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Flutter performance of large-scale wind turbine blade with shallow-angled skins

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ABSTRACT

The application of shallow-angled skins with off-axis fiber angle less than 45°, increases the bending stiffness and strength of the large-scale wind turbine blade but reduces its torsional stiffnesses, making it susceptible to the classical flutter instability problem. Single-blade quasi-steady eigenvalue analyses using HAWCStab2 were performed to evaluate the flutter performance of a 5 MW pitch-regulated wind turbine blade with shallow-angled skins configurations. The results showed that the application of shallow-angled skin design concept to the 5 MW blade model does not pose the flutter instability problem.

1. Introduction

The wind turbine market is growing rapidly and has become increasingly competitive. To improve efficiency and cost-effectiveness, the size of utility-scale wind turbines has been increased [1–5]. The use of large-scale turbines with flexible blades increases the risk of dynamic instabilities, particularly classical flutter for pitch-regulated wind turbines. Classical flutter refers to a dynamic unstable condition that, once reached, can lead to catastrophic structural failure [6].

Traditionally, classical flutter has not been an issue for utility-scale horizontal-axis wind turbines (HAWTs) [7]. However, it is expected to become one of the principal design drivers as rotor diameters are continuously increased [4]. The earlier work by Lobitz and Veers on a 20 kW HAWT having blades of 5 m length, shows that the predicted flutter limits were several times the operating speed of wind turbine [8]. In another work on a MW-sized wind turbine blade, Lobitz confirmed that the flutter speed computed from quasi-steady aerodynamics is conservative than that estimated using unsteady (Theodorsen) aerodynamics [9]. Investigations by Hansen [10,11] demonstrated that the single-blade and full-turbine analyses for a wind turbine produce similar flutter predictions, suggesting that the single-blade flutter analysis is adequate. Using single-blade flutter analyses of a MW-sized wind turbine blade, Hansen also showed that lowering the torsional stiffness and shifting the center of mass towards the trailing edge decreases the flutter speed limit [11]. There have been other similar findings that decreasing the torsional frequency decreases the flutter limit [10–12].

This work focuses on predictions of the flutter limit of a 5 MW wind turbine blade with shallow-angled skins. Two shallow-angled symmetric and asymmetric skin configurations (as detailed in Section 2.2) with 35° and 25° off-axis fiber angles were previously proposed in [13], based on the observation that considering the slenderness of the large-scale blade the conventional 45° off-axis fiber angle of the blade skins is not optimal. The shallow-angled skins were evaluated by their application to a utility-scale variable-speed and collective-pitch controlled 5 MW wind turbine blades, in terms of tip deflection, modal frequencies, buckling load factor and strength failure index. The results demonstrated that the application of shallow-angled skins improves the bending stiffness and strength of the blade, accompanied with a reduction of torsion stiffness. The increased bending stiffness and strength of the blade with shallow-angled skins were then reduced to match that of the blade with the conventional 45°-angled skins by thinning the spar

Abbreviations: AC, Aerodynamic center; BEM, Blade element momentum theory; BX, Bi-axial; CLT, Classical laminate theory; CG, Center of gravity; CP, Collocation point; DOF, Degree of freedom; EA, Elastic axis; HAWTs, Horizontal-axis wind turbines; HEC, Higher education commission; LE, Leading edge; LHS, Left hand side; MLTM, Ministry of land, transportation and maritime affairs; MW, Mega Watt; NACA, National Advisory Committee for Aeronautics; NCF, Non-crimp fabrics; NREL, National renewable energy laboratory; PS, Pressure side; RHS, Right hand side; SNL, Sandia National Laboratories; SS, Suction side; TE, Trailing edge; TX, Tri-axial; UD, Unidirectional.

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caps. Consequently, the blade overall mass was lowered while meeting the stiffness, strength and buckling stability requirements. The reduced torsional stiffness of blade with shallow-angled skins increases its susceptibility to the potential danger of classical flutter instability; thus, needs to be evaluated in greater detail.

This paper begins with a brief discussion of the theoretical background on the classical flutter instability mechanism, and then discusses the development of a 5 MW wind turbine blade with implemented the shallow-angled skins design concept. The verification of the eigenvalue flutter analysis approach using HAWCStab2 is then presented, followed by the results and discussion section, and finally conclusions are presented.

2. Classical flutter instability mechanism

Classical flutter refers to a violent unstable dynamic condition in which the blade structure under the influence of incident aerodynamic loads undergoes the high-amplitude vibrations due to the coupling of the flapwise and torsional modes. Below the flutter limit, the blade response is stable, and vibrations are dampen out by the structural damping. Upon reaching the flutter limit, however, the vibrations start to grow exponentially in the amplitude. Beyond the flutter limit, the blade response becomes unstable because of negative aero-elastic damping, and high-amplitude vibrations become self-exciting and sustainable, subsequently, leading to rapid structure failure [6,14–16].

To understand classical flutter, the instability mechanism of a simple blade section model, taken from Ref. [16], is discussed here. Fig. 1 shows a typical blade section, consisting of two degrees-of-freedom (DOFs), subjected to quasi-steady aerodynamic lift. The incident wind inflow is parallel to the blade chord c. The flapwise translation DOF, denoted by h, is perpendicular to the wind inflow direction, and the torsional rotation DOF, denoted by θ, is about the elastic axis (EA). The elastic axis is located at a distance ca_{CG} in front of the blade center of gravity (CG). The aerodynamic lift force L is acting at the aerodynamic center (AC), located at a distanceca_{AC} in front the elastic axis. The linear equations of motion of the blade section are:

$$\begin{aligned} m\ddot{h} - mca_{CG}\ddot{\theta} + k_f h = L \\ -mca_{CG}\ddot{h} + m(c^2 r_{CG}^2 + c^2 a_{CG}^2)\ddot{\theta} + k_t\theta = ca_{AC}L, \end{aligned} \tag{1}$$

where m is the mass per unit length of the blade section, r_{CG} is the radius of gyration about the center of gravity normalized by the blade chord length, $\ddot{h}$ and $\ddot{\theta}$ are derived by taking twice time-derivatives of the flapwise translation and the torsional rotation DOFs, and k_f and k_t represents the flapwise and torsional stiffnesses.

