Journal of Sound and Vibration 422 (2018) 48–61

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Sound-structure interaction analysis of an infinite-long cylindrical shell submerged in a quarter water domain and subject to a line-distributed harmonic excitation

Wenjie Guo [a, b], Tianyun Li [a, b, c], Xiang Zhu [a, b, c, *], Yuyue Miao [d]

[a] *School of Naval Architecture and Ocean Engineering, Huazhong University of Science & Technology, Wuhan, 430074, China*
[b] *Collaborative Innovation Center for Advanced Ship and Deep-Sea Exploration, Shanghai, 200240, China*
[c] *Hubei Key Laboratory of Naval Architecture & Ocean Engineering Hydrodynamics, Wuhan, 430074, China*
[d] *China Ship Development and Design Center, Wuhan, 430064, China*

A R T I C L E I N F O

Article history:
Received 4 May 2017
Received in revised form 27 January 2018
Accepted 14 February 2018
Available online 22 February 2018

Keywords:
Submerged cylindrical shell
Free surface
Rigid surface
Vibration
Acoustic radiation
Quarter water domain

A B S T R A C T

The sound-structure coupling problem of a cylindrical shell submerged in a quarter water domain is studied. A semi-analytical method based on the double wave reflection method and the Graf's addition theorem is proposed to solve the vibration and acoustic radiation of an infinite cylindrical shell excited by an axially uniform harmonic line force, in which the acoustic boundary conditions consist of a free surface and a vertical rigid surface. The influences of the complex acoustic boundary conditions on the vibration and acoustic radiation of the cylindrical shell are discussed. It is found that the complex acoustic boundary has crucial influence on the vibration of the cylindrical shell when the cylindrical shell approaches the boundary, and the influence tends to vanish when the distances between the cylindrical shell and the boundaries exceed certain values. However, the influence of the complex acoustic boundary on the far-field sound pressure of the cylindrical shell cannot be ignored. The far-field acoustic directivity of the cylindrical shell varies with the distances between the cylindrical shell and the boundaries, besides the driving frequency. The work provides more understanding on the vibration and acoustic radiation behaviors of cylindrical shells with complex acoustic boundary conditions.

1. Introduction

Thin cylindrical shell structures are widely used in engineering, such as marine, mechanical, aerospace, and civil engineering. A significant amount of research on the vibration and sound radiation of the cylindrical shell has been carried out and reported. For the case of a cylindrical shell immersed in water, the shell was usually assumed to be submerged in an infinite fluid domain in the vibroacoustic analysis, thus the influence of the boundary of the fluid domain on the vibration and acoustic radiation was usually not taken into consideration [1,2]. However, in many situations, the fluid boundaries have effects on the vibration and sound radiation of structures when they are close to the fluid boundaries. One of the typical fluid acoustic boundaries is the free surface, the effect of which is important when a ship sails on the sea or an underwater structure approaches the sea surface. The other typical fluid boundary is the rigid boundary. When the underwater structures

* Corresponding author. School of Naval Architecture and Ocean Engineering, Huazhong University of Science & Technology, Wuhan, 430074, China.
E-mail address: zhuxiang@hust.edu.cn (X. Zhu).

https://doi.org/10.1016/j.jsv.2018.02.031

are close to the seabed, the fluid boundary can be approximately considered as a rigid boundary. For the cases of the structures approach both the free surface and the rigid boundary, such as a submarine approaches the dock, the influence of the complex acoustic boundary, which includes the free surface and the vertical rigid boundary, cannot be ignored, and the analytical solution for the vibroacoustic response is very challenging.

For cylindrical shells partially submerged into the water, some researchers carried out the vibration and sound analyses of cylindrical structures in consideration of the free surface. Salaün [3] investigated the sound radiation of 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. In order to impose an appropriate boundary condition on the free surface, Ergin and Temarel [4] 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. The sound pressure radiated from a semi-submerged infinite cylindrical shell filled with fluid was studied by Li and Wu [5]. 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. Ye et al. [6] studied the characteristics of the sound radiation and vibrational power flow of the partially submerged cylindrical shell under a harmonic excitation, and the structure-fluid coupling equation was established based on the Flügge shell theory and Helmholtz wave equation.

