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Analysis of vibration and acoustic radiation of submarines under transfer modes of propeller excitation force

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Abstract: The hull system is an important path for radiating propeller noise. Propeller excitation must be transmitted by the thrust to the hull system. As such, the study of the relations between force transmission and the vibration and sound power of submarines is very important. To this end, this paper aims at axial excitation force, lateral excitation force and vertical excitation force of propeller. The transmission modes of the force loaded by the thrust system are analyzed, and the combined fluid-structure interaction, vibration and sound power of the finite element model of the submarine are analyzed. This provides a new method for analyzing the vibration and radiation of submarines under propeller excitation force.

Key words: transmission modes; fluid-structure interaction; vibration; acoustic radiation; hull structure

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0 Introduction

The noise source on a submarine includes mechanical noise, hydrodynamic noise and propeller noise generated by the excitation force of various operating machineries, among which the propeller noise includes the direct radiation noise of propeller and the excitation force noise of propeller. In the advance process of submarine, the excitation force noise of propeller is an important component of the submarine noise. The propeller excitation force is transmitted to the hull through the bearing in connection with the shaft system, causing the hull vibration, and then this part of noise is radiated through the hull[1]. Therefore, it is very important to carry out the study on the law that the propeller excitation force is transmitted to the hull through the stern bearing, neck bearing and thrust bearing which are connected with the shaft system, causing the hull vibration and noise radiation[2].

In order to study the effect of propeller excitation force on the vibration and acoustic radiation characteristics of hull, it is a common practice to analyze the shaft-hull coupled structure as a whole at present. For example, Dylejko et al.[3] established a shaft-hull coupled system model and a vibrational equation of the coupled system through the four-pole parameter method, and further carried out the analysis on the hull vibration under the axial excitation force of propeller; Li[4] studied the effect of vibration of shaft subsystem on the acoustic radiation of stern structure of the hull; Feng et al.[5] established a complete model of the submarine stern and studied the influence of the stiffness variation of thrust bearing under the axial excitation force of propeller on the vibration and noise reduction of hull. The vibration or acoustic radiation characteristics of the integral structure can be obtained in a way that the shaft-hull coupled structure is analyzed as a whole; however, the effect of the excitation force transmitted

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through the shaft system on the vibration and acoustic radiation characteristics of hull cannot be obtained. Therefore, in this paper the isolation method is used to divide the submarine structure into the shaft system structure and hull structure, which not only takes into account the coupling between the shaft system and the hull, but also obtains the characteristics of the excitation force transmitted to the hull from the shaft system.

This paper will analyze the vibration and acoustic radiation characteristics of the hull under the propeller excitation force from the perspective of the force transmission between the shaft system and the hull based on the shaft-hull coupled model shown in Fig. 1. First, in order to obtain the interaction between the shaft system and the hull, the isolation method is used to divide the shaft-hull coupled system into the shaft system structure and hull structure. As the shaft system is connected with the hull through a number of bearings, the shaft system structure transmits excitation force to the hull structure through multiple degrees of freedom. The excitation force transmitted to the hull structure by the shaft system structure is also called the counterforce of the shafting system to the hull. And then, based on the thought of "mode analysis", the shaft-hull coupling problem on many degrees of freedom is analyzed and the acting force of the shafting system structure on the hull structure is divided into the superposition of some unrelated "force transmission modes". Finally, based on the additional mass and damping algorithm combining structural finite element with fluid boundary element, the frequency response curves of mean-square normal velocity level and radiated acoustic power level of the hull when single order force transmission mode acts on the hull structure alone are obtained through calculation, so as to explore the influence of the force transmission mode of different orders on the vibration and acoustic radiation of hull structure.

1 Structural finite element model

As shown in Fig. 1 (unit: mm), the analysis object in this paper is a single-shell model submarine structure with ring frame and the internal structure of the hull is simplified. The structure includes the main parts such as bulkhead, ring frame and shaft system, among which the shaft system includes the propeller, the thrust shaft, counter shaft and stern shaft. Their geometrical dimensions and material parameters are shown in Table 1. The submarine shaft has three sections: thrust shaft, counter shaft and stern shaft, the lengths of which are respectively 0.9 m, 1 m and 0.22 m.

