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Turbulence effects on the wake flow and power production of a horizontal-axis wind turbine

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ABSTRACT

This study experimentally investigated the effects of ambient turbulence on the wake flows and power production of a horizontal-axis wind turbine. The approaching flows included low-turbulence smooth flow and grid-generated turbulent flow. The profiles of time-averaged velocity, turbulence intensity and Reynolds stress from the intermediate to the far-wake regions were measured and compared for smooth and turbulent flows. Based on the measured data, prediction models for the centerline velocity deficit, turbulence intensity, wake radius and velocity profile were proposed. In addition, the experimental results showed that the power productions in the grid-generated turbulent flows were slightly higher than that in the smooth flow. But the power loss due to the velocity deficit in the wake flow was larger than 50% when the downwind distance was less than 12*D* (*D* is the rotor diameter). An empirical relation between the power production and the downwind distance *x* and lateral distance *y* was proposed.

1. Introduction

It is important to understand the interaction between the atmospheric turbulence and the wake flow of a wind turbine in order to predict its structural load and power performance (Magnusson et al., 1996; Thomsen and Sorensen, 1999). For example, the wake flow of upwind turbine will affect the performance of downwind turbines in wind farms. Numerous studies have used experimental and numerical approaches to investigate the wind turbine wakes. Most studies divided the wake flow into the near-wake and far-wake regions (Vermeer et al., 2003). The near-wake region is considered to extend downwind of the rotor up to 1–3 rotor diameter. This region is characterized by the blade aerodynamics and the evolution of tip vortices (Whale et al., 2000). The far-wake is the region beyond the near-wake, and the influence of the actual rotor on the wake flow is less crucial. However, El Kasmi and Masson (2008) pointed out that the transition from the near-wake to far-wake region is not yet completely understood.

For the far-wake region, several studies (Hogstrom et al., 1988; Crespo and Hernandez, 1996) have found that the velocity distribution in the turbine wake exhibits a self-similar behavior. The velocity deficit U_{fc} ($=U_o - U_c$) at the centerline of the turbine wake (see Fig. 1) can be described by the following equation:

$$\frac{U_{fc}}{U_o} = k\left(\frac{R}{x}\right)^n \tag{1}$$

where U_o is the undisturbed wind velocity at the hub height, U_c is the time-averaged velocity at the centerline of wake flow, R is the rotor radius, x is the downwind distance from the turbine, k and n are constants. The experimental results show that these constants are in the range $1 < k < 3$, and $0.75 < n < 1.25$ (Hogstrom et al., 1988; Vermeer et al., 2003).

The experimental studies on turbine wakes can be categorized into two types: laboratory experiments and field studies of full-scale turbines. For the laboratory studies (Whale et al., 1996; Medici and Alfredsson, 2005) carried out in wind tunnels, the approaching flows were steady, uniform flow with low turbulence intensity.

Medici and Alfredsson (2005) used wind tunnel experiments to study the wake flows of a horizontal-axis wind turbine under various wind directions. They found a low-frequency oscillation appeared in the turbine wake when the tip speed ratio was high. This oscillation was found both with and without free stream turbulence, and can be expressed as a dimensionless Strouhal number:

$$St = \frac{fD}{U_o} \tag{2}$$

where f is the frequency of the oscillation. Their results showed that the Strouhal number of turbine was independent of the free stream velocity or turbulence level. They found that the Strouhal number of the tip vortex decreased as the tip speed ratio increased, and reached a constant value 0.18.

Sicot et al. (2006) used wind tunnel experiment to investigate the effect of turbulence on the power production of a horizontal-

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Nomenclature

A	swept area of rotor (m^2)
b	wake radius (m)
C_T	thrust coefficient (dimensionless)
D	diameter of rotor (m)
C_p	power coefficient (dimensionless)
$I_u=\sigma_u/U_o$	stream-wise turbulence intensity (dimensionless)
I_+	added turbulence intensity (dimensionless)
L_u	longitudinal integral length scale (m)
P_o	power output of wind turbine in undisturbed wind (Watt)
r	distance in the radial direction
R	radius of rotor (m)
St	Strouhal number (dimensionless)
U_c	time-averaged centerline velocity of wake flow (m/s)
$U_{fc}=U_o-U_c$	velocity deficit at the centerline of wake flow (m/s)
U_o	undisturbed wind velocity at the hub height (m/s)
x	downwind distance behind the wind turbine
X_1	downstream distance behind the grid
σ_u	standard deviation of turbulent velocity (m/s)
$-\overline{u'w'}$	Reynolds stress (m^2/s^2)

axis wind turbine. They measured the power and thrust coefficients in three turbulence levels (4.4%, 9.0% and 12%). Their results showed that the influence of turbulence on turbine power output is insignificant. Chamorro and Porte-Agel (2009) used wind tunnel experiments to investigate the wake flow of a small wind-turbine placed in a turbulent boundary layer flow. They found that the wind turbine induced a large enhancement of turbulence intensity in the upper part of the wake. But the turbulence intensity was reduced with respect to the incoming flow in the lower part of the wake.

