VIBRATION AND SOUND RADIATION ANALYSIS OF PROPELLER-SHAFT-HULL COUPLED SYSTEM IN SURFACE VESSELS UNDER PROPELLER EXCITATION

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To analyse the vibration and sound radiation characteristics of the propeller-shaft-hull coupled system in surface vessels under propeller excitation, the coupled FE/BE method is employed to establish the water-propeller-shaft coupled subsystem and the coupled FE method is utilized to model the hull-water coupled subsystem. The dynamic properties of the bearings are modelled as flexible joints. Then, the mobility of the connecting points of bearings on both subsystems is calculated. Frequency response function based synthesis method is utilized to formulate the forced responses under propeller excitation. Then, the acoustic response is analysed with boundary element method. The method proposed can take the elasticity of the propeller, the coupling effect of the propeller-shaft and the hull into consideration. Analysis results show that the characteristic frequencies of sound radiation power are the 1st longitudinal mode of coupled water-propeller-shaft and the 1st, 2nd umbrella wet modes of the propeller. The optimal designs on reducing sound radiation under propeller excitation are mainly concentrated on parameters of shaft and propeller. Meanwhile, the proposed method has high efficiency and advantages in terms of parameter analysis for shaft and propeller in the coupled system, which is of great significance in practical engineering.

Keywords: Propeller-shaft-hull coupled system, Surface vessel, Frequency response function based synthesis method, acoustic radiation, vibration control.

1. Introduction

Vibration and sound radiation characteristics are the key design parameters for surface vessels [1]. Therefore, many researchers pay attention to the modelling and optimization of vibration and sound radiation characteristics of surface vessels. Surface ship and many marine structures are mainly composed of large amount of complex stiffened plates and shells. Vibration and sound radiation properties of these complex stiffened shell have attracted many researchers' attention. Analytical, semi-analytical, assumed mode method and finite element method has been extensively used in researches [2,3].

Qu Y [4] investigated the vibration and sound radiation properties of the fluid-loaded stiffened cylindrical shell. A semi-analytical method is developed to predict the vibration and acoustic responses of submerged coupled shells stiffened by circumferential rings and longitudinal stringers. The contributions of different circumferential wave modes to the vibration responses, sound power are examined and the n=0 circumferential modes contribute to sound radiation most. Caresta [5,6] studied the structural responses of submerged vessel calculated by solving the cylindrical shell equations of motion using a wave approach and the conical shell equations with a power series solution.

The influence of the various complicating effects such as the bulkheads, ring-stiffeners and fluid loading on the structural and acoustic responses of the finite cylindrical shell are discussed. However, researches are mainly concentrated on the structure in vacuum or completely submerged in water. Partially submerged structure such as surface vessels are analysed relatively less. Moreover, the coupling effects of the propeller and shaft on the underwater acoustic radiation of surface vessels are not yet analysed.

The propulsion shaft is the main power transmission path for surface ships. To study the vibration properties of propulsion shafting, the Timoshenko beam model with discrete springs is widely adopted to analyse the dynamic properties. The longitudinal, bending, torsion vibration and coupling vibration of the beam model system are extensively studied [7,8]. Some researchers have also studied the elastic coupling dynamic characteristics between the shaft and stiffened shells. Dylejko P G [9] carried out optimization research on the low frequency structural and acoustic responses of a simplified axisymmetric submarine model to fluctuating propeller forces along the submarine axis. A simple, passive vibration attenuation system known as a resonance changer (RC) is examined in the shaft-hull coupled system to reduce vibration transmission. Li C [10] presented the propeller-shaft-hull coupled vibration and sound radiation properties under propeller excitation. In the model, the shaft-hull coupling effects are considered. The symmetrical distributed thrust bearing foundation structure is proved beneficial for reducing vibration transmitted to the hull from the propulsion shaft.

