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Fluctuations of angle of attack and lift coefficient and the resultant fatigue loads for a large Horizontal Axis Wind turbine

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ABSTRACT

Unsteady loads are a major limiting factor for further upscaling of HAWTs considering the high costs associated to strict structural requirements. Alleviation of these unsteady loads on HAWT blades, e.g. using active flow control (AFC), is of high importance. In order to devise effective AFC methods, the unsteady loading sources need to be identified and their relative contribution to the load fluctuations experienced by blades needs to be quantified. The current study investigates the effects of various atmospheric and operational parameters on the fluctuations of α and C_L for a large HAWT. The investigated parameters include turbulence, wind shear, yawed inflow, tower shadow, gravity and rotational imbalances. The study uses the DTU's aeroelastic software *HAWC2*. The study identifies the individual and the aggregate effect of each source on the aforementioned fluctuations in order to distinguish the major contributing factors to unsteady loading. The quantification of contribution of each source on the total fatigue loads reveals $>65\%$ of flapwise fatigue loads is a result of turbulence while gravity results in $>80\%$ of edgewise fatigue loads. The extensive parametric study shows that the standard deviation of C_L is 0.25. The results support to design active load control systems by highlighting the magnitude of C_L and α variations experienced by HAWTs, and thus the dC_L that needs to be delivered by an AFC system.

1. Introduction

Previous studies have shown that increasing the size of wind turbines is a driving factor towards more environmentally friendly and cost-efficient wind energy [1,2]. However, as wind turbines become larger, the rotating blades subsequently become longer. Longer blades necessitate the use of more slender and flexible designs, which lead to larger tip deflection in steady state, near rated wind speed. Larger deflection for the slender blades may be also a result of structural mode coupling due to unsteady, spatially inhomogeneous, wind fields and loads. This imposes strict requirements, leading to thicker blade laminates with higher structural strength and stiffness in order to withstand the inherently higher loads, due to the effects of gravity and non-uniform inflow conditions, and to limit the resultant larger deflections, ultimately leading to more expensive blades.

In order to refrain these undesirable high costs, the sources of unsteady loads on the blades need to be identified and their resulting fatigue damage needs to be determined. Furthermore, the resultant load fluctuations of each source need to be quantified. Identification of the load fluctuations helps to effectively design the active load control systems in order to alleviate the identified fluctuations [3]: the dC_L that needs to be delivered by an AFC system will be known.

The atmospheric boundary layer imposes a range of operating conditions on wind turbine blades during their lifetime. These include unsteady fluctuations in wind speed and direction as well as gradients of mean velocity in both vertical and lateral directions. Previous studies have shown atmospheric characteristics such as turbulence [4–6] and stability [7–9] are important for wind turbine unsteady loading. Additionally other effects including wind shear [10–12], yawed inflow [13], gravity, tower shadow, mass and aerodynamic imbalances and wake effects [14–16] also have a significant contribution to load fluctuation experienced by HAWT rotor blades.

Unsteady loading can lead to structural resonance and fatigue damage and finally structural failure and reduction of lifetime for wind turbine blades [17]. Part of the unsteady loading are caused by fluctuations in the angle of attack and consequently fluctuations of forces and moments on blades. Therefore, quantification of the fluctuations in angle of attack and lift coefficient under various loading conditions is important for wind turbine blades.

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Nomenclature

A	Weibull distribution scale factor
C_D	Coefficient of drag
C_L	Coefficient of lift
D	Fatigue damage
D_P	Fatigue damage scaled with wind speed probability density function
$D_{P,norm}$	Normalized fatigue damage scaled with wind speed probability density function
F_i	Fatigue loads ranges
F_{EQ-TOT}	Lifetime equivalent fatigue load (LEFL), kNm
F_{EQ}	Equivalent fatigue load (EFL), kNm
I_{ref}	Expected value of hub-height turbulence intensity at a 10 min average wind speed of 15 m/s
M_x	Flapwise blade root bending moment, kNm
M_y	Edgewise blade root bending moment, kNm
M_z	Torsional blade root bending moment, kNm
P	Probability density function of wind speed
R	Blade radius, m
U_{in}	Cut-in wind speed, m/s
U_{out}	Cut-out wind speed, m/s
α	Angle of attack, °
$\overline{U}$	Mean wind speed, m/s
$\overline{U}_\tau$	Mean wind speed at the reference height, m/s
σ	Standard deviation
k	Weibull distribution shape factor
m	Wöhler exponent
n_i	Fatigue loads cycles
n_{EQ}	Number of equivalent cycles
r	Radial position on blade, m
rR	Normalized radial position with blade radius$\frac{r}{R}$
z	Height, m
z_τ	Reference height, m
des	Design values for angle of attack and force coefficients

