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Vibro-acoustic characteristics of cylindrical shells with complex acoustic boundary conditions

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ABSTRACT

The structural–acoustic radiation problem of cylindrical shell structures with complex acoustic boundary conditions is investigated in the present study. The structural–acoustic radiation problem of a cylindrical shell is solved by using the double reflection method, in which the acoustic boundary conditions consist of a free surface and a rigid wall surface. The expression of the acoustic radiation function is also derived for cylindrical shell structures in a quarter-infinite acoustic domain. Finally, the influence of the acoustic radiation power and the acoustic directivity caused by the acoustic boundary characteristics, the acoustic source location, and the radiation frequency in a thin cylindrical shell structure is discussed. Thus, the results provide a new method to analyze the acoustic radiation problem with complex acoustic boundaries.

1. Introduction

The structural–acoustic radiation problem is a hot topic in marine, aerospace, and automotive engineering design and manufacturing. The three main approaches involved in structural–acoustic radiation analysis are theoretical analysis, numerical calculation, and experimental investigation. In the numerical analysis method, the finite element method (FEM) and boundary element method (BEM) are two common methodologies. The BEM is an efficient method for acoustic radiation analysis and can reduce the dimension of acoustic domain to one. In acoustic radiation analysis, either the Helmholtz differential equation or the Helmholtz integral formulation is an essential function. However, the analytical solution of the acoustic Helmholtz equation in free space can only be applied to a small number of simple structures, such as the simply supported plate structure, spherical shells, and infinitely periodic cylinder shell structure. In many practical acoustic radiation problems, the acoustic boundary conditions may be irregular or complicated, and these conditions may affect the acoustic radiation characteristics. For example, the acoustic radiation in water is distorted by the seabed or the water surface. By contrast, with compliant acoustic boundary surfaces, the acoustic pressure is dismissed (zero acoustic pressure) and the acoustic wave is reflected on the rigid wall acoustic boundary surfaces (zero normal velocity). Thus, the influence of the acoustic boundary characteristics must be analyzed in the acoustic radiation problem, particularly its effect on the control acoustic domain.

Many studies have been conducted to analyze the influence of the acoustic boundary characteristics. In several studies, the essential solution of the acoustic Green's function is discussed. Green's function for a harmonic acoustic point source in seawater was investigated by Al-Khaleefi et al. (2002), and a modified Green's function for acoustic wave propagation was presented. Lu and Jeng (2007) established Green's function to analyze the acoustic radiation in deep water, in which the seawater was defined as a half-space with a saturated porous medium. Chen et al. (2016) investigated the acoustic radiation problem in the quarter-infinite domain by using the conformal transformation method, in which the influence of the acoustic boundary characteristic on acoustic radiation power and acoustic directivity are discussed. Bapat et al. (2009) applied the half-space acoustic Green's function to address the acoustic radiation problem by boundary integral formulation, in which the function only needs to be applied to the acoustic boundary of the real domain instead of employing a true structure that contains the real domain and its mirror image. O'Neil et al. (2014) developed a new, hybrid representation that uses a finite number of real images (dependent only on the source location) coupled with a rapidly converging Sommerfeld-like integral. Santiago and Wrobel (2004) constructed modified Green's functions through different techniques, namely, the image method, eigen function expansions, and Ewald's method. Chan et al. (2009) used double-wave reflection to solve the structural wave reflection problem in a corner domain while considering the

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simply supported or roller-supported boundary conditions.

Thin cylindrical shell structures are widely used in complex structures, such as aerospace, marine, mechanical, and civil constructs. Studies on the vibration and acoustic radiation problem of the cylindrical shells have recently been the focus of considerable attention, and extensive research has been conducted on the dynamic response and the acoustic radiation of cylindrical shells. Farshidianfar and Oliazadeh (2012) investigated different cylindrical shell theories and compared the results of numerical simulations and experiments in relation to the free vibration of circular cylindrical shells under simply supported boundary conditions. Loock et al. (2013) examined the underwater acoustic radiation of cylindrical shells in a low-frequency tube where an experiment was conducted to validate the result obtained. Zhou et al. (2012) also investigated the free vibration characteristics of cylindrical shells for a general class of elastic support boundary conditions, in which the deep-water pressure was considered. Amabili (2003) investigated the dynamic response of cylindrical shells subjected to external harmonic excitation at low natural frequencies and compared five different nonlinear cylindrical shell theories through numerical simulation. Liu and Huang (2001) discussed the influence of rigid or compliant acoustic boundaries on the cylindrical shell acoustic radiation in the half-space domain. By using the fast multipole BEM method, Hasheminejad and Azarpeyvand (2004) investigated the cylindrical shell structure radiation problem in the 3D half-space domain and examined the convergence of the Hankel functions. By defining the finite duct as a "virtually closed cavity," Shao and Mechefske (2005) analyzed a finite cylindrical duct based on Green's functions and derived the modified Green's function for a cylindrical shell. Ye et al. (2012) examined the acoustic radiation problem of a cylindrical shell with complex acoustic boundary conditions, in which the acoustic radiation equations for a cylindrical shell with free and rigid wall surfaces are derived. Zhu et al. (2013) proposed a new analytical method to nondestructively predict the elastic critical acoustic pressure of a submerged cylindrical shell based on the wave propagation method.