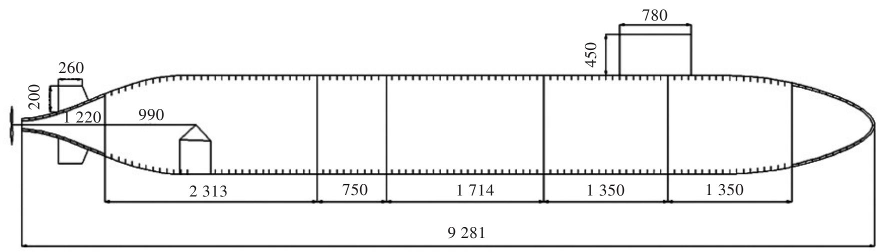
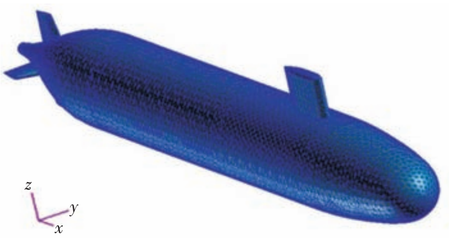


Fig.1 Structure of the submarine model

Table 1 Basic parameters

Parameter	Value
Length of hull/m	9.281
Diameter of the pressure hull/m	1.075
Thickness of the pressure hull/m	0.004
Dimension of the frame section/m	0.04×0.003
Frame interval/m	0.075
Diameter of the shaft section/m	0.075
Mass of the propeller/t	0.008 3
Mass of stern shaft and counter shaft/t	0.003
Mass of the thrust shaft/t	0.006
Poisson's ratio	0.3
Density of steel/($kg \cdot m^{-3}$)	7 800

The software Patran is used for finite element modeling of the submarine structure. The finite element models for the framing and outer hull of the submarine structure are shown in Fig. 2. The outer FE model of the submarine includes hull structure and shaft system structure. The shaft system structure includes the propeller and shaft, and the propeller model is established through the mass point; the hull structure includes the hull and three bearings which are all simplified into the mass points. The shaft system structure is connected with the hull structure through bearings. And in accordance with the transmission characteristics of the excitation force of the shaft system, the constrained relationship between the shaft system and the hull is established as follows: at the stern shaft and the counter shaft, the shaft system can only transmit the vertical and lateral excitation forces; at the thrust shaft, the excitation force can be transmitted to the hull along the lateral, axial and vertical directions, and the schematic diagram is shown in Fig. 3. The above relations can be achieved through multi-point constraints. Therefore, the shaft system can transmit the excitation force to the hull through seven degrees of freedom.



(a) Outer hull of the coupled system model

(b) Framing system

Fig.2 FE model for the submarine structure

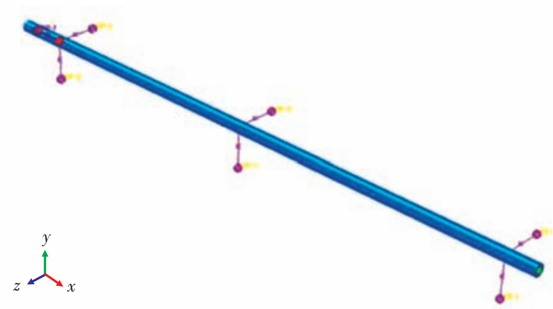


Fig.3 Relation between shaft structure and the hull

In this paper, under the axial, lateral, and vertical excitation forces of propeller of the model submarine with the amplitude of 1 N and the frequency of 1-100 Hz, the transmission modes of the excitation force between the shaft system and hull as well as the characteristics of vibration and acoustic radiation of the hull under the single order transmission mode of the excitation force will be respectively calculated. In this paper, the characteristics of vibration and acoustic radiation of the model submarine will be analyzed by using the algorithm of additional mass and damping; the computation structure is located 10 meters below the water surface and the hull structure is in a completely free state.

2 Additional mass and damping algorithm and force transmission mode theory

In order to analyze the influence of the excitation force transmitted from the shaft system to the hull on the vibration and acoustic radiation of hull, the following steps should be done: first, the submarine structure is divided into the shaft system structure and the hull structure, and the acting force between the shaft system structure and the hull structure is obtained through the structural dynamics theory; then, the acting force between the shaft system structure and the hull structure is divided into the superposition of unrelated force transmission modes in accordance with the mode analysis method; finally, the frequency response curves of mean-square normal velocity level and radiated acoustic power level of the hull structure under a specific order force transmission mode are calculated with the additional mass and damping algorithm.

