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Review

Vibration analysis of a cylindrical shell coupled with interior structures using a hybrid analytical-numerical approach

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ABSTRACT

In present paper, a hybrid analytical-numerical approach is developed to investigate vibration characteristics of a finite cylindrical shell with interior structures, e.g. plates and other complicated structures. The cylindrical shell is analyzed through exact wave based method (WBM). Flügge theory is adopted to describe motion equations of the shell and displacement functions are expressed as wave functions. Interior structures are modelled by means of finite element method (FEM) and coupled to the shell through the artificial spring technique. By allowing a wide variation range of spring stiffness constants, different coupling conditions between the shell and interior structures can be easily simulated. Comparisons of results individually obtained from this hybrid method and FEM demonstrate the high accuracy of the hybrid method. Some numerical examples are given herein to further study effects of coupling conditions and boundary conditions on vibration responses of the shell with interior structures.

1. Introduction

Cylindrical shells are widely used as basic components to simulate aerospace, submarine and pipe structures, and so forth. Over the past few decades, considerable attention has been paid to investigating vibration characteristics of cylindrical shells, and most of these works were well documented in the publications (Leissa, 1993; Qatu, 2002a, 2002b). In practical engineering applications, various irregular-shaped facilities may be mounted inside the hull. Nevertheless, the majority of literature were concerned with pure cylindrical shells (Bert and Malik, 1996; Stanley and Ganesan, 1995; Xiang et al., 2002; Zhang and Xiang, 2007), and shells with simple attachments such as ring stiffeners (Wah and Hu, 1968; Mustafa and Ali, 1989; Jafari and Bagheri, 2006), circular plates (Smith and Haft, 1967; Cheng and Nicolas, 1992) as well as longitudinal floors (Missaoui et al., 1996; Wang et al., 2004). Due to the difficulty in modelling and solution process, it is laborious to study vibrations of complicated structures through theoretical methods. As a discretization approach, FEM is a powerful tool to approximately deal with structural vibration problems. One advantage of FEM is the ability to model complex structures which can't be dealt with by analytical methods. However, to ensure the accuracy of FEM results, the number of elements will increase sharply as the frequency increases, which seriously reduces computational efficiency and increases storage space. Therefore, in terms of the cylindrical shell with interior structures, developing an efficient approach which combines advantages of the analytical method and numerical method is meaningful. Unfortunately, owing to the complexity involved in the coupling of the two methods, the number of researches on structural vibrations utilizing the hybrid analytical-numerical approach is rather limited.

To the authors' best knowledge, there are some but not many literature concerning structure vibrations by means of the hybrid method. Grice and Pinnington (2000a) investigated forced vibration characteristics of a beam-stiffened plate. The complete structure was divided into two independent parts, namely a beam and a plate. The beam was analyzed by FEM while the plate was modelled using analytical impedances (Grice and Pinnington, 2000b). The two components were eventually coupled together through a standard sub-structuring procedure. In a subsequent study (Grice and Pinnington, 2002), the hybrid method was used to study flexural vibrations of a thin-plate box, and the results were validated by laboratory measurements. Li et al. (2014) developed a hybrid finite element-Fourier spectral method to analyze free vibrations of beams and plates based on energy principle. The analytical and numerical domains, which were respectively studied through Fourier spectral method and FEM, were coupled by introducing artificial springs. Ettouney et al. (1994) investigated vibrational and acoustical characteristics of a submerged cylindrical shell with two hemispherical end closures and an interior beam. A finite difference method was adopted to model the shell and the beam was tackled using FEM. However, ignoring

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rotations, only continuity conditions in three translational directions were considered at the coupling point of the shell and the beam. Zou (2014) studied forced vibrations of an underwater cylindrical shell with an inner base. The mode superposition method and FEM were adopted to analyze the shell and the base, respectively. Continuity conditions at coupling points were utilized to couple the two substructures. Nevertheless, as a result of trigonometric functions being chosen as axial displacement functions, only the simply supported cylindrical shell was taken into account. Maxit and Ginoux (2010) proposed a substructure method called the Circumferential Admittance Approach (CAA) to predict vibro-acoustic behavior of a submerged cylindrical shell non-periodically stiffened by axisymmetric interior frames (stiffeners, bulkheads, hemispherical end caps and so on). The shell was solved in the wavenumber domain. Interior frames were tackled adopting axisymmetric FEM and coupled to the shell in three translational directions and tangential rotation. CAA was also used to predict scattering pressure of the similar model in a succeeding study (Maxit, 2014). As an extension of CAA, the Condensed Transfer Functions (CTF) method (Meyer et al., 2016) was subsequently developed to consider not only axisymmetric frames but also non-axisymmetric ones. CTF and CAA were combined to study vibrations and acoustics of cylindrical shells with more complicated interior frames. However, it was a remarkable fact that non-axisymmetric frames were connected to axisymmetric frames which were still coupled to the shell in four degrees of freedom (Dofs), with the couplings in axial and radial rotations being neglected.

