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The effect on the vibration and acoustic radiation of the whole submarine due to the vibration of propeller blades under vertical excitation

WANG Lucai[*1], *ZHOU Qidou*[2]

1 Department of Navigation, Dalian Naval Academy, Dalian 116018, China

2 College of Naval Architecture and Ocean Engineering, Naval University of Engineering, Wuhan 430033, China

Abstract: [**Objectives**] The effect of propeller on the structural vibration and acoustic radiation of submarine is studied. [**Methods**] As such, the acoustic transfer function (ATF) of SUBOFF submarine is established by using the propeller unsteady exciting force as an input, and the outer wet-surface vibration and radiated noise of the propeller, hull and whole submarine as outputs accordingly. The three ATFs of above-mentioned wet-surfaces are compared in accordance with spectral peaks and the propeller's modal frequencies as well as the modal shapes, the effect analysis of propeller blades' vibration on the structural vibration and acoustic radiation under vertical excitation is highlighted. [**Results**] The results show that the effect of the propeller on the vibration and acoustic radiation of the whole submarine is mainly related to the propeller blades' modal frequencies and the single blade cross-vibration modes. The frequency response curves of the mean-square normal velocity level and the radiated acoustic power of the propeller's wet-surface will be plumped up at the single blade cross-vibration modes' frequencies, and so do curves of full submarine's wetsurface, but those of the hull's wet-surface are quite the contrary. At other frequency bands, the ATF of the hull's wet-surface can reflect the whole submarine's vibration and acoustic radiation characteristics. [**Conclusions**] These results can serve as a reference for the acoustic design of submarine propellers, and also offer new insight into the analysis and identification of noise sources.

Key words: propeller; vibration; radiated noise; acoustic transfer function

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0 Introduction

The underwater vibration and noise reduction of submarines is very important for stealth performance, and the effective prediction of the underwater vibration and acoustic radiation of submarine structures is a key point for vibration and noise reduction design. With the development of the finite element and boundary element methods[1-2], especially realizing the fluid-structural decoupling of the added mass and damping coefficient algorithm in solving large and complex structures[3-6], predicting the underwater vibration and acoustic radiation of large and complex structures such as submarines has become possible. But at present, in the prediction of the underwater vibration and acoustic radiation of submarine structures, the propeller is generally replaced by a mass point[7], namely using the hull structure to predict the vibration and acoustic radiation of the whole submarine, and the influence of the vibro-acoustic properties of the propeller itself on the whole submarine structure is ignored.

Propeller noise can be categorized into cavitation noise and non-cavitation noise. Previous studies on propeller noise have mainly focused on cavitation noise. With the development of science and technol-

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Authors: WANG Lucai, male, born in 1986, Ph.D., lecturer. Research interest: ship stealth technology. E-mail: wanglucai@163.com
ZHOU Qidou, male, born in 1962, professor, doctoral supervisor. Research interest: vibration and noise control, hydrodynamics. E-mail: qidou_zhou@126.com

***Corresponding author**: WANG Lucai

ogy, and the improvement of the propeller design level, the critical cavitation speed has gradually increased, it has become possible to ignore the influence of propeller cavitation noise[8], and the prediction of propeller non-cavitation noise has gained increasing importance. Zhang et al.[9] investigated the formation, identification and control of ship abnormal noise from the perspective of engineering practices. He pointed out that under non-cavitationconditions, the propeller, as a finite rigid body, also radiates noise, which is related to the modal frequency and mode shape[10] of the blade frequency in the narrow-band spectrum of the discrete component of strength in the radiated noise of the ship. From the point of view of submarine vibration and acoustic radiation prediction, the influence of propeller vibration and sound radiation on the submarine's structural vibration and acoustic radiation characteristics should be quantified under non-cavitation conditions, also, whether the hull can be used to replace the whole submarine structure in structural acoustic radiation prediction should be studied.

In this paper, based on the SUBOFF submarine model[6], the modal frequencies of the propeller are calculated and the vibration modes at each modal frequency described. At the same time, the acoustic transfer function (ATF) of the hull channel is established, taking the propeller unsteady excitation force as an input, and the outer wet-surface vibration and radiated noise of the propeller, hull and whole structure as the outputs. Then, the ATFs of the three parts of the wet surface are compared, and the spectrum peak frequency of the ATF and the modal frequency and mode shape of the propeller are compared to analyze the influence of the propeller on the structural vibration and acoustic radiation of the submarine.

