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Vibration and acoustic radiation of a finite cylindrical shell submerged at finite depth from the free surface

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ABSTRACT

The far-field acoustic radiation of a cylindrical shell with finite length submerged at finite depth from the water surface is studied. Two steps are utilized to solve the problem. The first step is to determine the vibration response of the submerged cylindrical shell by using an analytical method and the second one is to determine the far field sound radiation with the boundary element method. To address the vibration responses of the shell analytically, the cylindrical shell and surrounding fluid are described by the Flügge shell equations and Laplace equation in the cylindrical coordinate system respectively. The free surface effect is taken into consideration by using the image method and the Graf's addition theorem. The reliability and efficiency of the present method are validated by comparison with the finite element method. Then, based on the vibration responses of the shell obtained from the first step, the far-field sound pressure is computed by using the boundary element method. It is found that the vibration of the cylindrical shell submerged at finite depth from the free surface tends to be the same as that in infinite fluid when the submerged depth exceeds a certain value. The frequency and the submerged depth have crucial effects on the fluctuation of the far-field sound pressure, while for the curve of sound pressure level versus immersion depth, the ratio of the distance between the adjacent peak points of sound pressure to the wavelength is independent of the frequency. Moreover, the petal number of the directivity of the far-field sound pressure increases with the increase of the frequency and the submerged depth. The work provides more understanding on the vibration and acoustic radiation behavior of a finite cylindrical shell submerged at finite depth.

1. Introduction

A significant amount of research on the vibration and sound radiation of the cylindrical shell has been carried out and reported. The cylindrical shell was usually assumed to be submerged in an infinite fluid, thus the influence of the boundary of the fluid region on the vibration and acoustic radiation of the cylindrical shell was usually not taken into consideration [1–4]. In engineering practice, however, the fluid region surrounding the cylindrical shell is bounded.

Some researchers carried out the vibration and sound analyses of cylindrical structures in consideration of fluid

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boundary. Ergin [5] analyzed the dynamic characteristics of a flexible cylinder vibrating in air and at fixed positions below a free surface in water of finite depth based on the experimental data and theoretical predictions derived from a three-dimensional hydroelastic mathematical model. In order to impose an appropriate boundary condition on the free surface, Ergin [6] introduced a boundary integral equation method and the image method to study the free vibration of a partially liquid-filled and submerged, horizontal cylindrical shell. Jouaillec and Jacquart [7] studied the far-field sound pressure radiated from an infinite cylindrical shell half-immersed in the fluid with an analytical theory and presented a numerical method based on finite elements and integral equations for the case of a partially immersed finite cylindrical cylinder. The main result was that the far-field pressure is reduced when the structure is driven by a point force above the free surface. Pierre Salaün [8] investigated an open cylindrical shell and a closed cylindrical shell half-immersed in the fluid and excited by a point force at high frequencies. It was found that the sound pressure is not always reduced but dependent on the excitation position on the shell, i.e., the dry part or the wet part. The effect of damping on the sound pressure radiated from the shell was also investigated. The sound pressure radiating from a semi-submerged infinite cylindrical shell filled with fluid was studied by Li and Wu [9] The effects of the parameters such as the Mach number of the filled fluid, the thickness of the shell and the structure damping on the far-field sound pressure were examined. Based on the image method, the Graf's addition theorem and the stationary phase method, Li et al. [10] proposed an analytical method to investigate the far-field sound radiation of an infinite cylindrical shell submerged at finite depth below the free surface. It was found that the submerged depth had a significant influence on the far-field sound pressure radiated from the submerged cylindrical shell due to the free surface effects. Wang et al. [11] developed an approach for predicting the vibro-acoustic characteristics of a semi-submerged infinite cylindrical shell based on the sound-structure coupling theory, in which a diagonal coupling algorithm was put forward to increase the computational efficiency. Actually, the forced vibration of a submerged finite cylindrical shell at finite water depths makes sense in engineering, and the analytical solution had not been reported in previous works to the authors' knowledge.

The analytical solution for the acoustic radiation of the cylindrical shell with finite length is difficult to obtain due to the complex boundary condition caused by the free surface. The partly immersed finite cylindrical shell or the finite cylindrical shell at finite depth from the free surface can be seen as structures in half space, and the numerical approach combining finite element with boundary element methods is often employed to calculate the acoustic field radiated from underwater or partly immersed structures. Chen et al. [12] used a coupled finite element and boundary element method to compute the response and acoustic radiation for structures partially immersed in fluid. The response of the structure is assumed to be symmetric about a plane, and the numerical efficiency was improved by employing a variable banded storage method and invert of the matrix. Zhou and Joseph [13] combined the finite element method with the boundary element method to analyze the dynamic response and acoustic radiation from an underwater ribbed cylindrical shell. Brunner et al. [14,15] proposed a fast BE-FE coupling scheme (the fast multipole boundary element method coupled with the finite element method) to investigate the vibro-acoustic behavior of a partly immersed finite cylindrical shell and a ship model. This coupling BE-FE method was also adopted and developed by Junge et al. [16,17].

The numerical approaches are commonly used for solving the vibration of complex structures, however, the pretreatment and the computational cost are usually expensive. Given these, in this paper, an analytical method is proposed to solve the vibrational response (the radial displacement and velocity) of a submerged finite cylindrical shell at finite water depth firstly. The radial displacement obtained with the analytical method agrees well with that obtained with the numerical simulation method, and the computational cost is markedly reduced. Then the far-field acoustic radiation of the submerged finite cylindrical shell is studied by employing the boundary element method: the outer surface of the finite cylindrical shell is divided into a number of quadrilateral elements and the radial velocities of the nodes of these quadrilateral elements are substituted into the boundary integral equation to calculate the sound pressure. A series of interesting phenomena are observed and the mechanism of these phenomena is explained based on the superposition principle of acoustic dipole.

2. Theoretical analysis of shell vibration

As shown in Fig. 1, a simply supported finite thin circular cylindrical shell of length L, thickness h, radius R, Yong's modulus E, Poisson's ratio μ, and density ρ, is considered to be submerged in a fluid with the density ρ_f and the sound

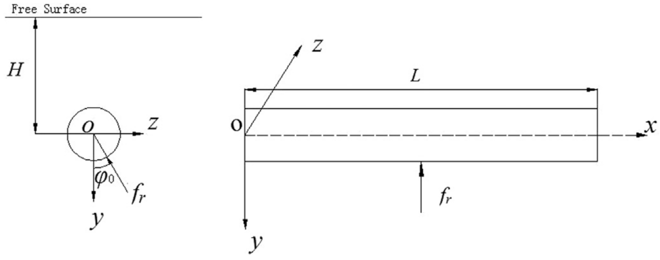

Fig. 1. A submerged cylindrical shell and the corresponding coordinate system.

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