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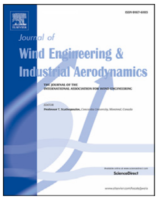

Investigation of wake characteristics of a yawed HAWT and its impacts on the inline downstream wind turbine using unsteady CFD

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ABSTRACT

Unsteady CFD simulations for influences of the yawed wake on the wake trajectory and the downstream wind turbine were carried out using the full rotor model (FRM) of a 5 MW wind turbine, in order to investigate the mechanism of wake deviation. A control strategy based on the yaw angle was adopted to skew the upstream wake trajectory, thereby avoiding the downstream wind turbine and improving the efficiency of whole wind farm power generation. In this paper, the commercial CFD software STAR-CCM+ was used to simulate the wind farm with two tandem wind turbines operating in the neutral atmospheric boundary layer (ABL) condition. The results show that the wind farm's total power increases when the upstream wind turbine applies a positive yaw angle intentionally. According to the analysis of velocity contours, wake centerlines and vortex structures, a counter-rotating blade tip vortex pair is observed to be responsible for the wake deviation effects. It also reveals that the influence of a yawed wake on the downstream wind turbine may be slightly underestimated in some empirical wake model.

1. Introduction

With the rapid growth of requirement for renewable energy in current society, the size of wind turbines and wind farms increase as well to maximize the wind resources with limited available lands. However, a consequent drawback from a large wind farm is the wake interaction among wind turbine arrays. Statistics show that the annual average loss caused by wakes in a large wind farm is approximately 10%–20% of the total production (Gaumond et al., 2014). A wake within low wind speed and increased turbulence intensity reduces the efficiency and lifespan of downstream wind turbine (Kim et al., 2015; Rupert et al., 2013; Vermeer et al., 2003). Therefore, many research efforts have been made to minimize the wake effects and increase the efficiency of whole wind farm. A conventional method is to optimize the wind farm layout based on the local wind rose so that avoiding wind turbines locate in a line when align to the inflow wind as much as possible (Stevens et al., 2013; Chowdhury et al., 2013; Chowdhury et al., 2012). But the effectiveness of this fundamental method is passive and limited when the inflow conditions of wind farm change. Actually, lots of factors affect the local wind conditions and subsequently affect the wind farm power production, such as a complex terrain which can accelerate wind speed and change the wind direction (Castellani et al., 2015; Makridis and Chick, 2013), or a relatively dense wind turbine layout which result in more complicated interactions of multiple wakes (Nikolić et al., 2015; Gaumond et al., 2014). Once the inflow condition changes, wind turbines with the yaw control system automatically align to the wind, which is possible to cause a new wake interaction.

Consequently, recent researches shift to develop an active wake control strategy to minimize the influence of wake interaction. An alternative approach is to alter the yaw angle of a wind turbine intentionally when it is aligned to the inflow wind direction so that the wake trajectory of this yawed wind turbine deviates from the inline downstream wind turbine. As a result, the energy capture of the downstream turbine increases and compensates the power loss of the upstream turbine in a global view. This approach is first proposed and simulated by Jiménez et al. (2010) using an actuator disk model (ADM) and then verified experimentally by Wagenaar et al. (2012) and Andresen (2013). Fleming et al. (2013, 2014) further developed some new strategies to deflect the wake trajectory using an open source CFD tool called Simulator for Offshore Wind Farm Applications (SOWFA) combined with the actuator line model (ALM). But the results (Fleming et al., 2013) and a similar investigation (Weipao et al., 2016) show that the most effective

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method for wake deviation is the one based on yaw angle. Gebraad et al. (2016) built a parametric yawed wake model and constructed an optimal function for the wind farm power production using the game theory. Park and Law (2015) further created a continuous parametric model for the yawed wake.

However, there are some shortages for above researches that most results used the actuator models (ADM or ALM) or a parametric wake model to conduct results. The actuator models simplifying the rotation of blades cannot correctly simulate the flow features near the rotor and may underestimate the sustainability of velocity deficit effects compared with the simulation using the full rotor model (FRM) for a wind turbine (Wilson et al., 2015). As for the parameter wake model, it is more difficult to build an accurate yaw model (Rahimi et al., 2016). Furthermore, above researches did not reveal how the yaw-based wake control strategy works when it deflects the trajectory. Therefore, in order to better understanding of the mechanism of the yaw wake control strategy, an unsteady CFD simulation for two 5 MW wind turbines aligned in a line using the FRM were performed in this paper. The simulations were carried out by a commercial CFD code, STAR-CCM+ 10.02. Taking into consideration the effect of the atmospheric boundary layer (ABL), we focus on investigating the mechanism of wake deviation and its influence on the downstream wind turbine.

2. Simulation description

2.1. Wind turbine configuration

The wind turbine used in present work is the NREL (National Renewable Energy Laboratory) offshore 5 MW reference wind turbine (Butterfield et al., 2009) with detailed specifications in Table 1. The solid modelling is presented in Fig. 1, including the used coordinate system, rotation and yaw directions and azimuthal position. Note that this 5 MW wind turbine is equipped with a 2.5° upwind precone and a 5.0° shaft tilt to increase tower clearance, in order to avoid the blade-tower collision. Compared with the actuator models, the FRM with tilt and cone angles may modify the spanwise flow around blades.

