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Sound radiation modes of cylindrical surfaces and their application to vibro-acoustics analysis of cylindrical shells

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A B S T R A C T

In this paper, sound radiation modes of baffled cylinders have been derived by constructing the radiation resistance matrix analytically. By examining the characteristics of sound radiation modes, it is found that radiation coefficient of each radiation mode increases gradually with the increase of frequency while modal shapes of sound radiation modes of cylindrical shells show a weak dependence upon frequency. Based on understandings on sound radiation modes, vibro-acoustics behaviors of cylindrical shells have been analyzed. The vibration responses of cylindrical shells are described by modified Fourier series expansions and solved by Rayleigh-Ritz method involving Flügge shell theory. Then radiation efficiency of a resonance has been determined by examining whether the vibration pattern is in correspondence with a sound radiation mode possessing great radiation efficiency. Furthermore, effects of thickness and boundary conditions on sound radiation of cylindrical shells have been investigated. It is found that radiation efficiency of thicker shells is greater than thinner shells while shells with a clamped boundary constraint radiate sound more efficiently than simply supported shells under thin shell assumption.

1. Introduction

Vibro-acoustic behaviors of cylindrical shells have been widely discussed because cylindrical shells are regarded as typical models of a variety of industrial structures such as pipes, aircraft fuselages, and submarine hulls etc. Early studies considered particular vibration patterns of cylinders and the assumption of cylindrical baffle combined with Green's function in cylindrical coordinates provided sound pressure expressions in closed form. Robey [1] presented the self and mutual radiation resistance of uniformly vibrating cylindrical surfaces and discussed the effect of distance between cylindrical surfaces on radiation resistance. Greenspon and Sherman [2] studied the mutual radiation impedance of a rectangular piston on a rigid cylinder, in which mutual radiation resistances between pistons on planes, spheres, and cylinders were compared for small and large ka, respectively. Butler [3] considered the modal radiation impedance of 0–2 circumferential modes of an infinite cylinder employing Fourier series. By expressing the velocity distribution using Fourier series expansion, Stepanishen [4]

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investigated the radiation impedance of cylinders with specific velocity distributions of impulsive harmonic radial, axisymmetric uniform and a simply-supported-cylindrical-shell-like. Stepanishen [5] further presented the asymptotic expression of radiation impedance of elastic cylindrical shells introducing shell theory. Moreover, the mutual coupling effect between different vibration modes on sound radiation was reported. Wang [6] analyzed the modal-averaged sound radiation efficiencies of acoustically thick cylindrical shells from a statistical energy perspective. Lin [7] studied the modal radiation efficiencies of finite cylindrical shells by finite element and boundary element method.

Radiation efficiency of vibration modes provides a measure to examine the vibro-acoustic behavior of cylindrical structures. However, mutual couplings between vibration modes on sound radiation not only make the analysis complicated but also indicate that the suppression of vibration may not cause definite noise reduction. Moreover, the results are dependent upon structural and material parameters which limit their generality. More specifically, the variation of dimensions, boundary conditions [7] and internal strengthens [8,9], even shell theory [10] will affect the radiation efficiency results. Note that there are complicated couplings between in-plane and out-of-plane motions of a cylindrical shell while sound radiation is mainly contributed by out-of-plane motion. The dimensional and material parameter, boundary conditions and internal strengthens etc. are actually involved in the motion couplings. Then the complicated relationship between parameters and out-of-plane vibration of a cylindrical shell combining with the implicit transfer function between bending motion and sound radiation inevitably give rise to unclear and case to case results.

Sound radiation modes or acoustic radiation modes refer to a set of basis vectors contributing independently to the total sound radiation power from a structure. This concept originated from the study of Brogotti [11] and is developed by Elliott [12] etc. Sound radiation modes theory comprehends the vibro-acoustic behavior of a structure by decomposing the sound radiation resistance matrix to identify effective sound radiation patterns. Comparing with vibration modes, sound radiation modes contribute independently to sound radiation power and they are irrelevant to material parameters, thickness, boundary conditions and internal strengthens. There are a series of articles considered the sound radiation modes of panel structures [12–16]. They are not only helpful to understand the sound radiation behaviors [12–14] but also provides insights for active structural acoustical control [15–19]. Elliott [12] investigated the sound radiation modes of a rectangular plate and stated that the 1st radiation mode of a plate played a dominant role in sound radiation. Correspondingly, considerable noise reduction can be achieved by filtering the vibration component complying with the 1st radiation modal shape. Li and Chen [14] studied the coupling between vibration modes and sound radiation modes of plates. By identifying the dominant radiation modes, noise attenuation can be guaranteed for a wider frequency range. Regarding cylindrical shells, there has not much analysis on sound radiation modes like on plates. The work done by Naghshineh [17] can be regarded as the earliest attempt to expand the concept of sound radiation modes to cylindrical structures. By employing wave superposition method, the weighting coefficients of acoustic basis functions (sound radiation modes) were calculated numerically. Johnson [18] depicted modal shapes of sound radiation modes of a cylindrical shell by obtaining radiation resistance matrix inversely using boundary element method. Considering the case of flat plates, the properties of sound radiation modes are derived based on explicit expression of radiation resistance matrix. Dai [20] presented sound radiation modes of cylindrical shells using stationary phase approximation of far-filed sound pressure expressions. Although modal shapes and radiation efficiencies of sound radiation modes of cylindrical shells can be obtained using the aforementioned wave superposition method, stationary phase approximation and BEM method, an expression of sound radiation resistance matrix of cylindrical shells as clear and explicit as the sound radiation resistance matrix of a baffled plate has not been given.

Recent studies focus on the sound radiation from complicated and fluid-loaded cylindrical shells [21–23] and active control of sound radiation from cylindrical structures [24–29]. Caresta and Kessissoglou [21] studied the low-frequency vibrational behavior and radiated sound of a fluid-loaded cylindrical hull with structural discontinuities. Cao et al. [22] investigated the acoustic radiation from cylindrical shells stiffened by two sets of rings with constrained layer damping. Jin et al. [25] presented a numerical and experimental study on active control of radiated sound from an elastic cylindrical shell. Cao et al. [27] analyzed active control performance of sound radiation from a fluid-loaded finite stiffened cylindrical shell with rigid end-caps. In these studies, far-field approximation involving stationary phase method or boundary element method was generally employed to obtain far-field sound pressure.

In this paper, the radiation resistance matrix is derived analytically and the properties of sound radiation modes are examined in detail. Then, vibro-acoustics behavior of cylindrical shells is studied by examining the coupling between vibration modes and sound radiation modes and the radiation coefficients of sound radiation modes. This viewpoint also provides a tool to understand the sound radiation characteristics of a cylindrical shell with different boundary conditions and thickness.

1.1. The concept of sound radiation modes

Sound power radiated from a structure can be regarded as a summation of the contribution from small elementary pistons on the vibrating surface as [12],

$$W_{rad} = \mathbf{v}^{\mathrm{H}}\mathbf{R}\mathbf{v}, \tag{1}$$

in which $\mathbf{v}$ represents the velocity distribution vector of a radiator. $\mathbf{R}$ is the surface radiation resistance matrix which can be related to the sound radiation impedance matrix $\mathbf{Z}$ by $\mathbf{R} = s/2^{*}\mathrm{Re}(\mathbf{Z})$. Where s is the area of an individual elemental radiator.