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Optimization of Wake Effect Performance in a Downstream Turbine by using Wind Tunnel Test

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Abstract:- **In this project we have discussed about the optimization of wake effect and then characteristics of the three blade horizontal axis of wind turbine and performance of downstream turbine by wind tunnel test. This project also involves the single turbine model for the flow characteristic performance of parameters like velocity, turbulence intensities and correlation in a wake flow effect. The performance of the upstream turbine of the blades flow of a small pitch angle provides a disturbance to create a blade turned faster, and drastic change in the velocity of blade and then turbulence occurred in wake in the wind turbine. Then gradually decrease the wake velocity of turbine swept area on the free stream. This also describes the performance of the stream wise velocity and tangential velocity in a blade swept area.**

Keywords: Wind turbines; wind tunnel test; turbine wake; tandem arrangement

INTRODUCTION

In the modern era, environmental pollution, climate change, as well as the energy crisis are big challenges for the whole of mankind. Wind energy, as a renewable and clean energy, is one of the most profitable energy sources and has attracted great attention. There are basically two types of wind turbines according to their hub direction, namely, the horizontal axis wind turbine (HAWT) and the vertical axis wind turbine (VAWT). The three-blade horizontal axis turbine, which has a relatively large Efficiency has been widely implemented and the principle of its performance is briefly introduced here. There have been numerous wind tunnel tests, numerical simulations, and field experiments related to research on HAWTs and many remarkable achievements have been made. The power coefficient is a key index to describe turbine performance and is closely related to the tip speed ratio (TSR). The TSR represents the rotational speed of the turbine to the wind velocity and is a selected by the aerodynamic shape of the blades, such as the pitch angle. Many researchers have been trying to optimize the shape of the blade and improve the power coefficient of the HAWT in diherent ways. Through wind tunnel tests, Xie et al. [1] studied the performance of a pitch-regulated three-blade wind turbine model with a small size. Apart from the ability to adjust the power coefficient, the innovative blade design was also capable of adjusting the blade operating TSR in the range between2.94 and 6.45 for the unfolded blade and between 1.07 and 2.55 for the 40_ folded angle. Xie et al. investigated the aerodynamic performance of an umbrella-type wind turbine using experimental and theoretical methods and showed that the power coefficient and TSR of this turbine drop significantly when its blades are folded. Sutrisno et al. [3] tested a small-scale wind turbine with a designed TSR of 3.65 and considered two types of blades, with one having a backward swept at the tip and the other a helicopter-head tip. The tested results were further used to estimate the power generation of a real-scale turbine. With computational fluid dynamics (CFD) simulations, Lee et al. [4] studied the aerodynamic performance of a wind turbine with two diherent blades. One blade design was based on the blade element momentum theory and its maximum power coefficient was 0.469 at a TSR of 5.61. The other design was a non-twisted type with an unchanged chord length, and the maximum power coefficient of this type was 0.3 at TSR 5.08. Lin et al. [5] studied a 150 kW wind turbine and found the maximum power coefficient at 0.42, which was achieved with a blade at a 5_ pitch angle and a TSR of 3.6. With field experiments, Li et al. [6] studied a 30 kW wind turbine with a rotor diameter of 10.0 m and a hub height of 13.4 m, and the maximum power coefficient was 0.35 at a TSR of 7.5. Howard and Guala [7] studied the effects of turbulent flow conditions on the performance of a 2.5 MW wind turbine with an optimal TSR of approximately 8.5, and the blockage effect on the mean wind speed profile of the incoming flow was found.Although wind tunnel testing can provide an e effective and reliable way to predict the performance of a wind turbine, reduced-scale turbine models have to be used due to the limited sizes of wind tunnels. There is inevitably a large difference in the Reynolds numbers between the real-sized turbine the model turbine. This Reynolds number effect may affect the scaling of experimental results from the model scale to the full scale. The Reynolds number is usually expressed as Re = Uc/_, where U is the incident wind velocity; c is the chord length of the airfoil; and _ is the kinematic viscosity. Chamorro et al. [8] suggested that stronger Reynolds number dependence occurs in the near wake region, while the main flow statistics