Propeller is one of the most important noise source for ships. The broadband pulsating propulsion force induced by the propeller is a major excitation force for hull vibration and sound radiation [11]. The broadband propeller excitation force can be decomposed into three directions and the longitudinal excitation force is the largest among the three direction. Duo to the elasticity of the propeller and propulsion shaft, the propeller exciting force will be magnified during the transmission to the hull [12]. Since the geometric of the propeller are complex, analytical and semi-analytical dynamic model of the propeller is difficult to establish. The propeller is generally modelled as concentrated mass and inertia. Thus, the water-propeller coupled dynamic characteristics can't be revealed. Merz. et al [13] investigated the vibration of the shaft and the sound radiation of the hull induced by propeller excitation force. In the model, the propeller is simulated as a spring-mass unit. However the high-order dynamic characteristics and the water-propeller coupling effects have not been studied. Pan J. et al [14] carried out experiment investigation to analyse the transmission characteristics of propeller-induced structural vibration through the thrust bearing. Then, the influence of unstable flow field on the propeller excitation force is obtained. In general, few researches have taken the elastic of the propeller into consideration in the propeller-shaft-hull coupling systems.

In this paper, the acoustic radiation characteristics of the propeller-shaft-hull coupled system of surface vessel under propeller excitation force are investigated. Based on the frequency response function based synthesis method and the FE/BE coupled method [9], the sound power of the hull under the propeller excitation is obtained. Analysis results show that the characteristic frequencies of sound radiation power are the 1st longitudinal and the 1st, 2nd umbrella wet modes of the propeller. The optimal designs on reducing sound radiation under propeller excitation are mainly concentrated on parameters of shaft and propeller. Meanwhile, the proposed method has high efficiency and advantages in terms of parameter analysis for shaft and propeller in the coupled system, which is of great significance in practical engineering.

2. Dynamic model of propeller-shaft-hull coupled system

2.1 Frequency response function based synthesis method

As shown in Fig.1, the propeller-shaft-hull coupling system of surface vessel is divided into substructure A and B. Substructure A is the hull-water coupled system and Substructure B is the water-propeller-shaft coupled system. The subscript *i* denotes non-interface coordinates and the subscript *c* represents the connection point.

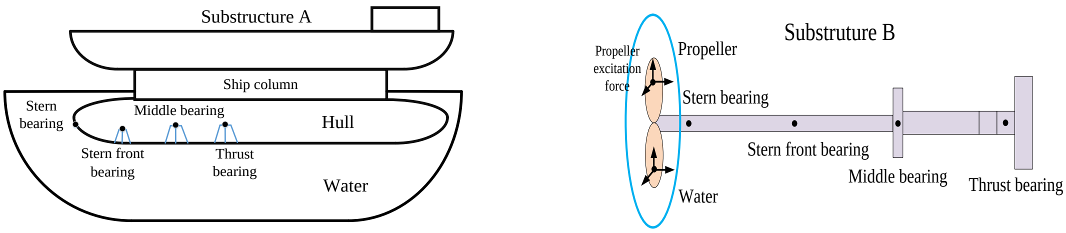


Fig.1 Illustration of substructures A and B.

The frequency response analysis [15] is applied to study the substructure A and B. The frequency response matrix of subsystem A and B can be written as:

$$\begin{Bmatrix} \mathbf{x}_i^A \\ \mathbf{x}_i^B \\ \mathbf{x}_c^A \\ \mathbf{x}_c^B \end{Bmatrix} = \begin{bmatrix} \mathbf{H}_{ii}^A & 0 & \mathbf{H}_{ic}^A & 0 \\ 0 & \mathbf{H}_{ii}^B & 0 & \mathbf{H}_{ic}^B \\ \mathbf{H}_{ci}^A & 0 & \mathbf{H}_{cc}^A & 0 \\ 0 & \mathbf{H}_{ci}^B & 0 & \mathbf{H}_{cc}^B \end{bmatrix} \begin{Bmatrix} \mathbf{f}_i^A \\ \mathbf{f}_i^B \\ \mathbf{f}_c^A \\ \mathbf{f}_c^B \end{Bmatrix} \quad (1)$$

The dynamic properties of the bearings are modeled as flexible joints. The flexible joints are represented by impedance matrix. The values of the impedance are the equivalent stiffness of the bearings.

