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Rotating nanocomposite thin-walled beams undergoing large deformation

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ABSTRACT

A computational model was developed to study the nonlinear steady state static response and free vibration of thin-walled carbon nanotubes/fiber/polymer laminated multiscale composite beams and blades. A set of nonlinear intrinsic equations describing the response of rotating cantilever composite beams undergoing large deformations was established. The main assumptions were small local strains and local rotations, large deflections and global rotations. Halpin–Tsai equations and fiber micromechanics were used to predict the bulk material properties of the multiscale nanocomposite. The carbon nanotubes (CNTs) were assumed to be uniformly distributed and randomly oriented through the epoxy resin matrix. Discretized by the Galerkin approximation, eigenvalues and vectors and nonlinear steady state static response of the nanocomposite beams and blades were calculated. The volume fraction of fibers, weight percentage of single-walled and multi-walled carbon nanotubes (SWCNTs and MWCNTs) and their aspect ratio were investigated through a detailed parametric study for their effects on the nonlinear response of nanotubes-reinforced moving beams. It was found that natural frequencies are significantly influenced by a small percentage of CNTs. It was also found that the SWCNTs reinforcement produces more pronounced effect in comparison with MWCNTs on the nonlinear steady state static response and natural frequencies of the composite beams.

1. Introduction

Nanocomposite materials reinforced with high aspect ratios and low density carbon nanotubes and microscale high strength fibers are a new generation of multifunctional, high-performance engineering composites that have attracted considerable attention in recent years due to their unique properties [1–8]. The most important characteristics of carbon nanotubes are their extremely high strength combined with excellent resilience. Therefore, the introduction of carbon nanotubes into polymeric composites may improve their applications in the fields of reinforcing composites, electronic devices and more. With carbon nanotubes, the change in reinforcement scale relative to carbon fibers offers an opportunity to combine the potential benefits of nanoscale reinforcement with those, well-established, of fibrous composites to create multiscale hybrid micro/nanocomposites.

The problem of modeling thin-walled laminated composite beam, or beam-like slender structures having an open or closed cross-section, using one dimensional condensed beam elements has drawn a significant amount of attention over the last decades. A number of investigations have been carried out to study different aspects of this problem [1–3,9–54]. The advent of advanced composite materials has been a strong stimulus for such developments. Moreover, their incorporation is likely to expand the use and capabilities of thin-walled beam structures. The new and stringent requirements imposed on aeronautical/aerospace, turbomachinery and shaft structural systems will be best met by such new types of material structures.

An intrinsic formulation developed by Hodges and his co-workers [9,10,16,20] which covers the anisotropic beams with large deformations and small strains. The approach extracted from a three-dimensional elasticity formulation provides two streams of analyses: one stream is concerned with the cross section, providing elastic constants that might be used in a suitable set of beam equations, and the other stream being the beam equations themselves. Kim and Dugundji [11] studied the nonlinear large amplitude vibration of composite helicopter blade under large static deflection. Their model is based on the use of Euler angles, harmonic balance, and the finite difference solution of the basic large deflection equations. Thin-walled composite beam have been extensively

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investigated by Librescu and Song [13,14,21] and their co-workers, e.g. [17–19]. These authors developed and refined thin-walled beam models of an arbitrary, closed or open cross-section. A number of non-classical effects such as the anisotropy and heterogeneity of constituent materials, transverse shear, primary and secondary warping phenomena (Vlasov effect) are considered in their works, with the assumption that the cross-section is rigid in its own plane. In the analysis performed on rotating systems [14], the effects of the centrifugal and Coriolis forces were taken into account as well. Furthermore, the importance of shear effects in composite material was emphasized. A complete theory for free torsion and bending of anisotropic thin-walled beams with closed cross-sectional contours was developed by Johnson et al. [15] using the stress formulation. Fazelzadeh et al. [22] performed the vibration analysis of functionally graded thin-walled rotating blades under high temperature supersonic flow using the differential quadrature method. Ghorashi and Nitzsche [23] studied the nonlinear dynamic response of an accelerating composite rotor blade using perturbations. Shooshtari and Rafiee [24] developed a mathematical model to study the nonlinear free and forced vibration analysis of clamped functionally graded beams. The nonlinear analysis of the dynamics of articulated composite rotor blades was performed by Ghorashi et al. [25]. Patil and Althoff [26] and Althoff et al. [27] developed a nonlinear model based on the Galerkin method to investigate the nonlinear response of rotating composite blades using intrinsic equations. Allahverdizadeh et al. [28] investigated the effects of electrorheological fluid core and functionally graded layers on the vibration behavior of a rotating composite beam. Deepak et al. [29] presented a comparative study between CNT-reinforced polymer composite beams and laminated composite beams in dynamic analysis using spectral elements. Arvin and his coworkers [30,31,40] presented a geometrically exact approach to the overall dynamics of elastic rotating blades. In another set of studies, Arvin and Bakhtiari-Nejad [32,33] studied the nonlinear vibration analysis of rotating composite Timoshenko beams. Bekhoucha et al. [34] investigated the nonlinear forced vibrations of rotating anisotropic beams. Rafiee et al. [35,36] studied the nonlinear free and forced thermo-electro-aero-elastic vibration and dynamic response of piezoelectric functionally graded laminated composite shells. Large amplitude, free and forced oscillations of functionally graded beams were analyzed by Hosseini et al. [37]. Sinha [38] studied the transient response of a multilayered composite rotating airfoil under slicing-impact loading. The equations of motion for a rotating composite beam with a nonconstant rotation speed and an arbitrary preset angle were derived by Georgiades et al. [39]. Sina and Haddadpour [41] analyzed the axial–torsional vibrations of rotating pre-twisted thin-walled composite beams.

