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A parametric study of flutter behavior of a composite wind turbine blade with bend-twist coupling

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ABSTRACT

Now a days wind turbine blades are generally designed to have length as high as 60 m or more to maximize power production. Aeroelastic instabilities such as flutter are major concerns for these long, flexible and slender blades. Stiffness coupling between bending and twisting modes can be used to improve the aeroelastic performance of such blades. In composite blades bend twist coupling can be achieved by imparting unbalance in the lamination sequence. In the present work, a parametric study has been conducted to study the effect of unbalances in different parts of a wind turbine blade on flutter instability. An eigenvalue-based approach has been used for flutter analysis. It has been observed that flap-torsional stiffness has high impact on critical flutter speed. The critical flutter speed is increased by 40% with flap-torsional stiffness due to the unbalance in the entire section of the blade with symmetric skin, while for asymmetric skin; the achievable increment is 100%. The unbalance in the spar cap of the blade has less critical flutter speed as compared to the unbalance in the entire section of the blade. Unbalance in the entire section of the blade with asymmetric skin can lead to highest flutter speed.

1. Introduction

In last few years length of wind turbine blades has increased from 5 m to 60 m to achieve an increment in power production from 50 kW to 6 MW. Such long, slender, flexible blades are more prone to aeroelastic instabilities. For example, the flutter speed of the stiff blades of 20 kW wind turbine is several times higher than its normal operating speed while that of a flexible blade of 1.5 MW wind turbine is approximately 1.75 times than its normal operating speed [1]. Flutter speed comes closer to the normal operating speed of blade due to increment in blade length, so it is more likely to experience the flutter during the operation.

Hansen [2] presented an aeroelastic eigen value analysis framework considering both full turbine with three blades and a single blade separately. The structural modelling was done using finite element method and aerodynamic loads were calculated using blade element momentum method coupled with a Leishman-Beddoes type dynamic stall model. In another study [3] he analyzed stall induced vibration and classical flutter in wind turbine blade and showed the decrease in flutter speed with decrease in torsional stiffness. Liu et al. [4] investigated the effects of vibration on the aerodynamic load for NREL 5 MW wind turbine blade. They showed that the fatigue bending moment is increased in both flapwise and edgewise directions due to blade vibration at the tip of the blade considering the vibration induced velocities. Due to vibration at the blade root, fatigue bending moment is increased in flapwise direction and reduced in edgewise direction. In last few years several researchers have focused on passive aeroelastic tailoring for improved aeroelastic performance and aerodynamic load mitigation [5–11]. Such passive tailoring is generally achieved through stiffness coupling between the bending and twisting modes. Pourazarm et al. [7] studied the influence of the natural frequencies of the torsional and flapwise modes on the critical flutter speed. They showed that increase in only the flapwise natural frequency with the torsional natural frequency kept constant reduces the flutter frequency. However, the torsional frequency has comparatively more predominant effect on the aeroelastic stability. With reduction in torsional natural frequency, the flutter can occur even at a speed lower than the rated speed. Stablein et al. [8] studied the modal properties and stability of DTU 10 MW wind turbine. They investigated the flap-edge and twist coupled blade by eigenvalue analysis in steady state equilibrium using the aero-servo-elastic tool HAWCStab2. They showed that the damping of the first edgewise mode increases in the presence of edge-twist to feather coupling and reduces in the presence of edge-twist to stall coupling. In case of flap-twist to feather coupling, the frequency of the flapwise mode increases and damping of the same mode reduces, while in case of flap-twist to stall coupling, frequency of the flap wise mode decreases and

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damping of the same mode increases. In another study, Stablein et al. [9] showed that the structural coupling mainly affects frequency and damping of the coupled modes. Edge-twist flutter instability occurs at much lower inflow speeds for blade sections with edge-twist coupling than an uncoupled blade section. A moderate reduction in flutter speed has been reported for flap-twist to feather coupling and divergence for flap-twist to stall coupling.

