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Modeling and control for rotating pretwisted thin-walled beams with piezo-composite

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ABSTRACT

In this paper, a rotating thin-walled beam theory incorporating fiber-reinforced and piezo-composite is developed and used to study the active control for vibration suppression. The structural model accounts for transverse shear strain, primary and secondary warpings, pretwist and presetting angles. In addition, the centrifugal stiffening effect, tennis-racket effect, flapping-lagging-transverse shear and extension-twist couplings are accounted as well. Based on a negative velocity feedback control algorithm, the effective damping performance is optimized by studying anisotropic characteristics of piezo-actuators and elastic tailoring of the host structure. Moreover, relations between damping control authority and design factors, such as rotor speed, presetting and pretwist angles are investigated in detailed.

1. Introduction

In recent years a large amount of work are devoted to the modeling and behavior of composite rotor blades [1–5]. Among there works, Rehfield et al. [6] discussed the non-classic behavior of a closed cross-section composite thin-walled beam. Chandra et al. [7] investigated the vibration characteristics of rotating composite box beams on both experimental and theoretical aspects. Song et al. [8,9] developed a rotating composite thin-walled beam theory feathering lateral bending-vertical bending elastic coupling effect. Oh et al. discussed effects of pretwist and presetting on coupled bending vibrations [10]. He also investigated the twist-extension elastic coupling effect on rotary composite structure [11].

Rotor blades operate in a unsteady and complex aerodynamic environment. They are also characterized by a complex structural behavior. For these reasons active control is deemed to te a promising technology for the design of new high performing blades [12,13]. Because piezoelectric materials have a series of desirable characteristics, such as self-sensing, structure embeddability, fast response and covering a broad range of frequency, they are often proposed for the design of active blades [14–16]. In order to overcome the drawbacks of the typical piezoceramic actuator, such as the vulnerable ability to damage and the fact that they can hardly conform to a curved surface, piezo-composite actuators, e.g., Active Fiber Composite (AFC) [17] and Macro-Fiber Composite (MFC) [18] were developed. In the existing literatures, a lot publications on modeling or studying adaptive thin-walled structure are based on a piezoelectric bending moment control system [19–24], but they lack explicit discussions for transverse shear force and twist moment actuations. Thus a comprehensive study allowing to get a better insight into the influence of piezoelectric extension, transverse shear, twist, bimoment and bending actuations on rotary thin-walled structures is still interesting.

In this paper, a geometrically nonlinear rotating thin-walled beam theory incorporating piezo-composite is developed. In addition, transverse shear strain, primary and secondary warping inhibitions, three-dimensional strain, centrifugal stiffening and tennis-racket effects [25] are taken into account. The circumferentially uniform stiffness (CUS) [26] lay-up configuration that yields lateral bending-vertical bending and twist-extension couplings is applied for the rotary structure [11,27,28]. The governing equations and the boundary conditions are derived via Hamilton's principle. Numerical studies are based on the Extended Galerkin's Method. Based on a negative velocity feedback control methodology, active control for vibration suppression is optimized via the study of tailoring technology and anisotropic characteristic of piezo-composite. In addition, the influences of design parameters, such as rotor speed, presetting and pretwist angles are investigated, and pertinent conclusions are outlined.

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Nomenclature

a_{ij}	1-D global stiffness coefficients
$\mathcal{A}_i^X$	piezo-actuator coefficients, see Eq. (22)
b_w	bimoment of the external force per unit span
b_{ij}	inertial coefficients
$2b, 2d$	width and depth of the beam cross-section, see Fig. 2
B_w	bimoment
F_w, $a(s)$	primary and secondary warping function, respectively
k_i	control gains in the velocity feedback control in Eqs. (39) and (40)
L	length of the beam, see Fig. 2
m_x, m_y, m_z	external moments per unit span, about x-, y- and z-axes, respectively
M_x, M_z	bending moments about x and z axes, respectively
M_y	torque about y axis
N_{hp}, N_h, N_p	numbers of all layers, host layers and piezo-composite layers, respectively
p_x, p_y, p_z	external forces per unit span
$P(y)$	distribution function along span for the actuator
$\overline{Q}_{ij}$	reduced elastic coefficients
Q_x, Q_z	transverse shear forces in the x- and z-directions
R_0	radius of the hub, see Fig. 2
$\mathbf{R}$	position vector of a point on the deformed beam, see Eq. (3)
(s, y, n)	local coordinate system on the cross-section, see Fig. 2
T_y	axial force in the y-direction
u_0, v_0, w_0	displacement components of the cross-section along x, y, z axes, see Fig. 2
V_i	voltage parameters, see Eqs. (23)
(x, y, z)	rotating axis system located at the blade root, see Fig. 1
(x^p, y^p, z^p)	local coordinate system for an arbitrary beam cross-section, see Fig. 2
(X, Y, Z)	inertial reference system attached to the center of hub
$\beta(y)$	pretwist angle, see Eq. (2)
β_0, γ_0	pretwist angle at beam tip and presetting angle at beam root, respectively
$\rho_{(k)}$	mass density of the kth layer in Eq. (15a)
Γ_t	nonlinear force related to twist motion
θ_h, θ_p	ply-angles of host structure and piezo-actuator
θ_x, ϕ, θ_z	rotations of the cross-section about the x, y and z axes, see Fig. 2
Ω	rotating speed of hub
δ	variation operator
δ_p, δ_s	tracers that take the value 1 or 0
$\dot{()}, \ddot{()}, ()', ()''$	$\partial()/\partial t, \partial^2()/\partial t^2, \partial()/\partial y, \partial^2()/\partial y^2$
$\mathbf{X}^T$	transpose of the matrix or vector $\mathbf{X}$
$\oint_c, \int_0^L$	integral along the cross-section and the span, respectively

