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Wake Characteristics of Closely Spaced Vertical Axis Wind Turbines

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Abstract

In order to optimally arrange the vertical axis wind turbines in the wind farm, it is necessary to understand the wake distribution behind the turbines. In this study, wind tunnel tests were conducted on two adjacent Darrieus rotors with straight blades to evaluate the wake expansion, wind speed reduction and wind speed distribution. The wind speed was measured using a hot-wire anemometer from just behind the rotor to a distance of 12 times the rotor diameter. The dual turbines rotating at the arrangements of clockwise and counter-clockwise revealed different wake distributions. On the side where the rotating direction of the rotor coincided with the inflow wind, the wind velocity accelerated and the wind speed decelerated on the opposite side. As the distance from the wind turbine increases, the wind speed recovery through the space between the two rotors was greatly affected by the direction of rotation of the two rotors, and the wind speed varied by up to 11% at distance of 12 times the rotor diameter

Introduction

The recent research suggested the use of counter-rotating vertical axis wind turbines to achieve higher power output per unit land area than existing wind farms consisting of horizontal axis wind turbines [1]. It is necessary to know the characteristics of the wake distribution behind the turbines in order to optimally arrange the vertical axis wind turbines in the wind farm.

However, the existing researches on the wake characteristics of a single vertical axis wind turbine have been focused mainly on the near wake and there is little research on the far wake field. Moreover there is very limited study on the far wake field of closely spaced two vertical turbines.

This study conducted wind tunnel tests of two adjacent Darrieus rotors with straight blades to evaluate the wake expansion and wind speed distribution. The wind speeds were measured from just behind the rotor to a distance of 12 times the rotor diameter. The test results for dual Darrieus rotors in counter-rotating arrangements are presented in this study.

Experimental setup

The wake measurement was carried out at a small wind tunnel in the KOCED Wind Tunnel Center of Chonbuk National University, Korea. The size of the test section was 1.0 m wide, 1.5 m high, and 5 m long. The wind turbine used in the study was a Darrieus type with two straight blade of NACA0012 airfoil. The blade length and chord length were 0.9 m and 0.03 m respectively, and the rotor diameter (D) was 0.15 m. The blades were made using basswood, and the surface was coated with FRP. The level of the surface roughness was an arithmetic average of 0.49 μm, a root mean squared value of 0.66 μm.

The center distance between the two rotors was 1.9D, and the pure separation distance was 0.9D. Figure 1 shows dual Darrieus rotors installed in the wind tunnel. In order to measure the wake distribution, the wind speeds were measured by a DANTEC hot-wire anemometer and associate hotwire probe at 2D ~ 12D in the along-wind direction and at every 1~2cm in across-wind direction. A schematic view of the wake measurement is shown in Figure 2.

Figure 1. Closely spaced dual Darrieus rotors in wind tunnel.

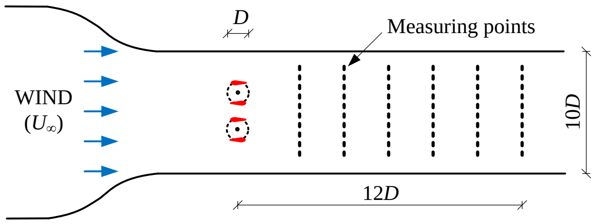

Figure 2. Measuring points behind Darrieus rotors.

In order to investigate the effect of rotational direction of each rotor on wake distribution, the rotation direction of the dual rotors was divided into an arrangement of clockwise (CW) rotor and counter-clockwise (CCW) rotor, and an arrangement of counter-clockwise (CCW) rotor and clockwise (CW) rotor. Figure 3 shows rotational direction of dual rotors.

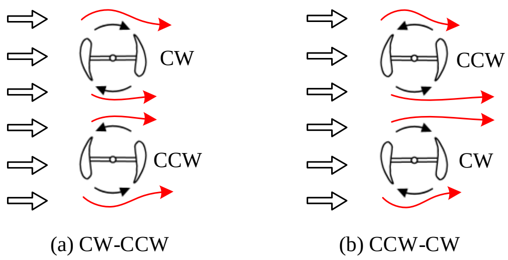

Figure 3. Arrangement of rotation in dual rotors.