Modern wind turbines are made of composite materials such as glass fiber, carbon fiber etc. Unbalance in the layup sequence of composite laminates in different airfoil components such as spar caps, skin, leading edge, trailing edge of the blade results in bend-twist coupling. Such a material coupling is a stiffness coupling that can be used for increasing the flutter speed. Stiffness coupling is also used to alleviate wind turbine loads passively [10]. The idea of using such a coupling for reduction of aeroelastic instabilities originated from helicopter blade application [11]. Hong and Chopra [11] studied the aeroelastic stability of bend-twist and extension coupled composite rotor blade in hover. Finite element method was used for structural model and quasi-steady strip theory for aerodynamic model. They reported that positive ply angle change increases flapwise mode frequency and decreases damping, while negative ply angle change has less effect on damping but greatly reduces the frequency. Ha et al. [12] studied the buckling stability, failure and deflection of wind turbine blade by changing the off-axis fiber angles. They reported a reduction in failure index for shallow-angled skins by reducing the blade mass. Hayat et al. [13] investigated the flutter performance of NREL 5 MW wind turbine blade with shallow-angled skin configurations. They showed that the critical flutter speed of asymmetric skin blade is higher than the symmetric skin blade, with or without mass reductions in spar cap of the blade. In another study, Hayat et al. [14] investigated the flutter characteristics of bend twist coupled wind turbine blades. They showed that the flutter speed slightly decreases with change in ply angle. Use of high stiffness and lightweight carbon fiber in composite blades can lead to an increment in flutter speed. Very recently, Zhou et al. [15] studied the flutter behavior of composite wind turbine blade using both linear and nonlinear beam model. Hellinger-Reissner variational principle was used for nonlinear beam model. The nonlinear beam model showed 23% less flutter speed as compared to the linear model. They showed that the unbalance in skin laminate has no significant influence on flutter speed and edgewise instability speed of the blade. However, the effects of other parameters such as asymmetry in the skin, unbalance in the spar cap etc. have not been explored with significant details to best of the authors' knowledge.

This paper presents a parametric study conducted to investigate into the effect of unbalances in various parts of a laminate composite wind turbine blade on flutter. We investigated the flutter characteristics of flapwise bend and twist coupled blade subjected to aerodynamic loading. Bend twist coupled structure model is derived using Hamilton's principle. Theoderson's theory is used for unsteady aerodynamic loads acting on wind turbine blade elements. NREL 5 MW and SNL 61.5 wind turbine blades are used for eigenvalue analysis using different ply angle orientation. A detailed parametric study showing the effect of changing ply angle in various fashion at different parts of the blade is presented.

2. Aeroelastic model of wind turbine blade

The aeroelastic model consists of two parts: structural and aerodynamic model. In structural model, Euler-Bernoulli beam has been considered for modelling wind turbine blade because of its slender structure. Corresponding governing differential equation has been derived using Hamilton's principle. Theodorsen's theory is used for unsteady aerodynamic load calculation.

2.1. Structural model

Hodges and Dowell [16] derived the differential equations of

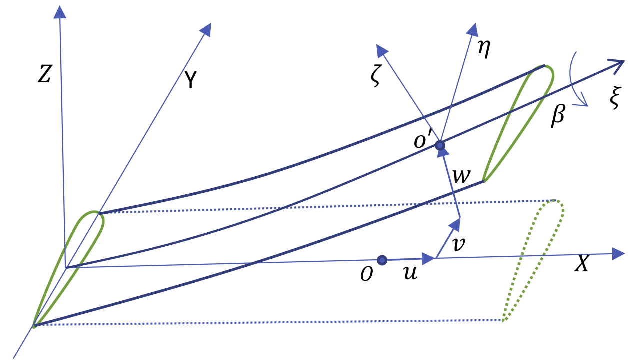

Fig. 1. Coordinates of the blade and its elastic displacements.

