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Free vibration analysis of saturated porous FG circular plates integrated with piezoelectric actuators via differential quadrature method

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ABSTRACT

The free vibration analysis of a circular plate made up of a porous material integrated by piezoelectric actuator patches has been studied. The plate is assumed to be thin and its shear deformations have been neglected. The porous material properties vary through the plate thickness according to some given functions. Using Hamilton's variational principle and the classical plate theory (CPT) the governing motion equations have been obtained. Simple and clamped supports have been considered for the boundary conditions. The differential quadrature method (DQM) has been used for the discretizations required for numerical analysis. The effect of some parameters such as thickness ratio, porosity, piezoelectric actuators, variation of piezoelectric actuators-to-porous plate thickness ratio, pores distribution and pores compressibility on the natural frequency, radial and circumferential stresses has been illustrated. The results have been compared with the similar ones in the literature.

1. Introduction

Porous material is a material containing pores filled by a fluid. The skeletal part of the material is called matrix or frame and is usually a solid. The porosity is the main property of a porous material and the other properties such as permeability, tensile strength and electrical conductivity are made up of the properties of the matrix and those of the fluid within the pores. Porous beams, plates and shells are extensively designed in structures. Biot is the pioneer who has studied the poro-elasticity. He has introduced the Bulk kinematical and dynamical parameters, namely the total stress tensor σ_{ij}, the fluid pressure P_p, the solid strain tensor ϵ_{ij} and the fluid volume in the pores ξ. His poro-elasticity has been reformulated by the concept of partial stresses. In his model, a porous material is composed of two phases namely solid and fluid [7]. The stress-strain relationship of a porous material has been expressed in terms of the elastic constants of the solid and the fluid by Detournay and Cheng [19]. During the last several years, the problem of deflection, buckling and vibrations of plates with varying properties has been studied by many authors. Several plate theories have been developed to describe the static and dynamic behavior of plates. Many of them, such as classical, first and higher-order shear-deformable theories, have been established on the basis of displacement approximation. In CPT the transverse shear strains are zero, and consequently, the transverse stresses do not enter the theory. So this theory is used for thin plates and will give erroneous results when being used for thick plates. To account for the transverse shear strains, shear-deformable plate theories have been developed. In FSDT the basic equations are derived by assuming that the in-plane displacements are linearly distributed across the plate thickness. This leads to the transverse shear stresses being constant across the plate thickness, so the zero shear stress condition on the plate face is not satisfied. FSDT has been extensively used in the analysis of shear flexible plates and shells [20]. Also, other states of this theory have been used in recent researches. For example a simple FSDT (S-FSDT) was formulated in [59,58] by partitioning the transverse deflection in to the bending and shear components. Compared with the traditional FSDT, one unknown can be saved and the shear locking is free in the S-FSDT. However, the S-FSDT requires C1 continuity of the generalized displacements leading to the second-order derivative of the stiffness formulation which is awkward in conventional finite element analysis based on the C0 continuity [71,69,72]. Senjanovic et al. [50] studied Natural vibrations of thick circular plate based on the modified FSDT theory. Ebrahimi et al. [22] analyzed smart moderately thick shear deformable annular FG plate based on FSDT.

To properly approximate the nonlinear distribution of transverse shear strains along the plate thickness, quite a number of higher order shear deformation plate theories were developed. Such HSDTs have proven to be highly applicable to laminated composite plates. Similar to FSDT, for higher order theories there are other states. Shi [54] successfully formulated a novel improved yet simple third-order shear deformation plate theory (TSDT) based on rigorous kinematics of displacements, initially applied to static analysis of isotropic and

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orthotropic beams and plates. The results obtained by the Shi's TSDT have shown to be more reliable and highly accurate than many other higher-order shear deformation plate theories [12,70]. Or a novel simple quasi-3D hyperbolic shear deformation theory (S-Q3HSDT) has been used in some researches. In S-Q3HSDT fashion, five unknowns per node are included; both shear deformation and thickness-stretching effects across the thickness are taken into account; and the awkward shear locking phenomenon is avoided. The requirement for C1-continuity in terms of the S-Q3DHSDT is straightforwardly possessed with the aid of inherent high-order continuity of non-uniform rational B-spline (NURBS), which serve as basis functions in our IGA formulation [37]. Reddy and Khdeir [45] studied buckling and vibration of laminated composite plates using various plate theories consist of the classical, first-order and third-order laminate theories under various boundary conditions. They considered the effects of side to thickness ratio, aspect ratio and lamination schemes on the frequencies and critical buckling loads. Exact analytical solutions, as well as the finite element numerical solutions, were developed in their studies. Mojahedin et al. [43] analyzed buckling of functionally graded circular plates made of saturated porous materials based on higher order shear deformation theory. They used the energy method for the buckling analysis of plate made of pore material and derivation based on the higher order shear deformation plate theory (HSDT) because the higher order theory is more accurate compared to the classic or first order plate theories due to the consideration of the shear forces. Their most important findings were that by increasing the coefficient of porosity the buckling load will be reduced and the buckling load increases by increasing the thickness. Chen et al. [15] investigated free and forced vibration of functionally graded porous beams with symmetric and nonsymmetric porosity distributions. Natural frequencies and transient dynamic deflections were obtained for porous beams under different loading conditions. Rezaei and Saidi [47] presented an exact solution for vibration of rectangular plates made of porous materials. An analytical solution based on Reddy's third-order shear deformation theory introduced for vibration analysis of rectangular porous plate. They found that the natural frequency of fluid free plates decreases as the plate's porosity increases. Shooshtari and Razavi [55] investigated free vibration of a magneto-electro-elastic rectangular plate which was rests on an elastic foundation based on the Reddy's third-order shear deformation theory under different boundary conditions. Ebrahimi and Habibi [21] Ebrahimi Studied deflection and vibration of higher order shear deformable compositionally graded porous plate. The finite element formulation based on HSDPT developed to analyze the deflection and free vibration in the functionally graded plates made of saturated porous material. He found out by increasing the porosity, the normalized center deflection would be increased.