2. Basic assumptions and kinematics

2.1. Basic assumptions

The geometric configuration and the chosen coordinate systems of the rotary thin-walled beam are shown in Figs. 1 and 2. The inertial reference system (X, Y, Z) is attached to the center of the hub O (considered to be rigid), while the rotating axis system (x, y, z) is located at the blade root with an offset R_0 from the rotation axis O, see Fig. 1. The unit vectors associated with the frame coordinates (X, Y, Z) and (x, y, z) are defined as $(\mathbf{I}, \mathbf{J}, \mathbf{K})$ and $(\mathbf{i}, \mathbf{j}, \mathbf{k})$, respectively. Besides the rotating coordinate system (x, y, z), a local coordinate system (x^p, y, z^p) is also defined, where x^p and z^p are the principal axes of an arbitrary beam cross-section, see Fig. 2. In addition, a surface coordinate system (s, y, n) on the mid-line contour of the cross-section is considered in Fig. 2. Coordinate systems (x, y, z) and (x^p, y, z^p) are related by the following transformation

$$\begin{cases} x(s,y) = x^p(s)\cos\beta(y) + z^p(s)\sin\beta(y), \\ z(s,y) = -x^p(s)\sin\beta(y) + z^p(s)\cos\beta(y), \end{cases} \tag{1}$$

where the linear pretwist angle $\beta(y)$ can be assumed as

$$\beta(y) = \gamma_0 + \beta_0 y/L, \tag{2}$$

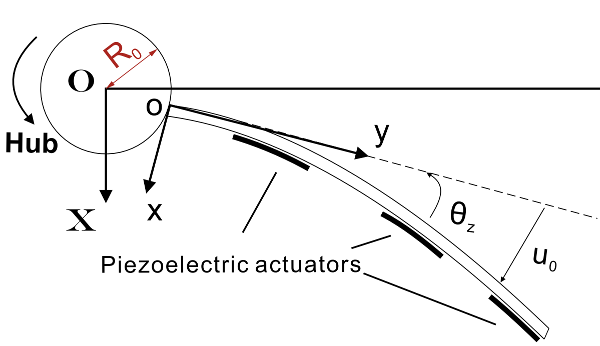

Fig. 1. A schematic description of the blade.

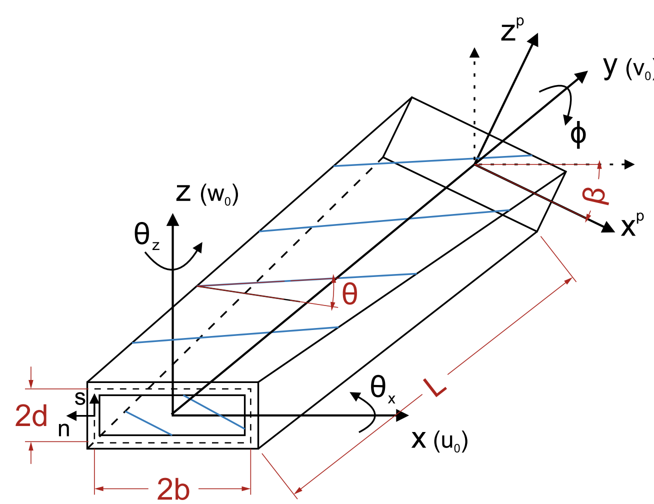

Fig. 2. Geometry of the pretwisted beam with a rectangular cross-section (CUS lay-ups).

in which γ_0, β_0 and L denote the presetting angle, the pretwist angle of the cross-section at the beam tip and the length of the beam, respectively.

The rotary thin-walled structure is modeled assuming that the cross-section is preserved during the deformation. Beside this assumption, already adopted e.g. in Ref. [29], no other significant assumptions to the kinematic description are introduced; in particular, both the primary and secondary (thickness) warping effects are included and the transverse shear effect are taken into account. Note also that the centrifugal stiffening and tennis-racket effects [25] are accounted for in the present approach.

2.2. Kinematics

It is useful to express the position vector $\mathbf{R}$ of an arbitrary point $M(x, y, z)$ belonging to the deformed beam, measured from a fixed