$$\begin{Bmatrix} \mathbf{f}_1^m \\ \mathbf{f}_2^m \end{Bmatrix} = \begin{Bmatrix} \mathbf{Z}_{11} & \mathbf{Z}_{12} \\ \mathbf{Z}_{21} & \mathbf{Z}_{22} \end{Bmatrix} \begin{Bmatrix} \mathbf{x}_1^m \\ \mathbf{x}_2^m \end{Bmatrix} \quad (2)$$

where $Z_{11} = k + jk\eta,\ Z_{12} = -(k + jk\eta)$, $Z_{21} = -(k + jk\eta),\ Z_{22} = k + jk\eta$, k denotes stiffness of the bearings and η represents the structure damping of the bearings. By the conditions of displacement compatibility and force balance at the connection point, the relationship is written as:

$$\begin{Bmatrix} \mathbf{X}_C^A \\ \mathbf{X}_C^B \end{Bmatrix} = \begin{Bmatrix} \mathbf{x}_c^A \\ \mathbf{x}_c^B \end{Bmatrix} = \begin{Bmatrix} \mathbf{x}_1^m \\ \mathbf{x}_2^m \end{Bmatrix} \text{ and } \begin{Bmatrix} \mathbf{f}_c^A \\ \mathbf{f}_c^B \end{Bmatrix} = \begin{Bmatrix} \mathbf{F}_C^A \\ \mathbf{F}_C^B \end{Bmatrix} - \begin{Bmatrix} \mathbf{f}_1^m \\ \mathbf{f}_2^m \end{Bmatrix} \quad (3)$$

As for the interior point, the excitation force and the displacement remains the same with substructures.

$$\begin{Bmatrix} \mathbf{X}_I^A \\ \mathbf{X}_I^B \end{Bmatrix} = \begin{Bmatrix} \mathbf{x}_i^A \\ \mathbf{x}_i^B \end{Bmatrix} \text{ and } \begin{Bmatrix} \mathbf{F}_I^A \\ \mathbf{F}_I^B \end{Bmatrix} = \begin{Bmatrix} \mathbf{f}_i^A \\ \mathbf{f}_i^B \end{Bmatrix} \quad (4)$$

By combining Eq.(1)~Eq. (4), the relationship between the displacements of connecting points and interior point in each subsystem and the excitation force is obtained. The frequency response function matrix of the coupled system is:

$$\begin{Bmatrix} \mathbf{X}_I^A \\ \mathbf{X}_I^B \\ \mathbf{X}_C^A \\ \mathbf{X}_C^B \end{Bmatrix} = \begin{bmatrix} \mathbf{H}_{II}^A & \mathbf{H}_{II}^{AB} & \mathbf{H}_{IC}^{AA} & \mathbf{H}_{IC}^{AB} \\ & \mathbf{H}_{II}^B & \mathbf{H}_{IC}^{BA} & \mathbf{H}_{IC}^{BB} \\ & & \mathbf{H}_{CC}^A & \mathbf{H}_{CC}^{AB} \\ sym & & & \mathbf{H}_{CC}^B \end{bmatrix} \begin{Bmatrix} \mathbf{F}_I^A \\ \mathbf{F}_I^B \\ \mathbf{F}_C^A \\ \mathbf{F}_C^B \end{Bmatrix} \quad (5)$$

By the frequency response function based synthesis method, once the three-directional excitation force is specified, the displacement response of the bearings transmitted from the propeller and shaft can be computed with Eq.(5). Then, the excitation force transmitted to the vessel hull is calculated by Eq.(2). Since the excitation force is harmonic, the power flow of the propeller and the bearings is obtained at the same time which is an effective method for evaluating vibration and acoustic radiation level.

2.2 Dynamic properties of the propeller

The coupled FE/BE method is utilized to analyse the water-propeller coupled system. The coupled analyse model is shown in Fig.2. The propeller is modelled as solid elements and the water is modelled as acoustic boundary elements. The analysis of the water-propeller coupled dynamic properties is based on the modal reduction algorithm. The displacement response and the sound radiation power of the propeller under unit harmonic axial excitation force is exhibited in Fig.3 and Fig.4.