Wind speed was measured for 40 seconds with sampling rate of 8 kHz at each measurement. During the experiment, the inlet wind speed was 4 m/s and the tip speed ratio (TSR) was controlled to 1.1. An AC motor and an inverter were used to control the TSR of the blades. The AC motor used was a Siemens three-phase four-pole motor with a rated output of 0.37 kW and a rated speed of 1670 rpm. The inverter used to control the rpm of the motor is LS Industrial Systems, with a maximum output frequency of 400 Hz.

Test requirements

There are some requirements for wind tunnel test of a vertical axis wind turbine in order to properly simulate the far wake flow field behind the rotor. The first requirement is the blockage effect by the blockage If the blockage ratio is higher than 5%, the experimental results such as the wind pressure and the drag coefficient should be appropriately corrected [2]. However, it is known that the effect of the blockage ratio is not significant in the case of the wake field measurement behind the turbine, and there are many studies performed without correction of the blockage effect at the blockage ratio of 10% or more [3-5]. In the present study, the blockage ratio at the time of experiment was 20%. It was confirmed from the preliminary test that the blockage effect on the wake field was not significantly up to 12*D* even if the blockage ratio was 20%.

The second requirement is that the tip speed ratio (TSR) of the model rotor in the wind tunnel should match the prototype rotor. The rotor wakes depend on the output varying with the TSR, so the TSR must be properly controlled. In this study, the TSR was adjusted by using a motor which is widely used for wind tunnel test of wind turbine and easy to control the rotating speed.

The third requirement is the influence of the Reynolds number. It is almost impossible to satisfy both TSR and Reynolds number simultaneously in scaled model test of a rotating wind turbine. To avoid the influence of Reynolds number, the Reynolds number should be 4×10^4 or more for the horizontal axis wind turbine and 2×10^5 or more for the vertical axis wind turbine [6, 7]. It is known, however, that the effect of Reynolds number is not significant in the case of far wake, and the basic wake characteristics can be reproduced even in a low Reynolds number range [8]. In this study, Reynolds number is not taken into account because main goal of this study is to investigate the far wake field behind the vertical axis wind turbine.

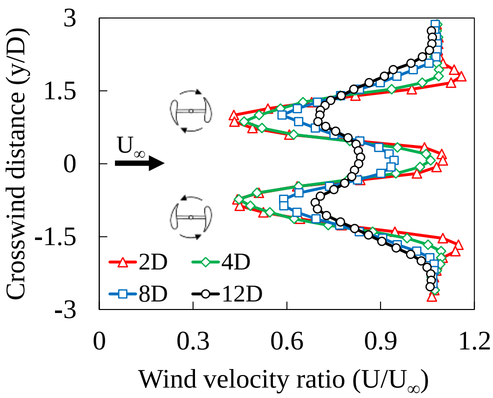

Figure 4. Wake distribution of CW-CCW array

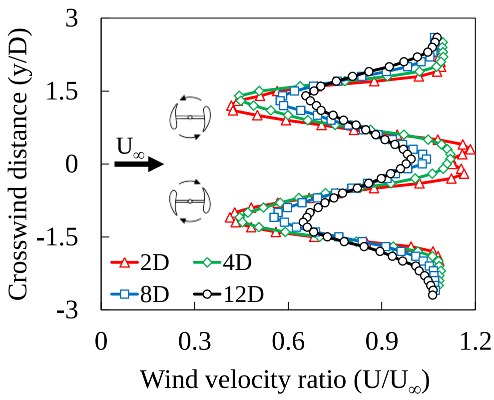

Figure 5. Wake distribution of CCW-CW array

Test results

Figures 4 and 5 show the change of wind speeds at the distance of 2*D* ~ 12*D* according to the blade rotation directions. The results show that the CW-CCW array has a wind speed increase at both outside of the wind turbine, and the CCW-CW array has a wind speed increase in the space between the two rotors. As the blade rotates, the point at which the wind speed becomes minimum moves in the same direction as the rotation of rotor. In the CW-CCW array, the points where the minimum wind speeds of the two rotor wakes occur are close to each other. Conversely, in the CCW-CW array, the minimum wind speed origin is farther away.

