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Load mitigation of wind turbine blade by aeroelastic tailoring via unbalanced laminates composites

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ABSTRACT

The parametric study of unbalanced tri-axial non-crimp fabrics laminates, typically used in the blade skin layup, showed that the highest bend-twist coupling up to 0.56 was achieved when all three kinds of unbalances (i.e. ply-angle, ply-material and ply-thickness unbalances) were simultaneously present in the laminates. Based on aeroelastic tailoring via unbalanced laminates, the bend-twist coupling towards feather of various degrees was implanted to the skin layup of a variable-speed collective-pitch controlled 5 MW wind turbine rotor blades and fully-coupled aero-servo-elastic analyses were performed. The results showed that when the ply-thickness unbalance is added in the skin layup, in addition to already existing ply-angle and ply-material unbalances, an average increase in the coupling magnitude by approximately 51% along the blade length and a reduction in fatigue load and collective-pitch demand by approximately 1.6–2.9% and 5.5–19.9% across the range of applied stochastic winds ranging from 7 m/s to 23 m/s.

1. Introduction

The life of wind turbine blades can be enhanced by reducing the wind induced fluctuating loads with active and/or passive controls. For the former approach, the blade is actively controlled by changing the blade pitch or using active devices like the trailing-edge flaps [1]. However, the latter approach, so-called passive load mitigation technique, is more attractive due to its simplicity, relatively quick response and cost-effectiveness.

The passive control is realized by implanting bend-twist coupling to the wind turbine blades. The term 'bend-twist coupling (BTC)' is used to describe the dynamic relationship between bending and torsion deformations of an adaptive blade. Under the influence of aerodynamic loads the adaptive blade twists as it bends, which causes a change in the angle of attack, thus, directly affecting the incident wind loads [2].

A desired BTC can be achieved by using blade sweep-geometry [3–5], and/or tailoring the composite lay-ups [6,7]. The design and analysis of a swept-blade is a daunting task, and its manufacturing is cumbersome and uneconomical. On the other hand, modern wind turbine blades are made of composite materials, therefore, an adaptive blade design utilizing the composite material anisotropy, can be more effective and economical. The process of achieving a desired BTC by modifying the composite layup of an aerodynamically-shaped blade is known as aero-elastic tailoring.

An adaptive blade can be designed to twist either towards stall (towards the region of high angle of attack with flow separation) or towards feather (towards the region of low angle of attack to reduce lift). Early BTC concept with twist-to-stall for the stall-controlled wind turbines, showed a potential for increasing the turbine efficiency and reducing the peak loads [2,6,8], but resulted in a substantial fatigue damage and the danger of flutter instability [8,9]. The recent research focuses on the BTC with twist-to-feather because of its quick response to the fluctuating winds and effective fatigue load mitigation [9,10]. The load reduction can also be accomplished with the active pitch control; however, the response to incident wind variations is quite low. On the other hand, the use of active pitch control and the BTC towards feather can generate a synergic effect that can significantly reduce the fatigue loads. The study of a 2 MW wind turbine using integrated passive (i.e. BTC towards feather) and active individual-pitch controls showed that higher fatigue load reduction can be achieved than that would be possible by separate passive and active controls [11].

Numerous studies have been performed to implant the highest BTC in the wind turbine blades. Ong and Tsai evaluated the effect of ply-angle and ply-material unbalances on the coupling magnitude for a D-spar configuration [12]. The highest coupling achieved was for a range of ply-angles 15–30°and using high stiffness carbon fibers. The coupling value attained for carbon and glass

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Abbreviations

AC	aerodynamic center
ADAMS	automated dynamic analysis of mechanical systems
AOA	angle of attack
BE	blade-element
BEM	blade element moment
BTC	bend twist coupling
BX	bi-axial
CAS	circumferentially asymmetric stiffness
CLT	classical laminate theory
DEL	damage equivalent load
DLL	dynamic link library
DOFs	degrees of freedom
EC	elastic center
FAST	fatigue, aerodynamics, structures, and turbulence
HEC	higher education commission
GDW	generalized dynamic wake
IEC	international electro-technical commission
Ip	in-plane
LE	leading-edge
LNG	liquefied natural gas
MBD	multi-body dynamic
MC	mass center
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
UD	unidirectional
TE	trailing-edge
TX	tri-axial
Oop	out-of-plane
PS	pressure-side
SNL	sandia national laboratories
SS	suction-side
SC	shear center
TE	trailing edge

