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Vibration of higher-order-shearable pretwisted rotating composite blades

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Abstract

The free and forced vibration of a rotating, pretwisted blade modeled as a laminated composite, hollow (single celled), uniform box-beam is studied. The structural model includes transverse shear flexibility, restrained warping, and centrifugal and Coriolis effects. A key element of this model is its ability to satisfy the zero shear–traction requirement on the external bounding surfaces. The governing system possesses complicated and eigenvalue-dependent natural boundary conditions. Hence an extended Galerkin method using admissible functions is employed. Free-vibration results obtained for the present higher-order shearable model are compared with those of the existing first-order shearable and the non-shearable models. For the data considered, the present theory provides conservative predictions. This suggests that through-the-thickness variations of transverse shear strains are significant and should be considered when pursuing non-resonant designs. The effect of pretwist, while marginal for the lowest eigenfrequency, is substantial for the higher ones especially for lower rotation speeds and larger ply angles. A combination of softening and stiffening effects are also possible for the same eigenfrequency when pretwist is varied. Tailoring studies using the present model show an enhancement of eigenfrequency characteristics and also reveal the potential for passive mitigation of forced response.

Keywords: Coupled vibrations; Shear deformation; Hollow beams; Rotating composite beams

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Nomenclature

R_0; h; L	hub radius; wall thickness; span
Ω; θ; β; ω_i	angular speed; ply-angle; pretwist; natural frequency
(x,y,z); (x^P,y^P,z^P); $(\bar{x},\bar{y},\bar{x}^P,\bar{y}^P)$	beam coordinates; local principal coordinates; mid-surface quantities
(s,n)	local surface coordinates (tangential, normal to mid-surface)
u, v, w	lag, flap, extension displacements
u_o, v_o, w_o, ϕ, θ_x, θ_y	displacement field (lag, flap, extension, twist, x and y rotations)
$(\gamma_{xz}, \gamma_{yz})$; $(\varepsilon_{xx}, \varepsilon_{yy}, \varepsilon_{xy})$; $(\bar{\gamma}_{xz},\bar{\gamma}_{yz})$	transverse shear strains; inplane strains; mid-surface shear strains
m^P, l^P	direction cosines between local principal and local surface coordinate directions
F_ω, a	primary, secondary warping functions
δ_e, δ_t, δ_h	tracers for classical, FSDT, HSDT models
$\bar{Q}_x$, $\bar{Q}_y$, $\bar{T}_z$, $\bar{T}_r$, $\bar{M}_x$, $\bar{M}_y$, $\bar{M}_z$, $\bar{M}_{xa}$, $\bar{M}_{xb}$, $\bar{M}_{ya}$, $\bar{M}_{yb}$, $\bar{B}_\omega$	1D resultant forces/moments for pretwisted beam
$(I_1,\ldots,I_{10})$; $(I^P_{xx}$, I^P_{yy}, $\tilde{I}^P_{ll}$, $\tilde{I}^P_{mm}$, $I^P_{\omega\omega}$, m_4, m_6, $b^P_1)$	inertia quanties; associated structural and mass quantities
$\tilde{a}_{ij}[z]$	global stiffnesses with HSDT and pretwist
p_y	line load
$\Phi_\mathbf{i}$; $\mathbf{q_i}$	N-dimensional vectors of trial functions; generalized coordinates
$\mathbf{M}$; $\mathbf{K}$; $\mathbf{Q}$	mass matrix; stiffness matrix; forcing vector

1. Introduction

Rotor blades are critical components of helicopters, tilt rotor aircrafts, etc. and determining their forced/resonant response and flutter behavior is essential. Composite materials technology, offering superior strength/weight-savings characteristics and better response control via structural tailoring, has significantly influenced their design. Fiber-reinforced laminated composite hollow beam constructions are being increasingly used in designing rotor blades. Various elastic couplings, resulting from the directional-dependent properties of composites and the ply-stacking sequences available, can be exploited to enhance their response.

A robust approximate formula for the fundamental frequency of a rotating beam, offset about its rotation axis, was derived by Hodges [1] by using asymptotic expansions involving the offset parameter and its inverse. Rosen et al. [2] used non-physical coordinates combined with generalized coordinates (taken as the eigenvibration modes of an untwisted blade) in order to de-couple the two plane bending. A review of work on pretwisted beams was presented by Rosen [3]. Yoo et al. [4] analyzed a rotating, pretwisted blade with a tip mass, while Banerjee [5] showed that pretwist has a greater effect on mode shapes than on natural frequencies of a non-rotating beam. Rehfield et al. [6] studied the elastic bend–shear coupling and restrained warping effects for thin-walled composite beams.