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Interaction of a plane progressive sound wave with anisotropic cylindrical shells

Majid Rajabi [1], Mehdi Behzad *

Department of Mechanical Engineering, Sharif University of Technology, Azadi Avenue, Tehran, Iran

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ABSTRACT

An exact analysis based on the wave function expansion is carried out 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. Using the laminated approximation method, a modal state equation with variable coefficients is set up in terms of appropriate displacement and stress functions and their cylindrical harmonics to present an analytical solution based on the three-dimensional exact equations of anisotropic elasticity. Taylor's expansion theorem is then employed to obtain the solution to the modal state equation, ultimately leading to calculation of a transfer matrix. Following the classic acoustic resonance scattering theory (RST), the scattered field and response to surface waves are determined by constructing the partial waves and obtaining the background (non-resonance) and resonance components from it. The solution is particularly used for the isolation and identification of excited resonances of an air-filled and water submerged Graphite/Epoxy cylindrical shell as the circumnavigating helically propagating waves. In addition, the sensitivity of resonances associated with various modes of wave propagation appearing in the backscattered amplitude to the perturbation in the material's elastic constants is examined. Furthermore, non-axisymmetric dynamic behavior of the anisotropic shell is illustrated by analyzing the directivity pattern associated to the angular distribution of the far-field form function amplitude. The effects of winding angle of filaments and the shell wall-thickness on the frequency response of the shell are also investigated. For verification, the wave propagation characteristics of the anisotropic shell (which have been extracted from the main body of the solution) and the far-field form function amplitude of a limiting case are considered and fair agreement with the solutions available in the literature are established.

1. Introduction

The operating conditions as well as the high diversity of demands imposed on structural elements by today's advanced technologies have resulted in the need for novel types of structures providing elevated performance such as fiber-reinforced composites essentially because of their adaptability in providing enhanced mechanical properties and lightweight. In particular, with the development of manufacturing technology of composite materials, there has been a growing interest in the application of the filament-wound cylindrical composite structures.

Because such materials demonstrate often highly anisotropic behavior, it is difficult to determine the material properties or to monitor the state of health or damage, by traditional static methods, in the stages before, during and after consolidation and curing or when they are in their operating condition.

Recently, *resonance acoustic spectroscopy* (RAS) technique has been proven to be an effective way for material characterization purposes and non-destructive testing/evaluation of materials [1–4], remote classification of submerged targets [3,4], and on-line monitoring of elastic components [5–7]. In this method, the resonance effects of the target component may be caused by the excitation of its eigenvibrations by an incident acoustic wave. They are inherent characteristics of the object which are completely independent of the source of excitation and depend only on its bulk physical properties (e.g., bulk density and elastic constants). When a submerged elastic target is insonified by an acoustic wave, various types of surface waves as well as a geometric reflection is returned from the target. The resonance scattered field (i.e., after elimination of the geometrical reflection effects from the scattered acoustic field) from the target contains helpful information about

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* Corresponding author. Tel.: +98 21 66165509.
E-mail addresses: majid_rajabi_yahoo@yahoo.com (M. Rajabi), m_behzad@sharif.ir (M. Behzad).
[1] Tel.: +98 21 66165556.

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the characteristics of the target [9–14]. For nondestructive evaluation (NDE) and on-line monitoring purposes, these resonances are utilized to evaluate the various properties of cylindrical structures such as stiffness properties, by fitting the measured data to theoretical ones through iterative numerical algorithms (e.g., the measured resonance frequencies in resonance acoustic spectroscopy technique [5,12–14]). Therefore, this method strongly weighed down by the highly complicated response function expected from an even undamaged specimen. Hence, a theoretical resonance scattering model and a good understanding of the complicated scattering phenomena is vital.

Cylindrical components (e.g., manufactured rods, pipes, tubes, shells, pressure vessels, wires, cables, fibers etc.) are frequently used in practical engineering. Consequently, there have been numerous investigations on their acoustic response, and in particular, the propagation of elastic waves in such structures has been an active area of research for over a century. The first pioneering investigation of acoustic wave scattering from submerged solid elastic cylinders based on a normal-mode expansion is due to Faran [15]. 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. [16]. The similar problem for a cylindrical shell was studied by Veksler [14]. Comprehensive reviews of these topics and extensive bibliographies can be found in the works of Gaunaurd [12], Uberall [13] and Veksler [14]. Just recently, the authors have tried to extend the resonance scattering theory for non-classical configurations for resonance acoustic spectroscopy purposes of cylindrical shells. In the first configuration [17], the steady-state sound radiation characteristics of a cylindrical component of infinite length subjected to an arbitrary time-harmonic on-surface concentrated radial drive is investigated and the resonance characteristics of the object are extracted and isolated by introducing a non-resonant background field hidden in the radiation field. In the second configuration [18], the synthesized quantity for resonance spectroscopy purposes is the exerted static radiation force on the cylindrical body. Utilizing the resonance scattering theory, it is shown that the radiation force is the superposition of three components: background part, resonant part and their interaction. It is shown that the resonance contribution can be synthesized as the Breit–Wigner form for adequately none-close resonant frequencies.