1 Finite element model of SUBOFF submarine

In order to study the effects of the propeller on the vibration and acoustic radiation of a submarine structure, it is necessary to establish a finite element model of the submarine structure including the finite element of the propeller. In this paper, the finite element model of a SUBOFF submarine structure (9.91 m in length) is taken as the research object, which is established in Reference [6]. Fig.1 shows the finite element model of the SUBOFF submarine, including the propeller, shafting and hull. Fig. 2 shows the finite element model of the inner structure of the SUBOFF submarine's stern section. The stern bearing and stern shaft are connected by multiple point constraints, and the stern shaft can slide freely in the stern bearing. As shown in Fig.3, the blade is modeled from 4-node, 4-facet elements (Tet4), and the shaft is discretized into 8-node, 6-facet elements (Hex8) and 6-node, 5-facet elements (Wedge6) as far as possible.

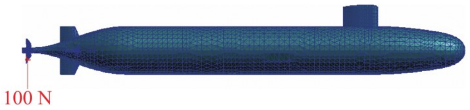


Fig. 1 FE model of SUBOFF submarine

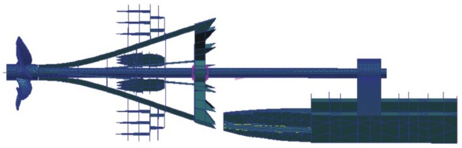


Fig. 2 FE model of the inner structure of stern section for SUBOFF submarine

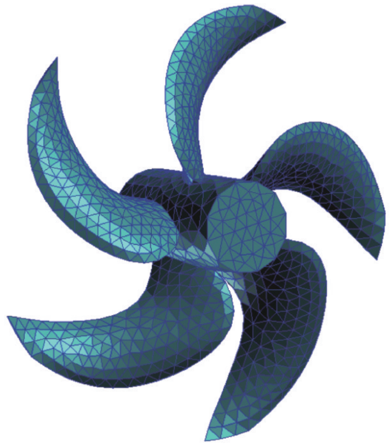


Fig. 3 FE model of propeller

2 Acoustic transfer function

Zhou et al. [11] put forward the concepts of ATF and spectral peak frequency. The ATF of a ship channel is the ratio of a certain quantity characterizing the acoustic features of the hull to the excitation force at any point in the hull, that is, the ratio of output to input. If the output is the mean-square normal velocity of the vibration at one part of the hull, and the input is the excitation force at any point in the hull, then the ATF of the hull channel with the mean-square normal velocity as the acoustic characteristic quantity of the hull is

$$H = \frac{< \bar{V}^2 >}{F} \tag{1}$$

where $< \bar{V}^2 >$ is the mean-square normal velocity and F is the excitation force.

The transfer function can also be understood as the acoustic characteristic value of the hull under the unit excitation force. For submarines, if the excitation force is a stationary random process, then the mean-square normal velocity of the vibration is also a random process. If the input is the excitation force spectrum acting on the propeller, which is $S_F(f)$, and the corresponding transfer function is $H_{<\bar{V}^2>}(f)$, its spectrum function can be expressed as

$$S_{<\bar{V}^2>F}(f) = \left|H_{<\bar{V}^2>}(f)\right|^2 S_F(f) \qquad (2)$$

To some extent, the peak characteristic of the mean-square normal velocity spectrum function represents the vibration peak characteristic of the submarine structure under the excitation force spectrum, and the peak characteristic of the acoustic radiated power spectrum function represents the acoustic radiation peak characteristic of the submarine structure under the excitation force spectrum. Staggering the spectrum peak frequency of the ATF and excitation force is an effective way to reduce the vibration and acoustic radiation of the submarine structure. Therefore, controlling the vibration and acoustic radiation of the submarine structure through the ATF of the ship channel is the core mechanism of vibration and acoustic radiation control, as well as the most important problem in the structural design of quiet submarines.

