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Nacelle-based Lidar Measurements for the Calibration of a Wake Model at Different Offshore Operating Conditions

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Abstract

Commonly, wake models are calibrated in wind tunnels or using flow simulations with a wide degree of physical details. In general, it is assumed that these methods cannot fully reproduce the real operating conditions of wind turbines. This research aims at investigating the calibration of an analytical single wake model in relation to full-scale measurements. Within this scope, we fitted the wake model to wake measurements realised with a lidar installed on the nacelle of an offshore wind turbine. We studied the parameters returned by the fit separating cases at different levels of atmospheric turbulence and thrust on the wind turbine rotor. Comparing the results with a published calibration based on few LES wind fields representative for partial load conditions, we achieved good agreement when the considered wind turbines operated in similar conditions. For other situations, i.e. at full load, we found different calibrations of the model parameters. Our results show that and how nacelle-based lidar measurements can be complementary in the development of wake models.

Keywords: nacelle lidar, full field experiment, wake recovery, wake expansion, model verification

1. Introduction

In a wind farm, the upstream turbines slow down the wind to generate electrical energy thereby creating a wake flow with reduced wind speed behind their rotors. As a consequence, downstream turbines generally produce less energy and are subject to more severe fatigue loads [1].

To predict the energy yield of a wind farm, engineering wake models are applied to estimate the corresponding energy losses. These models need to have reasonable computational costs. Therefore, they describe the shape of the wake deficit using simplified analytical formulas based on few parameters. The drawback of this simplification is a reduced ability to fully resolve the turbulent structures composing the wake flow. It follows that engineering wake models have a much lower accuracy than more physically detailed models, but this is the price to pay to have simulation tools suitable for industrial applications.

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Walker et al.[2] indicate that 50 % uncertainty is to be expected for the estimation of energy wake losses with current engineering wake models. In new offshore wind projects, the size and costs have increased fast leading to a strong impact of the uncertainty on the financial risk of the project and on the confidence of possible investors. For this reason, the accuracy of engineering wake models has become a main concern of the wind energy community.

More extensive and precise calibration of these models could reduce their uncertainty. For a long time their development and validation have relied on the indirect verification of the power production and not on the spatial description of the flow. Today, the advancement in simulations and full field measurements allow to develop and validate models using the flow itself.

Very detailed wake simulations, such as large eddy simulations (LES) with wind turbines modelled by means of an actuator line or an actuator disk model, can simulate the wind farm flow with a high degree of fidelity. For instance Niayifar and Porté-Agel[3], Trabucchi et al.[4] and Keck et al.[5] used LES for the evaluation and calibration of engineering wake models. This approach offers realistic wake data, but its results cannot always be generalised since often only few exemplary test cases are addressed due to the high computational costs of the simulations.

Measurements of scaled wind turbine wakes with different level of complexity have been widely used to study wakes [6–8]. The advantage of wind tunnel measurements is the possibility to well define the environmental conditions of the measurements. They could also be applied for the calibration of engineering wake models, however, it is not always possible to entirely reproduce the physics of the interaction between the wind turbine rotor and the atmospheric boundary layer in wind tunnels.

Full field experiments with remote sensing technology could partly compensate some limitations of wind tunnel experiments. Käsler et al.[9], Trujillo et al.[10] and Bingöl et al.[11] were among the first ones using lidars for wake measurements. In recent studies, Aitken et al.[12] and Iungo[13] applied long-range scanning lidars to study the wake recovery under different atmospheric conditions. Furthermore, Vollmer et al.[14] used offshore dual Doppler lidar measurements [15] to validate the implementation of a modified actuator disk model in LES [16].

Nonetheless, there is a strong demand for full-scale experiments to determine and verify the empirical rules implemented in codes for the estimation of wake losses. The present work aims to investigate an analytical wake model by means of full-scale offshore measurements. Specifically, we chose the model proposed by Bastankhah and Porté-Agel[17], which had been calibrated with wakes from an actuator disc model within an LES wind field. Our study addresses the development of the wake profile and is based on wake measurements taken with a long-range scanning lidar installed on the nacelle of a wind turbine during different atmospheric and operating conditions.

2. Measurements

The research of this paper is based on wind measurements in the wake of an offshore wind turbine performed with a long-range scanning lidar installed on the wind turbine nacelle. In the following we describe the setup of the instrumentation and how the data were prepared for the evaluation of the wake model.

2.1. Experimental setup

The measurement campaign was conducted in the offshore wind farm Nordsee Ost which is located 35 km northwest of the island Heligoland in the German North Sea. This wind farm consists of 48 turbines of type Senvion 6.2M126 (rotor diameter D = 126 m, hub height z_H = 96.5 m and rated power 6.15 MW) and shares its southern border with the wind farm Meerwind Süd/Ost (see Fig. 1a).

A long-range scanning lidar Leosphere WLS200S was deployed for a period of 7 months starting from November 2015 on the nacelle of the wind turbine NO48 (diamond in Fig. 1b). The lidar scanned downstream through the wake emitting 200 ns long laser pulses at 20 kHz, sampling the light back-scattered from the aerosol particles in the atmosphere using a so-called range gate window of about 256 ns. With these settings, the lidar physical range resolution was about 44 m in terms of full-width-half-maximum [18].

Each measurement cycle took about 200 s including five consecutive horizontal and one vertical scans, indicated as PPI (Plan Position Indicator) and RHI (Range Height Indicator) respectively; all scans covered a 30 ° sector. The trajectory patterns were scanned continuously at 1 °/s and the radial wind speed v_R, i.e. the wind speed component parallel to the pointing direction of the laser beam, was simultaneously measured every 15 m in the range between