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Acoustic scattering from submerged laminated composite cylindrical shells

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ABSTRACT

The scattering of an oblique plane progressive monochromatic acoustic field upon a laminated composite cylindrical shell is studied based on the three-dimensional exact equations of anisotropic elasticity. Each layer of laminated structure is made of helically filament wound (fiber reinforced) homogeneous material whose degree of anisotropy is considered as monoclinic type. An approximate laminate model along with the local transfer matrix solution is used to solve the state space governing formulation within each layer. Considering the perfect bonding between the adjacent layers, the global transfer matrix is constructed as the product of the local transfer matrices employed to solve for the unknown scattering coefficients. The so-called back-scattered form function amplitude is evaluated for two cases of (strong anisotropy) Graphite/Epoxy and (weak anisotropy) Glass/Epoxy multilayered cylindrical shells, for different number of layers and different stacking sequence. Furthermore, the axisymmetric and non-axisymmetric dynamic behavior of the composite shells are studied by evaluating the directivity patterns of the far-field form function amplitude at the selected resonance frequency corresponding to the first overtone of $n = 2$ vibration mode. Some limiting cases are considered and good agreements with the solutions available in the literature are obtained.

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1. Introduction

Cylindrical components are frequently used in engineering structures. Consequently, there have been several investigations on their interaction with acoustic wave field, and in particular, the scattering of acoustic waves from such structures has been an active area of research for over a century. The first study of acoustic wave scattering from submerged solid elastic cylinders based on a normal-mode expansion is due to Faran [1]. The more general problem, when the propagation direction of the incident wave makes an arbitrary angle with the normal to the cylinder, was considered by Flax et al. [2]. The similar problem for a cylindrical shell was studied by Veksler [3]. Comprehensive reviews of extensive bibliographies can be found in the works of Gaunaurd [4], Uberall [5] and Veksler [3].

The growing use of anisotropic materials in engineering applications has lead in research activities in this area in recent years. In particular, fiber reinforced laminated composite cylinders and cylindrical shells have been introduced as novel types of structures providing superior performance because of their flexibility in providing improved mechanical properties and lightweight. Kundu and Bostrom [6] analyzed the scattering of a plane wave by a circular crack in a transversely isotropic solid medium. Honarvar and Sinclair [7] presented an exact normal-mode expansion for the scattering of an acoustic wave from an immersed, transversely isotropic solid cylinder. Kaduchak and Loeffler [8] employed exact three dimensional elasticity theory to examine oblique acoustic scattering from a multilayered transversely isotropic cylindrical shell. Ahmad and Rahman [9] used normal mode expansions to study the effect of the angle of incidence on the scattering of an acoustic wave by a transversely isotropic cylinder immersed in a fluid. They found an extra critical angle of incidence for this type of materials. Kim and Ih [10] employed the normal mode expansion technique in association with the resonance scattering theory to isolate the resonance behavior of an air-filled, transversely isotropic cylindrical shell immersed in water, subjected to oblique incidence of a plane acoustic wave, for material characterization

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purposes. Hasheminejad and Rajabi [11] used the laminate approximate model in the context of state space formulation to study the acoustic scattering problem from a submerged orthotropic cylindrical shell. They extend their work to the laminated case along with the RST approach to investigate the imperfect bonding effects on excited resonance frequencies [12]. Just recently, Rajabi and Behzad [13] presented an exact analysis based on the wave function expansion to study the scattering of a plane harmonic acoustic wave incident at an arbitrary angle upon an arbitrarily thick helically filament-wound (anisotropic) cylindrical shell submerged in and filled with compressible ideal fluids. Their main attention was focused on the resonance isolation and classification of an air-filled and water submerged Graphite/Epoxy cylindrical shell according to their modes of propagation. The above review shows that in contrast with the isotropic and anisotropic shells, there seem to be no rigorous investigations on the oblique acoustic wave scattering from a laminated composite cylindrical shell with monoclinic degree of anisotropy associated with each layer. The primary purpose of the current work is to fill this gap. For this idea, an approximate laminate model along with the local *T*-matrix solution is used to solve the state space governing formulation within each layer with monoclinic anisotropy. Considering the perfect bonding between the adjacent layers, the global *T*-matrix is constructed as the product of the local transfer matrices and employed to solve for the unknown scattering coefficients. Finally, some numerical examples are given to study the general behavior of the solution. The present investigation may be regarded as a benchmark for related future studies based on finite element or boundary element methods or other shell theory formulations. Furthermore, it may serve as a direct acoustic scattering model for non-destructive testing/evaluation, material characterization and monitoring of laminated composite cylindrical components.

2. Formulation

The configuration of problem is illustrated in Fig. 1(a) where (x, y, z) is the Cartesian coordinate system with origin at O, the z direction is coincident with the axis of the cylindrical shell and (r, θ) is the corresponding cylindrical polar coordinate system. The laminated cylindrical shell of infinite length, inner radius a_0 and outer radius a_q, is fabricated of q individual layers and is insonified by a plane acoustic wave with the circular frequency ω, obliquely incident at an angle α. The uniform thickness of kth layer is denoted by $h_k = a_k - a_{k-1}$, for $k = 1, 2, \ldots, q$ and its filament angle from z-axis is ϕ^k, as shown in Fig. 1(b).