2.1 Force transmission mode theory based on the shaft-hull coupled system

When propeller excitation force is exerted on the submarine, the displacement of the shaft system structure at the shaft-hull joint will be affected by the propeller excitation force and the hull counterforce; however, the displacement of the hull structure at the shaft-hull joint will only be affected by the counterforce of the shaft system exerted on the hull. In accordance with the linear structural dynamics theory, the displacements $\boldsymbol{u}_{\mathrm{t}}$ and $\boldsymbol{u}_{\mathrm{s}}$ of the shaft system structure and the hull structure at the shaft-hull joint and can be respectively expressed as[6]:

$$\boldsymbol{u}_{\mathrm{t}}=\boldsymbol{u}_{\mathrm{p-t}}+\boldsymbol{Z}_{\mathrm{t}}\boldsymbol{F}_{\mathrm{t}} \tag{1}$$

$$\boldsymbol{u}_{\mathrm{s}}=\boldsymbol{Z}_{\mathrm{s}}\boldsymbol{F}_{\mathrm{s}} \tag{2}$$

where $\boldsymbol{u}_{\mathrm{p-t}}$ is the displacement response column vector of the shaft at the shaft-hull joint under the propeller excitation force; $\boldsymbol{Z}_{\mathrm{t}}$ and $\boldsymbol{Z}_{\mathrm{s}}$ are respectively the mechanical compliance matrices of the shaft system structure and hull structure at the shaft-hull joint; $\boldsymbol{F}_{\mathrm{t}}$ and $\boldsymbol{F}_{\mathrm{s}}$ respectively represent the interaction force column vector of the shaft system structure and hull structure at the shaft-hull joint.

The interaction force between the shaft system structure and the hull structure at the joint is a pair of acting force and counterforce, and the motion of the two subsystems at the joint is equal, i.e.:

$$\boldsymbol{F}_{\mathrm{t}}=-\boldsymbol{F}_{\mathrm{s}} \tag{3}$$

$$\boldsymbol{u}_{\mathrm{t}}=\boldsymbol{u}_{\mathrm{s}} \tag{4}$$

Combining Eq. (1)–Eq. (4), one can obtain:

$$\boldsymbol{u}_{\mathrm{p-t}}=(\boldsymbol{Z}_{\mathrm{t}}+\boldsymbol{Z}_{\mathrm{s}})\boldsymbol{F}_{\mathrm{s}} \tag{5}$$

According to the characteristics of elastic structure, the mechanical compliance matrices $\boldsymbol{Z}_{\mathrm{t}}$ and $\boldsymbol{Z}_{\mathrm{s}}$ should be symmetric matrices, therefore, $(\boldsymbol{Z}_{\mathrm{t}}+\boldsymbol{Z}_{\mathrm{s}})$ is also a symmetric matrix. By eigenvalue analysis, $(\boldsymbol{Z}_{\mathrm{t}}+\boldsymbol{Z}_{\mathrm{s}})$ is expressed as $\boldsymbol{\varphi}\boldsymbol{\Lambda}\boldsymbol{\varphi}^{\mathrm{T}}$, and there is

$$\boldsymbol{u}_{\mathrm{p-t}}=\boldsymbol{\varphi}\boldsymbol{\Lambda}\boldsymbol{\varphi}^{\mathrm{T}}\boldsymbol{F}_{\mathrm{s}} \tag{6}$$

In the equation, $\boldsymbol{\Lambda}$ is a diagonal matrix; $\boldsymbol{\varphi}^{\mathrm{T}}\boldsymbol{\varphi}=\boldsymbol{\varphi}\boldsymbol{\varphi}^{\mathrm{T}}=\boldsymbol{I}$, where $\boldsymbol{I}$ is a unit matrix and the superscript T represents the transposition of the matrix. Furthermore, the column vector $\boldsymbol{F}_{\mathrm{s}}$ of counterforce of the hull structure exerted by the shaft system structure at the shaft–hull joint can be obtained:

$$\boldsymbol{F}_{\mathrm{s}}=\boldsymbol{\varphi}\boldsymbol{\Lambda}^{-1}\boldsymbol{\varphi}^{\mathrm{T}}\boldsymbol{u}_{\mathrm{p-t}}=\sum_i \alpha_i\boldsymbol{\varphi}_i=\sum_i \boldsymbol{f}_i \tag{7}$$

