PIV MEASUREMENTS OF A SCALED-DOWN WIND FARM SUBJECT TO ATMOSPHERIC BOUNDARY LAYER CONDITIONS

By

José Lebrón-Bosques

A Thesis Submitted to the Graduate

Faculty of Rensselaer Polytechnic Institute

in Partial Fulfillment of the

Requirements for the Degree of

DOCTOR OF PHILOSOPHY

Major Subject: Mechanical Engineering

Approved by the
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Deborah Kaminski, Member

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Assad Oberai, Member

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Jian Sun, Member

Rensselaer Polytechnic Institute
Troy, New York

November 2011
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ABSTRACT

The amount of electricity that wind turbines convert is affected by the wind conditions to which they are subjected. Wind conditions affect their availability and efficiency, that is, how much time they are operating and how much energy they extract during their operation. For example, in highly turbulent conditions, wind turbines have to constantly adjust the pitch angle of the blades to adapt to rapidly changing wind speeds, incurring in a loss in efficiency. This also affects their life span due to fatigue of its components. Moreover, costly repairs as soon as 7 years after installation reduce profit and the availability of wind turbines. Many of these problems can be attributed in part to the lack of accurate, yet simple wind turbine and wind farm design tools.

In order to come up with accurate and simple models, it is important to gain a deep understanding of the flow in which wind turbines operate. This inherently complex flow varies in time and in space, because of the turbulence and shear generated by the atmospheric boundary layer (ABL), terrain topography, thermal stratification and wakes of upstream turbines.

In order to improve the understanding of this flow, two wind tunnel experiments of a scaled-down wind turbine array subject to neutral ABL-like conditions and surface roughness have been carried. The flow within inside of the arrays of wind turbines is measured using Particle Image Velocimetry (PIV). Two analysis are carried out using the PIV data. The two analysis look at the interchange of kinetic energy that occurs between wind turbines and the flow field at two different scales. At the wind turbine level, the streamtube analysis is considered, and, at the wind farm level, the horizontally averaged structure of the wind turbine array is analyzed.

Since the classical wind turbine streamtube has been studied by coupling Bernoulli's equation and the actuator-disk model it has been useful to relate the fluxes of kinetic energy and power extraction. However, the classical analysis neglects turbulence, which can play a crucial role in the recovery of the wake and the

interactions with the turbulent atmospheric boundary layer.

The present study aims at examining the fluxes of kinetic energy on a wind turbine streamtube including the effects of turbulence. For this purpose, acquired PIV data is used to evaluate the most relevant fluxes of kinetic energy on the control volume defined by the streamtube. It is found that, besides the flux due to mean axial velocity, the flux due to the radial shear stress is also of the same order of magnitude as the wind turbine power. It is also found that the sum of smaller fluxes, such as those due to dissipation of mean kinetic energy and axial normal Reynolds stress constitute 33% of the power of the wind turbine. The flux of angular kinetic energy (wake rotation) is also quantified.

The flow inside wind farms is highly three-dimensional, which is attributed to the combination of wind turbine wakes, terrain topography and the atmospheric boundary layer. In this paper, PIV data from wind tunnel experiments on a scaled-down wind turbine array are used for the purpose of horizontally-averaging the flow. A horizontal average of the mean flow two-dimensionalizes the problem in order to apply classic boundary layer theory. The effective roughness scale is estimated from the horizontally-averaged profiles. When the Lettau [1] formula is used to estimate this value, the result is 21% larger than that measured from the data. In addition, a formula derived by Frandsen [2] for the same purpose, with a correction for the pressure gradient, gives a value that is 12% smaller than the one measured. The vertical entrainment of mean kinetic energy into the wind turbine array, which is the dominant mechanism for power extraction in large arrays, is also quantified from the PIV data. It is found that the flux due to the Reynolds shear stress is more than twice of that extracted by the wind turbines. Moreover, it is found that the flux due to dispersive stresses", which arise when the boundary layer equations are horizontally averaged to account for the spatial non-homogeneity of the mean flow, are of the same order as the power extracted by the wind turbines. In conclusion, in this thesis, it is demonstrated the important role that turbulence has on wind energy.