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Dynamic Stiffness Method for free vibration of composite cylindrical shells containing fluid

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ABSTRACT

The present work deals with a theoretical investigation on free vibration of composite circular cylindrical shells containing fluid. A new precise analytical model using the Dynamic Stiffness Method (DSM) or Continuous Elements (CEM) based on the Reissner–Mindlin theory and non-viscous incompressible fluid equations has been proposed for the studied structures. Numerical examples are given for analyzing natural frequencies and harmonic responses of clamped-free cylindrical shells partially and completely filled with fluid. To compare with the theoretical results, some experimental results have been obtained on the free vibration of a clamped-free glass fiber/polyester cylindrical shells partially filled with water by using a multi-vibration measuring machine (DEWEBOOK-DASYLab 5.61.10). Results calculated by the proposed computational model for studied composite cylindrical shells are in good agreement with experiments.

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1. Introduction

In recent years, the use of partially fluid-filled laminated composite circular cylindrical shells in engineering industry has been steadily increasing. In the design of such structure, dynamic response is still a major concern. The free vibration analysis of the partially fluid-filled composite shells is very useful indeed to better study and understand of the dynamic behavior. Owing to the significance of the problem, a few investigators have carried out the vibration analyses of partially fluid-filled laminated composite circular cylindrical shells. Xi et al. [1,2] analyzed the free vibration of a laminated composite circular cylindrical shell partially filled with fluid using a semi-analytical finite element technique based on the Reissner–Mindlin theory and compressible fluid equations. Sharma et al. [3] have presented analytical solutions to free vibrations of fluid-filled vertical cantilever composite cylindrical shells. Chen and Ding [4] determined the natural frequencies of non-axisymmetric vibrations of an anisotropic elastic spherical shell filled in a compressible fluid medium. Katsutoshi et al. [5] analyzed the free vibrations of a laminated composite circular cylindrical shell partially filled with liquid. Toorani and Lakis [6] studied the effect of shear deformation in the dynamic behavior of anisotropic laminated open cylindrical shells filled with fluid and later they investigated the dynamic behavior of axisymmetric and beam-like anisotropic cylindrical fluid-filled shells (Toorani and Lakis [7]). Using linearized boundary conditions of fluid free surface, Pal et al. [8] made a study on the sloshing dynamics in a fluid-filled laminated composite open cylindrical tank and later accomplished their work assuming nonlinear free surface boundary conditions using Finite Element Method (Pal et al. [9]). Amabili [10,11] has performed a non-linear vibration analysis of fluid filled cylindrical shells. A semi-analytical approach has been utilized by

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Toorani and Lakis [12] to determine the swelling effect on the dynamic behavior of composite cylindrical shells conveying fluid and recently Larbi et al. [13] presented the theoretical and finite element formulations of piezoelectric composite shells of revolution filled with compressible fluid. Senthil and Ganesan [14] performed a dynamic analysis on composite conical shells filled with fluid. Kuo et al. [15] investigated acoustic-structure interaction of sound by considering various fluid filled composite shells of different stacking sequences. In the study of Firouz-Abadi et al. [16], a modal based finite element model of structural dynamics in combination with a boundary element formulation of fluid dynamics has been used to determine the free vibration frequencies of the composite tanks partially filled with fluid.

In those studies, low natural frequencies are generally investigated. For medium and high frequency range, the CEM can be applied with many advantages: high precision, rapid calculating speed, reduction of the model size and of the computing time. Numerous CEM researches have been performed for isotropic and composite beams: Lunden and Akesson [17], Banerjee [18], plates: Nguyen [19], Fazzolari et al. [20], Thinh et al. [21] and shells: Casimir et al. [22], Khadimallah et al. [23], Thinh and Nguyen [24], Fazzolari [25].

