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Nonlinear dynamical analyses of eccentrically stiffened functionally graded toroidal shell segments surrounded by elastic foundation in thermal environment

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ABSTRACT

In this study, the nonlinear vibration and dynamic buckling of eccentrically stiffened functionally graded toroidal shell segments surrounded by an elastic medium in thermal environment are presented. The governing equations of motion of eccentrically stiffened functionally graded toroidal shell segments are derived based on the classical shell theory with the geometrical nonlinear in von Karman-Donnell sense and the smeared stiffeners technique. Furthermore, the dynamical characteristics of shells as natural frequencies, nonlinear frequency–amplitude relation, nonlinear dynamic responses and the nonlinear dynamic critical buckling loads evaluated by Budiansky-Roth criterion are considered. The effects of characteristics of functionally graded materials, geometrical ratios, elastic foundation, pre-loaded axial compression and temperature on the dynamical behavior of shells are investigated.

1. Introduction

In the past, the dynamic problems of laminated composite structures studied by many authors. Hui [1,2] presented the effects of shear loads on vibration and buckling of typical antisymmetric cross-ply thin cylindrical panels under combined loads; effects of geometrical imperfections on the large amplitude vibration of shallow spherical shells as well as effects of structural damping. Dynamic fracture and delamination of unidirectional graphite/epoxy composites for end-notched flexure center-noted flexure pure mode II loading configurations using a modified split Hopkinson pressure bar were investigated by Nwosu et al. [3].

Functionally graded materials (FGMs) were invented by Japanese scientists in 1984 [4]. This composite material is a mixture of ceramic and metallic constituent materials by continuously changing in the volume fractions of their components. Mechanical and physical behavior of FGMs are better than fiber reinforced laminated composite materials with advantages of no stress concentration, high toughness, oxidation resistance and heat-resistance so FGMs are applied to heat-resistant, lightweight structures in aerospace, mechanical, and medical industry and so forth. Therefore, the nonlinear vibration and dynamic buckling problems of FGM structures have been attracted a vast amount attention of researchers.

Pradhan et al. [5] studied vibration of FGM cylindrical shells under various boundary conditions with the strain-displacement relations form Love's shell theory. Based on the Rayleigh method, the governing equations were derived and the natural frequencies were investigated depending on the constituent volume fractions and boundary condition. The general formulation for free, steady-state and transient vibration analyses of FGM shells of revolution subjected to arbitrary boundary conditions was presented by Qu et al. [6]. The formulation was derived by means of a modified variational principle in conjunction with a multi-segment partitioning procedure on the basis of the first order shear deformation shell theory. G. G. Sheng and X. Wang [7] investigated the nonlinear vibrations control of FGM laminated cylindrical shell based on

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Hamilton's principle, von Karman nonlinear theory and constant-gain negative velocity feedback approach. The thin piezoelectric layers embedded on inner and outer surfaces of the smart FG laminated cylindrical shell were acted as distributed sensor and actuator, which is used to control nonlinear vibration of the smart FG laminated cylindrical shell. The free vibration analysis of functionally graded cylindrical panels with cut-out and under temperature condition using the three-dimensional Chebyshev-Ritz method was noticed by Malekzadeh et al. [8]. Chen and Babcock [9] gave the large amplitude vibration of a thin-walled cylindrical shell using the perturbation method the steady-state forced vibration problem. Furthermore, the simply-supported boundary conditions and the circumferential periodicity condition were satisfied. The unified solution for the vibration analysis of functionally graded material (FGM) doubly-curved shells of revolution with arbitrary boundary conditions was given by Jin et al. [10]. The solution was derived by means of the modified Fourier series method on the basis of the first order shear deformation shell theory considering the effects of the deepness terms. Kim [11] performed free vibration characteristics of FGM cylindrical shells partially resting on elastic foundation with an oblique edge using an analytical method. The motion of shell was represented based on the first order shear deformation theory to account for rotary inertia and transverse shear strains. The nonlinear dynamic buckling and pre-buckling deformation of FGM truncated conical shells under axial compressive load varying as a linear function of time using the Superposition principle, Galerkin and Runge-Kutta methods were studied by Deniz and Sofiyev [12,13]. Shen and Yang [14] carried out the free vibration and dynamic instability of functionally graded cylindrical panels subjected to combined static and periodic axial forces and in thermal environment with theoretical formulations based on Reddy's higher order shear deformation shell theory taking into account rotary inertia and the parabolic distribution of the transverse shear strains through the panel thickness. The characteristics of free vibration and nonlinear responses were investigated using the governing equations of motion of eccentrically stiffened functionally graded cylindrical panels with geometrically imperfections based on the classical shell theory with the geometrical nonlinearity in von Karman-Donnell sense and smeared stiffeners technique by Bich et al. [15]. Moreover, Bich and Nguyen [16] presented the study of the nonlinear vibration of a functionally graded cylindrical shell subjected to axial and transverse mechanical loads based on improved Donnell equations. The dynamic behavior of moderately thick functionally graded conical, cylindrical shells and annular plates with a four-parameter power law distribution based on the First order Shear Deformation Theory were focused by Tornabene [17]. The materials were assumed to be isotropic and inhomogeneous though the thickness direction. Sofiyev [18–20] studied the dynamic behavior of FGM structures such as: the vibration of FGM conical shells under a compressive axial load using the shear deformation theory using Donnell shell theory; the parametric vibration of shear deformable functionally graded truncated conical shells subjected to static and time dependent periodic uniform lateral pressures based on the first order shear deformation theory; the theoretical approach to solve vibration problems of FGM truncated conical shells under mixed boundary conditions using means of the Airy stress function method to derive the fundamental relations, motion and strain compatibility equations. The vibration of thin cylindrical shells extracted from Ref. Függe's three equations of motion was investigated by Warburton [21]. This solution required the assumption of a natural frequency and the determination of the corresponding shell length for the prescribed end conditions. Based on strain-displacement relations from the Love's shell theory and the eigenvalue governing equation using Rayleigh-Ritz method, Loy et al. [22] gave the study at vibration filed of functionally cylindrical shells. The influences of shear stresses and rotary inertia on the vibration of FG coated sandwich cylindrical shells resting on Pasternak elastic foundation based on the modification of Donnell type equations of motion were examined by Sofiyev et al. [23]. The basic equations were reduced to an algebraic equation of the sixth order and numerically solving this algebraic equation gave the dimensionless fundamental frequency.

