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Analysis of vibration damping in a rotating composite beam with embedded carbon nanotubes

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ABSTRACT

This study presents a numerical model describing the vibration damping effects of carbon nanotubes (CNT's) embedded in the matrix of fiber-reinforced composite materials used in rotating structures. The energy dissipation from the incorporation of CNT's into the composite matrix is modeled with a stick–slip damping term to describe the interaction between the CNT's and surrounding matrix as the material deforms. A numerical model is developed using the Euler–Bernoulli beam equation in a rotating frame of reference and solved in a non-dimensional form using the finite element method. A parametric study is performed to examine the effects of various beam geometries, angular speed profiles, and CNT damping values on the vibration settling times of the numerically simulated beams. The results are illustrated in a dimensionless design space to demonstrate the use of CNT's for improving the vibration damping characteristics of a rotating composite beam.

1. Introduction

Rotating composite structures are found in systems across a broad spectrum of engineering applications, including robotics, wind turbine blades, and helicopter rotors [1–3]. The fluctuating loads which act on these rotating structures often introduce excess vibrations to the overall system which reduce the performance and lifespan of the composite structure. As the use of composites in rotating systems continues to increase, it is critical to explore the potential material benefits that may be designed into the physics of these composite structures using nanoscale reinforcement.

Numerous studies in the literature, as reviewed in [4], have focused on embedding CNT's in the matrix of composite materials for damping augmentation. Experimental measurements utilizing a thin film of CNT's grown by vapor deposition on a silica substrate have reported a 200% increase in damping over the baseline system without nanotubes [5,6]. Active constrained layer damping (ACLD) treatments utilizing CNT's and sandwich beams with a CNT-epoxy core have demonstrated a damping increase of 40–1400% compared to the same beam fabricated without CNT's [7–12]. A 400–1100% augmentation in material damping was measured when CNT's were incorporated into the matrix of neat resin composites [13–20], and fiber reinforced composites with matrix-embedded CNT's have exhibited a damping increase of 50–130% [21–24].

The additional damping provided by the CNT's in the composite may be explained in part by the poor bond that is exhibited between the surface of the CNT's and the surrounding composite matrix [25], resulting in energy dissipation through an interfacial stick–slip mechanism as these two surfaces slide over one another under strain [13,14]. This stick–slip damping was analytically modeled in [15], and the results predicted a material loss factor that agreed well with experimental measurements using an epoxy-based composite with embedded CNT's. In [19] a finite element model of the CNT-matrix interface was studied for different strains and CNT orientations within the matrix, and the simulated damping values demonstrated good agreement with experimental damping measurements. A stick–slip friction model considering the spatial distribution of the CNT's throughout the matrix material was investigated in [26], where the analytical results agreed well with experimentally measured damping values. In [27] the effects of nanotube–matrix and nanotube–nanotube interactions where investigated analytically using a stick–slip model to develop an expression of the damping as a function of strain, and the results were shown to predict a loss factor of 0.17 using one weight percent CNT loading in the matrix material. Viscous and coulomb damping values were calculated from the vibration response of fiber reinforced composite beams with a CNT-infused epoxy matrix in [23], where the viscous parameter was found to represent the material damping in the fiber-reinforced composite without CNT's and the additional damping provided to the composite material by the matrix-embedded CNT's was described by the coulomb parameter.

The damping effect of matrix-embedded CNT's in fiber-reinforced composites offers the potential for designing a passive damping mechanism into functional composite materials.

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Nomenclature

a	hub radius (m)
A	cross-sectional area (m^2)
c	coulomb damping coefficient (m)
E	modulus of elasticity (Pa)
F	force (N)
I	moment of inertia (m^4)
L	beam length (m)
s	stretch deformation (m)
t	time (s)
T	kinetic energy (J)
u	transverse deformation (m)
U	strain energy (J)
v	axial deformation (m)
x	x-direction coordinate (m)
y	y-direction coordinate (m)
z	z-direction coordinate (m)

Greek symbols

α	slenderness ratio
β	eigenvalue of first transverse vibration mode
ζ	viscous damping coefficient
ρ	density (kg/m^3)
Ω	angular speed (rad/s)

