Applied Mathematical Modelling 38 (2014) 308–324

Contents lists available at SciVerse ScienceDirect

Applied Mathematical Modelling

journal homepage: www.elsevier.com/locate/apm

Free vibration analysis of two-dimensional functionally graded cylindrical shells

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ARTICLE INFO

Article history:
Received 20 September 2012
Received in revised form 23 May 2013
Accepted 24 June 2013
Available online 4 July 2013

Keywords:
Free vibration
Cylindrical shell
2-D functionally graded material
Generalized differential integral quadrature

ABSTRACT

In this paper, the free vibration of a two-dimensional functionally graded circular cylindrical shell is analyzed. The equations of motion are based on the Love's first approximation classical shell theory. The spatial derivatives of the equations of motion and boundary conditions are discretized by the methods of generalized differential quadrature (GDQ) and generalized integral quadrature (GIQ). Two kinds of micromechanics models, viz. Voigt and Mori–Tanaka models are used to describe the material properties. To validate the results, comparisons are made with the solutions for FG cylindrical shells available in the literature. The results of this study show that the natural frequency of the material can be modified in order to meet the expected results through manipulation of the constituent volume fractions. A comprehensive comparison is then drawn between ordinary and 2-D FG cylindrical shells.

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1. Introduction

In recent years, the composition of several different materials is often used in structural components so as to optimize the responses of structures undergoing severe loadings. To reduce the local stress concentrations induced by abrupt transitions in material properties, some proposed the transition between different materials should be made gradually. This idea was presented for the first time by Japanese researchers [1], which lead to the concept of functionally graded materials (FGMs). Typically, FGMs are made from a mixture of metals and ceramics and are characterized in a way that composition of each one and the volume fraction of materials are changed gradually. By gradually varying the volume fraction of constituent materials, their material properties exhibit a smooth and continuous change from one surface to another, and as a result eliminating interface problems and abating thermal stress concentrations.

This property stimulated an increasing use in the shell constructions and several works have been published in this field. Loy et al. [2] studied the natural frequencies of simply supported FGM cylindrical shells using Ritz method based on Love's shell theory. This case was then extended by Pradhan et al. [3] to the case of FGM cylindrical shells with different boundary conditions. Woo and Meguid [4] gave an analytical solution for the large deflection of thin FG plates and shallow shells under transverse loading and temperature field. Najafizadeh and Isfandzibaei [5,6] studied free vibration of thin FGM cylindrical shells with ring support using Ritz method based on the first order and higher order shear deformation shell theories, respectively. Iqbal et al. [7] investigated free vibration of FGM cylindrical shells using the wave propagation approach. Sheng and Wang [8] performed the analysis of vibration, buckling and dynamic stability of FGM cylindrical shells embedded in an elastic medium and subjected to mechanical and thermal loads based on the first order shear deformation shell theory.

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0307-904X/$ - see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.apm.2013.06.015

Tornabene et al. [9] studied the dynamic behavior of functionally graded conical, cylindrical shells and annular plates using the first-order shear deformation theory. Shen [10] carried out an investigation on vibrational behavior of a FGM cylindrical shell of finite length, embedded in a large outer elastic medium and in thermal environments based on a higher order shear deformation shell theory. The dynamic behavior of moderately thick functionally graded conical, cylindrical shells and annular plates was studied by Tornabene [11] based on the First-order Shear Deformation Theory (FSDT) within the bounds of theory of linear elasticity using a four-parameter power-law distribution. A study on the curved shell elements implementing the B-spline Wavelet on the Interval (BSWI) with rectangular planform was done by Yang et al. [12]. Cylindercal shells, doubly-curved shallow shells and hyperbolic paraboloidal shells BSWI elements are formulated by the aid of general shell theory in this study. Hosseini-Hashemi et al. [13] developed an exact closed-form solution for the free vibration of piezoelectric coupled thick circular/annular FGPs subjected to different boundary conditions on the basis of the Mindlin's first-order shear deformation theory. On a different study, Hosseini-Hashemi et al. [14] presented an analytical solution based on a new exact closed form procedure for free vibration analysis of stepped circular and annular FG plates via first order shear deformation plate theory of Mindlin.