where the i –th column vector of $\boldsymbol{\varphi}$ stands for the "transmission mode" of the i –th order excitation force; α_i is the i –th element of the column vector $\boldsymbol{\Lambda}^{-1}\boldsymbol{\varphi}^{\mathrm{T}}\boldsymbol{u}_{\mathrm{p-t}}$, representing the contribution to "the transmitted excitation force" made by the excitation force corresponding to the i –th order transmission mode, and the transmitted excitation force is referred to as "the i –th order excitation force transmission mode amplitude"; $\boldsymbol{f}_i$ is the force transmission mode column vector of the i –th order shaft system and hull system. Since the shaft system can transmit excitation force to the hull through seven degrees of freedom, $(\boldsymbol{Z}_{\mathrm{t}}+\boldsymbol{Z}_{\mathrm{s}})$ is a 7–th order matrix, corresponding to the 7–th order force "transmission mode".

2.2 Additional mass and damping algorithm combining finite element method with fluid boundary element method

In order to calculate the underwater vibration and acoustic radiation power of the hull system, the additional mass and damping algorithm combining the structural finite element method with fluid boundary element method method is proposed in this paper[7-8]. The method employs the decoupling way from fluid variable to the structural variable[9], which has the advantage that the fluid–structure interaction decoupling can be achieved through the mixed programming with FORTRAN and DAMP languages, and combining with the analysis software Nastran, the acoustic radiation of the underwater structure can be calculated. The brief process of this method is as follows: the additional mass matrix $\boldsymbol{M}_{\mathrm{f}}$ and additional damping matrix $\boldsymbol{B}_{\mathrm{f}}$ of the fluid, and the source–sink distribution density matrix will first be solved through the discrete Helmholtz integral equation, and then the structural dynamic response equation of the decoupled structure will be obtained by adding additional mass matrix and additional damping matrix of the fluid to the global structure mass matrix and damping matrix generated through Nastran[10].

$$[-\omega^2(\boldsymbol{M}_{\mathrm{s}}+\boldsymbol{M}_{\mathrm{f}})-\mathrm{i}\omega(\boldsymbol{B}_{\mathrm{s}}+\boldsymbol{B}_{\mathrm{f}})+\boldsymbol{K}]\boldsymbol{\delta}=\boldsymbol{F} \tag{8}$$

where ω is the circular frequency; $\boldsymbol{M}_{\mathrm{s}}$ is the mass matrix of the structure; $\boldsymbol{B}_{\mathrm{s}}$ is the damping matrix of the structure; $\boldsymbol{K}$ is the stiffness matrix of the structure; $\boldsymbol{\delta}$ is the nodal displacement vector; $\boldsymbol{F}$ is the matrix of external force acting on the structural node.

Because under the same frequency, the transmitted excitation force to the hull by the shaft system under seven degrees of freedom has the same frequency and phase, $\boldsymbol{f}_i$ can be extended to nodal force column vector $\boldsymbol{F}_i$, which is acted on the submarine structure by the submarine. Substituting $\boldsymbol{f}_i$ of Eq. (7) into Eq. (8), there is

$$[-\omega^2(\boldsymbol{M}_{\mathrm{s}}+\boldsymbol{M}_{\mathrm{f}})-\mathrm{i}\omega(\boldsymbol{B}_{\mathrm{s}}+\boldsymbol{B}_{\mathrm{f}})+\boldsymbol{K}]\boldsymbol{\delta}_i=\boldsymbol{F}_i \tag{9}$$

where $\boldsymbol{\delta}_i$ is the nodal displacement vector of the hull under the i –order force transmission mode. And then the dynamic equation will be processed by the corresponding process of Nastran and the displacement of the wet surface is output. Finally, the far field sound pressure can be solved through the output wet surface displacement and the source–sink distribution density matrix. Furthermore, the mean–square normal velocity level and radiated acoustic power level of submarine structure can be obtained.

2.3 Theoretical verification of the force transmission modes

As for the axial excitation force of propeller, the curves of the mean–square normal velocity level and the radiated acoustic power level for the model submarine 10 m below the water surface under the action of 1–100 Hz unit axial excitation force of propeller can be obtained through the calculation. And then, through the force transmission mode theory, the counterforce $\boldsymbol{F}_{\mathrm{s}}$ that the shaft system exerts on the hull under the corresponding excitation force frequency can be obtained, and the mean–square normal velocity level and the radiated acoustic power level of hull are calculated when $\boldsymbol{F}_{\mathrm{s}}$ acts on the hull structure. Fig. 4 and Fig. 5 respectively compare the mean-square normal velocity level and the radiated acoustic power level of hull under the two conditions.

