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Vibration characteristic of moderately thick functionally graded carbon nanotube reinforced composite skew plates

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ABSTRACT

A set of first known vibration frequencies and mode shapes for functionally graded carbon nanotube-reinforced composite (FG-CNTRC) skew plates is presented. Moderately thick skew plates are considered while the first-order shear deformation theory (FSDT) is employed to incorporate the effect of transverse shear deformation. Using the IMLS approximation for the field variables, the discretized eigenvalue equation of the problem is derived via the Ritz procedure. Hence the vibration solutions can be obtained through solving the eigenvalue problem. The FG-CNTRC skew plates are studied with the consideration of different distributions of uniaxial aligned single-wall carbon nanotubes (SWCNTs). Material properties of the FG-CNTRCs are assumed to be graded through the thickness direction according to a linear distribution of the volume fraction of carbon nanotubes. Convergence studies are performed to establish the stability and accuracy of the IMLS-Ritz method. Since no existing results can be found for such FG-CNTRC skew plates, comparison studies can only be made with the isotropic case. Close agreement is found from these comparison studies. The influence of carbon nanotube volume fraction, plate thickness-to-width ratio, plate aspect ratio, and boundary condition on the vibration characteristics of the FG-CNTRC skew plates is examined. It is expected that these first known vibration results should serve as benchmarks for future studies.

1. Introduction

Skew plates are important structural components in the aircraft industry. To understand the detailed vibration characteristics of such plates are of interest to structural and design engineers in consideration of their dynamic response. To date, free vibration analysis of isotropic skew plates has been intensively studied [1–3]. Eftekhari and Jafari [4] have obtained the Ritz vibration solutions for thick skew plates. Srinivasan et al. [5] have reported the vibration frequencies of skew plates by experimental and finite element methods. Wu and Shu [6] have studied the free vibration and buckling of highly skewed plates using the least-squares finite difference method. McGee and Leissa [7] have examined the three-dimensional free vibration behaviors of cantilevered skew plates using the Rayleigh–Ritz method. Liew et al. [8] have studied the free flexural vibration of thick skew plates based on the first-order shear deformation theory using the pb-2 Rayleigh–Ritz method. Zhou et al. [9] have carried out the three-dimensional vibration analysis of skew thick plates using the Chebyshev–Ritz method. Wang et al. [10] have proposed a new version of the differential quadrature method to obtain a set of accurate vibration solutions of skew plates. Malekzadeh and Karami [11] have investigated the free vibration of variable thickness thick skew plates using the polynomial and harmonic differential quadrature methods.

Contrast to a vast body of literature on the isotropic case, only a limited amount of research work has been reported on the free vibration of anisotropic skew plates. In recent years, the development of new emerging advanced materials has created a strong quest for further theoretical work on the free vibration of anisotropic skew plates made of new materials, for example, the carbon nanotubes-reinforced composites (CNTRCs). The notable mechanical properties of CNTRCs have attracted much attention of researchers. A large amount of research work has been carried out for these CNTRCs because of their wide potential application prospects. Ajayan et al. [12] have demonstrated the extraordinary high stiffness-to-weight and strength-to-weight ratio properties

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of these CNTRCs. Mechanical properties have been uncovered by using experimental and theoretical methods so as to obtain their elastic moduli, thermo-mechanical properties, pure bending and bending-induced buckling, vibration behaviors, buckling behaviors of CNTRCs structures, like CNT-reinforced beams, rectangular plates or shells [13–15].

Inspired by the concept of FGMs, the functionally graded pattern of reinforcement has been adopted for functionally graded carbon nanotube reinforced composite (FG-CNTRC) materials. Alibeigloo [16] has studied the static behavior of functionally graded carbon nanotube reinforced composite (FG-CNTRC) rectangular host plate attached to thin piezoelectric layers subjected to thermal load and or electric field. Lei ZX et al. [17] have carried out the free vibration analysis of functionally graded carbon nanotube-reinforced composite plates using the element-free kp-Ritz method in thermal environment. The nonlinear bending of FG-CNTRC plates in thermal environment has been analyzed by Shen [18]. A nonlinear free vibration analysis of FG-CNTRC beams based on the Timoshenko beam theory has been performed by Ke et al. [19], and they have concluded that both linear and nonlinear frequencies of FG-CNTRC beam with symmetrical distribution of CNTs were higher than those of beams with uniform or asymmetrically distributed CNTs. The thermal buckling and postbuckling behaviors of FG-CNTRC plates and shells subjected to in-plane temperature variation have been reported by Shen and Zhang [20,21].

