Thin-Walled Structures 119 (2017) 795–819

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Review

Dynamics, vibration and control of rotating composite beams and blades: A critical review

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ARTICLE INFO

Keywords:
Rotating thin-walled beams
Composite rotor blades
Review
Dynamics
Vibration
Control

ABSTRACT

Rotating composite beams and blades have a wide range of applications in various engineering structures such as wind turbines, industrial fans, and steam turbines. Therefore, proper understanding of such structures is of a great importance. As a result, the behavior of rotating composite beam structures has received a lot of attention. This paper presents a comprehensive review of scholarly articles about rotating composite beams as published in the past decades. The review addresses analytical, semi-analytical and numerical studies dealing with dynamical problems involving adaptive/smart/intelligent materials (e.g. piezoelectric materials, electrorheological fluids, shape memory alloys, etc.), damping and vibration control, advanced composite materials (e.g. functionally graded materials and nanocomposites), complicating effects and loadings (e.g. added mass, tapered beams, initial curve and twist, etc.), and experimental methods. Moreover, the influence of Vlasov or restrained warping, out-of-plane warping, transverse shear, arbitrary cross-sectional geometry, trapeze phenomena, swept tip, size-dependent effect, as well as other areas that have been considered in research, are reviewed in depth. The review concludes with a presentation of the remaining challenges and future research needs.

1. Introduction

Over the last few decades, rotating beams and blades made of composite materials have been increasingly used in a variety of industrial areas due to their high stiffness and strength-to-weight ratios, long fatigue life, resistance to electrochemical corrosion, and other superior material properties of composites. The advantages of composite materials, coupled with the ability to tailor their designs to specific purposes, have given them a competitive edge when compared with normal engineering materials and led to their extensive use in rotary applications. Therefore, a thorough understanding of their structural dynamic behavior is required.

The number of research articles pertaining to various structural dynamics and vibration control aspects of rotating composite beams and blades, as published in English language Science Citation Index (SCI) journals, have steadily increased since 1990, as shown in Fig. 1. In response to the growing interest in this area, the present article aims to present a comprehensive review of the state-of-the-art. However, to limit the scope of the review, the emphasis has only been placed on the vibrations, dynamics and control aspects of rotating beams and blades. Publications directly related to other aspects of rotating composite beams and blades, such as damage mechanics and structural health monitoring, static bending, deflection and torsional analyses, cross-section design and optimization, have been excluded from this review.

Some surveys of structural dynamics and vibration suppression of rotating composite beams and blades can be found elsewhere. Review articles [1–3] covered much of the research done on the rotor blades dynamic characteristics and strategies for vibration reduction prior to the early 1990s. It should be mentioned that journal papers and books [4–9] treated some review aspects of composite rotor blades dynamics. However, to the best of the authors' knowledge, there has not been a comprehensive review of the structural dynamics and vibration control of rotating composite beams and blades in the literature.

In this review, the beam theories for rotating composite beams and blades that have emerged from prior research efforts are summarized first. Then, analytical, semi-analytical and numerical methods are comprehensively reviewed. Adaptive/smart/intelligent rotating composite beams, and damping and vibration control of such structures will be presented next. The application of advanced composite materials such as functionally graded materials and nanocomposites on the rotating beams will be discussed. Complicating effects, including the effect of tip mass, nonuniform

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http://dx.doi.org/10.1016/j.tws.2017.06.018
Received 5 January 2017; Received in revised form 12 April 2017; Accepted 17 June 2017

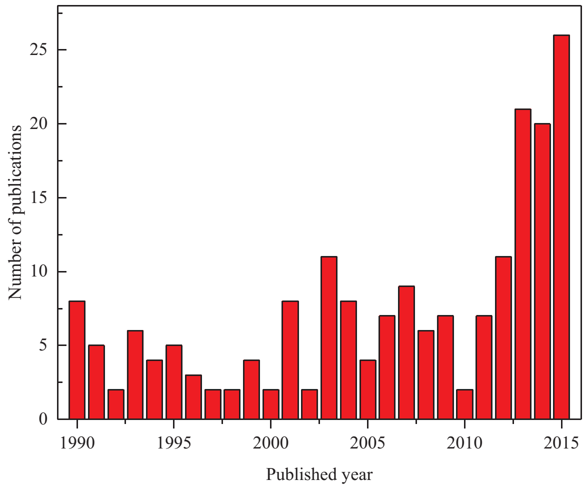

Fig. 1. Recent English language Science Citation Index journal papers directly related to structural dynamics and vibration control of rotating beams and blades made of composite materials.

cross-section, initial curvature/twist, swept tip, and size-dependent properties on the dynamics and vibration reduction of rotating composite beams will be addressed. Attention will also be given to experimental studies in the last section. The paper will conclude with recommendations for future research directions.

It should be noted that, in this review, multiple citations might be observed for a publication. For instance, a paper in which both a numerical model and an experimental study are presented will be cited in the "Numerical approaches" as well as the "Experimental investigations" sections.

