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Numerical and experimental investigation on vibro-acoustic response of a shaft-hull system

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ABSTRACT

The vibro-acoustic characteristics of a submerged shaft-hull system are investigated by numerical and experimental methods. A numerical model for the structure-fluid interaction of the system is formulated by the coupled finite element/boundary element methods. With this model, the influence of the shaft vibration on the dynamic and acoustic responses of the submerged shaft-hull system is analyzed via the modal decomposition technology. It is found that reduction of the stiffness of the stern bearing and symmetrization of the foundation can reduce the sound radiation from the submerged shaft-hull system subjected to transversal and axial force excitations, respectively. The numerical solutions are validated by the experimental results, and reasonable agreement is observed.

1. Introduction

The prediction of vibro-acoustic behavior of a submarine and an effective method for reduction of noise from a submarine are of great importance but present prominent challenges to the research community. Transmitting through the propulsion shafting system, the fluctuating forces induced by the rotation of propeller in a non-uniform wake may excite the vibration of the pressure hull of a submarine, and further result in a significant acoustic signature on sonar.

Owing to the complexity of physical configuration of modern submarines, a submarine is often simplified as a pressure hull coupled with a shaft in order to achieve a feasible theoretical analysis [1–3]. The pressure hull is treated as a stiffened cylindrical shell closed by conical or semi-spherical shells. Qu et al. [4] presented a theoretical analysis for a coupled spherical–cylindrical–spherical shells stiffened by ring and stringer reinforcements, in which the structural model of the shell and acoustic model of the fluid are derived by a modified variational principle and a spectral Helmholtz formulation. The displacement and sound pressure are represented in the forms of the Fourier series and the Chebyshev orthogonal polynomials, respectively. The modal contributions to the sound radiation from the shell are also studied. However, the semi-analytical solutions may be restricted to the fluid-structure interaction and sound radiation problems involving structures with simple geometrical configurations. For the virbo-acoustic analyses of a complex structure, such as the shaft-hull system, numerical or experimental methods are often implement. To solve a acoustic modelling problem, the boundary element method (BEM) has the advantage that all discretization and numerical approximations are placed on the surface of a vibrating structure. Moreover, when the fluid is of an infinite extent, the outgoing radiation condition at infinity is automatically satisfied in the BEM [5]. Merz et al. [1,2] utilized the finite element method (FEM) and boundary element method and analyzed the vibro-acoustic behavior of a submarine hull excited by axial excitation. However, they did not consider the vibro-acoustic responses of the model under vertical force excitation.

The experimental studies pertaining to the dynamic and acoustic characteristics of an underwater structure may be viewed complement and validation of the corresponding theoretical analyses. The literature [6,7] concerning the vibro-acoustic characteristics of a finite cylindrical shell by experiment is abundant, but the research effort related to the experiments of shaft-hull system or coupled shells is rare relatively. Cao [8] carried out a vibration test for a shaft-hull system in air, and pointed out that the transversal force applied at the propeller mainly transmits through the stern bearing to the hull. Liu et al. [9] and Pan et al. [10] performed a series of experiments on vibration and sound radiation of a torpedo-shaped structure in air and water.

The essences of free vibration and forced vibration of an elastic

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structure are wave motions in the structure [5]. Williams et al. [11] analyzed the *K* space of the radial displacements of a cylindrical shell to reveal the wave propagation in the shell. Peters and Kessissoglou [12] presented a modal decomposition technique to analyze the acoustic contributions from a certain vibration. The two methods mentioned above provide physical insights into the vibro-acoustic problem of a submerged structure by numerical or experimental methods.

To reduce the noise radiated from a shaft-hull system, different kinds of control methods, such as vibration isolation, absorption and active cancellation are introduced in Refs. [13–20]. An electronically controlled magnetic thrust bearing was utilized to control fluctuant propeller forces [13,14]. A semi-active dynamic vibration absorber (DVA), which is made of magneto-rheological elastomers, seems better than a passive DVA in attenuating the axial vibration of a marine shaft [15]. Active vibration control of a shafting system was studied by Zhang et al. [16]. The results have demonstrated that not only the longitudinal vibration in the shaft but also the lateral vibration in the plate/hull can be excited by axial force excitation and be attenuated by the active control. A resonance changer (RC) acting as a vibration absorber was implemented in the propeller-shafting system to reduce transmission of axial dynamic force from the propeller to the hull [1–3]. On account of the narrow working frequency of a RC, Merz et al.[17] combined the RC with an active control system to suppress the sound radiation from a shaft-hull system. A flanged foundation was employed to control the vibro-acoustic responses of a submarine hull [18], but the reason that the effects of the flanged foundation on sound radiation was not thoroughly discussed. Song et al. [19] investigated the influences of an integrated isolation which consists of a periodic isolator and a dynamic absorber on the radiated noise of an underwater vehicle. The numerical results have shown that effects of noise control the device can be enhanced using the stop band properties of the periodic isolator. For the vibration control of the transversal force excitation case, Feng [20] pointed out that the decrease of the stiffness of the stern bearing can be utilized to reduce the transmission of the power flow from the shaft to the hull in air.