To the best of our knowledge, the existing studies are only reported for FG-CNTRC plates of rectangular plan-form [22]. No free vibration solution has been published on FG-CNTRC skew plates so far. This study on the free vibration of FG-CNTRC skew plates will form the first know study that serves as benchmark data for future references. This problem can be solved by the analytical approaches and numerical methods. Because of the limitation of analytical approaches, we always rely on numerical methods such as the finite element methods [23–25], the boundary element methods [26–28] and the mesh/element-free methods [29–34]. Unlike the finite element method, numerical solutions using the mesh/element-free methods are approximated in terms of a set of nodes over the problem domain. In general, different approximation functions have been used for developing the mesh/element-free methods. The FSDT element-free method has been used to perform the bending analysis of folded laminated plate structures [35]. The local Kriging meshless method has been employed to carry out free vibration analysis of moderately thick functionally graded plates [36]. The kp-Ritz method has been utilized to study the dynamic stability, large deflection, buckling and postbuckling behaviors of FG-CNTRC plates and panels [15,29,34,37,38].

In this paper, we extended the element-free IMLS-Ritz method [39] to obtain approximate solutions for free vibration of various types of FG-CNTRC skew plates with moderately thickness. There are a number of existing plate theories that can be used to incorporate the transverse shear deformation and rotary inertia for vibration analysis. In this study, the first-order shear deformation theory (FSDT) is adopted. Based on the FSDT and the IMLS-Ritz method, a set of eigenvalue equations for the skew plate vibration is derived, from which the vibration frequencies and mode shapes can be obtained. Because no known results are available for the FG-CNTRC skew plates, we have to simplify the problem to an isotropic case so that the comparison studies can be carried out. A close agreement is achieved for the comparison studies of these isotropic plates. To investigate the detailed vibration behavior of FG-CNTRC skew plates, example problems are studied to examine the effects of CNT volume fraction, plate thickness-to-width ratio, plate aspect ratio, height-to-width ratio and boundary condition on the vibration solutions. The convergence studies are carried out to validate the stability and accuracy of the IMLS-Ritz method. A set of comprehensive and accurate free vibration frequencies and mode shapes for FG-CNTRC skew plates is presented.

2. Formulation of eigenvalue equation

Consider a CNTRC skew plate of length a, width b, thickness t and skew angle θ, as shown in Fig. 1. The theoretical model for the vibration analysis of CNTRC skew plates is constructed first by establishing the displacement field. The first-order shear deformation theory is employed to serve this purpose, i.e.

$$u(x,y,z) = u_0(x,y) + z\theta_x(x,y), \tag{1}$$

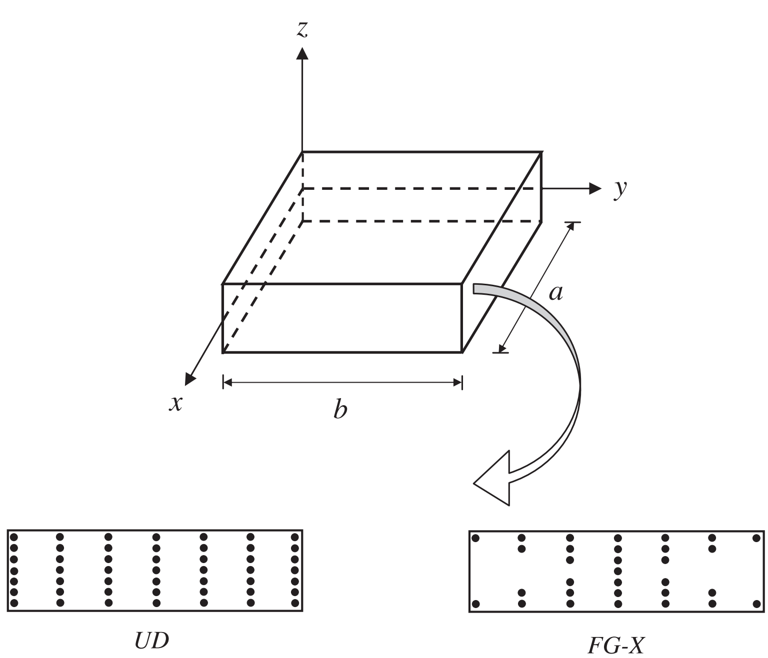

Fig. 1. Configurations of the CNTRC skew plates.