Through Fig. 4 and Fig. 5, it can be concluded that except when the excitation force frequency in the vicinity of 75 Hz, the mean-square normal velocity level and radiated acoustic power level of the hull structure caused by the counterforce of the shaft system are larger than those under the excitation force, the mean-square normal velocity level and the radiated acoustic power level of the hull caused by the two are the same under the other frequencies. Therefore, it can be found that the counterforce of shaft system obtained from the force transmission mode theory is correct.

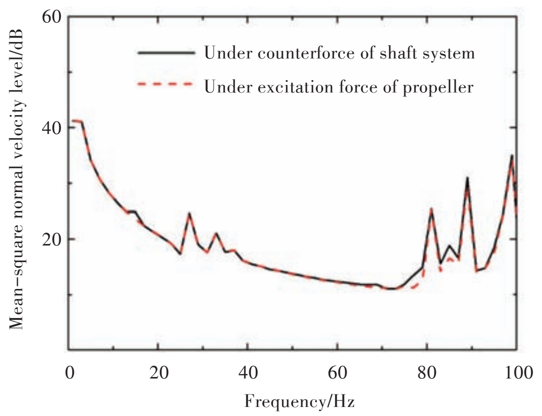


Fig.4 Frequency response curves of mean-square velocity level for two different forces

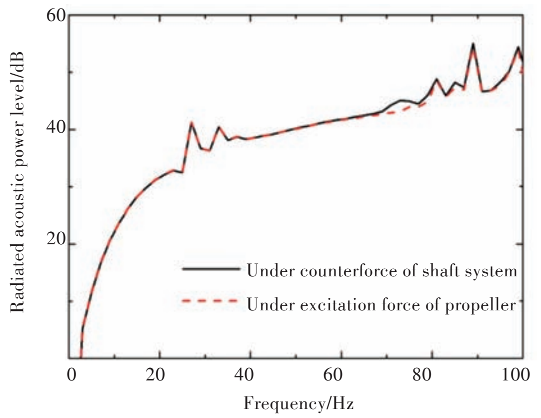


Fig.5 Frequency response curves of radiated acoustic power level for two different forces

3 Analysis of vibration and acoustic radiation under main transmission modes of propeller excitation force

For each frequency of 1 to 100 Hz, $|\alpha_i|$ is arranged in descending order; the largest is called as the first order, and the smallest is called as the seventh order. Fig. 6 to Fig. 8 respectively give the frequency curves of $|\alpha_i|$ of the shaft-hull coupled structure for the first 4 orders under axial excitation force, lateral excitation force and vertical excitation force of propeller. As $|\alpha_i|$ of the first 4 orders is much larger than that of the latter 3 orders, the transmission action of α_i of the latter 3 orders on the excitation force can be ignored.