2. Beam theories

Beams are three dimensional (3D) bodies in which one dimension is large compared to the other two. According to the current state-of-the-art, the theoretical framework around composite rotating beams and blades is quite advanced. The models based on 3D Finite Element Analysis (FEA) possess significant computational advantages. However, beam or one-dimensional (1D) models play an important role in structural analysis because they have smaller dimensionality and provide the designer with simple tools to analyze numerous problems. One-dimensional beam models can be investigated using classical or refined theories (See Fig. 2) in both

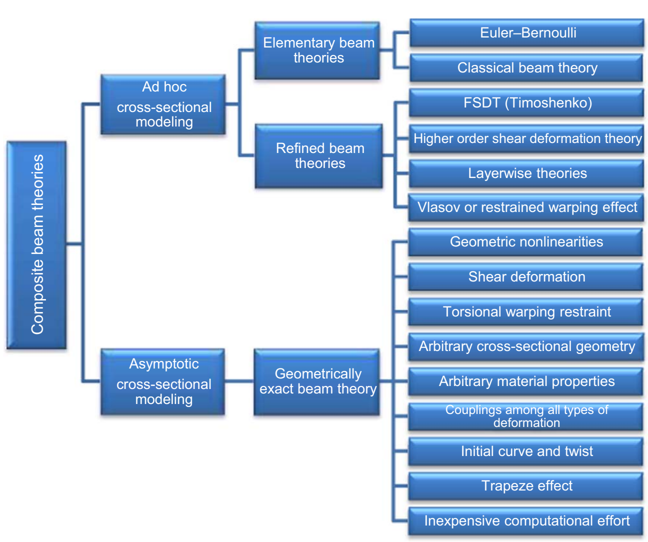

Fig. 2. Composite beam theories.

geometrically linear and nonlinear regimes that feature different levels of accuracy to evaluate the static and dynamic characteristics. An extensive discussion of various linear beam theories can be found in [10].

2.1. Elementary beam theories

2.1.1. Euler–Bernoulli beam theory (EBBT)

The Euler–Bernoulli beam theory (EBBT) is the most elementary one; it underestimates deflections and overestimates the natural frequencies because it disregards the transverse shear deformation and rotary inertia effects. The Euler-Bernoulli assumptions are: 1) The cross-section is infinitely rigid in its own plane; 2) the cross-section of a beam remains plane after deformation; 3) the cross-section remains normal to the deformed axis of the beam [11]. These assumptions are usually reasonably justified for isotropic homogeneous slender beams featuring simple cross-sections; however, they become questionable for beams of complex geometry made of general anisotropic, heterogeneous materials, such as composite rotor blades, especially at higher frequency. The shearing forces may be approximated as the derivatives of bending moments. Approximate bending and shear stresses may be recovered over a cross section.

Let us assume that u, v, and w are the elastic displacements of a point along x, y, and z-axes, respectively (right-hand axes system). The x-axis is aligned with the neutral axis of the beam (longitudinal direction), the y-axis is along the width of the beam (lateral direction), and the z-axis is aligned along the thickness direction (transverse direction). For such a beam, the Euler-Bernoulli approximation of axial displacement and strain can be defined as

$$u(x, z) = u_0(x) + z\phi_x(x), \quad w(x, z) = w_0(x), \tag{1a}$$

$$\varepsilon_x(x, z) = \varepsilon_0(x) - z\left(-\frac{\partial\phi_x(x)}{\partial x}\right), \tag{1b}$$

where $u_0(x)$ and $w_0(x)$ are longitudinal and vertical displacements at the neutral axis and $\phi_x(x)$ is the rotation of the transverse normal about the y-axis cane defined as $-\partial w(x)/\partial x$ and $\partial\phi_x(x)/\partial x$ is the bending curvature. The axial strain at the neutral axis can be defined as $\varepsilon_{x0}(x) = \partial u_0(x)/\partial x$ and $\varepsilon_{x0}(x) = \partial u_0(x)/\partial x + 1/2(\partial w_0(x)/\partial x)^2$ in geometrically linear and nonlinear (von-Kármán hypothesis) regimes, respectively.

2.1.2. Classical beam theory (CBT)

If the beam is twisted, the cross section will be warped and cannot remain plane after deformation in general. For this reason, Saint Venant relaxed the second Euler-Bernoulli assumption and derived the classical beam theory to recover the shear stresses that contribute to the torsional moment. Fig. 3 depicts the concept of different types of warpings associated with the Saint Venant theory of torsion (free warpings). Fig. 4 shows the influence of warping on the tip twist of bending-torsion coupled symmetric lay-up cantilever box-beams subjected to a unit tip torque. For composite beams, because of anisotropy, asymmetry of the cross-section, and non-uniform distribution of Poisson's ratio over the cross-section, all stresses and strains other than the ones along the span of the beam are non-zero. Hence, in-plane and out-of-plane warpings need to be known in order to obtain accurate structural stiffness values and account for 3D stress effects [12,13].

2.2. Refined beam theories

The most significant difference between the classical and refined beam theories is the inclusion of transverse shear deformation on the predicted bending deflections and natural frequencies. Fig. 5 shows a typical result for the effect of shear deformation on modeling of a composite box beam. These results clearly demonstrate