From the aforementioned review, some researchers were devoted to combining theoretical methods and numerical methods for vibration analysis of complicated structures. As for the cylindrical shell with interior attachments, the couplings between the shell and attachments were insufficient (Ettouney et al., 1994; Meyer et al., 2016), i.e., only three or four Dofs were considered. Recently, wave based method, which has been adopted by the research group of authors to investigate vibrations of cylindrical shells (Wei et al., 2013; Chen et al., 2015; Xie et al., 2017a), was extended to establish governing equations of the shell coupled with interior structures in six Dofs (Zhang et al., 2017). Unfortunately, similar to the cited publications (Ettouney et al., 1994; Zou, 2014; Maxit and Ginoux, 2010; Maxit, 2014; Meyer et al., 2016), interior attachments were still rigidly connected to the shell in authors' previous study (Zhang et al., 2017). In practical applications, the shell and attachments may be joined together by welds or bolts. However, due to welding defects or bolt looseness, displacement continuity may not be perfectly achieved at junctions. What's more, there are some machines elastically mounted in the hull. Under these circumstances, rigid couplings are not applicable. As a consequence, developing a method dealing with the elastic couplings between the shell and interior attachments is necessary.

In this paper, a hybrid approach combining WBM and FEM is presented to investigate vibration characteristics of a cylindrical shell coupled with interior structures. The whole structure is decomposed into the independent shell and interior attachments, which are analyzed through WBM and FEM, respectively. Flügge theory is used to establish motion equations of the shell and wave functions, which are the essence of WBM, are utilized as admissible displacement functions. Artificial spring technique is adopted to couple the two substructures in three translational directions and three rotations. Moreover, as a special case, rigid coupling conditions can be taken into account by assigning stiffness constants of artificial springs as a very large value (Xie et al., 2017b). Several numerical examples are given to demonstrate the accuracy of present hybrid method, and effects of coupling conditions as well as boundary conditions are further studied. The hybrid analytical-numerical approach developed in this paper is believed to include following novelties. First, the present method combines advantages of WBM and FEM for vibration analysis of cylindrical shells with various interior structures. Second, in contrast with the simplified processing method in literature, more accurate continuity conditions between the shell and interior structures are considered by present method, which is appropriate to arbitrary coupling conditions. Third, present hybrid method shows great potential in variable parameters analysis for optimization. For instance, if properties of interior structures are modified, there is no need to reanalyze the cylindrical shell and computation time can thus be saved.

2. Theoretical formulations

In present paper, the interior structures attached to the cylindrical shell are modelled by FEM, thus no limit existing in the geometric shape of interior structures. In other words, both simple plates and complicated structures can be analyzed. For illustrative purposes, a simplified base is adopted. It should be known that the interior structure is not only restricted to a base, and it is just a representative case. Due to the discretization of FEM, the displacement field of the base is discrete. As a result, line connections between the shell and the base are simulated by artificial spring systems distributed at coupling points along the junctions. The shell-base system and the corresponding global cylindrical co-ordinate system $O-r\theta X$ are schematically illustrated in Fig. 1. The derivation process is divided into three parts:

In Section 2.1, based on WBM, the displacement receptance functions at coupling points under coupling excitation and external excitation on the shell are derivated. In Section 2.2, the dynamic equations of the base are obtained by FEM. In Section 2.3, the shell and the base are coupled together through artificial springs, and the governing equations of the shell-base system are established.

2.1. Equations of the shell

2.1.1. Motion equations and admissible displacement functions

The cylindrical shell is made of the isotropic and elastic material with Young's modulus E_s, Poisson's ratio υ_s and density ρ_s. The damping is introduced by replacing Young's modulus E_s with a complex one $E_s = E_s(1+i\eta_s)$, where η_s is the material loss factor. L, R and h are the length, the radius and the thickness, respectively. Based on WBM, the cylindrical shell is divided into shell segments according to axial positions of excitations. The local co-ordinate system $o-r\theta x$ is adopted for one segment to establish the governing equations, as shown in Fig. 2. u, v and w are the orthogonal components of displacement in axial, circumferential and radial directions. $\phi = \partial w/\partial x$ is the slope. $\overline{N}$ is the axial force resultant. M is the bending moment resultant. $\overline{T}$ and $\overline{S}$ represent the circumferential and lateral Kelvin-Kirchhoff shear force resultants, respectively. On the basis of Flügge shell theory, motion equations of a thin cylindrical segment can be expressed as (Flügge, 1973)

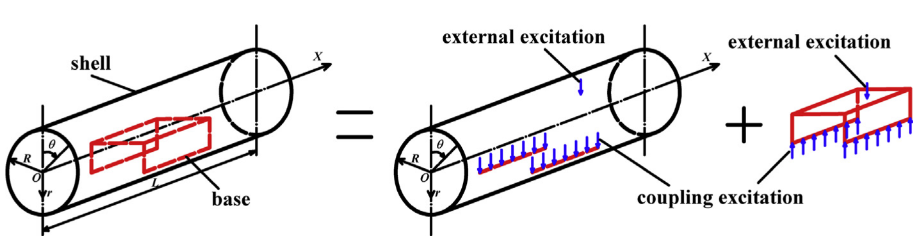

Fig. 1. Schematic diagram of the shell-base system.

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