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The study on the effect of the lateral vibration of shafting on underwater structural acoustic radiation

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Abstract

For the propeller running in the non-uniform wake fluid field, the lateral vibration of shafting is caused by the lateral propeller-excited force. The lateral vibration of shafting is transmitted through bearing supporting to underwater structure, which causes strong radiated noise from underwater structure. In this paper, the finite element method is adopted to build the finite element model of underwater structure with shafting, and calculate the vibration response of nodes on the interface between the structure and the fluid. The direct boundary element method is used to calculate the underwater structural acoustic radiation. Base on the finite element model, the effects of different stiffness of front or rear shafting bearing and different stiffness of supporting structure on reducing underwater structural acoustic radiation caused by the lateral vibration of shafting are discussed.

1. INTRODUCTION

For the propeller running in the non-uniform wake fluid field, the periods lifting and resistance are formed on blade surface. The resistance can be decomposed into two forces in horizontal direction and vertical direction and the lifting can be divided into two torques in horizontal direction and vertical direction, which cause the lateral vibration of shafting. The energy of shafting lateral vibration transfers from shafting to bearing supporting, thereby to the structure. The lateral vibration of shafting is one of the important sources which make underwater vehicle radiate strong noise.

In this paper, the finite element method[1][2] is adopted to build the model of underwater vehicle. The structure, the bearing supporting and the shafting are coupled together. The underwater structure radiated nose is calculated by direct boundary element method after the radial velocity of nodes on structure surface are gotten[3]-[6]. The effects of different stiffness of front or rear shafting bearing and different stiffness of supporting structure on underwater structural acoustic radiation caused by the lateral vibration of shafting are discussed.

2. FUNDAMENTALS

2.1 The fluid-structure coupled finite element equation

The fluid load is produced by vibration of structure at the fluid-structure interface, and the sound pressure exerts force on the structure at the same time. It is necessary to calculate the dynamic equation of structure and the wave equation of fluid simultaneously. The vibration equation of coupled fluid-structure can be written as

$$\begin{bmatrix} [M_e^s] & [0] \\ \rho[R_e^f] & [M_e^f] \end{bmatrix} \begin{Bmatrix} \{\ddot{u}_e\} \\ \{\ddot{p}_e\} \end{Bmatrix} + \begin{bmatrix} [C_e^s] & [0] \\ [0] & [C_e^f] \end{bmatrix} \begin{Bmatrix} \{\dot{u}_e\} \\ \{\dot{p}_e\} \end{Bmatrix} + \begin{bmatrix} [K_e^s] & -[R_e^f]^T \\ [0] & [K_e^f] \end{bmatrix} \begin{Bmatrix} \{u_e\} \\ \{p_e\} \end{Bmatrix} = \begin{Bmatrix} \{F_e^s\} \\ \{0\} \end{Bmatrix} \tag{1}$$

Using the Eq. (1) the displacement and pressure of the structure surface can be calculated at the same time. In Eq. (1), the matrix $[M_e^s]$ $[C_e^s]$ and $[K_e^s]$ is the mass matrix, damping matrix and stiffness matrix of structure respectively, and the matrix $[M_e^s]$ $[C_e^s]$ and $[K_e^s]$ is the mass matrix, damping matrix and stiffness matrix of fluid respectively. $[R_e^f]$ is coupling matrices. $\{u_e\}$ is the nodal displacement, and the $\{p_e\}$ is the nodal pressure.

2.2 Boundary element equation

The radiated pressure by structure vibration in fluid under harmonic force satisfies Hamholtz equation,

$$\nabla^2 p + k^2 p = 0 \tag{2}$$

Where $k = \omega/c$ is the wave number, p is the sound pressure, c is the sound speed, ω is the circular frequency of sound wave. At the fluid-structure interface, the coupling is related by the pressure gradient and the vibration velocity along the surface normal

$$\frac{\partial p}{\partial n} = -j\rho_f \omega v_n \tag{3}$$

Where n refers to surface normal vector, ρ_f is the fluid density, v_n is the normal velocity of node， respectively. The radiated pressure should be satisfied with the far field radiated condition

$$\lim_{r\to\infty}[r(\frac{\partial p}{\partial r} - ikp)] = 0 \tag{4}$$

$r = |Q - P|$, Q is any point on the surface S; P is any point in the fluid field. The equation (2) –(4) can be transformed to boundary integrate equation by Green's function

$$\int_s [P[Q\frac{\partial G(P,Q)}{\partial n}] + j\omega\rho v_n G(P,Q)]ds_Q = \begin{cases} P(r), r \in E \\ \frac{1}{2}P(r), r \in S \\ 0, r \in I \end{cases} \tag{5}$$