3D vibration analysis of circular and annular plates has been done by Zhou et al. [74] using the Chebyshev–Ritz method. The new schemes for buckling and vibration analyzing of FG plates. Seifi et al. [49] Studied critical buckling loads and modes of cross- ply laminated annular plates and used Trefftez rule in the stability equations. Also they considered the symmetric buckling of symmetric cross- ply laminates. They found in the plates with clamped boundary conditions the symmetric buckling assumption is not accurate, contrary to other boundary conditions. Heydari et al. [25] considered Buckling of circular functionally graded plate under uniform radial compression on the Pasternak elastic foundation. They provided two schemes for buckling analysis of FGCP based on HSDT and CPT. And moreover considered two types of thickness variations included linear and quadratic variations. The stability equation based on shear stress-free surface is solved by the spectral Ritz method. They investigated the effects of both linear and quadratic thickness variations and Poisson's ratio. They found that by taking small numbers of the basis, the outcomes in literature will improve. Abrate [1] studied about free vibration, buckling and static deflections of FG plates and it was shown that the natural frequencies of functionally graded plates are proportional to those of homogeneous isotropic plates. Also similar results were obtained for buckling and static deflections cases. Nonlinear vibration of a shear deformable FG plate presented by Chen [14]. In this study the material properties of a FG plate were graded continuously in thickness direction. By using Galerkin method the nonlinear partial differential equations were transformed into ordinary form and the linear and nonlinear frequencies were obtained by Runge-Kutta method. Krizhevsky and Stavsky [31], employed Hamilton's variational principle for derivation of equations of vibrations and buckling of laminated isotropic annular plates and a closed form solution was given for the mode shapes in terms of Bessel, power and trigonometric functions. The transverse shear, rotational inertia and boundary conditions effects were discussed. Magnucki and Stasiewicz [39] presented the elastic buckling of a porous beam of a rectangular cross section. The beam was made of an isotropic porous material and it's properties vary through the thickness. The critical loads were obtained from analytical and numerical solutions were similar with the maximum four percent difference. Axisymmetrical deflection and buckling of circular porous-cellular plate was provided by Magnucka-Blandzi [38]. He considered a circular porous plate with simply supported boundary condition under radial uniform compression and pressure. The obtained results were compared to homogeneous circular plates. Wattanasakulpong and Chaikittiratana [66] studied flexural vibration of imperfect FGM beams based on Timoshenko beam theory by using Chebyshev collocation method (CCM). Jin et al. [28] investigated three-dimensional free vibration of functionally graded annular sector plates with general boundary conditions. They considered two types of functionally graded annular sector plates and both the Voigt model and Mori-Tanaka scheme adopted to evaluate the effective material properties. Each of displacements of annular sector plate, regardless of boundary conditions, expressed as modified Fourier series which consists of three-dimensional Fourier cosine series plus several auxiliary functions. Also the effects of the material profiles and boundary conditions on the free vibration of the functionally sector plates studied. Wang et al. [64] presented a unified solution for vibration of functionally graded circular, annular and sector plates with general boundary conditions. Regardless of the shapes of the plates and the types of boundary conditions, the displacement of the plates were described as an improved Fourier series expansion which comprises of a double Fourier cosine series and several auxiliary functions introduced to accelerate the convergence of series representations. They understood that the proposed method was appropriate for general boundary conditions and enabled rapid convergence, higher reliability and accuracy. Also the change of the boundary conditions can be easily achieved by only changing the stiffness of the boundary restrain springs along all the edges of plates without involving any change to the solution procedure. Decha-Umphai and Mei [18] analyzed non-linear forced vibrations of circular plates by finite element method and obtained the relations of amplitude and frequency ratio for different boundary conditions and various load conditions. Eshraghi et al. [24] studied bending and free vibrations of functionally graded annular and circular micro-plates under thermal loading. They presented new techniques that facilitate solution of static bending and free vibrations problems involving thermally loaded functionally graded annular and circular micro-plates. They found out a graded micro-plate under static loading bends concave downwards when the temperature of the upper surface is greater than or equal to that of the lower surface. On the other hand, for freely vibrating annular and circular micro-plates that are under the influence of initial thermal stresses, increase in the body temperature leads to drops in the first dimensionless natural frequency. Wang et al. [65] presented free axisymmetric vibration of FGM circular plates based on three-dimensional theory, material properties obey the exponential law along the thickness direction of the plate. Camier et al. [13] presented non-linear vibrations of imperfect free-edge circular plates and shells. The dynamic analog of the von Karman equations for thin plates, with a stress-free initial deflection, was used to derive the imperfect plate equations of motion. To solve the governing equations,