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Blade number effects in a scaled down wind farm

A.Jensen Newman [a, *], Raúl Bayoán Cal [b], Luciano Castillo [a]

[a] Texas Tech University, Department of Mechanical Engineering, National Wind Resource Center, Box 41021, Lubbock, TX, 79409, USA
[b] Portland State University, Department of Mechanical Engineering, PO Box 751, Portland, OR, 97201, USA

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ABSTRACT

Two 3 × 4 scaled down wind farms were analyzed to understand differences in wind turbine boundary layers when turbines operating at identical power coefficients have two or three blades. Mean streamwise velocities in two bladed turbine near wakes ranged between 10 and 100% larger than those in the three bladed case with large differences just behind the nacelle. In the rotor swept region of far wakes, mean velocity differences between the two arrays were about 10% (max) and became smaller with increasing streamwise direction. Contrary to these findings, regions above and below rotors become less similar deep in the array. Incoming flow to downstream turbines was shown to have greater Reynolds streamwise normal stress for three bladed rotors. Percentage differences ranged between about 30% for the second turbine down to 10% for the fourth turbine. Additionally, there is qualitative evidence that suggests incoming streamwise Reynolds normal stress becomes similar between the two types of turbines, indicating that asymptotically two and three bladed turbines could have similar fatigue loading properties. These results show that use of two bladed turbines would have the most impact when used in a wind farm's first two rows.

1. Introduction

Two common problems facing the wind energy industry are that wind turbines fail earlier than their rated life [6], and that wind turbines do not produce their rated power [9]. These two problems typically stem from the fact that most turbines are operated in the wake of other turbines and their ratings are produced in more idealized conditions. Virtually all work on wind energy recently has sought to address one of these two problems in some way. Studies are generally either wind tunnel experiments, analysis of field data, numerical simulations, modeling or optimization studies.

1.1. *Experimental*

Many wind tunnel experiments with scaled turbines have been carried out in the last few years. Cal et al. [8] conducted Particle Image Velocimetry (PIV) experiments on a 3 × 3 array of 3 bladed turbines in order to compare power output from a turbine to the various terms in the transport equation of mean kinetic energy (MKE). It was found that output from a turbine was of the same order as the flux of MKE into the rotor swept region due to turbulent transport from the Reynolds shear stress. Lebrón et al. [26] also used these data to extend this analysis by considering a cylindrical control volume (i.e. streamtube theory). It was shown that axial flux from the mean streamwise velocity, radial flux due to turbulence and power produced by a turbine are of the same order of magnitude, again indicating the importance of MKE transfer by turbulence. Scaled wind farm experiments were also performed by Corten et al. [14]. Profiles of mean velocity and turbulence intensity were measured and showed that flow inside the wind farm experiences much less streamwise development than flow above the wind farm. Newman et al. [32] used PIV data from a wind tunnel study to quantify the streamwise change in various flow regions above, below and behind the rotors. By doing so, plausibility of two internal boundary layers within the wind turbine boundary layer was demonstrated – one above the rotors and one below. Chamorro et al. [12] examined differences between flow inside staggered and aligned turbine arrays. It was demonstrated that staggered configurations produce 10% more power than aligned configurations, and that turbulence characteristics vary greatly between the two arrangements. Chamorro and Porté-Agel [10] performed wind tunnel experiments with a single turbine to examine the turbulence structure in turbine wakes and study effects of ground roughness on wakes. It was found that turbine

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* Corresponding author.
E-mail address: j.newman@ttu.edu (A.Jensen Newman).

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Nomenclature

List of symbols

U	mean streamwise velocity
V	mean wall normal velocity
$\overline{U}$	mean streamwise velocity averaged over rotor plane
u'	fluctuating streamwise velocity
v'	fluctuating wall normal velocity
ΔU	$= U_{2b}/U_{3b} - 1$
$\Delta u'$	$=\langle u'u' \rangle_{2b}/\langle u'u' \rangle_{3b} - 1$
$\langle \rangle$	time average
u_*	friction velocity $= \sqrt{-\langle u'v' \rangle}$
κ	von Karmen constant = 0.4
x	streamwise coordinate
y	wall normal coordinate
y_0	roughness scale
D	rotor diameter
C_p	power coefficient
λ	tip speed ratio $= \omega D/2/\overline{U}$
N	number of samples
T	rotor torque
ω	rotor rotational frequency