Subscripts/Superscripts

$\bar{}$	dimensionless value
$\hat{}$	weighting function
0	constant parameter

Although vibrations in rotating composite structures such as wind turbine blades and helicopter rotors may be mitigated by other passive damping techniques (e.g. structural optimization [28]), these systems are predominantly controlled by active suppression methods including actively controlled flaps (ACF) [29], variable airfoil geometry [30], and the higher harmonic control (HHC) algorithm [31]. Fig. 1 presents the vibration reduction achieved in various rotor blades by these different control schemes compared to the CNT damping studies in [23,24], where the vibration reductions achieved by active and passive techniques vary between 36–86% and 29–55%, respectively. It is evident from the data in Fig. 1 that the vibration damping capability of CNT's is less than the active control techniques documented in [29–31]; however, matrix-embedded CNTs are integral to the structures and do not add any considerable weight or complexity to the system as with active control schemes. Therefore, CNT-based damping may be considered a viable passive damping mechanism to inherently augment the performance of rotating composite structures, with or without the use of additional active damping schemes, which serves as the motivation for the present study.

In this work the stick–slip damping model presented in [23] is applied along with viscous damping to investigate the effects of CNT-based energy dissipation on the dynamic response of a rotating composite beam. The model is developed using the dimensionless form of the Euler–Bernoulli equation and solved by means of the finite element method (FEM). The effect of rotation on the beam is considered by deriving the equations of motion in a rotating frame of reference and applying dynamic body forces that are dependent on the angular speed and acceleration experienced by the beam. The geometry is excited by a dimensionless angular speed profile related to the typical operating conditions of functional rotor blades [3,28–32], and the effects of CNT-based energy dissipation expressed using a coulomb parameter, viscous damping describing the composite without CNT's, geometry variation, and different angular speed profiles on the dynamic response of the rotating composite beam are explored in the results. The model development is outlined in Section 2, the results of the parametric study are presented and discussed in Sections 3, and 4 presents the conclusions of the study.

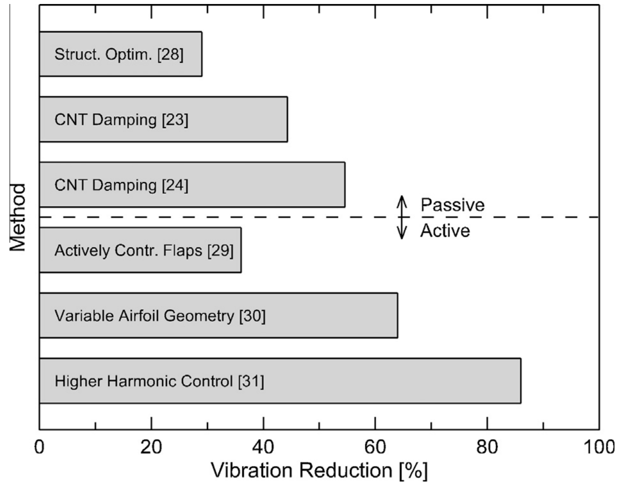

Fig. 1. Comparison of the active and passive vibration control schemes used in rotor technology [28–31] and the damping effects of embedded carbon nanotubes [23,24] in fiber-reinforced composites.

2. Numerical model

This section presents the geometric configuration along with the numerical model used to simulate the rotation and deformation of the composite beam. Fig. 2a presents the rotating hub of radius R to which the three-dimensional beam of length, L, thickness, a, and width, b, is connected, with the origin of the Cartesian coordinate system located at the center of the beam's base. The beam rotates around the vertical central axis of the hub at a time-varying angular speed, $\Omega(t)$, and the Cartesian coordinate vectors rotate with the hub at the same speed. The motion of the rotating beam is described in a non-dimensional form using the dimensionless parameters:

$$\alpha = \left(\frac{AL^2}{I}\right)^{1/2} \quad \bar{\Omega} = \Omega\left(\frac{\rho AL^4}{EI}\right)^{1/2} \quad \bar{t} = t\left(\frac{\rho AL^4}{EI}\right)^{-1/2}$$

$$\{\bar{c}, \bar{R}, \bar{u}, \bar{v}, \bar{x}, \bar{y}, \bar{s}\} = \{c, R, u, v, x, y, s\}/L$$

where α, A, L, I, ρ, and E are the slenderness ratio, cross-sectional area, length, moment of inertia defined as $a^3b/12$, density, and modulus of the beam, respectively. The angular speed profile specified at the base of the beam is shown in Fig. 2b and is expressed using the dimensionless angular speed, $\bar{\Omega}$, and the dimensionless time, $\bar{t}$. The dimensionless angular speed profile consists of a ramp period where the speed is increased steadily from zero and a hold period where the speed is held constant, where this profile is described