In this paper, mean-square normal velocity and acoustic radiated power are used to characterize the vibration and acoustic radiation of the wet surface of a submarine. Mean-square normal velocity and radiated acoustic power W are defined as follows:

$$<\bar{V}^2>=\frac{\omega^2 \sum\limits_{j=m_1}^{m_2} \left|\bar{U}_j^e\right|^2 S_j}{\sum\limits_{j=m_1}^{m_2} S_j};$$

$$W = \frac{1}{2}\mathrm{Re}\left\{\mathrm{i}\omega \sum_{j=m_1}^{m_2} \bar{p}_j^e \bar{U}_j^{e*} S_j\right\} \qquad (3)$$

where $\mathrm{i}=\sqrt{-1}$; ω is Circular frequency; $\bar{p}_j^e$ is pressure amplitude of No. j element; $\bar{U}_j^e$ is displacement amplitude of No. j element; S_j is area of No. j element; * is represents the corresponding amount of conjugate value; m_1 is starting number calculation of wetsurface element; m_2 is ending number calculation of wetsurface element.

According to Equation (3), the mean-square normal velocity and radiated acoustic power of the submarine propeller's wet surface can be calculated separately, and the integral calculation of the wet surface of the hull and whole submarine can also be carried out (the wet surface of the whole submarine is the sum of that of the propeller and hull).

The mean-square normal velocity level and radiated acoustic power level can be defined as[12]

$$L_{\bar{V}} = 10\lg\frac{<\bar{V}^2>}{V_{\mathrm{ref}}^2};\ L_W = 10\lg\frac{W}{W_{\mathrm{ref}}} \qquad (4)$$

where V_{ref} is the velocity reference fixed at 5×10^{-8} m/s and W_{ref} is the power reference fixed at 10^{-12} W.

3 Modal frequency and mode shape of propeller

Using the finite element software NASTRAN, the modal frequencies of the propeller in the range of 5−800 Hz are calculated. To describe the mode shapes of each modal frequency, the blade bending vibration, which has a great influence on the vibration radiation noise of astructure, is given priority; thus, the forward mode shape of a single blade is 1, the backward mode is 0 and the non-participating vibration mode is N. Table 1 shows the modal frequencies of the mode shapes of the propeller, and Fig. 4 shows the mode shapes of the propeller. It can be seen from Table 1 and Fig. 4 that the modal frequency of the propeller usually appears in the middle and high frequency bands. According to the calculation model used in this paper, the modal shapes are mainly divided into four types: type 01011, type 00111, type 00N11 and type 11111.

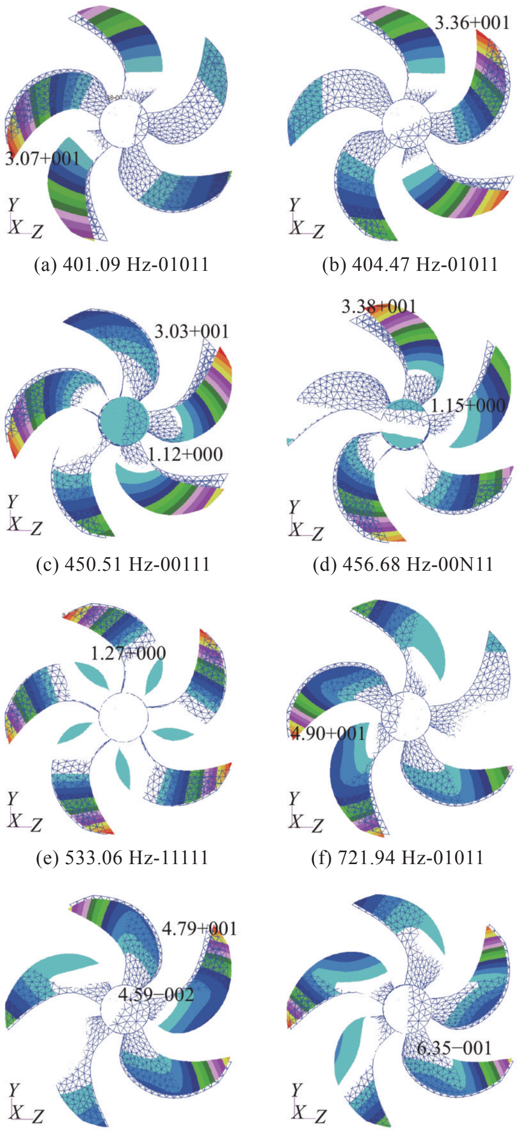
For a five-blade propeller, type 01011 is the maximum cross-vibration mode of a single blade; type 00111 and type 00N11 are continuous double blade cross-vibration modes; and type 11111 is the vibration mode of all blades in the same direction.

