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Free vibration analysis of moderately thick functionally graded open shells with general boundary conditions

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ABSTRACT

This paper presents the free vibration analysis of functionally graded open shells including cylindrical, conical and spherical ones with arbitrary subtended angle and general boundary conditions. The material properties of the open shells have continuous and smooth variation in the thickness direction based on general four-parameter power-law distributions in terms of volume fractions of the constituents. The formulation is derived by the modified Fourier series in conjunction with Rayleigh–Ritz method according to the first-order shear deformation shell theory. The modified Fourier series is expressed in the form of the linear superposition of a double cosine series and auxiliary functions which are introduced to ensure and accelerate the convergence of the series representations. The comprehensive investigations concerning the convergence and accuracy of the present method are performed by a number of numerical tests and comparisons. Some new results of FGM open shells with elastic restraints are presented. Parametric studies are carried out for FGM open shells with respect to the boundary conditions, material profiles and geometrical parameters.

1. Introduction

Open shells have been widely used in a variety of engineering fields such as civil, mechanical, architectural, aeronautical, and marine engineering. These structures possess carrying load capacity due to the special geometrical shapes, and they are often subjected to dynamic loads that cause vibrations. Hence, the study concerning vibration problems of open shells is of practical significance and great importance.

Due to the existing lacuna, the assumption of the whole periodic wave numbers in the circumferential direction is inappropriate for the open shells, which leads to mathematical and computational complexities. Therefore, compared with closed shells, the literature available concerning the open shells is relatively limited. Earlier investigations on the open shells dealt with the vibration of shallow shells [1–18]. Shallow shells are defined as shells that are open and have small curvature. Since they have lager radii of curvatures compared with other shells parameters (e.g. length and width), the shallow shell theories can be obtained by making certain additional assumptions to shells theories, which reduce the complexity in their computation. However, the shallow shell theories cannot provide accurate results for the deep shells. Thus, many studies were performed based on deep shells theories [19–39]. It should be noticed that those shell theories can be applied directly to shallow shells. Apart from shell theories, a number of analytical and numerical methods have been proposed recently, such as Ritz methods [5,11,40–42], meshless methods [22,29,44–52], differential quadrature method [27,36], discrete singular convolution method [30] and Haar wavelet method [43]. These methods can be used to deal with such shell structures.

Functionally graded materials (FGMs) are special composites whose material properties vary continuously and smoothly from one surface to another. The unique properties can overcome the defects of the conventional laminated composites, and extensive research work has been carried out about FGMs. Recently, the FGMs have been utilized to build various open shell structures in engineering applications. In order to use them effectively, a thorough understanding of the dynamic characteristics of the FGM open shells is necessary for designers. The purpose of this paper is to investigate the vibration of functionally graded open shells, including open cylindrical, conical and spherical shells, having arbitrary subtended angle.

Many research efforts have been devoted to the analysis of functionally graded open shells [53–73]. Duc and Tung [53] presented an analytical approach to investigate the stability of functionally graded cylindrical panels under axial compression

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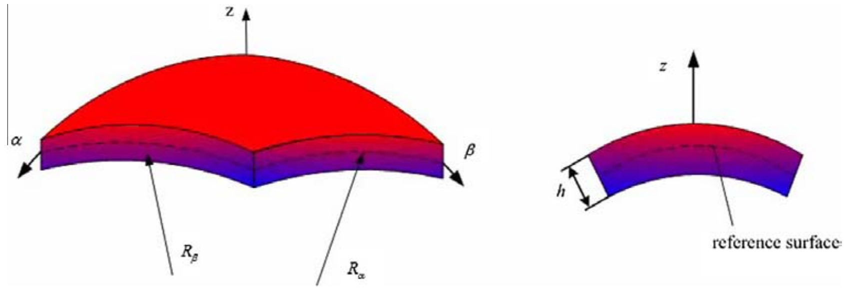

Fig. 1. Geometry and notations of a FGM open shell.