become independent of Reynolds number starting from Re _ 9.3 _ 104. Park et al. [9] showed that the power coeffcient of a wind turbine is very sensitive to the change in the model scale, but the thrust coefficient is not. Ge et al. [10] selected six airfoils and found they all exhibited better performance at a higher Reynolds number. Li et al. [11] studied the Reynolds number effect on four thick airfoils at two different wind tunnels and found that increasing Re makes the separation point move towards the leading edge. Tarhan and Yilmaz [12] investigated the Reynolds number effect on the lift, drag, and lift/drag coefficients of 14 small wind turbine airfoils with both wind tunnel tests and numerical simulations. Meanwhile, the Reynolds number effect on VAWTs has also received much attention [13,14]. With the increase in rotor size, the difference in the Reynolds numbers between the real-sized turbine and the model turbine becomes more obvious and its effect could not be omitted. Using multiple turbines in a wind field is a major trend used to generate more energy due to the limited land resources. However, downstream turbines usually have to operate in the wake of upstream turbines, which leads to tremendous power losses. The wake effect loss must be taken into account when calculating the effciency of large offshore wind farms [15], and the average power loss due to the wind turbine wake is on the order of 10% to 20% of the total power output [16]. Meanwhile, small changes in wind direction, i.e., yaw angle, have strong impacts on the total power output [17]. Therefore, it is of great importance to understand the wake characteristics of a turbine and the wake effect on the performance of a downstream turbine to arrange them reasonably and effciently. Apparently, the wake characteristics of an upstream turbine are closely related to its own TSR, and so is the performance of a downstream turbine. Medici and Alfredsson [18] suggested that the near wakes produced by wind turbines with similar TSRs show very similar characteristics. Hu et al. [19] investigated the evolution of vortices in the near wake of a turbine and the structure of the turbulent flow field. The TSR of the turbine model varied from 0 to 4.5, and the largest velocity deficit in the wake flow was observed at a TSR of approximately 3. Zhang et al. [20] showed that the near-wake region is characterized by high three-dimensionality, turbulence heterogeneity, and strong flow rotation. Bastankhah and Porté-Agel [21] predicted the wake characteristics of a yawed wind turbine, and the velocity measurement indicated that the wake velocity deficit becomes smaller and the wake deflection increases with the increase in yaw angle. Qian et al. [22] also showed that yaw misalignment has significant influence on the performance of a turbine as well as its wake. Chu and Chiang [23] studied the turbulent e_ect on wake characteristics and power production of a wind turbine and found that the power loss could be larger than 50%. On the other hand, researchers have been trying to improve the performance of the downstream turbine. Adaramola and Krogstad [24] found that the loss in the maximum power coefficient of the downstream turbine is mainly between 20% and 45%. When the upstream turbine is operated in a yawed inflow condition, the total power output from two wind turbines in a tandem arrangement is increased by about 12%. Considering the effect of a yaw angle as well, Bastankhah and Porté-Agel [25] studied the interaction of a turbulent boundary layer with a wind turbine operating under different TSRs. Talavera and Shu [26] found that the maximum power coeffcient of a single turbine could significantly increase from 0.125 under laminar inflow to 0.345 under turbulent inflow. A similar phenomenon was observed for two turbines in a tandem arrangement. While the aforementioned studies have improved our understanding of the performance and wake characteristics of three-blade horizontal axis turbines, the mechanism of how a turbine's wake affects the performance of another turbine has not yet been fully explored. In addition to a reduction of the wind velocities in the wake, other possible turbulence effects influencing the performance of the downstream turbine are seldom studied. For instance, the possibly altered spatial correlation of wind speeds in the turbine wake would affect the instantaneously available kinetic energy for the downstream turbine. Hence, in this study, wind tunnel tests were carried out to determine the

wake characteristics of a three-blade HAWT. In particular, wind velocities, turbulence intensities, and spatial correlation coefficients in the wake with

different TSRs were measured and analyzed. The instantaneous flow field behind the turbine was obtained by particle image velocity(PIV). The second part of the study focused on the effects of these characteristics on the performance of another downstream turbine.