Table 1 Modal frequencies and modal shapes of propeller

Order	Modal frequency /Hz	Mode descriptor	Order	Modal frequency /Hz	Mode descriptor
1	401.09	01011	5	533.06	11111
2	404.47	01011	6	721.94	01011
3	450.51	00111	7	726.79	01011
4	456.68	00N11	8	794.72	00111

4 Vibration analysis of whole submarine in vacuum

The vibration response of the whole SUBOFF submarine in a vacuum is calculated usingthe general finite element software NASTRAN. The amplitude of the excitation force acting on the center of the propeller (center of the propeller hub) is 100 N, and the direction is shown in Fig. 1. The frequency



(a) 401.09 Hz-01011 (b) 404.47 Hz-01011

(c) 450.51 Hz-00111 (d) 456.68 Hz-00N11

(e) 533.06 Hz-11111 (f) 721.94 Hz-01011

(g) 726.79 Hz-01011 (h) 794.72 Hz-00111

Fig. 4 Mode shapes of propeller

steps of the excitation force are shown in Table 2. The mean-square normal velocity of the wet-surface of the propeller, hull and whole submarine are integrated respectively to obtain the mean-square normal velocity level at each frequency. Fig. 5 shows the frequency response curves of the mean-square normal velocity level of the three wet-surface parts, and the rectangular shaded part in the figure shows the frequency of propeller mode 01011 (single blade cross-vibration mode). As can be seen in Fig. 5, for vibration in a vacuum, there is a large peak value on the frequency response curves of the wet surfaces of the propeller and whole submarine near the propeller blades' modal frequencies for type 01001, but no obvious spectral peak on that of the wet surface of the hull. The peak characteristic of the frequency response curve of the wet surface of the whole submarine is mainly related to the propeller. From the peak characteristics of the frequency response curves, except for the frequencies of propeller mode shape 01011, there is no obvious peak in the frequency response curve of the hull's wet-surface. In the other frequency bands, the peak characteristics of the wet-surface vibration frequency response curves of the propeller, hull and whole submarine are basically the same. Regarding the vibration of the submarine structure caused by the unsteady excitation force of propeller, it will directly cause the vibration of the propeller while being-transmitted to the hull structure through the shaft system, causing the vibration of the hull structure. Thus, the vibration of the hull structure is directly related to the transmission of excitation force. At the frequency of propeller mode shape 01011, the propeller induces resonance, but the hull structure does not produce an obvious resonance effect; that is to say, there is a significant difference between the vibration transfer functions of the propeller and hull structure at this frequency. If the influence of the propeller itself is ignored and only the hull is used to replace the whole submarine structure for frequency response analysis, there will be large errors at some frequencies, resulting in the loss of the spectral peak frequencies related to the propeller. These spectral peak frequencies are related to the cross-vibration modal frequency of the single blade of the propeller.

Table 2 Frequency steps of exciting force in vacuum

Frequency range/Hz	Step/Hz
10−200	1
200−800	2

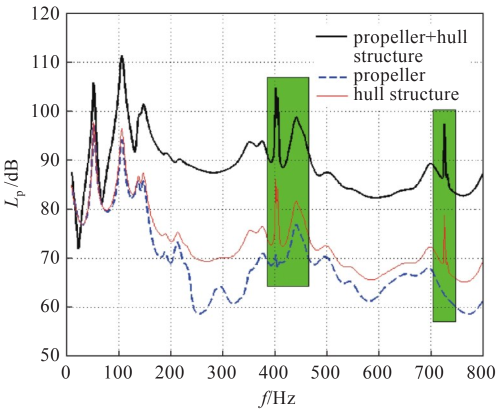


Fig. 5 Frequency response curves of mean-square normal velocity level of three parts of submarine's wet-surface

5 Vibration and acoustic radiation analysis of whole submarine underwater

By using an additional mass and damping coefficient algorithm[3], the underwater vibration and acoustic radiation characteristics of the whole SUBOFF submarine are calculated, and the position, amplitude and direction of the excitation force are consistent with those in a vacuum. The frequency steps of excitation force are shown in Table 3. The reflection effect of the horizontal plane is considered in the calculation. The center line of the hull is 25 m from the horizontal plane, as shown in Fig. 6.