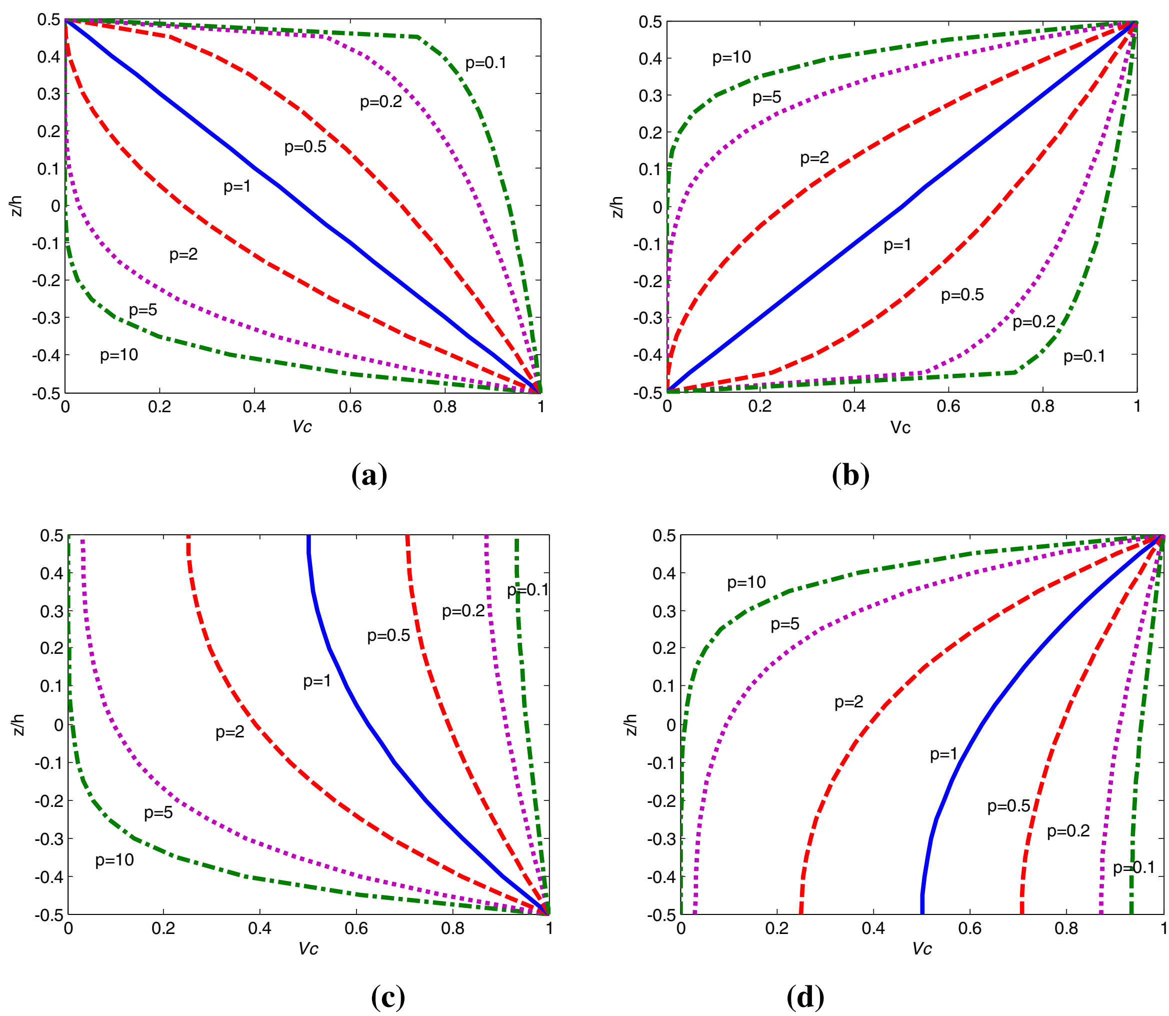

Fig. 2. Variations of the volume fraction V_c through the shell thickness for different values of power-law exponent p: (a) $FGM_{I(a=1/b=0/c/p)}$; (b) $FGM_{II(a=1/b=0/c/p)}$; (c) $FGM_{I(a=1/b=0.5/c=2/p)}$; (d) $FGM_{II(a=1/b=0.5/c=2/p)}$.

based on the classical shell theory (CST). The static response and free vibration of functionally graded shell panels under mechanical and thermomechanical loading were investigated by Zhao et al. [57] by using the element-free *kp*-Ritz method based on the first-order shear deformation shell theory (FSDT). Tornabene and Viola [60] studied the static behavior of functionally graded and laminated shell and panel structures by means of Generalized Differential Quadrature (GDQ) on the basis of the first-order shear deformation theory. Zhao and Liew [61] analyzed the free vibration of functionally graded conical shell panels with various classical boundary conditions by using a meshless method. An exact closed-form analysis for free vibration of moderately thick FGM spherical shell panels was developed by Fadaee et al. [63], and the formulation is based on Donnell and Sanders theories. Pradyumna and Bandyopadhyay [67] dealted with the free vibration analysis of functionally graded curved panels based on higher-order shear deformation theory. And a C^0 finite element formulation was used to carry out the analysis. Free vibration analysis of functionally graded shell including cylindrical and spherical panels with fully simply supported and clamped boundary conditions was reported by Neves et al. [70] using radial basis functions collocation and higher-order shear deformation theory. A semi-analytical three-dimensional solution for free vibration of Lévy-type functionally graded curved panels was obtained by