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Wind Tunnel Research, Dynamics, and Scaling for Wind Energy

Majid Bastankhah
DurhamUniversity, Durham

Raul Bayoan Cal
Portland State University, rcal@pdx.edu

Nicholas Hamilton
National Renewable Energy Laboratory, Golden

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Majid Bastankhah, Nicholas Hamilton and Raúl Bayoán Cal

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Majid Bastankhah,[1] Nicholas Hamilton,[2,a)] and Raúl Bayoán Cal[3]

AFFILIATIONS
[1]Durham University, Durham, United Kingdom
[2]National Renewable Energy Laboratory, Golden, Colorado 80401, USA
[3]Portland State University, Portland, Oregon 97201, USA

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[a)]**Author to whom correspondence should be addressed:** nicholas.hamilton@nrel.gov

ABSTRACT

The interaction of wind turbines with turbulent atmospheric boundary layer (ABL) flows represents a complex multi-scale problem that spans several orders of magnitudes of spatial and temporal scales. These scales range from the interactions of large wind farms with the ABL (on the order of tens of kilometers) to the small length scale of the wind turbine blade boundary layer (order of a millimeter). Detailed studies of multi-scale wind energy aerodynamics are timely and vital to maximize the efficiency of current and future wind energy projects, be they onshore, bottom-fixed offshore, or floating offshore. Among different research modalities, wind tunnel experiments have been at the forefront of research efforts in the wind energy community over the last few decades. They provide valuable insight about the aerodynamics of wind turbines and wind farms, which are important in relation to optimized performance of these machines. The major advantage of wind tunnel research is that wind turbines can be experimentally studied under fully controlled and repeatable conditions allowing for systematic research on the wind turbine interactions that extract energy from the incoming atmospheric flow. Detailed experimental data collected in the wind tunnel are also invaluable for validating and calibrating numerical models.

Wind turbines extract power from the wind using aerodynamic forces created on rotor blades. Improving the performance of wind turbine blades has, thus, strong impact on the overall efficiency of wind turbines. In wind tunnel studies, it is important to design and characterize turbine blades that are representative of those used in large-scale utility turbines. To achieve this goal, Hassanzadeh *et al.*[1] designed and manufactured a new 1 m blade equipped with surface pressure measurement sensors to measure unsteady loads at different spanwise and chordwise locations. Pressure measurements were coupled with inflow and wake measurements to characterize the turbine performance and to demonstrate that pressure on the blades correlates with the wake region downstream.

The performance of wind turbine blades degrades due to flow separation, dynamic stall (due to wind shear), and tip-vortex shedding, to name a few causes. Passive and active flow control strategies are rapidly evolving fields of research aiming to address, among others, airfoil load alleviation, reduction of flow-induced vibrations, or airfoil noise generation. Singh *et al.*[2] tested an active slat control and study its impact on load alleviation. They controlled aerodynamic forces on turbine blades by changing the gap between the slat and the main blade, demonstrating that active slat control can be implemented in an open loop control to effectively reduce load fluctuations, especially in the case of low-frequency inflow variations like a wind gust.

Wind turbines are immersed in the atmospheric boundary layer. It is, therefore, evident that power extraction and structural loads on wind turbines are directly affected by ABL properties. ABL conditions also strongly impact the structure and evolution of turbine wakes, which are one of the main sources of power losses in wind farms. Several articles in this collection study the impact of ABL properties on either the performance of the turbine or its wake structure. Abdulrahim *et al.*[3] performed wind tunnel experiments to investigate the effect of incoming flow shear in the atmospheric boundary layer on the wake region following a 12 cm porous disk with radially non-uniform porosity to model the wind turbine. Flow measurements at several downstream locations showed that the turbine wake region becomes asymmetric under the presence of a sheared inflow. They observed that the incoming flow shear deflects the wake center toward the ground, and it also leads to noticeable differences in turbulent kinetic energy distribution between the upper and lower sides of the wake that must be considered if we aim to determine the available kinetic energy for downwind turbines. Apart from mean flow shear, another important feature of ABLs is that they are highly turbulent. Due to the very high Reynolds number of ABLs, they contain a broad range of turbulent motions spanning from a few kilometers to a few millimeters. Gambuzza[4] used an active grid to generate a wide range of turbulent inflows with different levels of turbulent intensity and integral length scale. They found that the turbine power is significantly affected not only by turbulence intensity but also by the inflow turbulence scale. They showed that to realistically replicate conditions in the wind tunnel, energy distribution in various turbulent scales should be matched with those experienced by utility-scale wind turbines in reality.

Most wind tunnel studies are limited to neutrally stratified conditions, and the air is assumed to be dry with no vapor particles. However, we know that the ABL is most likely in conditions other than neutral due to solar heating. Famous pictures of Horns Rev wind farms in which wakes are naturally visualized due to vaper condensation are good examples to remind us that humidity plays an important role in the physics of atmospheric flows. To model the ABL more realistically in the wind tunnel, Obligado *et al.*[5] developed a new experimental setup that consists of a set of humidifiers to generate a stable humidity stratification. They found that the presence of the turbine leads to a lower humidity stratification in the near wake, but the effect is less clear in the far wake due to turbulence mixing.

Rapid growth in wind energy demand drives the need to cluster multiple wind turbines together within a farm to maximize power output. Interaction between turbines causes significant power degradation. Prior studies on wind farm aerodynamics have mainly focused on power losses due to wakes, i.e., the effect of upwind turbines on their downwind counterparts. More recent numerical and experimental studies have, however, shown that downwind turbines may also negatively impact the power generated by upwind turbines. Due to flow blockage of the whole wind farm, the incoming flow may decelerate, which in turn decreases the available kinetic energy, especially for turbines in front rows. In Segalini,[6] wind tunnel results of flow around a turbine array were used to validate a new wind-farm blockage model, developed by linearizing governing flow equations. The model can be coupled with existing wake models to allow for combined modeling of wake and blockage, thereby having a more realistic prediction of wind farm power production.

Wind turbine wake interactions continue to be a salient problem in the wind energy community, affecting performance and structural loads at the blade, wind turbine, and wind plant scales. This collection contains the results of scaled experiments that aim to explore new physics central to the aerodynamic interactions between the atmospheric boundary layer and wind turbines. The collection touches on areas of fluid mechanics, aerodynamics, acoustics, atmospheric physics, and flow control. The contributed research in this "Advances in Wind Plant Controls: Strategies, Implementation, and Validation" Special Topic in the *Journal of Renewable and Sustainable Energy* advances our understanding of turbulent fluid dynamics in wind plants and points toward remaining questions that merit further investigation in the coming years.

We thank the authors for their contributions and also the journal editors who assisted with the publications of the "Advances in Wind Plant Controls: Strategies, Implementation, and Validation" Special Topic.

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Majid Bastankhah: Conceptualization (equal). **Nicholas Hamilton:** Conceptualization (equal). **Raul Bayoan Cal:** Conceptualization (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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