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PERFORMANCE OF A SINGLE HAWT

Wind is the movement of air mass. After passing through a wind turbine, the velocity will drop,

and the power captured by the turbine can be expressed as RPM of the wind turbine. For a variable-pitch wind turbine,

starting and parking can be easily achieved by adjusting the pitch angle, and it can also be used to stabilize the output power above the rated wind speed. The effect of the root the pitch angle β on the TSR λ was first studied. The incoming flow was

kept unchanged with U□ at 4.4 m/s and a turbulence intensity of approximately 5% at the height of hub axis. Different root pitch angles ranging between 0° and 45° were considered, and the RPM of the wind turbine was measured by a digital laser tachometer. The results are listed in Table 1. When β is small, the blade causes less disturbance to the incoming flow, thus it rotates faster. With an increase in β, the flow resistance to the blade increases so λ decreases, leading to a reduction of

the power coefficient. However, the relationship between λ and β is not a linear trend, and λ is more sensitive to the change of β when it is between 7.5° and 22.5° (see Figure 2

TABLE 1. RELATIONSHIP BETWEEN THE TIP SPEED RATION (TSR) AND ROOT PITCH ANGLE.

Items	**Root Pitch Angle β (°)**					
	0	**7.5**	**15**	**22.5**	**30**	**45**
RPM	880	810	585	420	316	220

WAKE CHARACTERISTICS OF A SINGLE HAWT

In this section, three root-pitch angles were used in the wind tunnel tests, i.e., 7.5_, 15_, and 22.5_ It the

Among which the turbine performance changed significantly. The wind velocity of the incoming flow (U0) was fixed at 4.4 m/s, and the corresponding TSRs of the wind turbine with the three root-pitch angles were 3.5, 2.5, and 1.8, respectively. It should be noted that the Reynolds number for the turbines in the experiments was 8.8 _ 103, which was much smaller than those in most commercial wind tunnel installations Even though the Reynolds number effect should be significant, as discussed in Section 1, the primary wake characteristics behind the turbine may be reproduced with less inaccuracy at relatively low Reynolds numbers.