Subscripts

ib	parameter measured with i bladed turbines
unc	uncertainty in quantity
rms	root mean square quantity

Superscripts

n	turbine streamwise position. Number 1 is furthest upstream, 4 is furthest downstream

generated turbulence was still present even 15 rotor diameters (D) downstream. It was also found that wake asymmetry was increased by ground roughness. Hamilton et al. [18,19] used PIV to study the flow field inside staggered and aligned turbine arrays. It was shown that the staggered array has increased efficiency over the aligned configuration. Further, a POD analysis was performed which showed that very few modes are needed to capture the dynamics of the Reynolds shear stress. Additional information about single wind turbine and wind farm wind tunnel experiments was collected by Vermeer et al. [37].

1.2. Field studies

Much useful insight can be gained by examining data from wind turbines operating in the field. Many such measurements have been collected by Barthelmie et al. [2,3,5] which demonstrate significant power losses, wake effects and test the applicability of various models. Dabiri et al. [15,24] have studied the energy entrainment and power optimization in vertical axis wind farms. They demonstrated that vertical axis turbines have a much smaller wake recovery region than horizontal axis turbines and that vertical flux of energy is a significant source of the turbine's power. Also, by considering an optimized layout they showed a potentially achievable increase in power density.

1.3. Numerical simulations

Numerical simulation tools are increasingly being used to study wind energy. A review of computational work on wakes was published by Sanderse et al. [35] and general review of computational aerodynamics of wind energy is provided by Sørensen [36]. Some specific studies include those of Calaf et al. [9] which investigated similar quantities as those looked at by Cal et al. [8] and Lebrón et al. [25] from an experimental point of view. Calaf et al. [9] found results which closely matched those of the experimental studies even though flow in the streamwise direction was forced to be periodic in the streamwise and spanwise directions approximating an “infinite” array. Johnstone and Coleman [21] performed an actuator disk array study to investigate effects of wind turbine arrays on the Ekman spiral. It was found that the spiral becomes more pronounced and that the power output of the array is directly linked to the integral of the ageostrophic wind over the boundary layer depth. Yang et al. [40] used a Large Eddy Simulation (LES) to study effects of turbine spacing. It was shown that increasing the streamwise spacing has a more pronounced impact on farm efficiency than increasing spanwise spacing. A new roughness model to account for the effects of spacing in the different directions was also introduced. Porté-Agel et al. [33] developed a LES simulations using actuator disks as well as actuator lines, and demonstrated that their computed wakes were in good agreement with hot-wire data collected from scaled turbine wind tunnel experiments. A modified version of this suite of simulations with actuator disks which accounted for rotation was then used to investigate flow in staggered and aligned wind farms [39]. It was shown that the staggered case has more lateral wake interaction leading to a more spanwise homogenous wind farm flow and that turbines in the staggered case had greater efficiency with lower fatigue loading.

1.4. Wake models

Wake models are an important tool from the standpoint of wind farm design and optimization. One of the best known is that of Frandsen [16]. Additional wake models have been developed by Frandsen et al. [17] and Barthelmie et al. [4]. Vermeer et al. [37] have compiled a good summary of the theory of wind turbine wakes. The park wake model, originally developed by Jensen [20], and later modified by Katic et al. [23] is one of the most popular analytical wake models used in wind farm modeling. The modified park wake model and the Eddy Viscosity wake model [1], are other standard wake models. Another modeling approach is to describe wind farms as roughness. Lettau [27] and Frandsen [16] put forth some of the earliest studies from this point of view. More recently Frandsen et al. [17] and Calaf et al. [9] have also made contributions to this area. Furthermore, the latter authors also performed a suite of LES of fully developed wind turbine array boundary layers to test these roughness models.

1.5. Optimization

Wind farm optimization in terms of power output and economic factors is also an important area of study. For instance, Meyers & Meneveau [31] used the Calaf et al. [9] roughness models to predict the hub height mean velocity as function of wind farm parameters such as wind turbine spacing. These predictions were then used to optimize total power per unit area or alternatively, total power per unit cost. Results suggest that for a large wind farm, an optimal