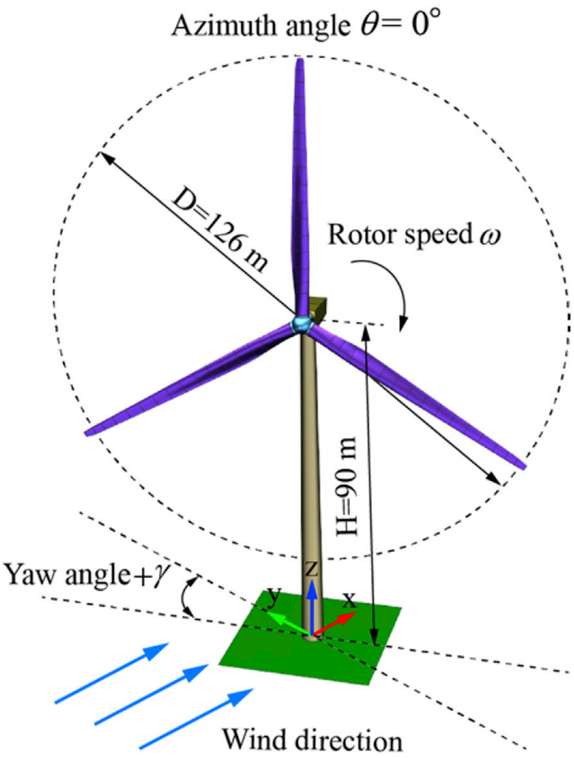

Fig. 1. The solid modelling of wind turbine and the definitions of global coordinate system, positive yaw angle, positive azimuth angle, rotation direction and wind direction.

2.2. Cases setting

The previous study (Fleming et al., 2014) indicates that the total power of two wind turbines varies with the yaw angle and shows a discrepancy between different yaw directions, as illustrated in Fig. 2. Two inline 5 MW wind turbines align in the inflow wind direction and are apart from 7 times rotor diameter (7D = 882 m). The upstream and downstream wind turbines are substituted by WT1 and WT2 respectively. For the purpose of better comparison, three different yaw angles are investigated in present study: the 0°case as a baseline (BSL case), 30° yaw case and −30° yaw case.

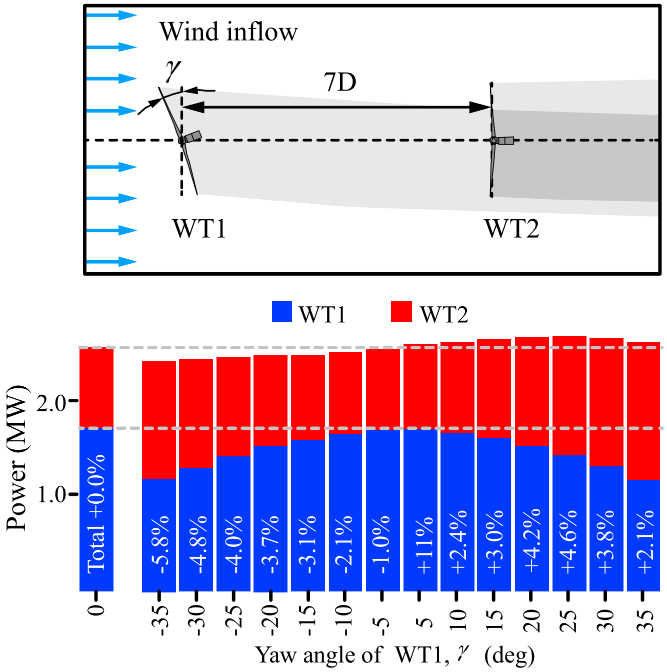

Fig. 2. Total power of two turbines varies with yaw angle.

The power production and lifetime of a downstream turbine are significantly affected by the separation distance between wind turbines. A larger separation offers the wake more spaces to recover its velocity deficit. However, due to some constraints such as the land surface availability or the cost of electrical connections (González et al., 2011, 2013; Son et al., 2014), an oversized separation is inappropriate. The inter-turbine distance in a wind farm needs to be carefully considered to balance the power output efficiency and construction costs. Choi et al. (2013) examined the separation distance from 3D to7D and found that the performance of downstream wind turbine decreases notably when the distance less than 6D. But there is a deficiency in their study that the simulations are performed as the steady state, in which the wake shows a

Table 1
Main specifications of the NREL 5 MW wind turbine.

Specifications	
Rated power, (MW)	5
Rated wind speed, (m/s)	11.4
Rated Rotor Speed, (rpm)	12.1
Rotor Diameter, (m)	126
Hub Diameter, (m)	3
Hub Height, (m)	90
Tower base diameter, (m)	6
Tower top diameter, (m)	3.87
Shaft Tilt, (°)	5.0
Precone, (°)	2.5