It should be noted that the majority of the conducted investigations were associated with only theoretical studies; however, not many experimental studies on free vibrations of empty and fluid-filled cylindrical shells are available in the literature. The main reason for this is that the measurement is extremely difficult to perform. Mixson and Herr [26] have determined natural frequencies and mode shapes of the clamped cylindrical shell made of aluminum and steel. Water was used as the contained liquid. Similar studies were conducted by Lindholm et al. [27] for a steel test cylinder. Chiba [28] tested two empty cantilevered circular cylindrical shells made of polyester sheets. Chiba [29] has also studied experimentally large-amplitude vibrations of two vertical cantilevered circular cylindrical shells made of polyester sheets, partially filled to four different levels of water with a free surface. Koval'chuk and Lakiza [30] experimentally investigated forced vibrations of large amplitudes in empty fiberglass cantilevered shells of revolution. In the work of Amabili et al. [31], the response of two water-filled circular cylindrical shells made of steel has been investigated in the neighborhood of the fundamental mode. The boundary conditions at the shell edges approximate the simple support type. Recently, a few studies can be found dealing with experimental modal analysis of composite cylindrical shells. Hosokawa et al. [32] have studied numerically and experimentally the free vibrations of angle-ply laminated carbon fiber reinforced plastic cylindrical shells with clamped edges. Okazaki et al. [33,34] experimentally determined the modal characteristics of a cross-ply composite cylindrical shell partially filled with fluid and followed the study by analyzing the free vibrations using finite elements. Wu et al. [35] performed an experimental study as well as a finite element analysis on the dynamic response of filament wound pressure vessels filled with liquid. They also provided the primary information which can be used for vibration-based damage detection of composite vessels.

In the present study, free vibrations of fluid-filled composite circular vertical cylindrical shells are investigated. For the theoretical study, a new Dynamic Stiffness model for partially fluid-filled composite cylinders based on the Reissner–Mindlin theory and incompressible fluid equations are constructed. This continuous element provides high precision results, saves computing time and can be applicable for high frequency range. For the experimental study, the natural frequencies of the composite specimens are determined by using a multi-vibration measuring machine (DEWBOOK-DASyLab 5.61.10). Theoretical solutions are compared to experimental results for analyzing free vibrations of partially and completely fluid-filled cross-ply composite circular cylindrical shells with clamped-free boundary condition. Emphasis will be placed on the advantages of the DSM and on the effects of the fluid filling on the natural frequencies of glass fiber/polyester composite circular cylindrical shells.

2. Formulation of cross-ply laminated composite circular cylindrical shells filled with fluid

2.1. Kinematics of cylindrical shells with fluid

Investigate a thick composite circular cylindrical shell of length L , thickness h and mean radius R ; H is the height of the contained fluid volume (Fig. 1). The shell consists of a finite number of layers which are perfectly bonded together. Following Reissner–Mindlin theory, the displacement components are:

$$\begin{aligned} u(x, \theta, z, t) &= u_0(x, \theta, t) + z\phi_x(x, \theta, t), \\ v(x, \theta, z, t) &= v_0(x, \theta, t) + z\phi_\theta(x, \theta, t), \\ w(x, \theta, z, t) &= w_0(x, \theta, t), \end{aligned} \quad (1)$$

where u , v and w are the displacement components in the x , θ and z directions, u_0 and v_0 are the in-plane displacements of the shell in the mid-plane, and ϕ_x and ϕ_θ are the rotations of the normal to the middle surface of the shell. The strain–displacement relations of cylindrical shells are expressed as:

$$\begin{aligned} \varepsilon_x &= \frac{\partial u_0}{\partial x} + z \frac{\partial \phi_x}{\partial x}, \quad \varepsilon_\theta = \frac{1}{R} \frac{\partial v_0}{\partial \theta} + \frac{z}{R} \frac{\partial \phi_\theta}{\partial \theta} + \frac{w_0}{R}, \quad \gamma_{x\theta} = \frac{1}{R} \frac{\partial u_0}{\partial \theta} + \frac{\partial v_0}{\partial x} + z \left(\frac{1}{R} \frac{\partial \phi_x}{\partial \theta} + \frac{\partial \phi_\theta}{\partial x} \right), \quad \gamma_{xz} = \phi_x + \frac{\partial w_0}{\partial x}, \\ \gamma_{\theta z} &= \phi_\theta + \frac{1}{R} \frac{\partial w_0}{\partial \theta} - \frac{v_0}{R}. \end{aligned} \quad (2)$$

Consider a composite shell composed of N orthotropic layers of uniform thickness with the principal material axis of the k th layer is oriented at an angle α with the x axis. The stress–strain relations of the k th layer by neglecting the transverse

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