motion of a rotating beam. They considered flapwise bending, edgewise bending, extension and twisting with a constant angular velocity. Isotropic beam properties were assumed in their derivation. The coordinate system (XYZ) represents a body coordinate system which is rigidly attached to the root of the blade such that the X axis corresponds to the undeformed elastic axis, the Y axis lies in the plane of rotation, and the Z axis is perpendicular to the plane of rotation as shown in Fig. 1. A point O undergoes displacement from the undeformed elastic axis to deformed elastic axis O' with a displacement of u_0, v, w in the direction of X, Y, Z respectively, where u_0, v and w represent axial, flapwise and edgewise deflections, respectively. Further, it undergoes a rotation of β about the deformed elastic axis where β denotes the total blade geometric pitch which is a summation of twist (ϕ) and pre-twist angle. The orthogonal coordinates associated with the cross-section of the deformed blade are ξ, η, ζ where ξ axis is tangential to the deflected elastic axis and η, ζ axes are the principal axes. The stress-strain relations for horizontal (skin, spar cap) and vertical laminates (shear web) [11] are given by the following two equations respectively.

$$\begin{Bmatrix}\sigma_{XX}\\ \sigma_{XY}\end{Bmatrix} = \begin{bmatrix}\bar{Q}_{11} & \bar{Q}_{16}\\ \bar{Q}_{16} & \bar{Q}_{66}\end{bmatrix}\begin{Bmatrix}\epsilon_{XX}\\ \epsilon_{XY}\end{Bmatrix}$$
$$\begin{Bmatrix}\sigma_{XX}\\ \sigma_{XZ}\end{Bmatrix} = \begin{bmatrix}\bar{Q}_{11} & \bar{Q}_{16}\\ \bar{Q}_{16} & \bar{Q}_{66}\end{bmatrix}\begin{Bmatrix}\epsilon_{XX}\\ \epsilon_{XZ}\end{Bmatrix} \tag{1}$$

where X, Y and Z are reference axes. The expressions of Q_{ij}'s is given in Ref. [23] in terms of material constants. The assumption for stress and strain are $\sigma_{XX} \approx \sigma_{\xi\xi}$, $\sigma_{XY} \approx \sigma_{\xi\eta}$, $\sigma_{XZ} \approx \sigma_{\xi\zeta}$, $\epsilon_{XX} \approx \epsilon_{\xi\xi}$, $\epsilon_{XY} \approx \epsilon_{\xi\eta}$ and $\epsilon_{XZ} \approx \epsilon_{\xi\zeta}$.

In this study, flapwise bending and twist have been considered for modelling of the rotor blade. The equations of motion are derived using Hamilton's principle.

$$\int_{t_1}^{t_2} (\delta U - \delta T - \delta W)dt = 0 \tag{2}$$

where δU is the variation in strain energy; δT is the variation in kinetic energy and δW is the virtual work done. Expression for δU and δT are derived by Hodges and Dowell [16] for a rotor considering isotropic properties. Hong and Chopra [11] modified the equation considering orthotropic properties of composite plies. Finally, the governing differential equations of a composite wind turbine blade considering only the flapwise bending and twisting come to be as follows:

$$\left[EIw'' - e\phi\left(\int_x^L \Omega^2\rho Axdx\right) + B_1\phi'\right]'' - \left(w'\int_x^L \Omega^2\rho Axdx\right)' - (\Omega^2 me\phi)' + m(\ddot{w} + e\ddot{\phi}) = L \tag{3}$$

$$-\left[\left(GJ + K_m^2\int_x^L \Omega^2\rho Axd\right)\phi' + B_1 w''\right]' + \Omega^2\rho A(K_{m2}^2 - K_{m1}^2)\phi + \rho AK_m^2\ddot{\phi} - \left(\int_x^L \Omega^2\rho Axdx\right)ew'' + \Omega^2 mxew' + me\ddot{w} = M \tag{4}$$

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