2.1. Acoustic field equations

The field equations for an inviscid and ideal compressible medium that can not support shear stresses may conveniently be expressed in terms of a scalar velocity potential as [14]

$$\mathbf{v} = -\nabla\varphi, \quad p = \rho\frac{\partial\varphi}{\partial t}, \quad \nabla^2\varphi + k^2\varphi = 0, \tag{1}$$

where $\mathbf{v}$ is the fluid particle velocity vector, p is the acoustic pressure, ρ is the ambient density, $k = \omega/c$ is the wave number for the dilatational wave, c is the speed of sound.

The solution of the acoustic field equations may be expressed in terms of appropriate scalar potentials that can be represented in the form of an infinite generalized Fourier series whose unknown scattering coefficients are to be determined by applying the proper boundary conditions. The expansion of the plane progressive incident wave field, propagating in the surrounding fluid medium, in cylindrical coordinate (see 1) has the form [14]

$$\varphi_{inc.}(r, \theta, \omega) = \varphi_0 \sum_{n=0}^{\infty} \varepsilon_n i^n J_n(k_r r) \cos(n\theta) e^{i(k_z z - \omega t)}, \tag{2}$$

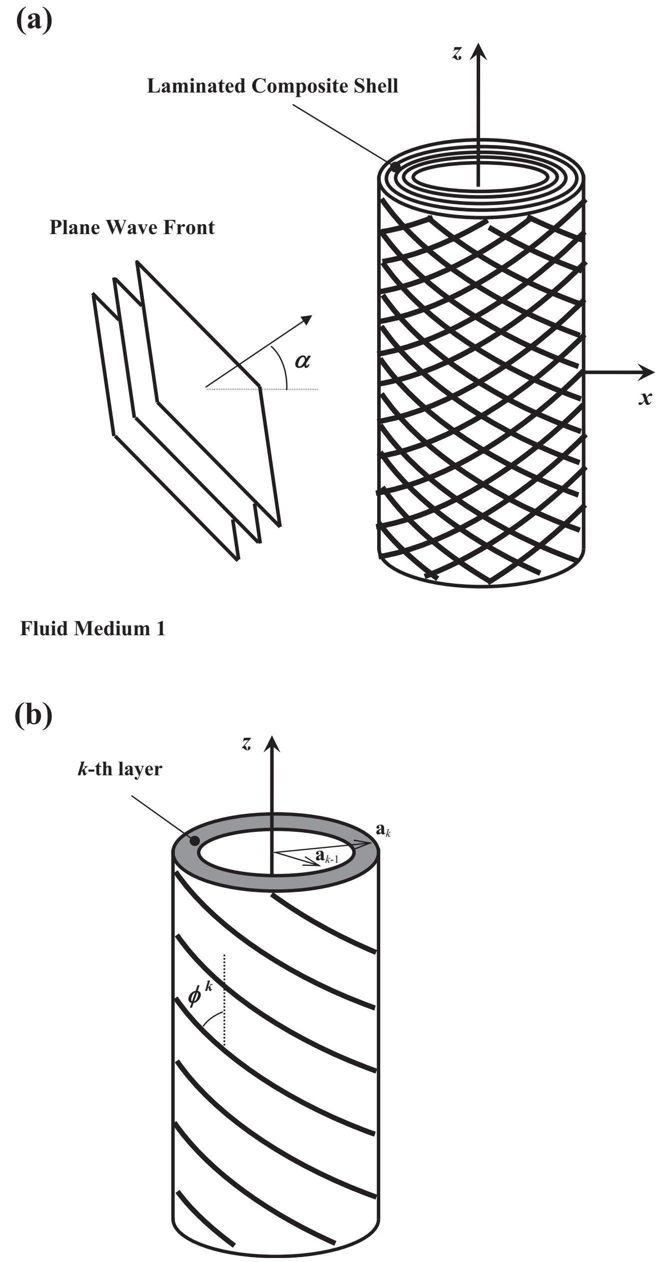

Fig. 1. (a) Configuration of problem: interaction of plane progressive acoustic wave with laminated composite cylindrical shell and (b) kth layer characteristics.

where $k_z = k\sin\alpha$, $k_r = k\cos\alpha$, $k = \omega/c_1$ is the wave number in the outer fluid medium 1 (see 1), φ_0 is the amplitude of the incident wave, symbol ε_n is the Neumann factor ($\varepsilon_n = 1$ for $n = 0$, and $\varepsilon_n = 2$ for $n > 0$), $i = \sqrt{-1}$, $J_n(x)$ is the cylindrical Bessel function of the first kind of order n. Considering the probable general angular directivity patterns of the scattered and transmitted acoustic fields, the solutions of the Helmholtz equation for the scattered potential in the surrounding fluid medium 1, and the transmitted potential in the inner fluid medium 2 can respectively be expressed as a linear combination of cylindrical waves as

$$\begin{aligned} \varphi_1(r, \theta, \omega) &= \sum_{n=0}^{\infty} \varepsilon_n i^n [A_n(\omega)\cos(n\theta) + B_n(\omega)\sin(n\theta)] H_n^{(1)}(k_r r) e^{i(k_z z - \omega t)}, \\ \varphi_2(r, \theta, \omega) &= \sum_{n=0}^{\infty} \varepsilon_n i^n [C_n(\omega)\cos(n\theta) + D_n(\omega)\sin(n\theta)] J_n(K_r r) e^{i(k_z z - \omega t)}, \end{aligned} \tag{3}$$

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