materials was found to be 0.6 and 0.4. The use of unidirectional (UD) carbon fibers, oriented at 20° with respect to the span axis, in the skin of a 9-meter long blade was reported in [13–15]. The implementation of BTC in the outer 60% of a 26.3 m long blade to capture more wind energy, was carried out using a hybrid glass-carbon layup, oriented at 25° with respect to the blade span [2]. To find an optimal off-axis fiber angle, a parametric study was conducted by varying the off-axis fiber angle from 5° to 25° and the volume fraction of off-axis fibers from 10% and 90% in the all-carbon spar cap of a 37 m long blade [16]. The optimal angle of 7.5° was found by minimizing the cost and satisfying the imposed constraints related to the blade stiffness and strength, however, no fatigue load reduction is reported. Another parametric study was performed by Griffin [17] to find the trade-off between the coupling magnitude and material cost, by applying various material types, fiber angles and structure configurations. The results showed that the structural configuration that incorporate biased/unbalanced layup in the spar cap is costly, but provides the highest coupling because the spar cap mainly endures the bending loads. The most effective combination of the coupling magnitude and cost is the use of biased hybrid skin with unbiased spar cap.

The magnitude of BTC depends on the amount of unbalance present in the composite layup. The coupling can be generated using the ply-angle, ply-material and/or ply-thickness unbalances. In the literature, only the ply-angle and ply-material based unbalances have been used to implant the BTC in the composite blades. No study describes the effect of ply-thickness unbalance on the coupling magnitude. In this work, it is demonstrated that the highest coupling intensity can be achieved when all 03 kinds of unbalances simultaneously exist in the composite layup of wind turbine blades. Thus, a considerable fatigue load reduction is possible using adaptive blades with BTC towards feather. The estimated couplings with twist-to-feather are then implanted to the skin layup of a 5 MW variable-speed and collective-pitch controlled wind turbine rotor blades. The couplings are applied to the blade skin layup only, because it provides the most effective combination of the coupling magnitude and cost [17]. The reduction in the fatigue load and the collective-pitch demands are then computed using coupled aero-servo-elastic multi-body dynamic analyses.

The paper begins with a discussion about the unbalance laminates and the estimation of BTC that can be implanted to an adaptive blade, followed by a brief description about the fully-coupled aero-servo-elastic analysis. The development of a 5 MW wind turbine blade, the adaptive rotor configuration and analysis procedure is then discussed. The effect of ply-thickness unbalance on the BTC magnitude and the reduction in the fatigue load and collective-pitch demand are described in the result and discussion section, and finally conclusions are presented in the end.

2. Adaptive blade design

2.1. Bend-twist coupling due to unbalanced laminates

The composite layup of a conventional blade comprises symmetric and balanced laminates. The magnitude of BTC that can be implanted to a blade structure depends on the amount of unbalance present in the composite laminate. A laminate is considered symmetric if the ply above and below the center-line of laminate are identical in the angle, material and thickness. On the other hand, a balanced laminate means that the material, angle, and/or thickness of the ply oriented in one direction, except 0° and 90°, is counter-balanced by another ply in the reversed direction. For example, the 03 kinds of unbalances can be developed in a bi-axial (BX) non-crimp fabrics (NCF) laminate are: ply-angle unbalance (Fig. 1a), ply-material unbalance (Fig. 1)b, and ply-thickness unbalance (Fig. 1c). For the BX laminate shown in Fig. 1, θ_1 and θ_2 refers to ply-angles, t_1 and t_2 refers to ply-thicknesses, and symbols G and C enclosed by curly braces refers to Eglass/Epoxy and Carbon/Epoxy ply-materials, respectively. Since, the intensity of BTC depends on the magnitude of unbalance existing in a laminate, therefore, the highest coupling can be achieved by simultaneously generating all 03 unbalances in a composite laminate.

2.2. Parametric study

A parametric study is conducted to investigate the effect of 03 kinds of unbalances on the BTC that can be implanted to a prismatic blade structure. For this purpose, a simple blade cross-section with a chord of 3 m width, zero pre-twist, and having no shear web, is selected. The airfoil NACA 64-A17 is used to define its aerodynamic shape (Fig. 2a). The blade suction-side (SS) and pressure-side (PS) consist of symmetric tri-axial TX: $[0_2\{G\}/+45\{G\}/-45\{G\}]_S$ NCF skin laminates. Where the symbol G enclosed by curly braces refers to Eglass/Epoxy material. It