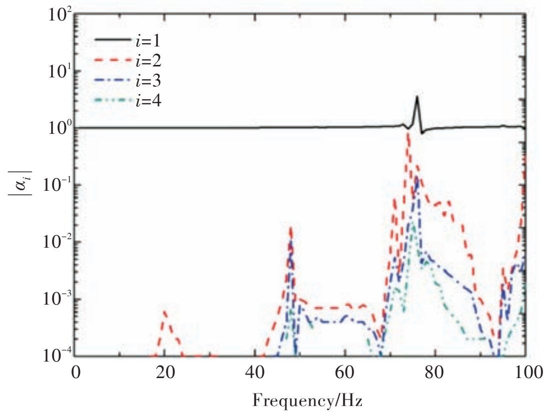


Fig.6 Frequency curves of $|\alpha_i|$ under propeller axial excitation force

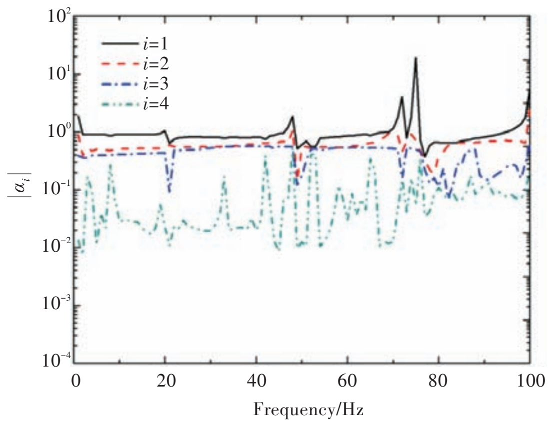


Fig.7 Frequency curves of $|\alpha_i|$ under propeller lateral excitation force

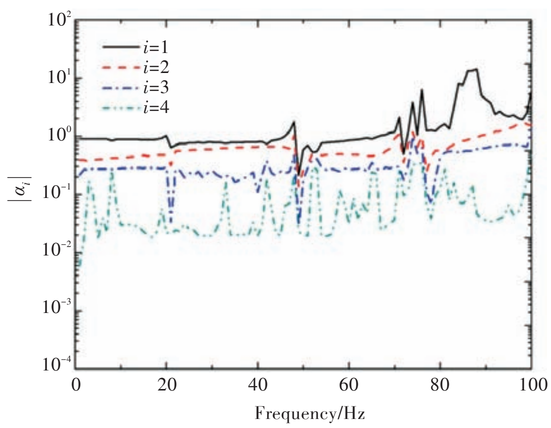


Fig.8 Frequency curves of $|\alpha_i|$ under propeller vertical excitation force

Fig. 6 shows that at the frequency bands of below 74 Hz and 85–98 Hz, $|\alpha_1|$ under the axial excitation force of propeller is much larger than the amplitude of other modes. Generally, $|\alpha_1|$ is more than 10 times as large as $|\alpha_2|$, which indicates that the transmission of the excitation force is the single–mode transmission at these frequency bands; at 70–85 Hz and 98–100 Hz frequency bands, the $|\alpha_2|$ value is close to the $|\alpha_1|$ value at most frequencies, so the transmission mode of the excitation force under these frequency bands is mainly characterized by multi–mode transmission. Through the similar analysis of Fig. 7 and Fig. 8, it can be noted that at the frequency band of below 100 Hz, $|\alpha_1|$, $|\alpha_2|$ and $|\alpha_3|$ are similar, and except for several frequencies, $|\alpha_4|$ is much smaller than the amplitude of other transmission modes under most frequencies. Therefore, for the lateral excitation force and vertical excitation force of propeller, the transmission of the excitation force is multi–mode and most of them are the transmission mode of the first 3 orders. The above analyses show that below 100 Hz, the transmission modes that mainly contribute to the excitation force change in number as frequency varies.

Since the shaft system can transmit the excitation force to the hull by 7 degrees of freedom, $\boldsymbol{f}_i$ is the seven–degree–of–freedom column vector and can be expressed as

$$\boldsymbol{f}_i=[f_{1y},f_{2y},f_{3y},f_{1z},f_{2z},f_{3z},f_x]^{\mathrm{T}}$$

The physical meanings of each degree of freedom are shown in Table 2. Through the force transmission mode theory, combined with Nastran programming, $\boldsymbol{f}_i$ can be calculated. And the calculated results of $\boldsymbol{f}_1$ and $\boldsymbol{f}_2$ under 20 Hz vertical excitation force of propeller at are listed in Table 3.

Table 2 Physical meaning of number with degree of freedom

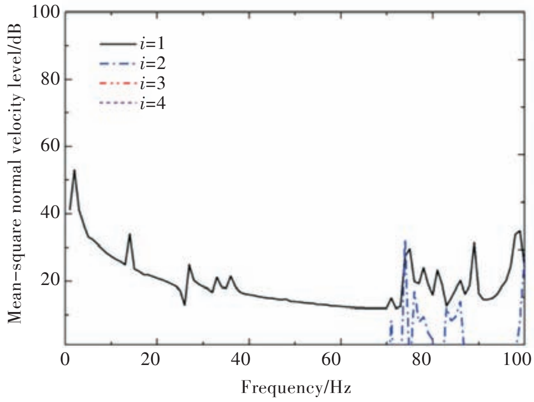
Number of degree of freedom	Physical meaning
1y	Lateral degree of freedom of the stern shaft
2y	Lateral degree of freedom of the counter shaft
3y	Lateral degree of freedom of the thrust shaft
1z	Vertical degree of freedom of the stern shaft
2z	Vertical degree of freedom of the counter shaft
3z	Vertical degree of freedom of the thrust shaft
x	Axial degree of freedom of the thrust shaft

Table 3 $\boldsymbol{f}_1$ and $\boldsymbol{f}_2$ under 20 Hz propeller excitation force of vertical