This movement of the minimum wind velocity origin is related to the energy taken by the blade [9]. The wake distribution of the horizontal axis wind turbine is symmetrical. However, in the case of a vertical axis wind turbine, the wake distribution becomes asymmetric because the energy level varies depending on the direction of rotation of the blade. The minimum wind velocity origin moves to a lower pressure side.

Looking at the recovery trend of the wake wind speed according to the distance, the wind speed which was reduced at the rotor centers rapidly recovered in the case of the CW-CCW arrangement. However, the wind speed in the space between the two rotors was decreased sharply to supply energy to the reduced wind speed at the rotor centers.

On the other hand, in the case of the CCW-CW arrangement, the increased wind speed at the two rotors gap does not reduce much even though the distance is as much as 12*D*. This is because the arrangement of the CW-CCW appears to overlap the two wake regions more closely than the CCW-CW arrangement. Due to this differently formed wakes, the wind speed at the rotors gap behind the 12*D* differs up to 1.1 times. Assuming that a third wind turbine is installed at this location, the power output may vary by about 1.3 times.

Wake model

In the previous research[2], we have proposed a wake model for single Darrieus turbine which was basically similar to that of a horizontal axis wind turbine. We added a new parameter representing the drift of the minimum velocity location which was distinct characteristics of a vertical axis wind turbine. The wake model is:

$$\frac{U}{U_\infty} = 1 - 2a \cdot \left\{\frac{D_o}{D(x)}\right\}^2 \cdot \exp\left[-\left\{\frac{y-c}{D(x)}\right\}^2\right], \qquad (1)$$

$$c = \pm\frac{1}{3}\left(\frac{1}{\sqrt{x}} \mp D_o\right) \qquad (2)$$

where the sign(±) in the equation is dependent on rotational direction of rotor, a is induction factor, c is minimum velocity location, D_0 is rotor diameter, $D(x)$ is wake diameter at downstream distance of x.

Figure 6 compares the streamwise mean wind velocities at 12*D*. deficit of present model. The superposed wake models for two turbines with CCW-CW arrangement good agreement with measured data. The CW-CCW arrangement, however, reveals a little difference on minimum velocity locations and needs further improvement on prediction.

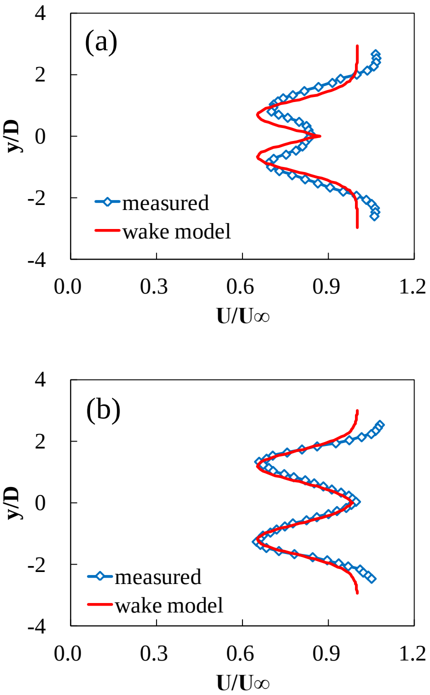

Figure 6. Streamwise mean wind velocities at 12*D*, (a) CW-CCW array, (b) CCW-CW array.

Conclusions

In this study, wind tunnel tests were carried out to investigate the wakes of two adjacent Darrieus wind turbines that were rotating in different directions. The results from the wind tunnel test are as follows.

The rotation direction of the rotor affected the wind speeds on both sides, so that wind speed at one side was accelerated and wind speed at the other side decelerated. In the CW-CCW arrangement, the points where the minimum wind speeds of the two rotor wakes occur are close to each other. Conversely, in the CCW-CW arrangement, the minimum wind speed origin is farther away.

The recovery rate of the wind speed at far wake field is different depending on the rotational direction of the two wind turbines. The wind speed at 12*D* from the two rotors gap is 1.1 times different according to the direction of rotation, that is 1.3 times the difference in power generation.

Acknowledgments

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