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Large amplitude vibration of FGM plates in thermal environment subjected to simultaneously static pressure and harmonic force using multimodal FEM

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ABSTRACT

A nonlinear finite element modeling is proposed to study the dynamic response of functionally graded material (FGM) plates subjected simultaneously to thermal, static, and harmonic loads. The material properties depended on the temperature are assumed to vary continuously in the thickness direction according to a simple power law distribution. Third-order shear deformation theory (HST) of Reddy is modified for FGM plates by considering physical/exact neutral surface. Extended Hamilton's principle is used to obtain the equations of motion in structural nodes degree of freedom (DOF). Using exact neutral surface in equations of motion, the in-plane and out of plane motions of FGM plates can be separated similar to homogenous plates. The order of equations of motion is reduced using modal reduction method. Shooting method is used to obtain the initial conditions for periodic response. Three bucked equilibrium positions (BEPs) are obtained for FGM plates with immovable boundaries under thermal load. The obtained BEPs are compared with those obtained if the middle surface formulation is used. Also the effects of initial conditions and static pressure on the dynamic response of the system are investigated. It is found that the FGM plate has different responses with the same frequency and amplitude of excitation.

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1. Introduction

Plates, as common structural components, have important engineering applications especially in the aerospace technology. With improvement of composite materials, the application of composite plates has become more extensive. Recently, FGM plates get more attention especially in aerospace structures such as supersonic/hypersonic vehicles in high temperature environments.

Many researchers studied the linear behavior of FGM plates. Reddy and Chin [1] studied the linear vibration of FGM plates and cylinders under mechanical and thermal loads. Vel and Batra [2] studied free and forced vibrations of simply supported FGM plates using three-dimensional exact solution. Static and dynamic responses of thick FGM plates were presented by Qian et al. [3] using HST and local Petrov–Galerking method. Abrate [4] showed that the natural frequencies of FGM plates are always proportional to those of homogenous isotropic plates with the same boundary conditions and geometry. Matsunaga [5] used power series expansion of displacement components to study the natural frequencies and buckling loads of simply supported FGM plates taking into account transverse shear deformation, normal deformation and rotatory inertia. Carrera et al. [6–9], Belabed et al. [10], Mantari [11] and Zenkour [12] studied linear behavior of FGM plates under static pressure considering thickness stretching using new shear deformation theories such as sinusoidal shear deformation and refined shear deformation theories. In the context of thermal effects on the static and dynamic responses of FGM plates, equilibrium and stability analyses of moderately thick FGM plates subjected to two types of thermal loadings, uniform temperature rise and temperature gradient through the thickness, were studied by Lanhe [13] based on the first order shear deformation theory (FST). Kim [14] developed a theoretical method based on HST to study the free vibration of initially stressed FGM plates in thermal environment using expansion of the displacements in the double Fourier series for the unknown displacements. Shariat and Eslami [15] obtained a closed-form solution for buckling loads of FGM plates under different types of mechanical and thermal loading using HST. Thai et al. [16] presented a closed-form solution for buckling of thick FGM plates on elastic foundation based on HST. In the context of nonlinear free vibration analysis in thermal environment, Sundararajan et al. [17] developed a finite element model

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to study the effects of various parameters such as gradient index, temperature, thickness, aspect ratio, and skew angle on the nonlinear free vibration of FGM plates based on FST. They concluded that temperature field and gradient index have significant effects on the dynamic behavior of FGM plates. Woo [18] developed an analytical solution based on mixed Fourier series to study the effects of material properties, boundary conditions, and thermal loading on the nonlinear free vibration behavior of FGM plates using FST. Lee et al. [19] presented a theoretical analysis for large amplitude vibration of symmetric and un-symmetric laminated plates using nonlinear finite element modal reduction method. Perturbation technique was employed by Shen [20] to obtain the buckling temperature and BEPs of symmetric FGM plates based on HST. Madhukar and Singha [21] presented a nonlinear finite element model based on the normal deformation theory to study the free and forced vibrations of sandwich plates. Recently nonlinear forced vibration of isotropic, laminated, and FGM plates have been studied in literature. A simple HST was presented by Reddy [22] to study the nonlinear behavior of laminated composite plates under static loads. Shankara and Iyengar [23] modified Reddy's HST [22] to study nonlinear free vibration of laminated plates. Reddy [24] presented theoretical formulation for linear analysis as well as finite element formulation for nonlinear analysis to study the effect of material distribution on the deflections and stresses of FGM plates. Huang and Shen [25] presented analytical solution based on improved perturbation techniques to study nonlinear frequencies and dynamic responses of FGM plates. Ribeiro [26] obtained stable and unstable solutions and characteristics of the motions of thin/thick isotropic beams and plates subjected to concentrated harmonic excitation based on FST using shooting and finite element methods. Parandvar and Farid [27] reduced the order of equations of motion using a novel approach for selection of the base vectors to study the dynamic response of FGM plates under random loads in thermal environment. Amabili [28] studied the large amplitude vibrations of Aluminum plates with different boundary conditions subjected to harmonic excitation based on FST using both theoretical and experimental approaches. Singha and Daripa [29] used finite element method to analyze the large amplitude flexural vibration characteristics of thin isotropic and laminated composite plates under transverse harmonic pressure and periodic in-plane load. Zhang et al. [30] investigated the nonlinear vibrations and chaotic dynamics of a simply supported FGM plate subjected to in-plane and transverse loads in thermal environment based on HST. They focused on the cases of 1:2:4 internal resonance, primary parametric resonance and subharmonic resonance of order ½. Non-linear dynamic instability of simply supported movable FGM plates subjected to in-plane static and harmonic excitation with frequencies in the neighborhood of twice of the fundamental frequency was studied by Alijani and Amabili [31] using double Fourier series expansion of the displacements based on HST. Alijani and Amabili [32] studied the effect of thickness deformation on the nonlinear forced vibration of moderately thick FGM plates subjected to concentrated harmonic force and uniform static pressure with two types of boundary conditions: simply supported movable and immovable edges. They showed that HST yields significantly accurate results for nonlinear vibration of highly pressurized FGM plates. Alijani et al. [33] studied geometrically nonlinear vibrations of simply supported FGM plates in thermal environments based on FST using multi-mode energy approach. They showed that in order to obtain accurate natural frequencies in thermal environments; an analysis based on fully nonlinear model is unavoidable. They also showed that the volume fraction variation does not have significant effect on the nonlinear response of the FGM plates. It is worth mentioning that Ibrahim et al. [34], Wu et al. [35], Shen [20,36], Park and Kim [37], Lee et al. [38], Yang [39], and Duc [40] studied thermal post-buckling behavior of FGM plates with immovable simply supported edges using various plate theories.