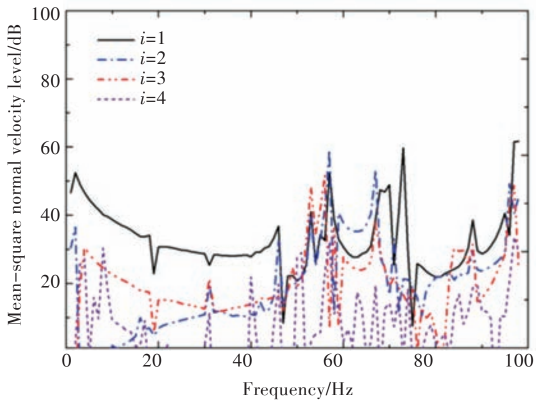
$\boldsymbol{f}_i$	$\boldsymbol{f}_1$ /N	$\boldsymbol{f}_2$ /N
f_{1y}	0.005 4	−0.008 8
f_{2y}	0.005 3	0.010 8
f_{3y}	−0.000 3	0.018 4
f_{1z}	0.858 7	−0.189 8
f_{2z}	0.569 5	0.230 1
f_{3z}	0.088 2	0.361 5
f_x	−0.001 3	0.000 0

Given that transmission mode of each order acts on the hull system alone, the mean–square normal velocity level and radiated acoustic power level of the hull system for the transmission mode of each order can be obtained by means of the additional mass and additional damping method. Fig. 9 and Fig. 10 respectively give the frequency response curves of mean–square normal velocity level and radiated acoustic power level for the first 4 force transmission modes under propeller excitation forces at the axial, lateral and vertical directions.

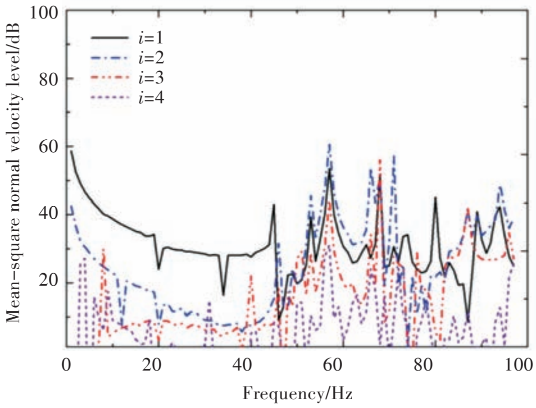
It can be found from Fig. 9 (a) and Fig. 10 (a) that under the axial excitation force of propeller below 50 Hz, when the first order force transmission mode acts on the hull structure, its vibration and frequency response curves are about 10 dB higher than those when the force transmission mode of other orders acts alone. With the increase of frequency, the transmission modes of other orders have more and more influence on the vibration and acoustic radiation of the submarine structure. At part frequencies, the mean–square normal velocity level and radiated acoustic power level of the hull structure caused by the transmission modes of lower orders can be even higher than those caused by the transmission modes of higher orders. The similar analysis can be performed on the lateral excitation force and vertical excitation force of propeller. It can be noted from Fig. 8 (b), Fig. 8 (c), Fig. 9 (b) and Fig. 9 (c) that under the lateral and vertical excitation forces of propeller, at the frequency below 45 Hz, the mean–square normal velocity level and radiated acoustic power level of the hull structure caused by the transmission mode of the first order are much higher than those caused by the transmission modes of other orders. At 45–100 Hz, the effect of transmission mode of other orders is more and more obvious; the effect of the first order force transmission mode is not very different from that of other order modes; at some frequencies, the frequency response curves of the lower order force transmission modes can be even higher than those of the higher order transmission modes.



