontal plane  
**Figure 7.** Sound pressure directivity diagram of the CFRP laminates at the maximum sound pressure frequency

### 5. Conclusion

In this work, the underwater acoustic performance of the CFRP laminate modified by PZT particle was studied by numerical simulation and experiment. The results show that the method by interlayer doping PZT particle has little influence on the mechanical properties of CFRP laminates and this method is effective to reduce the underwater noise of the CFRP laminate. It can also be found that the sound radiation resonance peaks of the CFRP laminate modified by PZT particle have higher frequency than that of the unmodified CFRP laminate, which is beneficial to attenuate underwater noise propagation. Moreover, the established numerical simulation in this work is proved to be useful to predict the underwater acoustic pressure of the CFRP composite laminates by comparison with the experimental results.
Acknowledgments
This work was financially supported by the Natural Science Foundation in Shandong Province under Grant No. ZR2017PA003, and Plan of Co-Development of University in Weihai under Grant No. 2017DXGJCE03.

References
[1] B. Song, D. Lyu, J. Jiang, Optimization of composite ring stiffened cylindrical hulls for unmanned underwater vehicles using multi-island genetic algorithm, J. Reinf. Plast. Comp. 37 (2018) 668-684.
[2] B. Li, Y. Pang, Y.X. Cheng, X.M. Zhu, Collaborative optimization for ring-stiffened composite pressure hull of underwater vehicle based on lamination parameters, Int. J. Nav. Archit. Ocean. 9 (2017) 373-381.
[3] Y. Hong, P.A. Wilson, X.D. He, R.G. Wang, Numerical analysis and performance comparison of the same series of composite propellers, Ocean. Eng. 144 (2017) 211-223.
[4] Y.L. Young, Fluid–structure interaction analysis of flexible composite marine propellers, J. Fluid. Struct. 24 (2008) 799-818.
[5] H.J. Lin, J.F. Tsai. Analysis of underwater free vibrations of a composite propeller blade, J. Reinf. Plast. Comp. 27 (2008) 447-457.
[6] C.H. Zhang, Z. Hu, G. Gao, S. Zhao, Y.D. Hang, Damping behavior and acoustic performance of polyurethane/lead zirconate titanate ceramic composites, Mater. Des. 46 (2013) 503-510.
[7] T. Tanimoto, A new vibration damping CFRP material with interlayers of dispersed piezoelectric ceramic particles, Compos. Sci. Technol. 67 (2007) 213-221.