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Review

Impact of uncertainty in airfoil characteristics on wind turbine extreme loads

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ABSTRACT

Wind tunnel test measurements to characterize the static lift and drag coefficients of airfoils used in wind turbine blades are shown to possess large uncertainties, which leads to uncertainties in the aerodynamic loads on the rotor. In this paper a rational stochastic model is proposed to quantify the uncertainty in airfoil static lift and drag coefficients based on field and wind tunnel data, aero-servo-elastic calculations and engineering judgment. The stochastic model is subsequently used to assess the effect of the uncertainty in airfoil static lift and drag coefficients on the prediction of extreme loads and structural reliability of large wind turbines. It is shown that the uncertainty in the static airfoil data has a significant impact on the prediction of extreme loads effects and structural reliability depending on the component, operating conditions (stand-still versus power production) and the correlations of aerodynamic variables along the span of the blades.

1. Introduction

Considerable effort and capital is invested in predicting the static aerodynamic lift and drag coefficients of airfoils as accurately as possible. The lift and drag coefficients are then used by the wind turbine designers as input to aero-servo-elastic simulations to predict extreme and fatigue loads in addition to stability margins in normal and extreme operating and stand still conditions. An airfoil's static aerodynamic data are almost exclusively derived from measurements acquired in wind tunnel tests. However, an airfoil section on the wind turbine rotor operates in 3-dimensional, unsteady and turbulent inflow under the guidance of a control system, none of which are accounted for in static wind tunnel tests. Some aspects of uncertainty in airfoil data (surface roughness, 3D corrections, effect of *Re* numbers, wind tunnel measurements or geometric distortions) have been studied in Refs. [1–7]. The general consensus is that uncertainties in airfoil data do affect a wind turbine's performance and structural loading. Aerodynamic uncertainties are widely acknowledged in the industry; this is demonstrated by cross validating wind tunnel measurements with CFD or cross validating wind tunnel measurements with full scale test data or performing wind tunnel measurements under various inflow conditions. Manufacturers also try to mitigate aerodynamic uncertainties by ensuring tight controls on the tolerances of blade geometry during manufacturing and handling. In addition, a widely performed practice is to tune the static airfoil data used in the aero-servo-elastic simulations using measurements from a prototype wind turbine. The tuning of aerodynamic data is usually done indirectly through performance metrics such as power production or structural loading. In wind turbine structural reliability analysis [8], an overall value of 10% is used as the coefficient of variation (COV) for airfoil uncertainty as affecting the structural loads. With the advent of advanced wind tunnel testing, computational fluid dynamics and full scale testing it is deemed necessary to review this value. In this paper we establish a stochastic model for the static lift and drag coefficients by tapping into publicly available aerodynamic tests, measurements and simulations on various aspects of aerodynamic uncertainties. The stochastic model is developed by (1) replicating the physical variations in airfoil characteristics by parameterizing the lift and drag coefficients curves, (2) allowing selected points on the lift and drag curves to be distributed randomly around the measured values and (3) simulating their impact on extreme loads using a Monte Carlo scheme with varying degree of correlation among the aerodynamic properties along the span of the blade. The proposed stochastic analysis

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Nomenclature

2D	two-dimensional
3D	three-dimensional
CL,max	max lift coefficient
AoAmax	angle of attack where CL,max occurs
CL,TES	lift coefficient where trailing edge separation starts
AoATES	angle of attack corresponding to CL,TES
CL,SR	lift coefficient where stall recovery starts
AoASR	angle of attack where stall recovery starts
CL,90	lift coefficient at 90° angle of attack
CD,90	drag coefficient at 90° angle of attack
TES	trailing edge separation
COV	coefficient of variation
Re	reynolds number
t/c	thickness to chord ratio
RootMyb1	blade root flap bending moment
Spn4MLyb1	blade ¾ span flap moment
RootMxb1	blade root edge bending moment
Spn4MLxb1	blade ¾ span edge moment
OoPDefl1	blade out of plane deflection
LSSTipMzs	low speed shaft yaw moment
LSSTipMys	low speed shaft tilt moment
LSShftMxa	low speed shaft driving moment (torque)
TwrBsMyt	for-aft tower bottom bending moment
TwHt4MLyt	for-aft ¾ height bending moment