(a) Propeller axial excitation force

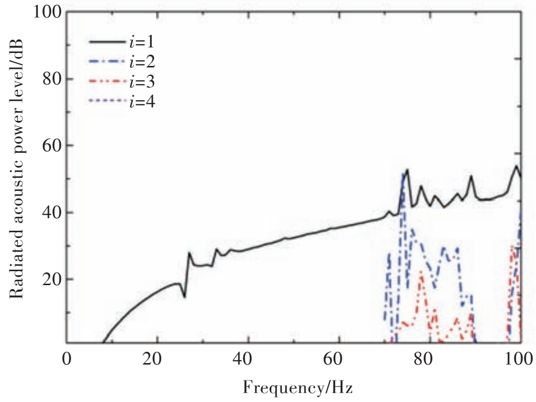


(b) Propeller lateral excitation force

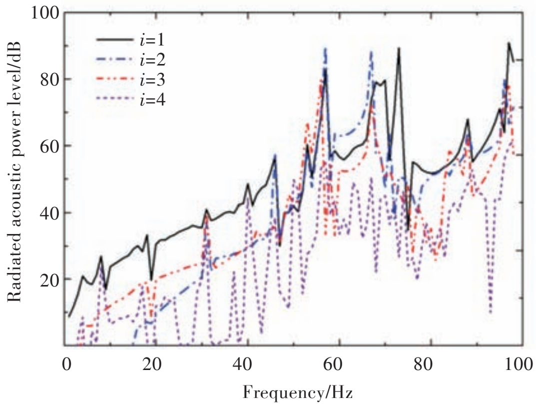


(c) Propeller vertical excitation force

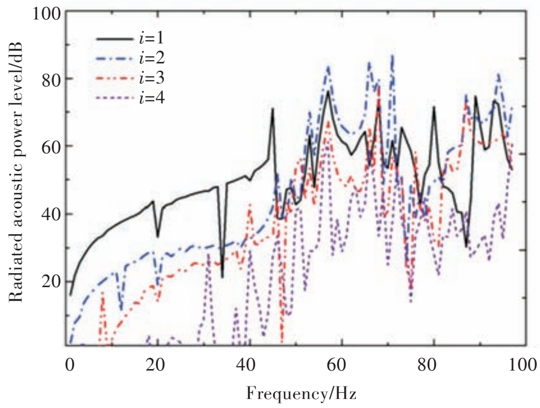
Fig.9 Frequency response curves of mean-square velocity level for the first 4 force transmission modes under propeller excitation force



(a) Propeller axial excitation force



(b) Propeller lateral excitation force



(c) Propeller vertical excitation force

Fig.10 Frequency response curves of radiated acoustic power level for the first 4 force transmission modes under propeller excitation force

4 Conclusions

In this paper, the submarine structure is divided into the hull structure and the shaft system structure, and the counterforce acting on the hull structure by the shaft system structure is decomposed into the superposition of the force transmission modes through the mode analysis method. And then when the force transmission mode with relatively high amplitudes acts alone on the hull structure, the frequency response curves of mean-square normal velocity level and radiated acoustic power level of the hull structure are obtained. As for the hull structure researched in this paper, through the analysis of the vibration and acoustic radiation of the hull structure from the perspective of force transmission, the following conclusions are obtained:

1) The transmitted excitation force between the shaft system and the hull can be divided into the superposition of multiple excitation force transmission modes, among which under axial excitation force of propeller below 70 Hz, the effect of the first-order

force transmission mode is much larger than that of other order force transmission modes, and at this moment, the transmission mode of the excitation force is single mode transmission. However, under the vertical and lateral excitation forces of propeller, the transmission mode of each order is not very different and the transmission mode of excitation force is generally multi-mode transmission.

2) When the propeller excitation force is at the frequency of below 45 Hz, the influence of the first-order force transmission mode on the characteristics of vibration and acoustic radiation of the structure is much larger than that of other order modes. With the increase of frequency, the influence of the force transmission mode of various orders on the vibration and acoustic radiation of the structure is more and more obvious. At some high frequencies, the influence of the lower order force transmission modes on the structural vibration and acoustic radiation can be even larger that of the higher order force transmission modes.

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螺旋桨激振力传递模式下的艇体振动和声辐射分析

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摘　要：潜艇的艇体结构是潜艇螺旋桨激振力向外辐射噪声的重要通道，而轴系是螺旋桨激振力传递到艇体的必经之路，因此有必要研究潜艇轴系向艇体传递的激振力对潜艇艇体振动和辐射声功率的影响。为此，分别针对螺旋桨轴向激振力、螺旋桨侧向激振力和螺旋桨垂向激振力工况，使用模式分析的方法，将轴系对艇体的作用力分解为互不相关的力传递模式的叠加。建立潜艇结构有限元模型，采用结构有限元耦合流体边界元的附加质量附加阻尼算法，分析单阶力传递模式作用于艇体时艇体的振动和声辐射特性。所做的研究可为分析螺旋桨激振力作用下的艇体振动和声辐射提供一种新的方法。

关键词：传递模式；流固耦合；振动；声辐射；艇体结构