On the other hand Hogstrom et al. (1988), Elliott and Barnard (1990) and Magnusson and Smedman (1999) analyzed the field studies of turbine wakes conducted in the atmospheric boundary layer flow. But the mean wind speed and turbulence parameters vary with height, which makes it difficult to distinguish the role of ambient turbulence as a factor affecting wake flow and power performance of wind turbine. For example Magnusson and Smedman (1999) studied the turbine wakes by analyzing data collected from a wind farm. They found that the thrust coefficient, C_T, and downwind travel time, t_o, can be used to describe the wake characteristics. The following equation can be used to describe the centerline velocity deficit U_{fc} of turbine wake:

$$\frac{U_{fc}}{U_o}=C_1 \ln\left(\frac{t_o}{t}\right)+C_T \quad (3)$$

where coefficient $C_1=0.4$ was determined by measured data, t is the downwind travel time, and t_o is the travel time of the first single peak at the centerline. Their results also showed that the centerline velocity deficit of a single turbine is larger than that of the combined wake of two turbines aligned with the wind direction, because of the turbulent flow generated by the upwind turbine. Gomez-Elvira et al. (2005) used an explicit algebraic model to simulate the anisotropic characteristics of turbulence in turbine wakes, in particular the shear layer in the near-wake region. Their predictions show good agreement compared with experimental results.

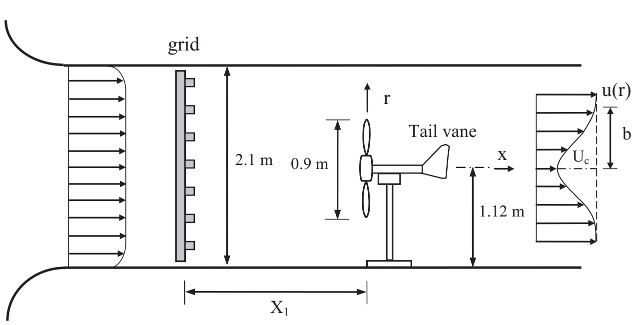

Fig. 1. Schematic diagram of the experimental setup.

Wind turbines in the field usually encounter two different kinds of turbulence: turbulence in the atmospheric boundary layer and the turbulence in the wake flow of other wind turbines, as in the wind farms. The turbulence intensity in the turbine wake I_{wake} can be calculated as (Chamorro and Porte-Agel, 2009):

$$I_{wake}=(I_o^2+I_+^2)^{1/2} \quad (4)$$

where I_o is the turbulence intensity of ambient flow, I_+ is the added turbulence intensity. Several studies (Quarton and Ainslie, 1990; Crespo and Hernandez, 1996; Frandsen and Thogersen, 1999) have proposed models to describe the added turbulence intensity as a function of downwind distance. But these models were limited to turbulence intensity at the hub height or averaged values, did not consider cross-sectional variation of the turbulence intensity (Chamorro and Porte-Agel, 2009).

Chen and Liou (2011) used wind tunnel experiment to investigate the tunnel blockage on the power coefficient of a horizontal-axis wind turbine. Their results demonstrated that the blockage effect is dependent on the rotor tip speed ratio, the blade pitch angle and the tunnel blockage ratio. The blockage correction is less than 5% when the blockage ratio of the swept area to the cross-sectional area of the wind tunnel is 10%. This is in good agreement with the previous studies (Pope and Harper, 1966; Schreck et al., 2007; Hirai et al. 2008) that no blockage correction is necessary for blockage ratio less than 10%.

In view of the above studies, there is a need to elucidate the role of ambient turbulence on the wake characteristics and power production of wind turbines. This study used wind tunnel experiments to investigate the influence of ambient turbulence on the characteristics of the intermediate to the far-wake region and the power performance of a horizontal-axis wind turbine. A lattice grid was installed in the wind tunnel to generate a uniform, homogeneous turbulent flow. The velocity profile, turbulence characteristics and power production, in the absence and presence of the grid, were compared to illustrate the turbulence effects on the turbine wake.

2. Experimental setup

The experiments were carried out in an open-circuit, suction-type wind tunnel. The total length of the wind tunnel was 30 m, and the test section was 18.50 m long, 3.05 m wide and 2.10 m high. A horizontal-axis wind turbine (Rutland 913, Marlec Inc.) was installed in the test section. The rotor diameter was $D=0.90$ m, the height of the hub was 1.12 m, and the diameter of the turbine tower (circular pole) was 0.05 m. The wind turbine has 6 blades, with chord length 0.07 m. The rated power output was 250 W. Fig. 1 is a schematic diagram illustrating the experimental setup. The rotational frequency of turbine was measured by a digital