Table 3 Frequency steps of exciting force in water

Frequency range/Hz	Step/Hz
10-200	2
200-800	5

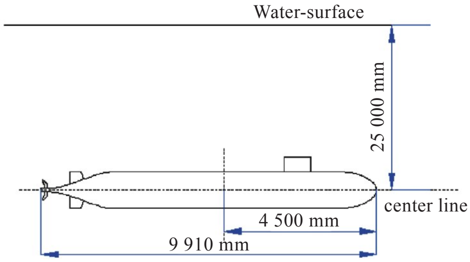


Fig. 6 Underwater position of SUBOFF submarine

The mean-square normal velocity and radiated acoustic power of the wetsurface of the propeller, hull and whole submarine are integrated respectively to obtain the mean-square normal velocity level and radiated acoustic power level at each frequency. Fig. 7 shows the frequency response curves of the mean-square normal velocity level of the three parts of the submarine's wet-surface, and Fig. 8 shows the frequency response curves of the radiated acoustic power level of the same. As can be seen, for the mean-square normal velocity level and radiated acoustic power level, the frequency response curves of the propeller's wet-surface have large spectral peaks at 355 Hz (rectangular shaded part in the figure), as do the curves of the whole submarine's wet-surface, while those of the hullhave no obvious spectral peaks at this frequency.

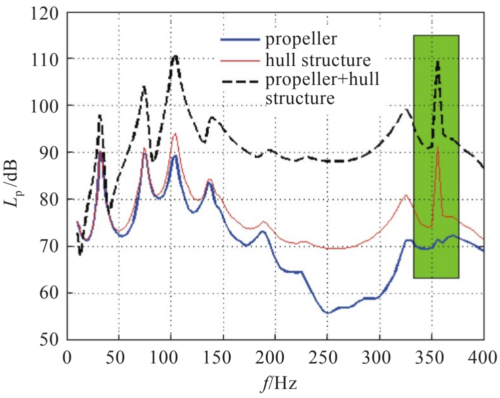


Fig. 7 Frequency response curves of mean-square normal velocity level of three parts of submarine's wet-surface

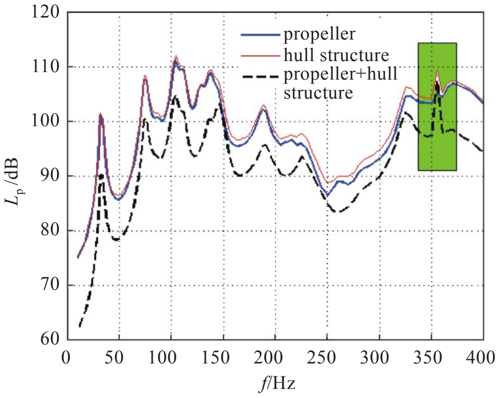


Fig.8 Frequency response curves of radiated acoustic power level of three parts of submarine's wet-surface

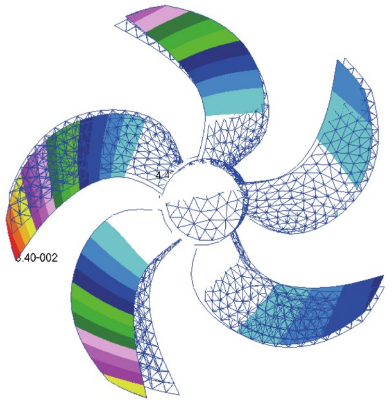


Fig.9 Modal shape of propeller at 355 Hz (style 01011)

The propeller's mode shape at 355 Hz is shown in Fig. 9. It can be seen that the propeller has obvious single blade cross-vibration characteristics at this frequency. By comparing the natural frequency and mode shape of the propeller, it is clear that 355 Hz is the modal frequency of the propeller underwater, and its mode shape type is 01011 (corresponding to the natural frequencies and mode shapes of 401.09 and 404.47 Hz). This is due to the fact that when the propeller vibrates underwater, its modal frequency moves to a lower frequency due to the influence of the water attachment coefficient. When the propeller mode shape type is 01011, the frequency underwater is lower than that in a vacuum.