Noda [24], Praveen et al. [25] first discovered the heat-resistant FGM structures and studied material properties dependent on temperature in thermo elastic analyses. Heydarpour and Malekzadeh [26] pointed out the free vibration analysis of rotating functionally graded cylindrical shells in temperature environment with the equations of motion and related boundary conditions derived to Hamilton's principle. The initial thermo-mechanical stresses were obtained by solving the thermo elastic equilibrium equations. Sheng and Wang [27] researched the nonlinear response of functionally graded cylindrical shells under mechanical and thermal loads using con Karman nonlinear theory. The coupled nonlinear partial differential equations are discretized based on a series expansion of linear modes and a multiterm Galerkin's method. Furthermore, Shen [28] took into account the nonlinear vibration of shear deformable FGM cylindrical shells of finite length embedded in a large outer elastic medium and in thermal environments. The motion equations were based on a higher order shear deformation shell theory that included shell–foundation interaction. The large amplitude vibration behavior of a shear deformable FGM cylindrical panel resting on elastic foundations in thermal environments based on a higher order shear deformation shell theory was investigated by Shen and Wang [29]. The thermal effects are also included and the material properties of FGMs are assumed to be temperature-dependent. The equations of motion are solved by a two step perturbation technique to determine the nonlinear frequencies of the FGM cylindrical panel.

Toroidal shell segment has been used in such applications as satellite support structures, rocket fuel tanks, fusion reactor vessels, diver's oxygen tanks and underwater toroidal pressure hull. Today, FGMs have received mentionable attention in structural applications. The smooth and continuous change in material properties enables FGMs to avoid interface problems and unexpected thermal stress concentrations. Some components of the above-mentioned structures may be made of FGM. Stein and McElman [30] carried out the homogenous and isotropic toroidal shell segments about the buckling problem. Moreover, the initial post-buckling behavior of toroidal shell segments subjected to several loading conditions based on the basic of Koiter's general theory was performed by Hutchinson [31]. Parnell [32] gave a simple technique for the analysis of shells of revolution applied to toroidal shell segments. Recently, there have had some new publications about toroidal shell segment structure. Bich et al. [33] has studied the buckling of eccentrically stiffened functionally graded toroidal shell segment under axial compression, lateral pressure and hydrostatic pressure based on the classical thin shell theory, the smeared stiffeners technique and the adjacent equilibrium criterion. Furthermore, the nonlinear buckling and post-buckling of ES-FGM toroidal shell segments surrounded by an elastic medium under torsional load based on the analytical approach are investigated by Ninh et al. [34,35]. Bich et al. [36,37] studied the post-buckling of FGM and S-FGM toroidal shell segment under external pressure loads by an analytical approach using the Galerkin method.

To the best of the authors' knowledge, there has not been any study to the nonlinear dynamical analysis of eccentrically stiffened FGM toroidal shell segments surrounded by an elastic foundation including temperature effects.