Validating kinematic wake models in complex terrain

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1. INTRODUCTION

The wind energy sector is currently experiencing a period of unprecedented growth. It is expanding worldwide, powering more of the world with renewable energy. Because of spatial and economic constraints, and because of the limited number of suitable sites, wind turbines are clustered in wind farms. This clustered arrangement may lead to interactions between the wind turbines. The effect of these interactions may have severe implications on the downstream turbines, which are located in the wake of the upstream ones. The turbine wake is characterized by streamwise (axial) velocity deficit, which leads to less power available for the downstream turbines and, it also causes high turbulence levels, which can increase the fatigue loads on the downstream rotor blades. Turbine wake characteristics and development depends on many factors that include the wind conditions, site topology and upstream turbine operating conditions (e.g., Grant et al., 1997; Krogstad and Adaramola, 2012)

In order to reduce the impact of wake losses (especially, on the power output) in a wind farm, wind farm designers rely on wake models and commercial software to optimize the turbine layout. In most cases, there is need for validation of selected wake models to ensure that they are able to reproduce reality in a satisfactory way. However, validating these models requires real data, gathered either in a wind tunnel or in a wind farm. Two main problems with wind tunnel data are scaling effects and wind tunnel wall interference (or blockage effect) of turbine model(s) tested (Adaramola and Krogstad, 2011). The benefit of using measurements from a wind farm is that the wake models are tested against non-controlled real-life conditions. However, the downside of using real-life data is, amongst others, the uncertainty in the data (Politis et al. 2012). In addition, validating wake models with real data is very complicated task and this complexity is more pronounced in complex terrain, which have a big impact on the local wind climate, influencing both wind speed and wind direction.

Several different types of wake models exist, each with its own pros and cons, and with a varying degree of complexity. However, kinematic wake models are commonly used because of their low requirement on computational resources. The simple linearized models have proven to fail in complex terrain, especially terrain with high slope regions (Landberg, 2012). The main objective of this study is to validate three kinematic wake models in complex terrain with the use of computational fluid dynamics (CFD) using data from a wind farm in Norway. The performance of the wake models are assessed by investigating how accurate they predict the measured wake, with regard to the normalized power deficit, the wake width and the energy loss.

2. METHODS

Measurements from Nygårdsfjellet wind farm located in northern Norway have been used in the validation process. The wind farm consists of fourteen 2.3 MW turbines with a rotor diameter of 93 meters and a hub height of 80 meters. Figure 1 shows the layout of Nygårdsfjellet wind farm. Assisted by the commercial WindSim software, which is based on computational fluid dynamics (CFD), the accuracy of the three models were tested in eight single-wake cases. The WindSim software is solving Reynolds Averaged Navier-Stokes equations (Crasto et al., 2012). One-year measurements data from both the turbines and the measurement mast were used for the validation. The simulation was performed with 1.3 million cells and tested for grid independence. A free-stream wind speed interval of 8 to 10 m/s was chosen for the validation procedure. It should be mentioned that, due to the complex terrain, a range of issues complicated the validation procedure. The selected wake models studied in this work are the Jensen model, Larsen model and Ishihara model. These models are briefly presented as follows.