In which $G(r)$ is free-free Green's function, $G(r) = e^{-jkr}/(4\pi r)$, E, S, I refers to the reference point out the structure, on the structure surface and in the structure respectively. The equation (5) can be obtained in matrix form

$$[B]\{P\} = [C]\{v_n\} \tag{6}$$

Where $[B]$ and $[C]$ are the coefficient matrix of dimension $N \times N$. $\{P\}$ is the matrix of node pressure. $\{v_n\}$ is the matrix of node normal velocity. The radiated sound power of structure can be achieved in the following equation

$$W_s = \frac{1}{2}\iint_s \mathrm{Re}\left[P_s \bullet (v_n)^*\right] dS \tag{7}$$

3. NUMBER RESULTS AND DISCUSSIONS

The model adopted in this paper is composed of four main parts, which are a conical shell, a cylindrical shell, a half sphere shell and the shafting. The shafting is connected with the shell by front bearing, rear bearing and thrust bearing.

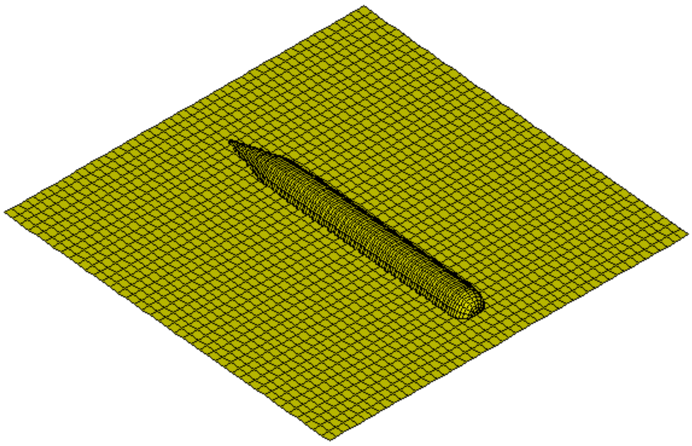


Fig.1. Structure model and acoustic field mesh

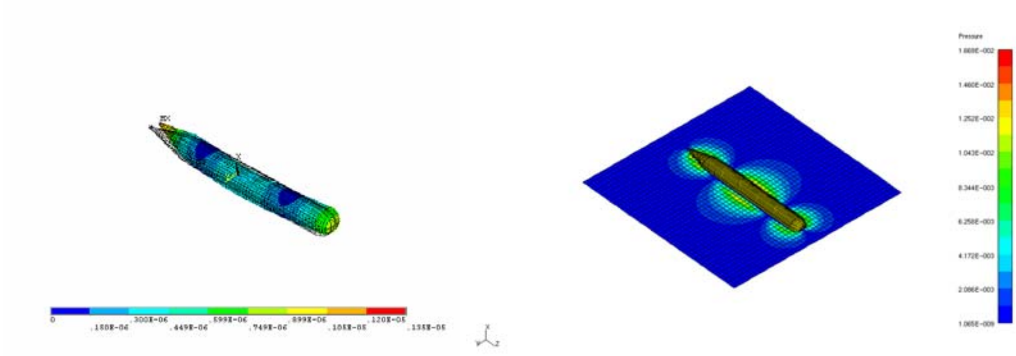
The structure is assumed to have a Youngs's modulus of E=2.06E11N/m^2, Poisson's ratio $\nu = 0.3$. The sound speed in the surrounding fluid is assumed to be 1500m/s. The density of fluid is assumed to be 1000 kg/m^3.

The shell is meshed into 9763 elements and 8364 nodes. Including the propeller and bearing, the shafting is meshed into 81 elements and 81 nodes. The thrush bearing supporting is assumed as a beam connected with the shell and the shafting. The propeller is predigested as a mass point. The unit lateral force and torque is applied at the propeller side. The reference power level is 1.0e-12W.

