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Analysis of Coupled Vibration Characteristics of Wind Turbine Blade Based on Green's Functions**

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ABSTRACT This paper presents the analysis of dynamic characteristics of horizontal axis wind turbine blade, where the mode coupling among axial extension, flap vibration (out-of-plane bending), lead/lag vibration (in-plane bending) and torsion is emphasized. By using the Bernoulli-Euler beam to describe the slender blade which is mounted on rigid hub and subjected to unsteady aerodynamic force, the governing equation and characteristic equation of the coupled vibration of the blade are obtained. Due to the combined influences of mode coupling, centrifugal effect, and the non-uniform distribution of mass and stiffness, the explicit solution of characteristic equation is impossible to obtain. An equivalent transformation based on Green's functions is taken for the characteristic equation, and then a system of integrodifferential equations is derived. The numerical difference methods are adopted to solve the integrodifferential equations to get natural frequencies and mode shapes. The influences of mode coupling, centrifugal effect, and rotational speed on natural frequencies and mode shapes are analyzed. Results show that: (1) the influence of bending-torsion coupling on natural frequency is tiny; (2) rotation has dramatic influence on bending frequency but little influence on torsion frequency; (3) the influence of bending-bending coupling on dynamic characteristics is notable at high rotational speed; (4) the effect of rotational speed on bending mode is tiny.

KEY WORDS wind turbine blade, mode coupling, dynamic characteristics, Green's function.

I. Introduction

A blade in a horizontal axis wind turbine (HAWT) experiences a vibration with four coupled components: axial extension, out-of-plane bending (named flap), in-plane bending (named lead/lag) and torsion, as seen in Fig.1. The analysis of the dynamic characteristics of rotating blades is an important part in the design and control processes of HAWT, which can provide necessary information for detecting cracks[1], avoiding structural resonance[2,3], and predicting aeroelastic stability[4,5].

Lots of existing work focused on the improvement of computational models to obtain accurate results or to analyze the influences of special properties of concrete wind turbines. Park et al.[6] proposed a systematic formulation consisting of rigid hub and flexible blade to calculate the natural frequencies of wind turbine blade. Based on the thin-walled structure theory and Timoshenko beam theory, Wang et

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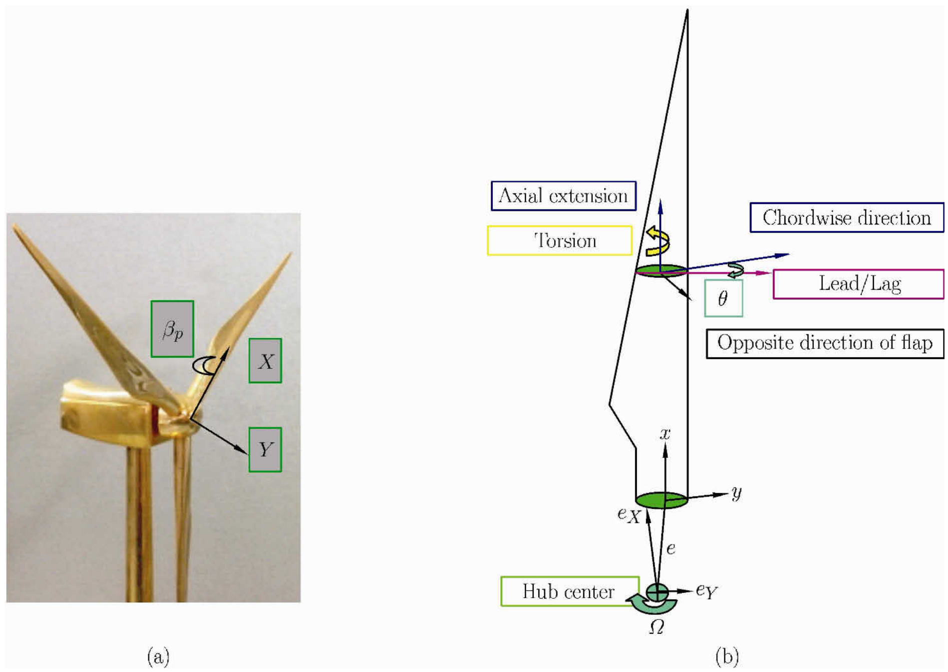

Fig. 1. Undeformed configurations of (a) a HAWT and (b) a blade.

al.[7] introduced a mathematical model to analyze the vibration characteristics of wind turbine blade; where natural frequencies and tip displacements were discussed using this model. Hsu[8] studied the vibration characteristics by applying the differential quadrature method; where the influences of pitch angle, rotational speed and number of sample points on natural frequencies were discussed. Maalawi and Badr[9] proposed a mathematical model to optimize the frequencies of pitching motion of wind turbine blade; where the effects of design variables including blade tapering ratio, chord, and shear wall thickness distribution were discussed. Stol et al.[10] studied the operating modes of a two-bladed wind turbine using the Floquet approach; where the effects of precone angle, teeter stiffness, yaw stiffness, teeter damping, and yaw damping on blade frequencies were discussed. Gangele and Ahmed[11] investigated the dynamic characteristics of a 1.5 MW wind turbine system, where the effects of geometric and material parameters were taken into account. Kumar et al.[12] gave a analyzed the dynamic characteristics of Al 2024 wind turbine blade using the finite element (FE) method. Sami et al.[13] studied the flap and lead/lag vibration characteristics of a 5 KW glass reinforced polyester composite wind turbine blade by applying the FE method with experimental tests. Tartibu et al.[14] studied the bending and torsional frequencies of a blade with variable length using the Matlab program and the FE method; where the influence of blade length was discussed. Luczak et al.[15] analyzed the influence of flexible support on blade section model, and proposed an updating FE model of blade section using experimental modal analysis results; and the vibration characteristics can be calculated by adopting this model. Osgood[16] presented a discussion on NREL's approach in designing and implementing a dynamic characterization test for commercial wind turbines. Larsen et al.[17] gave a discussion on the experimental methods for modal analysis of wind turbine blade; where different experimental procedures were considered and the most appropriate was selected to test the natural frequencies, damping characteristics and mode shapes of an LM19 m blade.

The above research was mainly by means of the FE method or experimental tests. A number of studies focused on the improvement of the approximation methods to analyze the vibration characteristics conveniently. Li et al.[18] investigated the flapwise vibration characteristics of blade by using the Rayleigh energy method, where the centrifugal stiffness effect was emphasized. Gürsel et al.[19] analyzed the natural frequencies of the rotor blades of NACA 4415 and NASA/Langley LS (1) 421MOD series by using the Raleigh energy method and the FE method. Surace et al.[20] introduced a numerical approach based on Green's functions (structural influence functions), using the method of which, Li et al.[21] discussed