Fig.2 Acoustic-structure coupling analysis model for the propeller

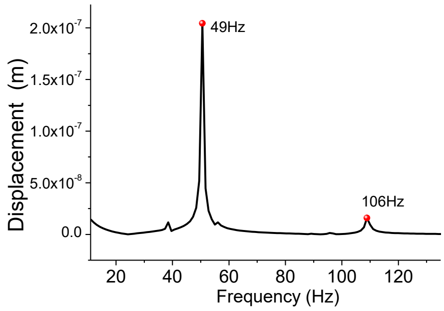


Fig.3 Displacement response of propeller

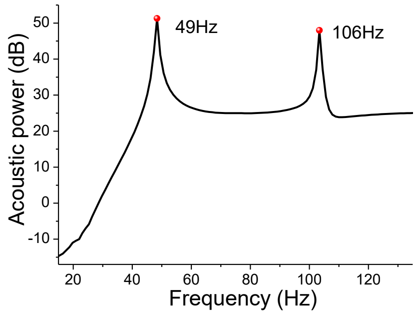


Fig.4 Acoustic radiation power of propeller

As depicted in the displacement response and the sound radiation power curve under propeller excitation, there are two characteristic peaks in the curve in low frequency range. The corresponding characteristic frequency is 49Hz and 106Hz. On the basis of the modal analysis of the water-propeller coupled system, the 1st umbrella wet mode frequency of the propeller is 49Hz and the 2nd umbrella wet mode frequency of the propeller is 106Hz. These umbrella wet modes determine the dynamic properties of the propeller in the low frequency range and the mode shapes are displayed in Fig.5 and Fig.6.

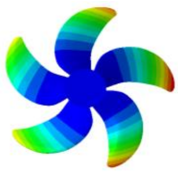


Fig.5 The 1st umbrella wet mode of propeller

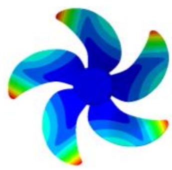


Fig. 6 The 2nd umbrella wet mode of propeller

2.3 Mobility matrix of the propeller-shaft coupled system

Fig.7 is the FE/BE coupled model of water-shaft-propeller coupling system. There are five blades in the propeller and several bearings in the shaft. In order to obtain the frequency response matrix of the propeller-shaft subsystem with high efficiency, the mode superposition method is employed instead of the multi-mode steady-state harmonic response calculation.

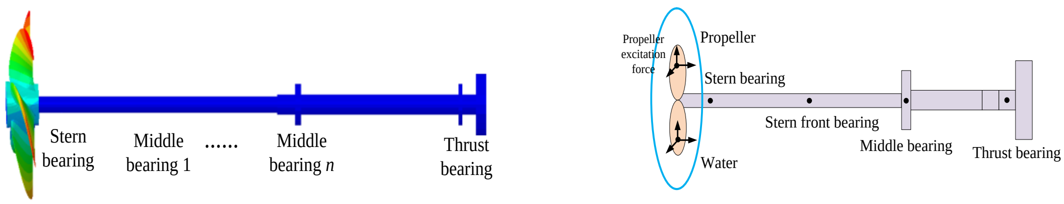


Fig.7 FE/BE coupled model of shaft-propeller subsystem.

The modal mass, modal frequency and modal displacement of the water-propeller-shaft coupled system are obtained from the FEM/BEM coupled modal analysis of the shaft-propeller subsystem. Then the frequency response matrix is computed with Eq.(6).

$$\mathbf{H} = \begin{bmatrix} H_{11} & \cdots & H_{1n} \\ \vdots & \ddots & \vdots \\ H_{n1} & \cdots & H_{nn} \end{bmatrix} \tag{6}$$

where $H_{pk}(\omega)=\sum_{r}^{N}\frac{\varphi_{pr}\varphi_{kr}}{M_r(\omega_r^2-\omega^2+i2\xi_r\omega_r\omega)}$, φ denotes modal displacement, M_r is modal mass, ω_r represents natural frequency, ξ_r denotes modal damping, ω is angular frequency and N stands for mode order. Besides, the coupled FE/BE method is also utilized to analyse the shaft- propeller subsystem. The bearings are modelled as flexible joints and the shaft-propeller is fixed to the ground through the flexible joints. The sound radiation power of the shaft-propeller coupled system under unit harmonic axial excitation force is shown Fig.8.