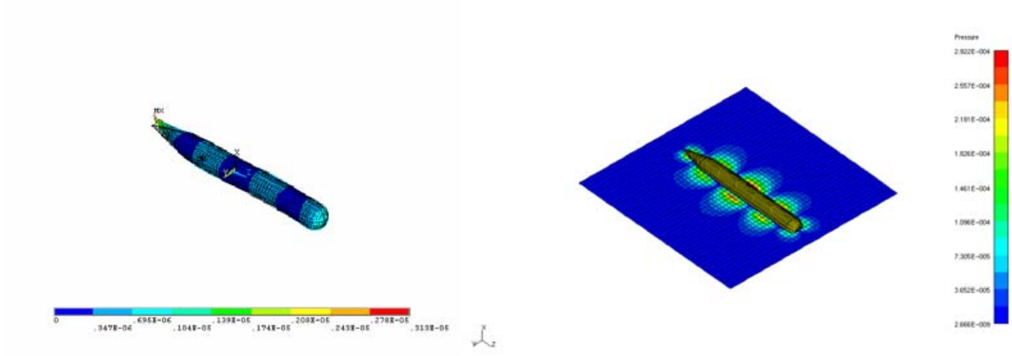
3.1 Forced vibration of underwater structure

In this section, the eigenvalue and modal shape of the underwater structure is calculated by FEM. The vibration response of structure is calculated when the excited force is applied at the propeller side. Using the radial velocity on the structure surface, the distribution of underwater structure radiated pressure is calculated by direct boundary element method.

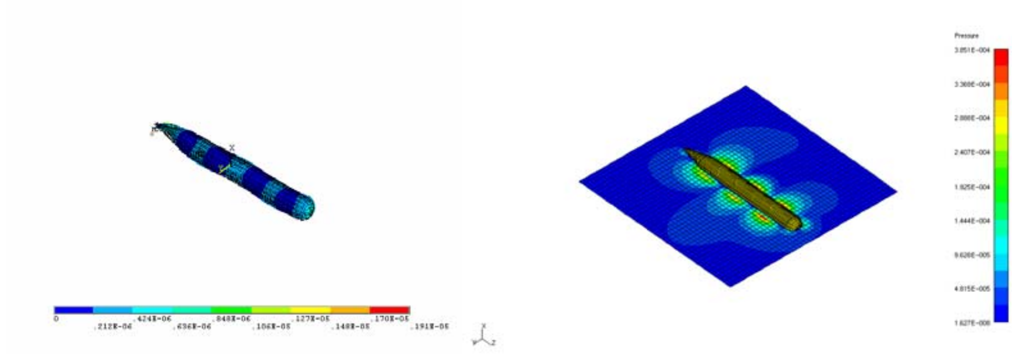
The modal shapes and distribution of pressure of structure in some typical frequencies are shown in Fig.2.



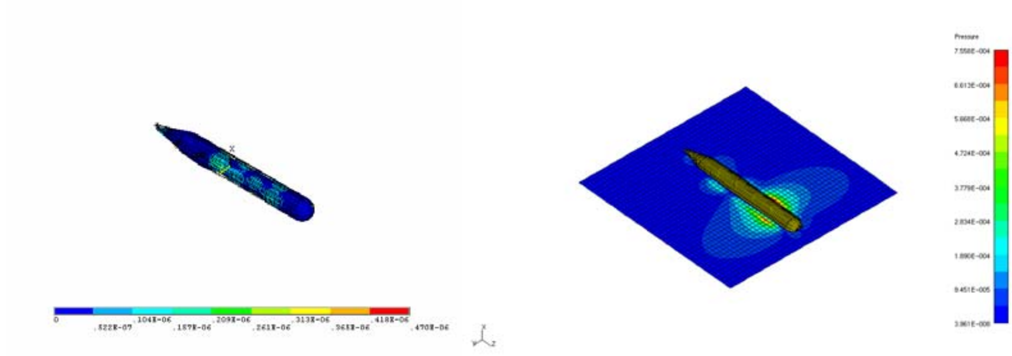
(a) The first flexible mode



(b) The second flexible mode



(c) The third flexible mode



(d) The first circumferential mode

Fig.2. modal shapes and distribution of pressure of structure in typical frequency

Comparing to the length of calculating model, the diameter of model is much smaller. In low frequency, the flexural mode shape is in the highest flight. The shape of distribution of radiated pressure is same as the modal shape of structure.