WAKE RECOVERY

Three-component flow velocities in the wake of the turbine were measured by a cobra probe, which could resolve the turbulent part of the velocity signals. For each measurement position, the velocity was measured at a rate of 2000 Hz for a sampling time of 60 s. The characteristic time scale of the flow past the turbine (D/U0) was about 0.08 s, so that the sampling time was sufficient to obtain statistically stable measurements. The measurement was taken within a region from 0.5 D to 12 D in the horizontal direction (x-direction, as shown in Figure 1) and from the tunnel floor level to 1.5 D in the vertical direction (z-direction). The stream wise velocity averaged over the sampling time at a point in the turbine wake was named Ux. Along the hub axis, the change in the ratio of U x to U0 is shown in T is the measurement time; N is the total number of a sample at a certain measurement position; and U x(t) is the instantaneous stream wise velocity at a certain time. velocity signal, from which the stream wise turbulence intensity I□ was calculated by Equation (3), shown in . α After passing through the turbine, the velocity of incoming flow decreased but the turbulence intensity increased. A small pitch angle produced smaller disturbances to the flow, but the blade turned faster, leading to larger changes in the wind velocities and turbulence intensities in the wake due to the more frequent disturbances of the wind turbine. As a result, the decreasing range of wake velocities and the increasing range of turbulence intensities were both the largest for the TSR of _ = 3.5, which was obtained with _ = 7.5_. At this situation, the wind velocity in the wake decreased first and then recovered slowly with the increase in X/D. The turbulence intensity showed an increasing trend when X/D was less than 4, and then it decreased. It is important to note that even when the downstream distance increased to X/D = 12, the wake velocity U x/U0 only recovered to 0.83 and the turbulence intensity was still obviously larger than that of the incoming flow. At the TSRs of 2.5 and 1.8, the variations of the wind velocity and the turbulence intensity with X/D show monotonically increasing and decreasing trends, respectively. The rotation of the blades became slower with the increase in _ to 15_ and 22.5_. Therefore, the turbine absorbed less energy from winds and exerted smaller effects on its wake. Wind velocities and turbulence intensities in the wake were less affected, and they recovered faster as well, as compared to the case for _ = 7.5_. At the position of X/D = 12, the wind velocity was slightly smaller than that of the incoming flow and the turbulence intensity was slightly larger. In the transverse vertical (y-z) plane, the wake effect generated by the wind turbine within its swept area is obvious. The wake effect on the wind velocity was the greatest around the hub axis, while the wake effect on the turbulent intensity was obvious near the blade tip, especially for the upper side. Both the effects decreased progressively when going outwards. With the increase in X/D, the decreasing range of the wind velocity and the increasing range of the turbulent intensity became small, but the flow field affected by the wind turbine became broader due to the growth of the wake width. Compared with the region above the hub axis, the wake below the turbine hub had smaller velocities with larger turbulent intensity due to the presence of the ground. The mean flow field of the turbine wake on the central x-z plane (y = 0) through the turbine hub was also measured by PIV. Considering the fact that the measurement area of the PIV camera was only 390 mm in length and 255 mm in height, the root pitch angle was set as 45_ because the wake of the turbine with this lower TSR could recover faster. The results are shown in the PIV measurement was made at four measurement areas and the measurement data were combined to obtain the flow field in an investigation region covering an axial distance from 0D to 1.8D along X direction and a vertical distance from □0.7D to 0.6D along z-direction. It shows the contour map of U x/U0 and Figure 4b shows the contour map of Ix. Compared to the results with larger TSRs (see the wake fields of the turbine with the smaller TSR show similar features in that the U x/U0 decreases behind the turbine hub and is accompanied by increased Ix but with a shorter distance for wake recovery. In the contour lines indicate that the largest wake velocity deficit originated from the turbine nacelle and the region of velocity deficit extended farthest around the However, the recovery rate became smaller as the wake recovered and the velocity increased. In the region below the hub axis, the velocity deficit was more significant due to the ground roughness and the disruption of the supporting pole. In Ix was relatively large behind the turbine hub but it recovered quite fast. In addition, large turbulence intensities were also observed ongoing nearer to the ground surface. Very large values of Ix were found in a region behind the supporting pole, but there appeared to be some PIV measurement error due to the poor lighting problem.

