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Structural vibration and acoustic radiation of coupled propeller-shafting and submarine hull system due to propeller forces

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ABSTRACT

This paper investigates the structural and acoustic responses of a coupled propeller-shafting and submarine pressure hull system under different propeller force excitations. The entire system, which consists of a rigid propeller, a main shaft, two bearings and an orthogonally stiffened pressure hull, is submerged in a heavy fluid. The shaft is elastically connected to the pressure hull by a radial bearing and a thrust bearing. The theoretical model of the structural system is formulated based on a modified variational method, in which the propeller, the main shaft and the bearings are treated as a lumped mass, an elastic beam and spatially distributed spring-damper systems, respectively. The rings and stringers in the pressure hull are modeled as discrete structural elements. The acoustic field generated by the hull is calculated using a spectral Kirchhoff-Helmholtz integral formulation. A strongly coupled structure-acoustic interaction analysis is employed to achieve reasonable solutions for the coupled system. The displacement of the pressure hull and the sound pressure of the fluid are expanded in the form of a double mixed series using Fourier series and Chebyshev orthogonal polynomials, providing a flexible way for the present method to account for the individual contributions of circumferential wave modes to the vibration and acoustic responses of the pressure hull in an analytical manner. The contributions of different circumferential wave modes of the pressure hull to the structural and acoustic responses of the coupled system under axial, transversal and vertical propeller forces are investigated. Computed results are compared with those solutions obtained from the coupled finite element/boundary element method. Effects of the ring and the bearing stiffness on the acoustic responses of the coupled system are discussed.

1. Introduction

The fundamental characteristic of a modern submarine is stealth, which can be considered a measure of the ability of the submarine to operate undetected against threats in designated mission areas. However, a number of significant sources of vibration and radiation noise exist in a submarine, which may be detected by the sonar arrays of enemy forces. An important

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proportion of the radiated noise from a submarine is due to the rotation of the propeller in a non-uniform wake, resulting in harmonically varying forces on the propeller [1,2]. These propeller forces are transmitted to the submarine pressure hull through the shaft, bearings and elastic foundations, leading to significant sound radiation of the hull. A deep insight into the vibration and acoustic responses of the coupled shafting and pressure hull system is of great importance to the practical design of a stealth submarine.

Considerable effort has been devoted to the prediction of structural-borne sound of underwater structures, which may serve as a foundation for the understanding of the vibration and acoustic behaviors of submarines. In a submarine, the pressure hull is the primary radiator of overall noise, which, in general, is a complex and non-homogeneous shell-shaped structure. At lower frequencies, the pressure hull is commonly simplified as a long, thin stiffened cylindrical shell. For the analysis of the acoustic radiation from a fluid-loaded cylindrical shell, analytical methods involving separation of variables may be successfully implemented. Important results from the application of analytical methods to the acoustic radiation of cylindrical shells immersed in heavy fluids have been reported by Williams et al. [3], Paslay et al. [4], Harari and Sandman [5], Stepanishen [6], Burroughs [7], and Laulagnet and Guyader [8], to name a few. Since the pressure hull in a practical submarine is far more complex than a cylindrical shell, the cylinder configuration may not be able to fully represent the structural and acoustic behaviors of the hull. Caresta and Kessissoglou [9] developed an analytical model for predicting the acoustic responses of a submarine hull under axial excitation, in which the hull was modelled as a ring-stiffened cylindrical shell with internal bulkheads and closed at each end by circular plates. Maxit and Ginoux [10] proposed a circumferential admittance approach for the acoustic analysis of an externally fluid loaded shell with non-uniformly spaced stiffeners and transversal bulkheads. Pan et al. [11] analyzed the active control of the low-frequency radiated sound pressure from submarine pressure hulls. The pressure hulls were modelled as finite cylindrical shells with circumferential ring stiffeners and rigid end plates, and the ends of the cylindrical shells were closed by hemispherical and conical shells. Caresta and Kessissoglou [12] presented a semi-analytical model to predict the structural and acoustic responses of a submerged vessel in the low frequency range, in which the submarine hull was modelled as a cylindrical shell with internal bulkheads and ring stiffeners. The cylindrical shell was closed by truncated conical shells, which in turn were closed at each end using circular plates. Later, Caresta [13] employed this model and investigated the use of inertial actuators to reduce the radiated sound from a submarine pressure hull in bending vibration and under harmonic excitation from the propeller. Qu et al. [14] developed a semi-analytical method to predict the vibration and acoustic responses of submerged spherical-cylindrical-spherical shells stiffened by circumferential rings and longitudinal stringers. Peters et al. [15] developed a modal decomposition method for predicting the acoustic responses of elastic structures submerged in a heavy fluid medium using fluid-loaded structural modes. The radiated sound from a fluid-loaded cylindrical shell closed at each end by hemispherical end caps was examined. Choi et al. [16] studied the acoustic radiation from submerged coupled spherical-cylindrical-spherical shells with non-axisymmetric internal substructures. Mertz et al. [17] employed the finite element method and boundary element method to predict the vibration and acoustic responses of a coupled propeller-shafting and submarine hull system, and a passive vibration attenuation system was introduced in their model. Caresta and Kessissoglou [18] investigated the reduction of the far-field radiated sound pressure from a submarine using a resonance changer implemented in the propulsion system. The propeller-shafting system was modeled by a modular approach using a combination of mass-spring-damper elements, beams, and shells. Peters et al. [19] developed a coupled finite element/boundary element model for predicting the acoustic responses of fluid-loaded cylindrical hulls closed by hemispherical end caps and with internal structures.

Although the conventional coupled finite element/boundary element methods using two-dimensional elements can be employed to analyze the structural-acoustic problems of the propeller-shafting and pressure hull system, the computational cost of these methods is quite expensive, and moreover, they provides poor physical insight into the vibro-acoustic behaviors of the system. On the contrary, an analytical method may be applied to the structural-acoustic problem of a simplified propeller-shafting and pressure hull system, providing greater physical insight into the physical mechanisms that are very valuable in the preliminary design process of a submarine. As indicated above, very limited research effort has been devoted to the structure-acoustic interaction analysis of a coupled propeller-shafting and submarine hull system using analytical/semi-analytical methods. In the previous analytical models of the coupled propeller-shafting and pressure hull system, only the axial motion of the propeller-shafting system has been considered, and the shaft was either modeled as a simple spring-mass-damper element [2,17] or a rod with longitudinal vibration [18]. In addition, to reduce the complexity of the analytical modeling, axisymmetric pressure hulls were mostly considered, and therefore, the structure-acoustic problem of the hull can be decoupled for each circumferential harmonic wave. In a real submarine, longitudinal stringers or frames are placed along the lengthwise direction of the pressure hull. This increases the complexity of the analytical modeling of the pressure hull and leads to a totally coupled system of all circumferential harmonic waves of the hull. When the transversal and vertical propeller forces are considered to excite the system, the radial and thrust bearings which connect the main shaft and the pressure hull should be considered in the modelling, and the flexural motions of the main shaft must be taken into account. All the previous analytical works have not taken into account the flexural motions of the propeller-shafting system in the vibro-acoustic analysis of a coupled propeller-shafting and pressure hull system. The focus of this work is to develop a semi-analytical model for predicting the structural and acoustic responses of the coupled propeller-shafting and pressure hull system in an underwater submarine. The propeller-shafting system is composed of a rigid propeller, an elastic shaft, a radial bearing and a thrust bearing. The pressure hull is modelled as a thin cylindrical shell closed by hemispherical end caps at two ends, and stiffened by a series of ring stiffeners and longitudinal stringers. The axial, transversal and vertical motions