The exciting force is vertical and the axial of structure is horizontal, which mainly cause the structure flexural modes being excited.

3.2 Changing parameters

The lateral exciting force is imposed on structure through front bearing, rear bearing and thrust bearing. The vibration and radiated noise of structure caused by lateral vibration of shafting can be reduced by changing the propagation path of exciting force or by decreasing the amplitude of exciting force. The lateral exciting forces imposed on structure are different in different position and the amplitude of exciting force is changing greatly with frequency changing, which make the vibration of structure caused by shafting lateral vibration difficult to be reduced.

3.2.1 Different stiffness of bearing

The structure and the shafting is related by bearing. The effect of different stiffness of front and rear bearing on radiated pressure level will be discussed in following section.

Different stiffness of rear bearing

In model2 and model3, keeping the stiffness of front bearing as a constant, the stiffness of rear bearing is changed to 0.1 and 10 times respectively. The underwater structure radiated sound power is calculated, and is shown in Fig. 3. The fc is circumferential frequency of cylindrical shell.

With the decreasing of stiffness of rear bearing, the exciting force imposed on structure is reducing at the rear bearing position, and the exciting force is increasing at the front bearing position. Fig. 3 shows that the stiffness of rear bearing has great effect on the radiated sound power of structure. The radiated sound power is reducing with the rear bearing stiffness reducing. That means that the vibration of structure caused by lateral vibration of shafting is mainly dependent on exciting force at rear bearing side.

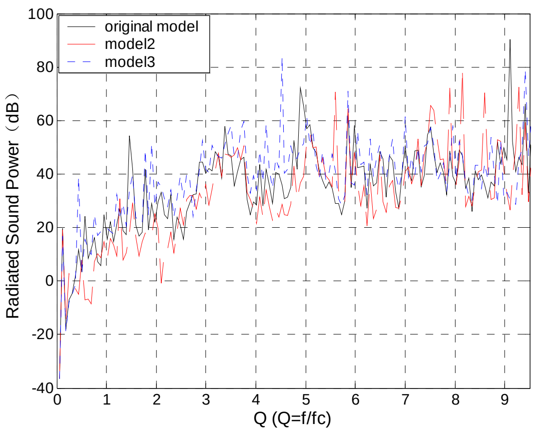


Fig.3. the radiated sound power in different stiffness of rear bearing

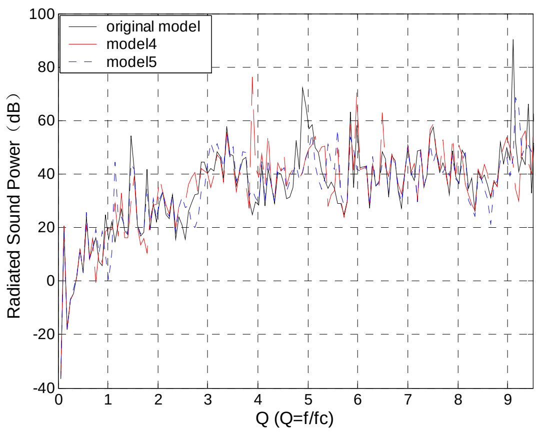


Fig.4. the radiated sound power in different stiffness of front bearing

Different stiffness of front bearing

In this section, two different calculating models are selected. The stiffness of front bearing is changing 0.1 times than original model in model4 with the rear bearing stiffness fixed and the stiffness of front bearing is changing 10 times in model5. The curves of underwater structure radiated sound power of three different models are compared and shown in Fig. 4.

The effect of different stiffness of front bearing on structure radiated sound power is not clearly. The lateral vibration natural frequency of shafting is reducing by decreasing the stiffness of front bearing. The peak value of exciting force is moving to lower frequency. The amplitude of exciting force has little reduce. Compared with the original model, the radiated sound power level is increasing in model4 near some frequency.