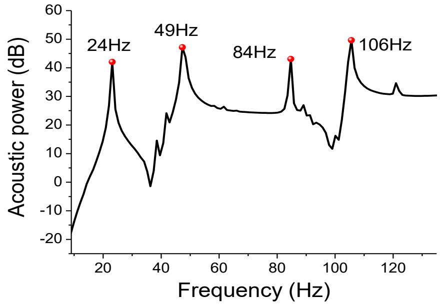


Fig.8 Acoustic radiation power of propeller-shaft system

2.4 Mobility matrix of the ship-water coupled system

Surface vessels are made up of numbers of complex shells and beams and the hull is partially submerged into water. For such a complex system, finite element method is a practical method to analyse the vibration properties of surface vessels. The water-ship coupled finite element model is established as Fig.9. There are 318232 elements in the ship structure model and 716731 elements in the water model. The unit harmonic excitation force is loaded to the hull from three directions through each bearing base. Then, the displacement responses of each bearing base are determined via steadstate harmonic response calculation. In another word, the origin mobility and cross-point mobility is specified. Then the frequency response matrix of ship-water coupled system is obtained.

Fig.9 Coupled FEM model of water and ship.

3. Vibration analysis of the propeller-shaft-hull coupling system

3.1 Force transmission and power flow of the system

The three directional propeller excitation force transmits to the ship hull through propeller-shaft subsystem. The axial excitation force is larger than the other two directions'. To analyse the acoustic radiation of surface vessels under longitudinal excitation, the axial unit harmonic excitation force is loaded at each propeller blade in the propeller model. Then, the force transmission and the power flow through the bearings to the hull can be evaluated with the proposed frequency response function based synthesis method.

The axial force transmission at the thrust bearing is displayed in Fig.10 and the input power flow at the propeller is shown in Fig.11. The characteristic frequencies of the response curves are 24Hz、49Hz、84Hz、101Hz. Based on the previous analysis of the propeller-shaft coupled subsystem, the first order longitudinal vibration frequency of the propeller-shaft is 24Hz. The 1st and the 2nd umbrella wet mode frequency of the propeller is 49Hz and 106Hz respectively. Besides, the resonance peak of 84Hz is induced by the coupling effect of the propeller and the bending mode of the shaft and the axial-bending coupling vibration of the shaft are worth noting.

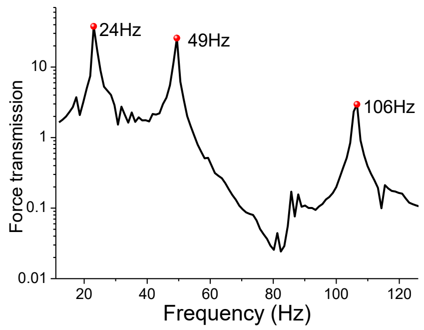


Fig.10 Longitudinal force transmission at thrust bearing.

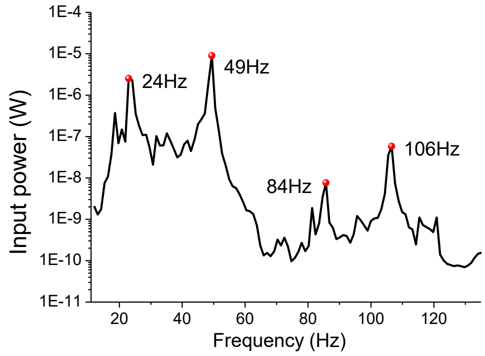


Fig.11 Input power at the propeller.

3.2 Sound radiation

With the frequency response function based synthesis method, the bearing forces of the ship is are obtained. Then, the bearing forces are applied as excitation source in the ship-water coupled model. After that, the coupled displacement response of the ship are determined. The vibration velocity of the hull surface serves as velocity boundary condition in sound field analysis. Finally, the underwater sound radiation power and distribution of sound field are computed.