When the apparent mass terms is neglected, the quasi-steady aerodynamic lift force L per unit length becomes,

$$L = \frac{1}{2}\rho c W^2 C_L(\alpha), \tag{2}$$

where ρ is the air density, W is the relative inflow wind speed, and C_L is the lift coefficient evaluated at the angle of attack α. To include the torsional velocity $\dot{\theta}$ effects, the angle of attack is defined at the collocation point (CP), located at the blade three-quarter chord length. The relative wind speed and the angle of attack are therefore:

$$W = \sqrt{W_0^2 + \dot{h}^2} \quad \text{and} \quad \alpha = \arctan\left[\frac{W_0 \sin\theta - \dot{h} - c\left(\frac{1}{2} - a_{AC}\right)\dot{\theta}}{W_0\cos\theta}\right], \tag{3}$$

where W_0 is the steady-state relative inflow wind speed. By inserting W and α into Eq. 2, and linearization about $\theta = \dot{h} = \dot{\theta} = 0$, results in the linear approximation to the aerodynamic lift force L:

$$L \approx L_0 + \frac{1}{2}c\rho W_0^2 C_L'\left[\theta - \frac{\dot{h}}{W_0} - \left(\frac{1}{2} - a_{AC}\right)\frac{c\dot{\theta}}{W_0}\right], \tag{4}$$

where L_0 is the steady-state lift force, and C_L' represents lift gradient (i.e. $C_L' = dC_L/d\alpha$) evaluated at the angle of attack $\alpha_0 = 0$. For thin airfoils, the value of C_L' is assumed to be 2π. The steady-state lift can be ignored as it has little influence on the airfoil instability. Thus, Eqs. (1) and (4) can be written in matrix form as:

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{0}, \tag{5}$$

where the vector $\mathbf{x} = [h/c, \theta]^T$ consists of non-dimensional DOFs. The blade structure mass matrix $\mathbf{M}$, aerodynamic damping matrix $\mathbf{C}$, and aero-elastic stiffness matrix $\mathbf{K}$ are:

$$\mathbf{M} = \begin{bmatrix} 1 & -a_{CG} \\ -a_{CG} & r_{CG}^2 + a_{CG}^2 \end{bmatrix}, \quad \mathbf{C} = \frac{c\kappa}{W_0}\begin{bmatrix} 1 & \frac{1}{2} - a_{AC} \\ a_{AC} & a_{AC}\left(\frac{1}{2} - a_{AC}\right) \end{bmatrix},$$
$$\mathbf{K} = \begin{bmatrix} \omega_f^2 & -\kappa \\ 0 & r_{CG}^2\omega_t^2 - \kappa a_{AC} \end{bmatrix}, \tag{6}$$

where $\omega_f = \sqrt{k_f/m}$ and $\omega_t = \sqrt{k_t/(mc^2 r_{CG}^2)}$ are the frequencies of flapwise and torsional modes without inertial coupling (i.e. $a_{CG} = 0$), and $\kappa = (\rho/2m)W_0^2 C_L'$ is the aerodynamic stiffness. Ignoring the aerodynamic damping matrix $\mathbf{C}$ and inserting the assumed solution $\mathbf{x} = \mathbf{v}e^{\lambda t}$ into Eq. (5) results in the following single-blade eigenvalue problem:

$$(\lambda^2\mathbf{M} + \mathbf{K})\mathbf{v} = 0. \tag{7}$$

Non-trivial solution of Eq. (7) leads to the following characteristic equation:

$$r_{CG}^2\lambda^4 + \left[(r_{CG}^2 + a_{CG}^2)\omega_f^2 + r_{CG}^2\omega_t^2 - \kappa(a_{AC} + c_{CG})\right]\lambda^2 + \omega_f^2\left(r_{CG}^2\omega_t^2 - \kappa a_{AC}\right) = 0. \tag{8}$$

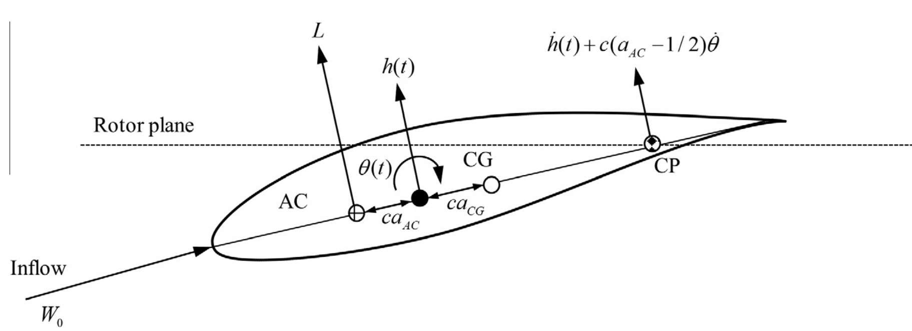

Fig. 1. Typical blade section with two degrees of freedom, reproduced from [16].