Different stiffness of front and rear bearing

The stiffness of front and rear bearing are changed together to 0.1 and 10 times as model6 and model 7 respectively, the changing trend of underwater structure radiated sound power can be shown in Fig.5.

When the stiffness of front and rear bearing are decreasing, the lateral vibration natural frequency of shafting is reducing. The peak value of exciting force is moving to lower frequency. The amplitude of exciting force on both bearing supporting is sharply reduced which causes the structure radiated sound power decreased greatly.

The exciting force imposed on rear bearing supporting increasing and the exciting force imposed on front bearing supporting has little decreasing when the stiffness of front and rear bearing are increasing. The structure radiated sound power caused by rear bearing force is higher, so the structure sound power radiate increased.

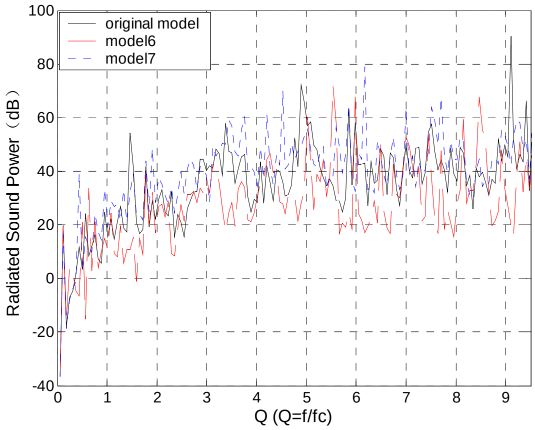


Fig.5. the radiated sound power in different stiffness of front and rear bearing

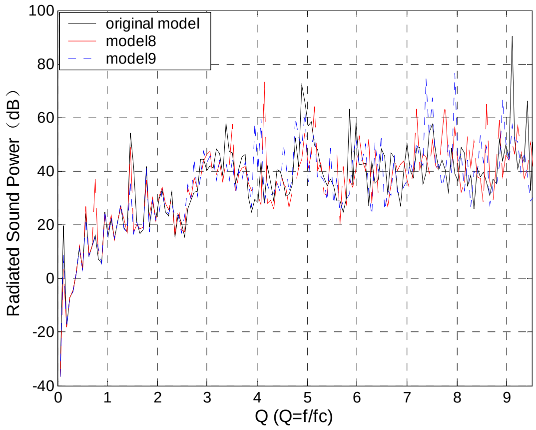


Fig.6. the radiated sound power in different supporting stiffness

The effect of stiffness of rear bearing on structure sound power radiated is great and the stiffness of front bearing has little effect on reducing radiated noise. The lower vibration and radiated noise can be achieved by reducing the stiffness of rear bearing properly.

3.2.2 Different stiffness of supporting

The lateral force of shafting transfers through the bearing to supporting, thereby to structure. Not only the stiffness of bearing can bring great influence on natural frequency of structure and exciting force, but the stiffness of bearing supporting can influence the lateral exciting force. In this section, the radiated sound power will be calculated in different stiffness of supporting.

Model1 is original model, and the thickness of supporting of model7 thin 2mm. In model8, the thickness of supporting is thicker than that of model1. Fig.8 shows that the radiated sound power is reducing with the decreasing of thickness of supporting structure. In high frequency, there are more natural frequencies of supporting structure, which causes more peak values in structure radiated sound power curve.

4. CONCLUSIONS

The finite element model of underwater vehicle with shafting is built, which can be used to calculate the underwater structure radiated noise caused by lateral vibration of shafting. In the same boundary condition, the effects of different stiffness of front or rear shafting bearing and different stiffness of supporting structure on reducing underwater structural acoustic radiation are discussed.

1. Because of different position and amplitude of exciting force, the radiated noise caused by exciting force through rear bearing is higher than other bearing for the same calculating model.
2. It has great effect for underwater structure radiated noise that the stiffness of rear bearing is changed, and the effect of different stiffness of front bearing on radiated noise is smaller. The lower radiated pressure can be achieved by reducing the stiffness of rear bearing.
3. The radiated noise can be little reduced by changing the stiffness of bearing supporting. The characteristic of vibration of exciting force imposed on structure can be changed after it transfer from the bearing supporting, which bring more peak values in radiated sound power curve.

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