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Experimental study of turbulence intensity influence on wind turbine performance and wake recovery in a low-speed wind tunnel

Miguel Talavera, Fangjun Shu*

Department of Mechanical and Aerospace Engineering, New Mexico State University, Las Cruces, NM, 88003-8001, USA

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ABSTRACT

Regarding the issue of the unmatched Reynolds number for down-scaled wind turbine tests, an experimental study of a single model wind turbine and an array with two turbines was performed under laminar and turbulent inflow conditions. Turbulent inflow was created using an active grid system installed between the contraction and test-section of the wind tunnel; the maximum turbulence intensity can reach 20%. Velocity fields upstream and in the wake of the turbine were measured using a 2D-PIV system. In the experiments with a single turbine, it was found that the power coefficient was strongly dependent on the inflow turbulence intensity, because turbulence influenced the flow separation in the suction side of the wind turbine blade. This was confirmed by PIV results taken under laminar and turbulent inflow conditions. For the wind turbine array case, the efficiency of both turbines was highly related to the turbulence intensity in the inflow. Furthermore, inflow turbulence intensity also influenced the wake recovery. The power coefficient of the wind turbines was similar to design value under controlled inflow turbulence. In conclusion, despite the unmatched Reynolds number, a realistic flow similar to the field can be reached using turbulent inflow created by an active grid system.

1. Introduction

Interest in large wind turbines increased with the oil crisis in the 1970s. Wind energy, as a clean and renewable energy source, is cost competitive even though it requires a large initial investment that does not necessarily pay off quickly. By the 1980s wind farms were built in countrysides all over the world. Wind energy infrastructure and production have been growing rapidly over the last few decades as wind energy has become one of the most profitable sources of renewable energy. Leading users of wind energy include Germany, the United States, Denmark, and Spain. India and China are the up-and-coming users of wind power. Wind energy is expected to play a major role in the future renewable energy portfolio. Despite the widespread use, there is still room for improvement in areas such as turbine efficiency, noise attenuation, and maximized output of wind farms.

These topics have attracted a lot of research in the field. Many of these investigations require experimental data in the field. However, it is very challenging to acquire experimental data from a full scale wind turbine in the field due to lack of controllability. Field tests are also expensive, especially when the turbine is still in the design stage. CFD simulations are challenging as a result of the characteristics of the wind [1] and turbulence modeling. In such situations, down-scaled wind turbine models tested in wind tunnels are usually preferred. However, using down-scaled turbines generates a big problem: an unmatched Reynolds number [2].

As mentioned by Giacomo [3], the use of down-scaled models represents a limitation due to discrepancies with respect to real wind turbine flows. Wind turbines in the field have a Reynolds number in the order of $10^6 - 10^7$. The Reynolds number in wind tunnel tests are usually in the order of $10^4 - 10^5$. This is due to down-scaled models and it creates differences in the boundary layer flows over the suction side of the blades and generates laminar separation on the blades ([2,4]). Boundary layer separation leads to a loss in aerodynamic lift, which results in a decrease in turbine performance [2]. For instance, Alfredsson [5] reported a lower power coefficient for down-scaled wind turbine models.

For wind turbines in array, a wind turbine operating in the wake of another turbine of the same model, the reduction in the maximum power coefficient of the downstream turbine is strongly dependent on the turbulence intensity, distance between the turbines, and the tip speed ratio of the upstream turbine ([6–8]). In

* Corresponding author.
E-mail address: shu@nmsu.edu (F. Shu).

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addition, at a given distance, the amount of area overlap between the upstream and downstream turbine will also affect the performance of the downstream turbine ([9–11]). Also, the minimum C_p of the downstream turbine is obtained when the upstream turbine is operating at its peak efficiency, due to lower kinetic energy in the wake of the upstream turbine [6].

