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Acoustic radiation of rotating and non-rotating finite length cylinders

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ABSTRACT

In this paper, a semi-analytical solution is presented for the problem of modal acoustic radiation efficiency of a finite-length rotating cylinder. The cylinder is immersed in an irrotational inviscid compressible fluid. Assuming the cylinder to vibrate sinusoidally in transverse direction and rotate at constant angular velocity, the scalar equation of sound propagation is decomposed into a coupled set of time independent equations. Using Galerkin method and employing spherical eigen-functions as a complete set of solution, modal acoustic pressure and acoustic radiation efficiency of the cylinder are calculated. Numerical solutions are presented to discuss modal radiation efficiency corresponding to forward and backward circumferential waves.

1. Introduction

Circular cylindrical shells are of great importance in the field of mechanical engineering as they have a very wide range of applications. A short survey in the literature shows there are many published researches concerning dynamic behavior of rotating and non-rotating cylindrical shells and their interaction with surrounding media. Among them, some have focused on the sound radiation and radiation efficiency of these kinds of structures. Importance of radiation efficiency arises whenever acoustic noise propagated by the vibrating structure is studied or indirect vibration measurements through acoustic waves are employed.

In most studies, the assumption of infinite length cylinder is considered in order to obtain an analytical solution for acoustic radiation of circular cylindrical shells. This assumption may result in considerable errors, especially in subsonic regions. Therefore, a special attention has been paid to finite length cylindrical models to have more realistic insight toward the problem.

In a very early study, Williams et al. [1] investigated the acoustic radiation of a beating (pulsating) finite length cylinder. They assumed that the cylinder is vibrating harmonically and perturbs the surrounding media. Assuming that Helmholtz equation governs the problem, they developed a semi-analytical solution for it. They provided some numerical solutions for a cylinder with specific characteristics and showed that the obtained pressure amplitude differs from that of infinite cylinder by having no zeros.

Lauvstad [2] studied the sound propagated by a sinusoidally rotating cylinder which is submerged in a viscous fluid with a slight compressibility. In this case, the oscillating boundary layer around the cylinder results in propagating shear (transverse)

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waves. To study the nature of this waves and the mechanism of sound generation, he considered the Navier-Stokes equations as governing ones and simplified them according to the symmetries of the system. Using a perturbation technic, the density and velocity fields were approximated by a finite series estimate. The final solution showed that the transverse waves are not sufficient to satisfy all the governing equations and the boundary conditions and it is essential to add longitudinal waves. The longitudinal waves propagate in the fluid as sound waves. Some qualitative analysis were presented in Lauvstad's work, but no numerical calculations were conducted.

Censor and Aboudi [3] studied the problem of sound scattering by an infinite cylinder rotating with a uniform velocity. They assumed that the incident wave travels with a specific angle with respect to the cylinder's axis and derived the corresponding wave equation with respect to a fixed coordinate system. Subsequently, they presented a semi-analytical solution for the mentioned problem and then, provided some numerical results for different values of rotational speed and incident angle. The obtained results show that for very low values of rotational speed, the scattered amplitude is almost symmetric with respect to the horizontal plane and dipole pattern is predominant. However, the results become asymmetric as rotational velocity increases and considerable asymmetries are observed as rotational velocity approaches to the speed of sound.

Fyfe and Ismail [4] studied acoustic radiation from a finite length cylinder which is vibrating in an arbitrary mode with a single specific frequency. For this purpose, they employed integral form of Helmholtz equation along with boundary element method. Subsequently, acoustic pressure in the exterior media was calculated by implementation of Green's Integration technic. In addition, the acoustic efficiency of the cylinder was calculated using the obtained sound pressure. To validate the accuracy of the presented method, they compared the obtained results with experimental measurements. A good agreement was observed between the theory and the experiments.

In a two part study, Wang and Lai [5and6] studied radiation efficiency of acoustically thick cylindrical shells which undergo mechanical excitations. In the first part, they developed an analytical formula for estimating the radiation efficiency of a finite length vibrating cylinder. For this purpose, they employed the assumption of an infinite cylinder which solely a finite part is vibrating. Employing the solutions of infinite cylinders already existing in the literature, they developed an analytical formula for estimating the radiation efficiency of the finite length cylinders. They validated the accuracy of the developed formula by comparing it with the results determined from boundary element method and experimental studies. Numerical calculations along with experimental studies showed that for acoustically thick cylinders, the variations of radiation efficiency versus excitation frequency is quite complicated and different from that of acoustically thin ones. In the second part of the study, the limitations of infinite models was investigated. They showed that for finite length cylinders, the type of boundary condition can affect the radiation efficiency, significantly.

Ramachandran et al. [7] employed a statistical energy method to investigate the modal density and the radiation efficiency of finite length vibrating cylinders which are equipped by axial stiffeners. With this aim, they used Lagrange energy method to determine the natural frequencies and the vibration modes of the stiffened and the unstiffened cylinders. These were used to calculate the modal density along with the radiation efficiency of the structure. The precision of the method was confirmed by experimental tests, except for low band of frequencies, where a correction factor was suggested to improve the analytical results. Numerical results showed that the shape of the stiffeners does not alter the modal density and the radiation efficiency that much. In addition, circumferential wavenumber has a small impact on these quantities.

Lin et al. [8] studied radiation efficiency corresponding to the different vibration modes of an open-end finite length cylinder. To evaluate the effect of acoustic couplings between internal and external regions of the cylinder, they employed boundary element method and finite element method which how less computational limitations and difficulties with respect to the analytical ones. After conducting numerical simulations for some wavenumbers, no considerable difference was observed between radiation efficiencies calculated for open-end cylinders and identical baffled ones.

Zhang et al. [9] studied sound radiation from a finite length cylinder with rigid baffled ends which is excited by a point or a line force on its internal surface. They used general theory of elasticity along with Helmholtz equation to simulate the interaction between the cylinder and the surrounding fluid media. Continuity of the normal displacement and that of the stress were used as the boundary conditions. Numerical simulations showed that as the excitation frequency increases, some differences appear between the results of the present method and those of Flügge shell theory. The authors attributed these differences to the precision deduction of classical shell theory since rotary inertia and transverse shear are omitted in this theory.

Zalev et al. [10] considered the problem of photoacoustic waves propagating by a finite length solid cylinder and presented an analytical solution for it. When an electromagnetic energy is absorbed instantaneously by a medium, it warms up and expands very rapidly and generates a pulse pressure which propagates in the surrounding media as acoustic waves. Assuming that the initial pulse pressure around the cylinder surface is homogenous, they solved the problem of wave propagation in the fluid media by implication of canonical elliptic integrals.

Zhao et al. [11] studied vibrational and acoustical properties of composite cylindrical shells which are subjected to hygroscopic conditions. In their study, a thin cylindrical shell of finite length with simply-supported boundary conditions and rigid baffled ends was considered. Then, assuming that the hygroscopic environment is homogenous, the governing equations were derived based on thin shell theory and by involving initial stresses resulted from moisture content. After implementation of numerical simulations, the authors concluded that the natural frequencies, the modal radiated power and the radiation efficiency decrease as its moisture content increases.

Meyer et al. [12] investigated the acoustic radiation efficiency of stiffened circular cylindrical shells which have non-axisymmetric internal frames and are subjected to point excitations. For this purpose, they used an experimental