Unlike submarines and other submerged marine structures, surface vessels are partially submerged in water. The underwater acoustic field of a surface ship is not free sound field. The water-air interface is an absolutely soft boundary. The boundary sound reflection of water-air interface needs to be taken into consideration. According to the mirror principle, a reverse virtual sound source is placed in the symmetrical position with the real sound source forming a combined dipole as shown in Fig.12. Then, the underwater sound pressure at any point *Q* can be calculated from the combined virtual dipole with Eq.(7).

$$p = \frac{A}{r_1} e^{j(\omega t - kr_1)} - \frac{A}{r_2} e^{j(\omega t - kr_2)} \qquad (7)$$

The boundary element mesh and the water-air interface are displayed in Fig.13. The sound radiation power and mean square velocity of the ship hull is exhibited in Fig.14 and Fig.15 respectively. The reference value of radiated sound power is $1\text{x}10^{-12}$w and the reference value of mean square velocity is 1m/s.

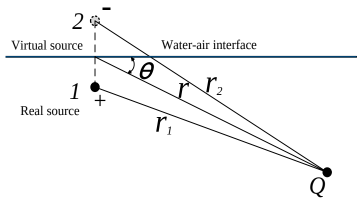


Fig.12 Description of acoustic dipole.

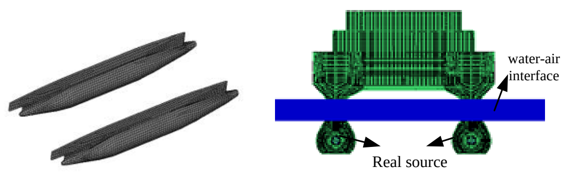


Fig.13 Boundary element mesh and simulation of free boundary.

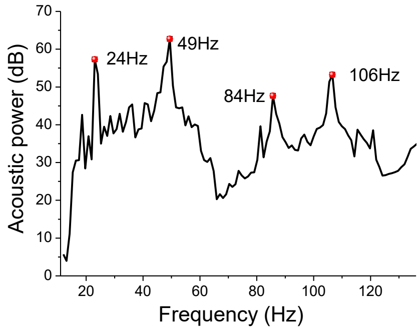


Fig.14 Sound radiation power.

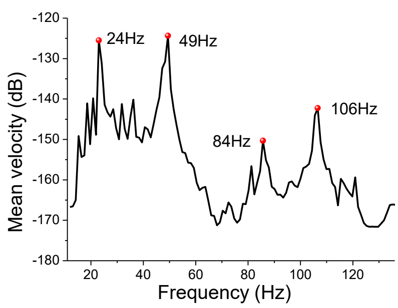


Fig.15 Mean square velocity.

The sound radiation power and the mean square velocity of the ship hull are shown in Fig.14 and Fig.15 respectively. By comparison Fig.14 with Fig.11, the main characteristic frequencies of the sound radiation power are the same with the power flow input from the propeller. The two curves are consistent with each other. Thus, the power flow input from the propeller can serve as an evaluation method for vibration and sound radiation of the ship which can be more efficiently obtained with the frequency response function based synthesis method instead of sound radiation calculation.

3.3 Effect of the acoustic radiation of the propeller

Since the sound power radiated from ship hull is calculated by the frequency response function based synthesis method, and the sound radiated directly by the propeller itself is not taken into account. Comparative analysis between the sound power radiated by the propeller and the ship hull are necessary. As shown in Fig.16, The sound radiation power of the ship hull is about 10 dB to 15 dB higher than sound radiation power of the propeller at the resonance peaks. So the sound power directly radiated by the propeller can be neglected compared to the ship hull radiation. The sound radiation level of ship hull can represent the sound radiation level of propeller-shaft-hull coupled system.

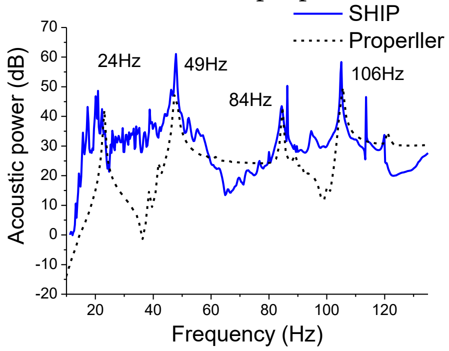
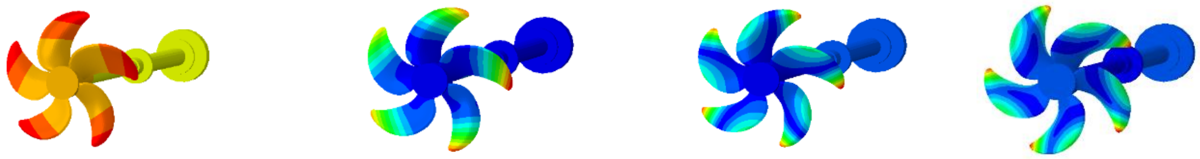