Though previous efforts [18,19] mainly focused on the investigation of mean value of α and C_L, few studies addressed the fluctuations of α and C_L. Moreover, such studies either investigated the effect of fluctuation of α on the turbine output power [20] or only studied the aggregate effect of all sources of unsteadiness on the fluctuations of C_L and fatigue damage [21]. Therefore, the quantification of the individual effect of unsteady loading sources on the fluctuations of α and C_L and the associated fatigue damage has received minimal attention to this point. The current study intends to investigate the influence of various unsteady loading cases on the fluctuations of α and C_L for a large HAWT in a systematic and holistic approach. Additionally, a comparison of lifetime equivalent fatigue loads of the blade root bending moment corresponding to each source of unsteadiness is performed.

As such, the present study can support the identification of the major contributors to unsteady loads on wind turbine blades. Moreover, quantification of the fluctuations in α and C_L can provide guidelines for the design of active load control systems for wind turbine blades [3,22,23].

The current study uses the BEM-based aeroelastic wind turbine design code ‘HAWC2’ from DTU Wind Energy. Although high-fidelity CFD calculation are also commonly employed to study the wind turbines [24–26], aeroelastic codes offer the advantage of being computationally much cheaper while offering a satisfactory level of agreement with higher-fidelity modeling and experiments (see subsection 2.1). This grants us with the opportunity to study a wide range of parameters at a reasonable computational cost.

The paper starts with a methodology section where the investigated wind turbine and the employed aeroelastic code are described in subsection 2.1. The simulations settings and test matrix is presented in subsection 2.2 and the employed method for calculation of fatigue loads are discussed in subsection 2.3. The results and discussion are presented in section 3 where the fluctuations of angle of attack and lift coefficient are discussed in subsection 3.1 and the resultant fatigue loads are elaborated in subsection 3.2. The conclusions are provided in section 4.

2. Methodology

2.1. Wind turbine and aeroelastic code

The 10 MW reference wind turbine (DTU-10MW-RWT) developed by DTU is employed in the current study. DTU-10 MW-RWT is a 3-bladed upwind horizontal-axis variable-speed pitch-regulated yaw-controlled wind turbine with schematic shown in Fig. 1. The turbine is selected as a representative of future trend of large wind turbines. Geometrical and operational characteristics of this turbine are described in Table 1. Further details can be found in Ref. [27]. The geometrical and operational characteristics of this turbine (aerodynamics, structure and controller) are used as inputs in the simulations.

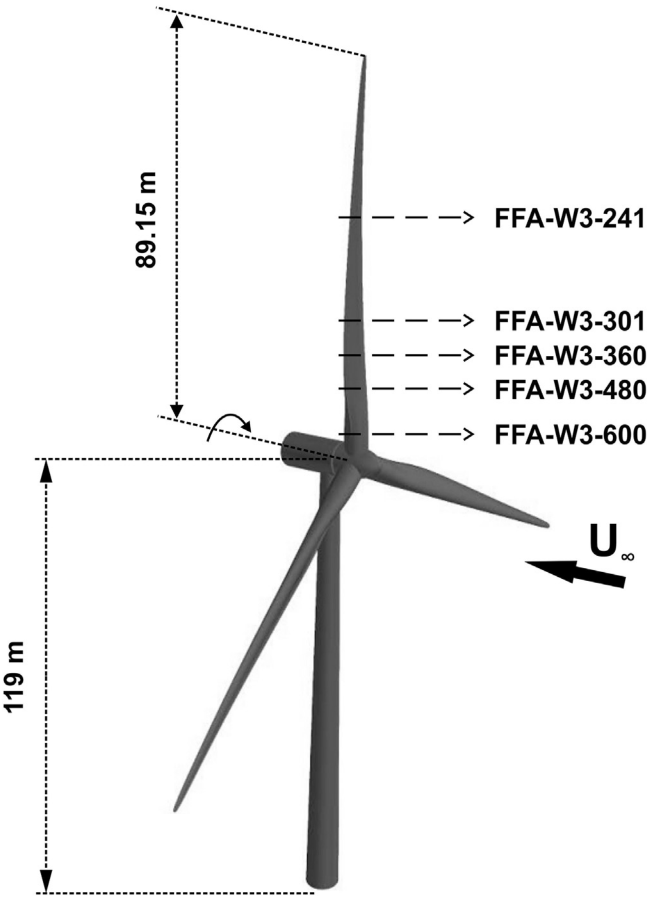

Fig. 1. Schematic of DTU-10MW-RWT modified from Ref. [27].