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Influences of hygrothermal environment and installation mode on vibration characteristics of a rotating laminated composite beam

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ABSTRACT

Flapwise vibration characteristics of a rotating laminated composite beam under hygrothermal environment are studied in this paper. The governing equation of the flapwise vibration for the rotating beam under hygrothermal environment is obtained applying D'Alembert's principle, in which the design parameters such as setting angle and pitch angle are considered. A numerical method based on Green's function to handle the vibration characteristics problem of a rotating composite beam is developed. Influences of the hub radius, rotating speed, pitch angle, setting angle, fiber orientation angles, temperature and humidity on natural frequencies of the rotating laminated composite beam are discussed. Results indicate that: (1) the rotating speed, hub radius, setting angle, pitch angle and fiber orientation angle have more prominent effects on natural frequencies than the temperature variation and moisture concentration do; (2) the influences of some parameters such as the hub radius, rotating speed, setting angle and pitch angle on the vibration characteristics are not independent, but coupled with each other.

1. Introduction

In recent years, composite structures have been used extensively in aerospace and other engineering applications. The composite materials, which provide the structural configuration possibilities, are vital to affect the dynamic behavior of rotating structures. The studies on the composite structures have been attracting attentions by more and more researchers [1–4] in recent years. These structures usually operate in complex environmental conditions, such as hygrothermal environment. On one hand, composite materials will be affected by aging behaviors resulted from hygrothermal environment, which can change the mechanical and physical behaviors of composites. On the other, the variation of temperature and moisture concentration can induce the change of material properties of the composite structures, which naturally reduces the stiffness and strength of the structures. Therefore the vibration analysis of such beam structures has attracted more and more attentions.

In order to explore this type of structural systems, a good knowledge of their vibration characteristics is essential. Numerous previous researches relating to this subject have been published over the last three decades. There are several approximate methods to analyze vibration characteristics of these rotating beams. The finite element method (FEM) has been found

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in a large number of literature. Sai Ram and Sinha [5] studied the effects of temperature and moisture on the vibration characteristics of a laminated composite plate using FEM, in which the influence of transverse shear deformation was taken into account. According to the shear flexible theory, the free flexural vibration of a laminated composite rotating beam was investigated using FEM in Ref. [6]. Numerical results were presented, in which the modular ratio, rotation speed and slenderness ratio were taken into account. Based on the first order shear deformation theory, Parhi et al. [7] analyzed the free vibration and transient responses of a multiple delaminated composite shell in hygrothermal environment by a finite element formulation. Rao and Gupta [8] applied the finite element technique to obtain the natural frequencies and mode shapes in the bending-bending vibration of rotating Timoshenko beams. The effects of twist angle, shear deformation and rotation speed on the natural frequencies of the vibration were studied. A finite element analysis was presented for rotating cantilever beams in Ref. [9], and the linear partial differential governing equations of the rotating beam were derived using Hamilton's principle. The effects of the rotation speed on the vibration of the beam were investigated. Naidu and Sinha [10] investigated the nonlinear free vibration of a laminated composite shell in hygrothermal environment by FEM. Maqueda et al. [11] obtained the eigenvalue solutions of a rotating beam by different nonlinear finite element formulations. The effect of centrifugal forces on these solutions was examined through numerical results. Liu and Jiang [12] studied the crack modeling of a rotating blade by an improved cracked finite element method.

In addition, there exist other methods used by investigators for studying the vibrations of such beams. For example, the frequency and mode shape analysis of a rotating beam were presented by a semi-analytic method in papers [13,14]. Murthy [15] obtained the coupled flapwise bending and torsion vibration characteristics of a rotor blade adopting the integrating matrix method. Özdemir and Kaya [16] acquired the natural frequencies of the flapwise bending vibration for a rotating cantilever Bernoulli-Euler beam using the differential transform method. The effects of some parameters such as angular velocity and hub radius on the vibration characteristics were discussed. Lang and Nemat-Nasser [17] determined the coupled vibration characteristics of a non-uniform rotating blade with the help of the transmission matrix method. Li et al. [18] solved the linear characteristic problem of a wind turbine blade applying the assumed modes method. And they discussed the effects of the rotation speed, pitch angle, and the wind velocity on flapwise dynamic response utilizing the multiple-scales method. Surace et al. [19] analyzed the modal characteristics of a non-uniform rotating blade subjected to the coupled vibration by a numerical method based on Green's function.

Further, the effects due to hygrothermal environment on the vibration of the rotating beam were investigated by some methods in the following papers. Shen [20] investigated the effects of hygrothermal environment on postbuckling behaviors of a laminated plate by Reddy's higher-order plate theory. Patel et al. [21] studied the static and dynamic characteristics of a thick laminated composite plate subjected to hygrothermal environment using a higher order theory. The effects of the temperature and moisture concentration on the hygrothermal behavior of a laminated composite plate were analyzed by a refined plate theory in Ref. [22]. Based on the D'Alembert's principle, the governing equation of flapwise vibration for a rotating laminated composite beam under hygrothermal environment was obtained by Jiang in Ref. [23]. And the modal problem was solved employing the assumed-mode method.

However, the influences of the design parameters such as the setting angle and the pitch angle on the vibration characteristics, which are essential in the engineering application of the wind turbine blade, were not considered. In this paper, the effects of the design parameters and hygrothermal environment will be all taken into account. The analysis of the vibration characteristics corresponding to the flapwise vibration of the rotating laminated composite beam is addressed. First, based on D'Alembert's principle and the constitutive equation of one single layer material due to the hygrothermal effects, the governing equation of the rotating laminated composite beam in hygrothermal environment is established in Section 2, in which the setting angle and the pitch angle are considered. Then, a numerical approach based on Green's functions is presented in Section 3 to obtain the vibration characteristics of the rotating beam. At last, in Section 4, the effects of the rotating speed, hub radius, fiber orientation, design parameters and hygrothermal environment on the natural frequencies are discussed.

2. Governing equation

2.1. Model of rotating composite beam

Fig. 1 shows a schematic diagram of a rotating composite beam, attached to a rotating rigid hub radius R. In addition, the length, width and total thickness are represented by L, b and h respectively. β_p denotes the pitch angle from the elastic axis to the vertical plane and θ is the setting angle between rotating direction and the chord line.

Several coordinate systems are used to describe the deformation of the beam. (xyz) is a body coordinate system, in which the x-axis corresponds to the undeformed elastic axis of the beam, the y-axis is along the lead-lag direction, and the z-axis lies along the flapwise direction. (XYZ) is a global coordinate system with the origin at the center of the volume of the hub. The X-axis is aligned with the horizontal direction. The Y-axis is parallel to the y-axis, and the Z-axis is perpendicular to the X-Y plane. Z-axis is the spindle of the rotating beam and $\mathbf{K}$ is the unit vector of it. The angular velocity can be expressed as $\mathbf{\Omega} = \Omega\mathbf{K}$, where Ω is the value of the rotating velocity. $\mathbf{\Omega}$ will points to the direction of positive axis Z when the value of Ω is positive, otherwise direction of negative axis Z.

Another new system ($X_rY_rZ_r$) can be obtained by translating the system (XYZ) from the hub center to the centroid of the fixed end of the beam, which will coincide with the system (xyz) if one rotate the X_r-Z_r plane counterclockwise about the