As the dynamic parameters play an important role in any design process, a significant number of investigations on dynamic characteristics of anisotropic cylinders and cylindrical shells can be found in the literature. However, the research works that will be surveyed here is on the interaction of acoustic waves with or free-vibration problems of fluid-loaded or embedded anisotropic cylinders and cylindrical shells. Berger [19] investigated the transient vibration of an infinite viscoelastic shell coated with an orthotropic cylindrical immersed in an acoustic medium. Koval [20] presented mathematical models for calculation of the transmission loss of oblique plane sound waves into orthotropic and laminated composite circular cylindrical shells. He found that the acoustic performance of the shell is quite sensitive to orthotropic parameters. Kurbakov et al. [21] used Laplace integral transform and its subsequent inversion by using a Volterra integral equation to examine the deformation of thin-walled orthotropic circular cylindrical shell subjected to nonstationary plane step waves in an acoustic medium. Chonan [22] employed a thick shell theory to study the acoustical features of infinitely long, two-layered orthotropic cylindrical shells excited by a low frequency plane sound wave traveling axially interior the shells. Upadhyay and Mishra [23] study the non-axisymmetric dynamic behavior of buried orthotropic cylindrical shells excited by combination of P, SV and SH waves. Mishra and Upadhyay [24] used a thick-walled shell model to investigate the nonaxisymmetric dynamic behavior of fluid-filled buried orthotropic cylindrical shells stimulated by plane longitudinal waves. Blaise and Lesueur [25] presented a two-dimensional mathematical model for the transmission of an oblique plane sound wave into a multi-layered orthotropic infinite cylindrical shell. They subsequently developed their work to the three-dimensional mechanical and acoustical behavior of an infinite multilayered orthotropic shell, by taking into consideration the bending, membrane, shear, longitudinal and rotational inertia effects [26,27]. Skobel'tsyn and Tolokonnikov [28] addressed the scattering of sound waves by a layered inhomogeneous anisotropic cylindrical shell with thick walls. De Billy [29] reported experimental measurements on scattering spectra from anisotropic cylinders in water. Honarvar and Sinclair [30] developed an exact normal-mode expansion for the scattering of a compression acoustic wave from an immersed, transversely isotropic solid cylinder. Kaduchak and Loeffler [31] used the exact 3-D elasticity theory to examine acoustic scattering from a multilayered transversely isotropic cylindrical shell excited by an obliquely incident plane wave. Sharma et al. [32] employed a modified exact analytical method to study the vibration characteristics of helically wound laminated composite cylindrical shells. Kim et al. [33] addressed the resonance scattering of acoustic waves by a transversely isotropic composite shell. Chen et al. [34] utilized the matrix form Frobenius series method to present a three-dimensional analysis for the free vibrations of fluid-filled orthotropic cylindrical shells. McCoy and Sun [35] used the finite-element method along with an effective modulus theory to analyze thick-section hollow composite cylinders subjected to underwater blasts. Lam et al. [36] used the equations of motion of orthotropic circular cylindrical shells in conjunction with the Reflected-Afterflow-Virtual-Source model and the finite difference method to present an analysis of submerged orthotropic cylindrical shells subjected to underwater planar shock waves. Ahmad and Rahman [37] 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. Xi et al. [38] presented a layer element method, formulated within the framework of the theory of three-dimensional elasticity, for analyzing frequency and group velocity dispersive behavior of waves in fluid-loaded laminated composite cylinders and cylindrical shells. Kim and Ih [3] extended Honarvar and Sinclair's [30] work by using the normal mode expansion technique to present a resonance scattering analysis for oblique incidence of a plane acoustic wave upon an air-filled, transversely isotropic cylindrical shell immersed in water. Hasheminejad and Rajabi [4] 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 where imperfect bonding is possible [8]. Li and Hua [39] presented an approximate solution based on the Sanders thin shell theory to the problem of the transient vibration of an elastic laminated composite cylindrical shell with infinite length exposed to an underwater shock wave. Chronopoulos et al. [40] developed A model for the prediction of the vibroacoustic performance of composite shells of various geometries within a statistical energy analysis (SEA) approach. Their solution predicted the dispersion characteristics of composite orthotropic shell structures of a range of geometries, namely curved panels and cylindrical shells by their proposed Wave Finite Element Method. Wang et al. [41] developed some finite element models using shell and three-dimensional solid elements for vibration analysis of thin- and thick-walled cylinders in order to assess and compare their accuracy with respect to solutions obtained from three-dimensional theory of elasticity. Asadi et al. [42] presented two shell theory for static and vibration analysis of a doubly curved deep thick composite shell. In the first theory, plate stiffness parameters are used for thick shells which reduced the