Comparing the frequency response curves of the hull and whole submarine, as shown in Fig. 7 and Fig. 10, it can be seen that, except for 355 Hz, the vibration and sound radiation characteristics of the hull are basically in accordance with those of the whole submarine, especially in the frequency response curves of radiated acoustic power level. This is because the contribution of the whole submarine's wet-surface to the radiated acoustic power is not large due to its small area, despite the large vibration amplitude of the propeller. When the modal shape type of the propeller is 01011, the vibration and sound radiation of its wet-surface are unusually obvious, and the frequency response curves of the mean-square normal velocity level and radiated acoustic power level show large peaks. Although the wet-surface area of the propeller is relatively small, its influence on the vibration and acoustic radiation of the wet-surface of the whole submarine is very obvious, resulting in obvious spectral peaks in the stage frequency response curves.

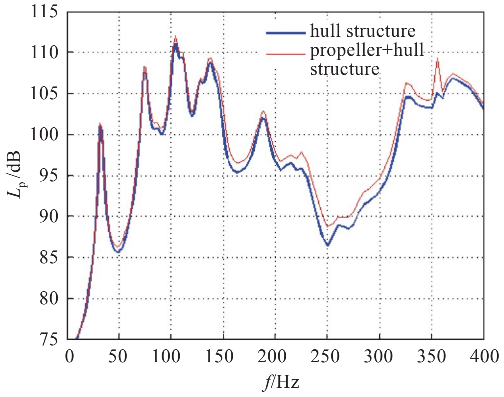


Fig.10 Frequency response comparison of radiated acoustic power level of hull and whole submarine's wet-surface

Based on the above analysis, the effect of the propeller on the vibration and acoustic radiation of the whole submarine is mainly related to the modal frequency of the propeller and the single propeller blade cross-vibration mode. When the single propeller blade cross-vibration mode appears, the relevant transfer function of the propeller and whole submarine will show anobvious spectrum peak, and the peak frequency of the spectrum will correspond to the modal frequency.At this time, if the contribution to vibration and acoustic radiation of the wet-surface of the propeller is ignored, and the vibration and acoustic radiation characteristics of the whole submarine are analyzed only in terms of the hull instead of the whole submarine, the peak frequency associated with the propeller will be lost. In other frequency bands, the ATF of the wet-surface of the hull basically dominates the vibration and acoustic radiation characteristics of the whole submarine.

6 Conclusion

In this paper, the ATF of a SUBOFF submarine is established using the unsteady excitation force of the propeller as the input, and the outer wet-surface vibration and radiated noise of the propeller, hull and whole submarine as outputs. The three ATFs of the above-mentioned wet-surfaces are then compared with the spectral peaks and the modal frequency and mode shape of the propeller, and the effect analysis of propeller blade vibration on structural vibration and acoustic radiation under vertical excitation is highlighted. The following conclusions are drawn:

1) The effects of the propeller on the vibration and acoustic radiation of the whole submarine are mainly related to the propeller blades' modal frequencies and the single blade cross-vibration mode. The frequency response curves of the mean-square normal velocity level and radiated acoustic power of the propeller's wet-surface are plumped up at the single blade cross-vibration modal frequencies, as are the curves of the full submarine's wet-surface, but those of the hull's wet-surface show the opposite effect.

2) At other frequency bands, the ATF of the hull's wet-surface dominates the vibration and acoustic radiation characteristics of the whole submarine.

These results provide valuable references for the acoustic design of submarine propellers, while offering new insights into the analysis and identification of noise sources.

References

[1] XIANG C L, WANG W P, LIU H. Numerical simulation of sound radiation on gearbox's housing[J]. Chinese Journal of Mechanical Engineering, 2008, 21(3): 26−30.