quantifies the model, statistical and measurement uncertainties of blade aerodynamics and its effects on the extreme structural loads. The stochastic model is first used in structural reliability optimization against extreme loading of a wind turbine tower in standstill in a 50-year storm, then for evaluating the structural reliability index and optimization of the partial load safety factors of a blade in power production. A commercial multi-megawatt offshore wind turbine is considered in the calculations of the extreme loads effects (nominal power>5 MW and rotor diameter>130 m).

2. Airfoils database

A database of airfoils lift and drag polars measurements is collected for this study and is presented herein. The database is largely built upon publicly available wind tunnel tests and 3D full scale measurements.

2.1. Wind tunnels

Table 1 lists the wind tunnels that have historically been widely used for testing airfoils for the wind turbine and aerospace industries. Publicly available data from these wind tunnels are collected and used as a basis for the stochastic model of the airfoils static lift and drag coefficients.

Table 1
List of wind tunnels and their characteristics.

Wind tunnel	Characteristics
Delft wind tunnel (Netherlands)	Max speed 120 m/s, max *Re* 3.5 million, Ti<0.02%, test section 1.25 × 1.80 m
Velux wind tunnel (Denmark)	Max speed 40 m/s, max *Re* 1.6 million, Ti~1%, open jet test section 7.5 × 7.5 m
LM wind power wind tunnel (Denmark)	Max speed 105 m/s, max *Re* 6.0 million, Ti~0.1%, test section 1.35 × 2.70 m
Stuttgart wind tunnel LWK (Germany)	Max speed 90 m/s, max *Re* 5.0 million, 0.0002% < Ti<0.0005%, test section 2.73 × 0.73 m
NASA Langley LTPT wind tunnel (USA)	Max speed 130 m/s, Max *Re* 6 million at Mach 0.3, Ti is N/A, test section 0.91 × 2.29 m,
Large scale low speed wind tunnel facility (LLF) of the German Dutch wind tunnel organization (Germany)	Max speed 80 m/s, open jet test section 9.5 × 9.5 m Max speed 152 m/s, closed wall test section 6.0 × 6.0 m Max *Re* 6 million at Mach 0.45, Ti<0.4%,
The NASA-AMES wind tunnel (USA)	Max speed 50 m/s, Ti<0.4%, test section 24.4 × 36.6 m

2.2. Full scale measurements

Table 2 presents a list of 3D wind turbine rotor measurement campaigns that are widely reported in the literature. Publicly available data from these tests are also collected and used as basis for the stochastic model.

2.3. Airfoil families

Table 3 shows an exhaustive list of airfoils used in this study as a basis for the stochastic model. The airfoils lift and drag curves for the airfoils listed in Table 3 are collected and categorized with regards to their fundamental sources of uncertainty studied in the referenced literature.

3. Airfoil aerodynamics

The rate of change of the lift coefficient with angle of attack, $dC_L/d\alpha$, can be inferred from thin airfoil theory to be 2π per radian change of angle of attack and slightly lower when taking the effects of airfoil thickness and fluid viscosity into account. Deviation from the linear slope is the start of the progressive movement of the turbulent flow separation point from the trailing edge (TE) towards

Table 2
List of 3D full scale wind turbine measurements campaigns.

Test	Description	Reference literature
DANAERO project	NM80 variable speed pitch regulated wind turbine (80 m rotor diameter)	[9]
NREL unsteady aerodynamics experiment phase VI	NASA/AMES wind tunnel test of an experimental two blades rotor with10 m rotor diameter stall regulated	[2]
MEXICO project	Wind tunnel test of a three bladed rotor of 4.5 m diameter including a speed controller and pitch actuator.	[10]