It should be mentioned that a conventional functionally graded material may also not be so effective in complex design problems since all outer surfaces of the body will have the same composition distribution and temperature distribution. Changes in advanced machine elements in two or three directions demand a more competitive design. Therefore, if the FGM has a 2-D dependent material property, a more effective material can be obtained. Accordingly, 2-D functionally graded materials (2-D FGMs) whose material properties are bi-directionally dependent are introduced. The manufacturing of multidimensional FGM may seem to be costly or difficult, but it should be noticed that while these technologies are relatively new, processes such as 3-D printing and laser engineering net shaping can currently produce FGMs with relatively arbitrary three-dimensional grading [15]. With further refinements, FGM manufacturing methods may provide the designers with more control over the composition profile of functionally graded components with reasonable costs. Therefore, some researchers are attracted to enter this field of work and conduct several investigations. The thermal stresses in two-directionally graded plates studied by Nemat–Alla [16] utilizing a finite element model. Kutiš et al. [17] presented the multilayering method and the direct integration method for modeling of a functionally graded material (FGM) beam with continuous spatially varying material properties. Sobhani Aragh and Hedayati [18] studied the free vibration and static response of a two-dimensional functionally graded open thick cylindrical shell using theory of elasticity by the GDQ method.

Computational methods can be classified as analytical and numerical methods. In general, the analytical methods require less computational effort than the finite element methods. However, they may not be convenient when compared to numerical methods in the cases of application to complicated problems. The numerical methods discretize the partial differential equations at each interior point and then reduce them into a set of algebraic equations. The eigenvalues of the resultant system of algebraic equations provide vibration frequencies of the problem. Commonly, the finite element methods require a lot of virtual storage and computational effort to yield accurate numerical solutions. To obtain accurate numerical results by the finite element method, as we know, one needs to use a small mesh size to minimize the truncated error. Consequently, a large number of grid points have to be used to keep the mesh size small. Among all the computed Eigen frequencies, only the low frequencies are of practical interest. The generalized differential quadrature (GDQ) method offers a promising way to obtain the accurate Eigen frequencies of cylindrical shells by using just a few grid points. The GDQ method which is a type of numerical method was developed by Shu and Richards [19] to improve the differential quadrature (DQ) method [20] for the computation of weighting coefficients. The GDQ approximates a spatial derivative of a function with respect to a coordinate at a discrete point as a weighted linear sum of all the functional values in the whole computational domain. This method has been successfully applied to simulate some fluid flow problems [21] and the structural dynamics of beams and plates [22,23] and laminated composite cylindrical shells [22] as well as vibration analysis of conical shells [24].

To the best knowledge of authors there is no work available in the literature on the subject of free vibration analysis of 2D FG cylindrical shells by the means of love's first approximation classical shell theory. Previous works on analysis of 2D FG cylindrical shells have been done using other methods. The primary advantage of the proposed fast converging method in this paper is maintaining credibility of the results for thin two-dimensionally graded shells while reducing the amount of computations and consequently truncation and round-off errors. The current study investigates the vibration of two-dimensional functionally graded circular cylindrical shells based on the Love's first approximation shell theory. The functionally gradient material is considered to be composed of Stainless Steel and Nickel where the volume fractions follow a power law distribution. Two types of micromechanics models namely, Voigt and Mori–Tanaka models, are used to describe the composite material characteristics. A novel approach is adopted in this work to solve the equations of motion. To solve the problem, the equations of motion and boundary conditions are discretized using generalized differential-integral quadrature method. The objectives of this study are to investigate the natural frequency characteristics and effects of constituent volume fractions on the free vibration frequencies. The effects of h/R and L/R ratio on natural frequencies of 2-D FG shells are also considered here and are compared with those of ordinary FG shells.

2. Problem formulation

Consider a cylindrical shell with length L, Radius R and thickness h, as is shown by Fig. 1. A reference cylindrical coordinate system (x, θ, z) is taken at the middle surface.

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