[2] CHEN M X, MOU B J, WEI J H, et al. Analysis of the vibration and sound radiation similarity between inner and outer shells of double cylindrical shell[J]. Journal of Ship Mechanics, 2012, 16(11): 1329−1336 (in Chinese).

[3] ZHOU Q, ZHANG W, JOSEPH P F. A new method of determining acoustic added mass and damping coefficient of fluid-structure interaction[C]//The Eighth International Symposium on Practical Design of Ships and Other Floating Structures. Amsterdam: Elsevier, 2001, 2: 1185−1195.

[4] ZHOU Q, JOSEPH P F. A numerical method for the calculation of dynamic response and acoustic radiation from an underwater structure[J]. Journal of Sound and Vibration, 2005, 283(3/4/5): 853−873.

[5] CHEN M X, DENG N Q, ZHANG C, et al. Vibration of submerged and ring stiffened conical shells[J]. Journal of Vibration and Shock, 2014, 33(14): 25−32 (in Chinese).

[6] WANG L C, ZHOU Q D, YANG C Q. Influence of stiffness constant of stern bearing on vibration and acoustic radiation of whole submarine[J]. Chinese Journal of Ship Research, 2018, 13(1): 17−23 (in Chinese).

[7] LI D L. Analysis and experiment on vibration and acoustic radiation of the shafting-hull coupled system [D]. Shanghai: Shanghai Jiao Tong University, 2012 (in Chinese).

[8] LI N. Prediction methods review of ship propeller noise [J]. Modern Industrial Economy and Informationization, 2017, 7(9): 33−34 (in Chinese).

[9] ZHANG G L, YU X, HE Q W, et al. Study on the identification and elimination of abnormal noise and vibration of warships[J]. Noise and Vibration Control, 2018, 38(3): 115−119, 180 (in Chinese).

[10] WU C J, WANG C X, CHEN Z G, et al. The analysis of a propeller's low-frequency vibration and sound radiation characteristics: Jellyfish mode[J]. Chinese Journal of Ship Research, 2020, 15(3): 75−80.

[11] ZHOU Q D, BI Y. Vibration and radiation sound field simulation of submarine structure[C]//The Eighth Symposium on Underwater Noise of Ships. Wenzhou: The Chinese Society of Naval Architects and Marine Engineers. 2001: 109−124 (in Chinese).

[12] LAULAGNET B, GUYADER J L. Sound radiation by finite cylindrical ring stiffened shells[J]. Journal of Sound and Vibration, 1990, 138(2): 173−191.

桨叶振动对螺旋桨垂向激励下潜艇结构振动与声辐射的影响

王路才[1]，周其斗[*2]

1 海军大连舰艇学院 航海系，辽宁 大连 116018

2 海军工程大学 舰船与海洋学院，湖北 武汉 430033

摘　要：［**目的**］研究螺旋桨对潜艇结构振动和声辐射造成的影响。［**方法**］以螺旋桨不定常激振力为输入，分别以螺旋桨、艇体和整艇外湿表面的振动及其辐射噪声为输出，建立SUBOFF模型艇的艇体通道声学传递函数（ATF），通过对比上述3部分湿表面的声学传递函数，对照传递函数谱峰频率与螺旋桨的模态频率及其振型，着重分析螺旋桨桨叶振动对螺旋桨垂向激励下潜艇结构振动与声辐射的影响规律。［**结果**］研究表明：螺旋桨对整艇结构振动和声辐射的影响主要与螺旋桨模态频率及单桨叶交叉振动振型有关。当螺旋桨出现单桨叶交叉振动振型时，螺旋桨和整艇湿表面的声学传递函数出现了明显的谱峰，谱峰频率与螺旋桨模态频率对应，而在艇体湿表面的声学传递函数中该谱峰并未被表现出来；在其他频段，艇体湿表面的声学传递函数基本反映了整艇结构的振动与声辐射特性。［**结论**］所得结果可为声学设计阶段潜艇螺旋桨的设计提供参考，亦可为整艇噪声源的识别分析提供新思路。

关键词：螺旋桨；振动；辐射噪声；声学传递函数