Scientists proposed modifications in the turbulence characteristics of the inflow to address the unmatched Reynolds number issue in wind tunnel testing. To accomplish this, an active grid turbulence generator can be used to make the inflow turbulent [13]. An active grid system was first introduced by Makita and Sassa [14]. It was compounded by several rotatable shafts with surmounted vanes that can be driven via stepper or servo motors. It was able to induce strong, homogeneous, and quasi-isotropic turbulence with a high turbulence intensity in a laboratory wind tunnel. The resultant turbulence had an intensity of more than 30% downstream of the generator. A similar turbulence intensity is observed in field tests [3]. Use of turbulent inflow not only suppresses the flow separation around the blade, but also resembles the flow characteristics in the real atmospheric boundary layer ([13,15]), which is very close to the Earth's surface, and is directly affected by the frictional and viscous effects of the ground. Also, the mechanical and electrical performances of wind turbines are highly affected by wind characteristics. Environmental parameters have a massive effect on the generated power [16]. In this manner, Adaramola, and Krogstad [6] discovered the importance of the turbulent mixing mechanism in the wake of the upstream turbine in order to increase the rate of wake recovery. So an atmospheric boundary layer was generated in a laboratory wind tunnel by regulating parameters of a turbulent shear flow generator [17] using the active grid system.

In this study, the influence of turbulence intensity on model wind turbine performance and wake recovery was investigated. Velocity fields upstream, downstream and around the turbine blades were measured using 2D PIV. Turbine power efficiency and velocity recovery in the wake were quantitatively measured and discussed.

2. Methods

2.1. Wind tunnel

The experiments were performed in a low-speed wind tunnel, which has an intake section of 4 *m* by 4 *m*, and a testing section of 1.2 *m* (W) x 1.2 *m* (H) x 14.6 *m* (L); speeds in the test section can reach up to 35 m/s (see Fig. 1). Wind turbines were installed immediately downstream of the contraction for laminar flow cases, where the turbulence intensity was less than 0.5%. For turbulent flow cases, an active grid system was used to generate turbulent inflow and wind turbines were installed in the last test section, which was approximately 13 *m* from the contraction.

2.2. Active grid system

The active grid system (AGS), first introduced by Makita and Sassa [14], is capable of generating turbulent flow with high turbulence intensity in relatively small facilities. The AGS was installed in the wind tunnel between the contraction and the test section. It had 6 vertical and 6 horizontal shafts mounted with flaps as shown in Fig. 2; all the shafts were driven by programmable stepper motors. A Matlab program was developed to control the motors.

To generate uniform turbulent flow, the motors were programmed to vibrate the flaps while they were parallel to the flow. In order to create the desired turbulent boundary layer velocity profile, the first three horizontal shafts were set at 18°, 36°, and 54°, respectively, as shown in Fig. 3 from a side view perpendicular to the flow. The vertical shafts were at 90°, so that the flaps were parallel to the flow. Hence, the flow was slower at the bottom giving a specific boundary layer at the testing section. The detailed velocity profile is presented in 2.4.2.

Fig. 1. The low speed wind tunnel used in the study.

2.3. Wind turbine set up

The down-scaled two-blade wind turbine model used in this experiment was designed using blade element momentum (BEM) theory; it had a diameter of 203 *mm* (8 inches). Each turbine was mounted on a 480 DD motor of 8.4 volts utilized as a generator. The experiments were conducted using either a single turbine or two turbines aligned with the flow, as shown in Fig. 4. The purpose for using two turbines was to investigate the wake recovery and its influence on the performance of the downstream turbine.

For the laminar inflow case, wind turbines were installed immediately downstream the wind tunnel contraction with the active grid system removed. In this section, the flow was uniform and had a low turbulence intensity. On the other hand, for the turbulent cases, the wind turbines were installed in the last section of the wind tunnel, approximately 13 *m* away from the AGS to allow big flow structures generated by the AGS to dissipate. A turbulent velocity profile was generated to mimic the atmospheric boundary layer.

2.4. Incoming flow conditions

2.4.1. Uniform incoming flow

For the laminar inflow case, a uniform velocity of 15 m/s was used, and the turbulence intensity was less than 0.5%. For turbulent inflow cases, two turbulence intensities, 8% and 3%, were used. The incoming velocity was 13 m/s, and 13.8 m/s for the high and low turbulence intensity inflow cases, respectively.

2.4.2. Velocity profile to mimic atmospheric boundary layer

It is important to know how a turbine interacts with the atmospheric boundary layer (ABL) ([13,15]). Mechanical and electrical performances of wind turbines are highly affected by wind characteristics [16]. These effects need to be considered during the analysis of wind turbine performance. According to Anderson [18], the ABL thickness at sea level is around 300 *m*; that means all the wind turbines are influenced by the ABL. By programming the AGS, a turbulent boundary layer flow was generated to mimic the ABL. In