The nonlinear response of multiscale nanocomposites and CNT-reinforced non-rotating composite beams and beam-type structures is also reported in the literature. A significant contribution in this area was made by Rafiee and his coworkers [1–3,42–48]. For example, they investigated the large amplitude free vibration [42,43], buckling and post buckling [44] and energy harvesting [45] in piezoelectric two-phase nanocomposite beams. They also considered large deformation and stress [1,46], post-buckling [46], nonlinear vibration [3,46], nonlinear dynamic stability [47] and piezoelectric power scavenging [48] in shear deformable piezoelectric laminated nanocomposite plates. Recently, He et al. [2] developed a study to investigate the large amplitude vibration of fractionally damped viscoelastic CNTs/fiber/polymer multiscale composite beams.

Even though the nonlinear analysis of rotating composite beams made of advanced materials is of a great importance, to date, no mathematical model has been available for the nonlinear deformation of CNTs-reinforced rotating composite beams or blades. Three dimensional finite-element methods (FEM), while possible, would be expensive. Ad hoc theories (e.g. von Karman and inextentional beam theories) based on the assumption of some a priori cross-sectional deformation, on the other hand, may lack accuracy [9] owing to one dimensional governing equations.

In the present work, we investigate the nonlinear steady state static response and vibration of CNTs/fiber/polymer laminated multiscale composite beams. A set of nonlinear, intrinsic equations describing the response of rotating cantilever composite beams undergoing large deformations is established. The main assumptions relate to small local strains and local rotations, large deflections and global rotations. The Halpin–Tsai equations and fiber micromechanics are used in hierarchy to predict the bulk material properties of the multiscale nanocomposite. The carbon nanotubes were assumed to be uniformly distributed and randomly oriented through the epoxy resin matrix. The nanocomposite beams and blades were discretized by the Galerkin approximation, and their eigenvalues, eigenvectors and nonlinear steady state static response calculated. The volume fraction of fibers, the weight percentage of single-walled and multi-walled carbon nanotubes (SWCNTs and MWCNTs), and their aspect ratio were investigated through a detailed parametric study for their effects on the nonlinear response of nanotubes-reinforced moving beams.

2. Theoretical formulation

The nonlinear, intrinsic, mixed equations for the dynamics of a general (nonuniform, twisted, curved, anisotropic) beam (See Fig. 1) undergoing small strains and large deformations are given below based on the generalized Timoshenko beam model [9]:

$$\mathbf{F}' + \left(\tilde{\mathbf{k}} + \tilde{\boldsymbol{\kappa}}\right)\mathbf{F} + \mathbf{f} = \dot{\mathbf{P}} + \tilde{\boldsymbol{\Omega}}\mathbf{P} \tag{1a}$$

$$\mathbf{M}' + \left(\tilde{\mathbf{k}} + \tilde{\boldsymbol{\kappa}}\right)\mathbf{M} + (\tilde{\mathbf{e}}_1 + \tilde{\boldsymbol{\gamma}})\mathbf{F} + \mathbf{m} = \dot{\mathbf{H}} + \tilde{\boldsymbol{\Omega}}\mathbf{H} + \tilde{\mathbf{V}}\mathbf{P} \tag{1b}$$

$$\mathbf{V}' + \left(\tilde{\mathbf{k}} + \tilde{\boldsymbol{\kappa}}\right)\mathbf{V} + (\tilde{\mathbf{e}}_1 + \tilde{\boldsymbol{\gamma}})\boldsymbol{\Omega} = \dot{\boldsymbol{\gamma}} \tag{1c}$$

$$\boldsymbol{\Omega}' + \left(\tilde{\mathbf{k}} + \tilde{\boldsymbol{\kappa}}\right)\boldsymbol{\Omega} = \dot{\boldsymbol{\kappa}} \tag{1d}$$

where the prime denotes the partial derivative with respect to the undeformed beam reference line defined by the curvilinear coordinate x, the over dot denotes the partial derivative with respect to the time t; and internal forces $\mathbf{F} = [F_1\ F_2\ F_3]^{\mathrm{T}}$, internal moments $\mathbf{M} = [M_1\ M_2\ M_3]^{\mathrm{T}}$, generalized force strains $\boldsymbol{\gamma} = [\gamma_{11} 2\gamma_{12} 2\gamma_{13}]^{\mathrm{T}}$,

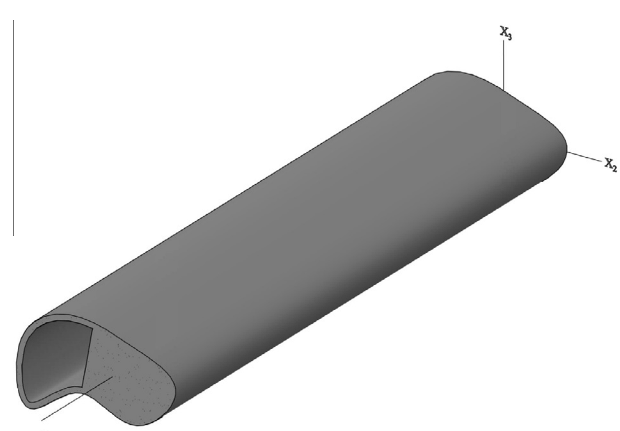

Fig. 1. General configuration of a nanocomposite beam with arbitrary cross-section.