In this study, first the Reddy's HST is improved using the warping functions and exact physical neutral surface for FGM plates. Then, the equations of motion are discretized using finite element method. Considering the exact physical neutral surface, the governing equations of motion of the FGM plates become similar to those of homogenous plates. In other words, stretching and bending effects in the linear governing equations of FGM plates are decoupled. Due to this separation, some liner modes contain only bending effects and others contain only in-plane ones. This leads to introducing new base vectors to reduce the order of equations of motion of FGM plates. In this work, the equations of motion are reduced using the approach proposed by Shi and Mei [41]. The dynamic response of FGM plates subjected to harmonic excitation and static pressure is obtained in thermal environment.

2. Theory

An FGM plate made of ceramic (top surface) and metal (bottom surface) is considered in this work. The material properties vary in the thickness direction based on a simple power law distribution in the following form [1]:

$$P_{\mathrm{eff}}(z) = P_c V_c(z) + P_m(1 - V_c) \tag{1}$$

where V_c, the volume fraction, is

$$V_c = \left(\frac{1}{2} + \frac{z}{h}\right)^n \quad -h/2 \le z \le h/2,\ 0 \leqslant n \leqslant \infty \tag{2}$$

z is the coordinate along the thickness (h) of FGM plate as shown in Fig. 1. P_{eff} is the effective material property of the FGM plate, while P_c and P_m are ceramic and metal properties, respectively. n is the volume fraction exponent. Each material property of metal and ceramic is a function of temperature in the following form [1]:

$$P(T) = p_0\left(\frac{p_{-1}}{T} + 1 + p_1 T + p_2 T^2 + p_3 T^3\right) \tag{3}$$

where the parameters P_0, P_{-1} and ... are constants.

2.1. HST based on exact neutral surface

Reddy [22] presented a simple HST for symmetric cross-ply laminates plates in the following form:

$$\begin{aligned} u(x,y,z,t) &= u_0(x,y,t) + z[\psi_y(x,y,t) - \tfrac{4}{3}(\tfrac{z}{h})^2(\psi_y(x,y,t) + \tfrac{\partial w}{\partial x})] \\ v(x,y,z,t) &= v_0(x,y,t) + z[\psi_x(x,y,t) - \tfrac{4}{3}(\tfrac{z}{h})^2(\psi_x(x,y,t) + \tfrac{\partial w}{\partial y})] \\ w(x,y,z,t) &= w_0(x,y,t) \end{aligned} \tag{4}$$

In the above equations u, v, and w are the displacements at any point of the FGM plate in x, y and z directions, respectively, and. u_0, v_0, and w_0 are those on the middle surface. ψ_x and ψ_y are the rotations about x and y axes, respectively. To study the static and dynamic responses of shells and plates using finite element

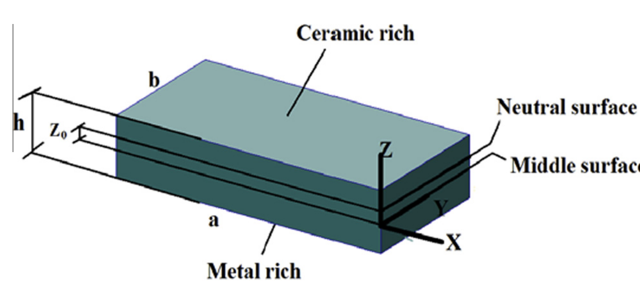

Fig. 1. Geometry and coordinate of a FGM plate.

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