When a cylindrical shell is submerged in an acoustic half space, the fluid boundary (the free surface or the rigid surface) was taken into consideration in some studies. By using the method of variable separation, the classical method of images and the Graf's addition theorem, Hasheminejad et al. [7,8] researched the acoustic radiation from an infinite cylinder with a given surface velocity distribution while positioned near the boundary of a semi-infinite fluid. Based on the Graf's addition theorem and the stationary phase method, Li et al. [9] 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. [10] developed an approach for predicting the vibroacoustic characteristics of a semi-submerged infinite cylindrical shell based on the sound-structure coupling model, in which a diagonal coupling algorithm was put forward to improve the computational efficiency. Guo et al. [11] studied the vibration and acoustic radiation of a finite cylindrical shell submerged at finite depth from the water surface. The vibrational response of the cylindrical shell was solved by an analytical method and then the acoustic radiation of the shell was analyzed by employing the boundary element method (BEM).

When a cylindrical shell is submerged in a quarter-infinite fluid domain, in which the acoustic boundary conditions consist of a horizontal boundary and a vertical boundary, both the horizontal and vertical boundaries should be considered. Hasheminejad et al. [12,13] investigated the scattering field of a two-dimensional cylindrical shell in an acoustic quarter-space. Chen et al. [14] employed the double wave reflection method and the Graf's addition theorem to deduce the sound radiation expression from a finite cylindrical shell near the boundary of a quarter-infinite acoustic domain. However, in their study, the cylindrical shell was defined as surface pulsated and the sound field was confined to the axial length interval of the shell. The vibration response and the sound-structure coupling were not involved in their study. Since the analytical solution for the vibration and acoustic radiation of the finite cylindrical shell near the boundaries of the fluid is difficult to achieve, some numerical approaches are employed to calculate the acoustic field radiated from underwater or partly immersed cylindrical structures. Jouaillec and Jacquart [15] studied the far-field sound pressure radiated from an infinite cylindrical shell half-immersed in the fluid with an analytical method and presented a numerical method based on finite elements and integral equations for the case of a partially immersed finite cylindrical cylinder. They found that the far-field pressure is reduced when the structure is driven by a point force above the free surface. Ergin and Price [16] analyzed the dynamic characteristics of a flexible cylinder vibrating in the 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 model. Zhou and Joseph [17] combined the finite element method (FEM) with the BEM to analyze the dynamic response and acoustic radiation from an underwater ribbed cylindrical shell. Brunner et al. [18] proposed a fast multipole BEM coupled with the FEM to investigate the vibroacoustic behavior of a partly immersed finite cylindrical shell. Zou et al. [19,20] used the three-dimensional hydroelasticity theory to study the sound radiation of structures in the ocean waveguide, and the influences of the free surface and the seabed on the acoustic pressure distributions in the fluid domain were discussed.

In this paper, a semi-analytical method is proposed to solve the sound-structure coupling problem of an infinite cylindrical shell submerged in a quarter water domain and subject to harmonic excitation. The complex acoustic boundary in the quarter water domain consists of a free surface and a vertical rigid surface. The sound-structure coupling equation of the cylindrical shell excited by an axially uniform harmonic line force in the quarter-infinite acoustic domain is established and the analytical expression of the vibration response and far-field radiated sound pressure from the cylindrical shell is obtained. The influences of the complex acoustic boundary conditions on the vibration and acoustic radiation of the shell are discussed.

2. The sound-structure coupling model

2.1. The physical model

As shown in Fig. 1, an infinite thin circular cylindrical shell of thickness h, radius R, Young'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 velocity c_f. The fluid domain is bounded