In this paper, the numerical and experimental models have been developed to investigate the fluid-structure interaction problem of a shaft-hull system submerged in water in the low-frequency range. The influence of the shaft on the vibro-acoustic responses of the shaft-hull system is discussed. Furthermore, to reduce the acoustic responses of the system, the performance of a symmetrical foundation is examined.

2. Experimental system

The shaft-hull system considered in this paper is illustrated in Fig. 1. All the components in the system are made of steel, and the material data is given as: the density 7800 kg/m^3, the Young's modulus 2.1×10^{11} Pa and the Poisson's ratio 0.3. The hull of 7.53 m length, 0.728 m diameter and 0.003 m thickness includes three cabins, the stern cabin, cylindrical cabin and forward cabin, joined together via the flange connections. Six T-section ring stiffeners are evenly spaced by 0.9 m in the axial direction of the cylinder. A series of ring stiffeners with rectangular cross section (0.02 m × 0.006 m) are equally placed along the length of the stern and cylindrical cabins. The axial spacing between two adjacent stiffeners is 0.115 m. The length and radius of the shaft are 1.53 m and 0.15 m, respectively. The propeller is a lumped mass block of 4 kg, which is numbered 1# in Fig. 1. For the sake of brevity, the rotation of the shaft in the model is not allowed, and therefore the journal bearings are not lubricated by oil or water. As shown in Fig. 1, the intermediate bearing is composed of rubber and steel cylinders. The stiffness of the intermediate bearing mainly depends on the stiffness of the hollow rubber cylinder, and is about 0.8–1.2×10^7 N/m by measuring the rubber. The stern bearing is of the same structure as the intermediate bearing, and the stiffnesses of the journal bearings are chosen as 1×10^7 N/m in the numerical model. Since the actuator has a constant force sensitivity over the test band, force transducers are unnecessary. Three actuators (4# and 8# in Fig. 1) are used to generate exciting forces in the axial, vertical and horizontal directions.

The experiment was carried out in a lake, which is for underwater acoustic experiment. The experimental system is shown in Fig. 2. In the system, the random signal provoked by the LMS signal generator is amplified by the power amplifier to drive the electromagnetic actuators, and the excitation forces were applied to the shaft in the vertical, horizontal and axial directions, respectively, to simulate excitation forces of the propeller. As shown in Fig. 3, sixty-six accelerometers were divided into 11 groups averagely, and mounted inside of the hull to measure the radial vibration of the hull. The angle between each accelerometers in one cross section is 60°. Five accelerometers are utilized to measure the vibration of the shaft. Six B&K

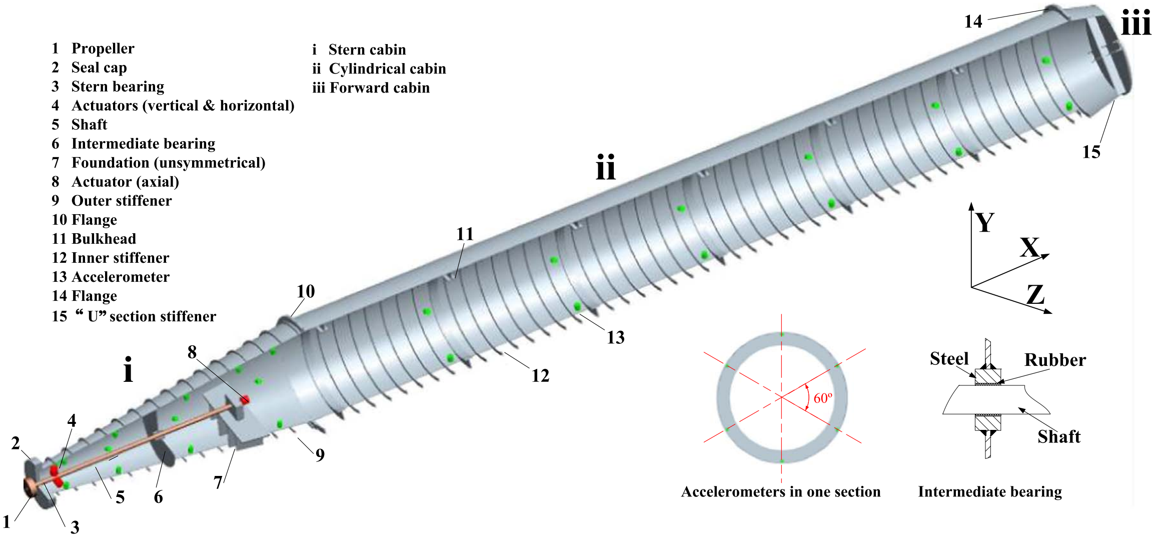

Fig. 1. The experimental shaft-hull system.