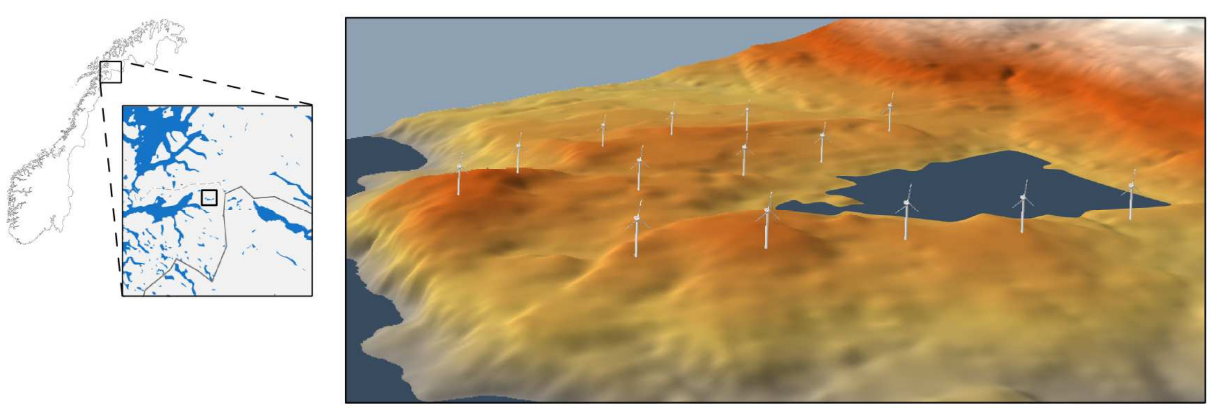

Figure 1: Map of Nygårdsfjellet Wind Farm, with a computer-generated 3D-view of the farm layout looked upon from southeast with the turbines facing east.

2.1 Jensen wake model

Assuming a linear expansion of the wake, this kinematic model developed by N. O. Jensen (Jensen 1983) is one of the simplest wake models. Katic et al., (1987) later refined the model. An important parameter is the wake decay constant *k*, which describes the expansion of the wake and by that also the decay of the wake. The normalized velocity deficit, δV , is given as:

$$\delta V = \frac{1-\sqrt{1-C_T}}{\left(1+\frac{2kx}{D}\right)^2} \tag{1}$$

Where C_T is the thrust coefficient, x is the downstream distance, and D is the rotor diameter.

2.2 Larsen wake model

Based on the Prandtl turbulent boundary layer equations, the "Larsen model" (Larsen, 1988) is more complex than the Jensen model. It assumes incompressible and stationary flow and it neglects the wind shear. The normalized velocity deficit is given as (Larsen, 1988):

$$\delta V = \frac{\left(C_T A x^{-2}\right)^{\frac{1}{3}}}{9}\left\{r^{\frac{3}{2}}\left(3c_1 C_T A x\right)^{\frac{1}{2}} - \left(\frac{35}{2\pi}\right)^{\frac{3}{10}}\left(3c_1^2\right)^{\frac{1}{5}}\right\}^2 \tag{2}$$

where A is the swept area of the turbine, c_1 is the Prandtl mixing length and r is the radial distance. Due to the models dependency of the radial distance, the velocity deficit varies in the cross-section of the wake.

2.3 Ishihara wake model

Ishihara et al., (2004) developed a new analytical wake model ("Ishihara model") that takes the effect of turbulence on wake recovery into account. This is different from the two former models in that the model predicts a constant wake recovery. The normalized velocity deficit is given as:

$$\delta V = \frac{\left(C_T\right)^{\frac{1}{2}}}{32}\left(\frac{1.666}{k_1}\right)^2\left(\frac{x}{D}\right)^{-p}\exp\left(-\frac{r^2}{b^2}\right) \tag{3}$$

Where k_1 (= 0.27) is a constant, and b is the wake width and p is the combined turbulence intensity, which is given as (Ishihara et al., 2004):

$$p = 6.0\left(I_a + I_w\right) \tag{4}$$

In Eq. (4) above, I_a is ambient turbulence and I_w is mechanical generated turbulence.

3. Overview of Results

Figure 2 shows the normalized power predicted by the wake models and the actual measurements for four of the investigated wake cases. The Ishihara model was found to overestimate the normalized power deficit in all cases. The Jensen model also overestimated the peak power deficit, although not to the same extent, while the Larsen model correlated well with the measured data. At the wake centerline, the Larsen model was by far the most accurate, with a mean absolute error of 7 %. The Jensen- and Ishihara model had a mean absolute error of 21 and 34 % respectively. The Larsen model widely overestimated the wake width in all cases, but with an almost constant offset. Both the Jensen- and Ishihara model agreed well with the observed wake width.