Fig.16 Acoustic radiation comparison between propeller and hull

Therefore, the characteristic frequencies of sound radiation power under axial excitation are the 1st longitudinal mode of coupled water-propeller-shaft subsystem and the 1st, 2nd umbrella wet modes of the propeller. The corresponding mode shapes of the characteristic frequencies of the propeller-shaft are exhibited in Fig.17. The optimal designs on reducing sound radiation under propeller excitation are mainly concentrated on parameters of the shaft and propeller. Meanwhile, the proposed method has high efficiency and advantages in terms of parameter analysis for shaft and propeller in the coupled system, which is of great significance in practical engineering.



24Hz（The 1st axial mode of propeller-shaft）

49Hz（The 1st umbrella wet mode of propeller）

84Hz（Axial-bending coupling mode of propeller-shaft）

106Hz（The 2nd umbrella wet mode of propeller）

Fig.17 Mode shapes for peak frequencies.

4. Parameter analysis of the system

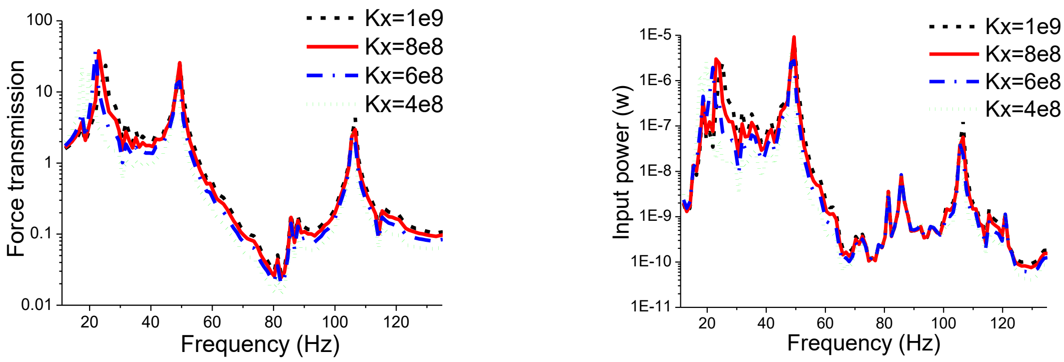


Fig.18 Force transmissions at thrust bearing and input power flow related to various axial stiffness of thrust bearing.

With the axial stiffness of thrust bearings changing in a certain range, based on the substructure synthesis method, the force transmission of the thrust bearing and the input power flow from the propeller are shown in Fig.18. Parameter analysis results indicates that the input power flow of the propeller and the force transmission at thrust bearing decrease as the axial stiffness of the thrust bearing decreases. From the previous analysis, it can be seen that the vibration and sound radiation power of the propeller-shaft-hull coupled system will be reduced.

5. Conclusion

In this paper, dynamic model of the propeller-shaft-hull coupling system of surface ship is established with frequency response function based synthesis method. The coupled FE/BE method is employed to establish the water-propeller-shaft coupled subsystem and the coupled FE method is utilized to model the ship-water coupled subsystem. Then, the vibration and acoustic radiation characteristics of the coupled system are analysed. The method proposed can take the elasticity of the propeller, the coupling effect of the propeller-shaft and the hull into consideration. The results show:

1. The characteristic frequencies of sound radiation power under axial excitation are the 1st longitudinal mode of coupled water-propeller-shaft subsystem and the 1st, 2nd umbrella wet modes of the propeller.
2. The characteristic frequencies of sound radiation power are mainly determined by parameters of the shaft and propeller. Therefore, the optimal designs on reducing sound radiation under propeller excitation are mainly concentrated on parameters of the shaft and propeller.
3. The proposed method has high efficiency and advantages in terms of parameter analysis for shaft and propeller in the propeller-shaft-hull coupled system, which is of significance in practical engineering.

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