In the present study, the acoustic radiations of cylindrical shell structures with complex acoustic boundary conditions are discussed. The acoustic radiation function in the quarter-infinite domain is derived via the double reflection method and mirror image method. Finally, the acoustic radiation power and acoustic directivity problem of the cylindrical shell structure in a quarter-infinite domain are discussed, and the influences of the acoustic radiation power and acoustic directivity caused by the acoustic boundary characteristics are compared in terms of location and frequency. The method proposed in the present study can be used to analyze the acoustic radiation problem of cylindrical shell structures with complex acoustic boundary conditions.

The remainder of the present paper is organized as follows: The acoustic radiation problem of a thin cylindrical shell structure is reviewed in Section 2. The double reflection method is discussed in Section 3. The acoustic radiation function of a cylindrical shell in quarter-infinite domain is established in Section 4. The acoustic radiation power and acoustic directivity problems in a quarter-infinite domain are solved in Section 5. The illustration of the feasibility of the proposed method and the numerical results and comparison analysis of acoustic radiation power and acoustic directivity are presented in Section 6. Finally, the conclusion is drawn in Section 7.

2. Structural–acoustic radiation equations for cylindrical shells

In the structural–acoustic radiation problem of cylindrical shell structures, a series of appropriate assumptions are proposed. The acoustic medium is assumed to be an inviscid and ideally compressible fluid, which cannot stand stress. In addition, the acoustic wave equation is linear, and only the low–middle frequency domains of the exterior acoustic radiation of the continuum structure are examined in present research. Moreover, this perspective considers only the steady-state response of the vibrating structure.

2.1. Free vibration formulations for cylindrical shells

The thin infinite cylindrical shells in the fluid medium are contained in the region Ω_S with the structure boundary Γ_S. A few assumptions are defined as follows: The structure material is isotropic and linearly elastic; the shell structure deformation is slight; the cylindrical shell and fluid gravity force are neglected; and shell thickness t is smaller in value than the mean radius of the cylindrical shell.

The cylindrical coordinate system (x, θ, r) is applied to define the position of the acoustic and structure domains. The coordinate axis x is selected to coincide with the cylindrical shell centerline, whereas the coordinate axes r and θ respond to the radial and circumferential directions, respectively, as shown in Fig. 1. u, v, and w are the orthogonal components of shell displacement in the axial, circumferential, and radial directions, respectively. R is the mean radius of the cylindrical shell structure, and h is the shell thickness.

Therefore, the dynamic displacement vector $\mathbf{u}$ in the cylindrical coordinate system can be expressed as follows:

$$\mathbf{u} = \{u_x(x, \theta, r, t), u_\theta(x, \theta, r, t), u_r(x, \theta, r, t)\}^T, \tag{1}$$

where u_x, u_θ, and u_r represent the dynamic displacements of an arbitrary point on the middle surface of the axial, tangential, and radial directions of the cylindrical shell structure, respectively. The superscript T is the transposition of a vector/matrix in Eq. (1). The harmonic motion of the structural–acoustic radiation system alone is considered. Thus, the dynamic displacement in the middle surface of the cylindrical shell structure can be determined according to traditional Flügge classical shell theory, which is based on the Kirchhoff–Love plate hypothesis and can be expressed as follows:

$$\begin{cases} u(x, \theta, r, t) = \sum_{n=0}^{\infty} \sum_{s=1}^{\infty} U_{ns} \cos n\theta \exp(i\omega t - ik_{ns}x) \\ v(x, \theta, r, t) = \sum_{n=0}^{\infty} \sum_{s=1}^{\infty} V_{ns} \sin n\theta \exp(i\omega t - ik_{ns}x) \quad , \\ w(x, \theta, r, t) = \sum_{n=0}^{\infty} \sum_{s=1}^{\infty} W_{ns} \cos n\theta \exp(i\omega t - ik_{ns}x) \end{cases} \tag{2}$$

where U_x, U_θ, and U_r are the amplitudes of the axial, circumferential, and radial shell structure spectral displacements, respectively; n is the circumferential mode number; and subscript s denotes a particular branch of the dispersion curve. The parameter k_{ns} denotes the axial wave numbers, and ω is the angular

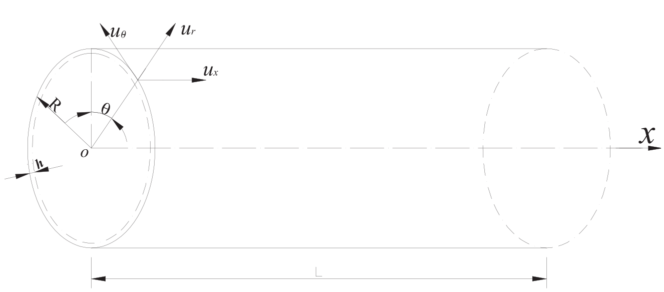

Fig. 1. Coordinate system of cylindrical shells.