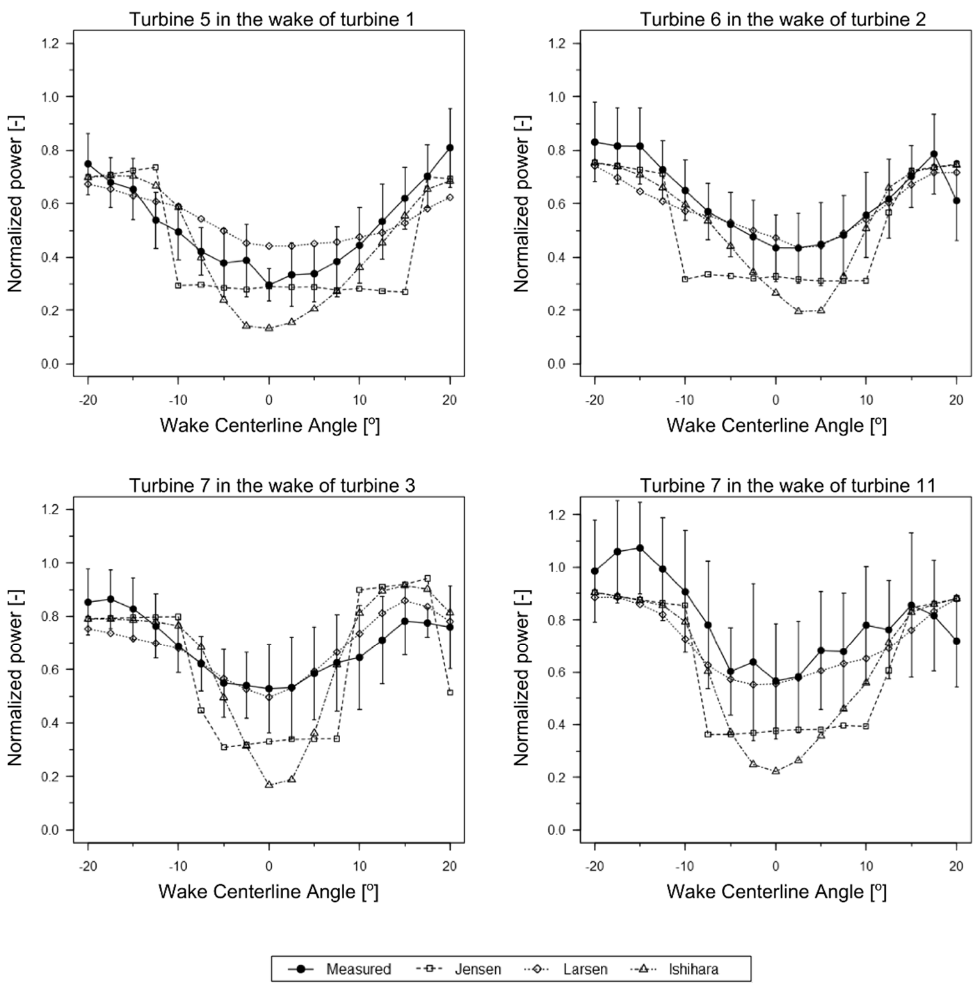

Figure 2.The normalized power for four of the wake cases, ± 20° of the wake centerline, for free-stream wind speeds of 9 ± 1 m/s. The plot shows the measured data and the data from the three wake models. Whiskers represents the standard deviation from the mean.

For the energy loss in the wake, the Larsen model performed best for the three investigated wake cases with a mean absolute error of 29 %, although all the three wake models showed a varying performance with a tendency to underestimate the energy loss. However, after employing a procedure to correct for simulation errors, the Ishihara model performed best with a mean absolute error for 10 %.

4. CONCLUSIONS

Significant differences in the prediction capabilities of the three wake models were found. Overall, findings indicated that the Larsen model performed best, although it constantly overestimated the width of the wake and shows tendencies to underestimate the energy loss in the wake. The Jensen model proved reasonable accurate while the Ishihara model showed clear signs of overestimating the energy loss. However, no clear-cut conclusion can be drawn on which of these wake models is the most accurate, due to both terrain-related issues that complicated the validation procedure and uncertainty in the measurements.

The results and accuracy of wake models are always, at least to some degree, site-dependent. It must be emphasized that validation studies in complex terrain require more than one measuring point, either in the form of multiple masts or LIDAR-measurements. In addition, the need for a fine mesh grid for computational analysis, requiring powerful computers, is necessary in complex terrain. It would also be of interest to employ LIDAR-devices in order to get better measurements of the wind field and the wake itself. The effect of changing different wake model parameters should also be investigated.

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