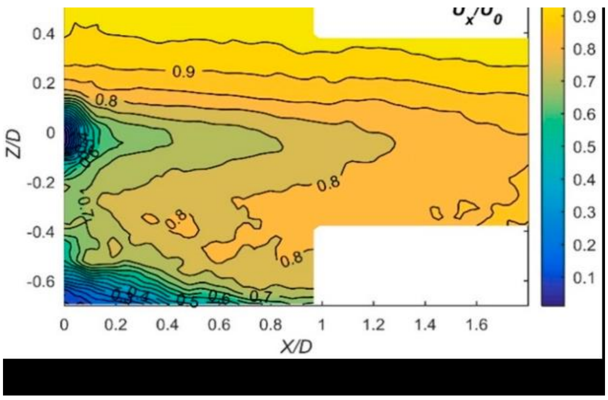

FIG: WAKE FIELDS OF THE TURBINE WITH A SMALLER TSR: STREAM WISE VELOCITY RATIO

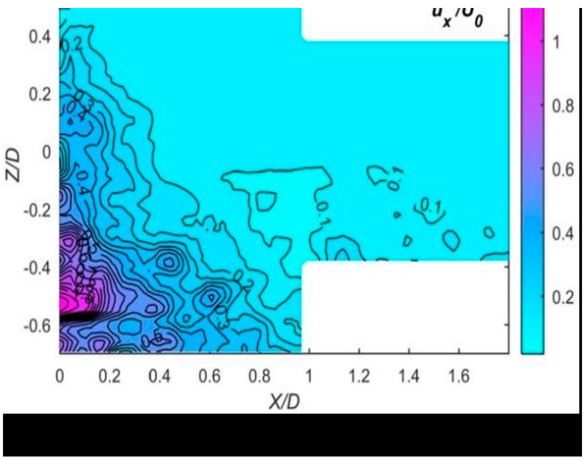

FIG: WAKE FIELDS OF THE TURBINE WITH A SMALLER TSR: STREAM WISE TURBULENCE INTENSITY

WAKE CORRELATION

One focus of this paper was to understand the change in spatial correlation of the fluctuating wind speeds in the turbine wake and whether this would a_ect the performance of the downstream turbine. For this purpose, two cobra probes were used for measuring the wind velocities simultaneously at two positions in the wake. One was placed at a fixed position, that is, the reference position p, and the other was moved along y- or z-direction, that is, the measurement position m. The sampling time was also set to 60 s with a sampling frequency of 2000 Hz. Two sets of correlation measurements were made, with the reference position was placed at a position downstream of the hub axis or the blade tip, as shown in the correlation coefficient with respect to the two positions was calculated by: where _ ranging from □1 to 1 is the correlation coefficient between time histories of the two fluctuating wind velocities at positions m and p; _m and _p are the standard deviations of the two histories; and Co v(m, p) is their co-variance during the sampling time of 60 s.

where ρ ranging from −1 to 1 is the correlation coefficient between time histories of the two fluctuating wind velocities at positions m and p; σ□ and σ□ are the standard deviations of the two histories; and $Cov(m,\ p)$ is their co-variance during the sampling time of 60 s.

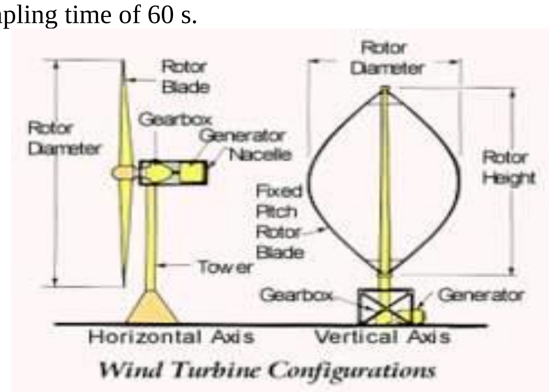

FIG: WIND TUNNEL

Taking the hub axis as the reference position first (y = 0, z = 0), it shows the correlation coefficient between the stream wise velocity at the wake centre and the stream wise velocity at a radial position along y- and z-directions, respectively. Measurements were made at different values of X/D ranging from 0 to 10. It can be seen from Figure 6 that the variations of _ along the two directions show similar trends. The turbine captures energy from the incoming flow and disturbs it, changing the spatial correlation of velocity fluctuations in the wake flow. The correlation coefficient at X/D = 0 reflects the characteristics of undisturbed incoming flow and this baseline curve is shown in all parts of the central zone of the blade swept area, the correlation coefficient decreases largely from the free field value at X/D = 0. This may be due to the impedance of the turbine nacelle to the wind flow. The decreased spatial velocity correlation recovered at slightly different rates among the different TSRs, especially when X was not larger than 4D. The faster the rotation, the more the decreased correlation coefficient recovers, and this may be caused by the hub vortex rotating with the turbine and increasing the velocity correlation. With the increase in Z/D, the correlation coefficients of the three cases were close to one another, and the effect from the turbine rotation speed reversed when Z/D was higher than a critical value marked as the reverse point . This means that at a large radial separation, a faster turbine rotational speed causes a larger decrease in the correlation coefficient. This may be attributed to the stronger impedance of the turbine blades at higher rotational speeds. This critical radial separation to the hub axis moves outwards with the increase in X. More concretely, the separation was observed at Z/D = 0.23 when X was equal to 2D while Z/D = 0.60 when X increased to 8D. The correlation characteristics were still affected to some degrees at X/D = 10. However, it is expected that at a sufficiently far downstream distance from the wind turbine, the wake effect will eventually die down and the correlation coefficients will return to those of the undisturbed incoming flow. In addition, a faster turbine rotational speed leads to stronger tip vortices with more correlated characteristics, but these vortices would diffuse outwards and have less influence on the inner zone of the blade swept area.

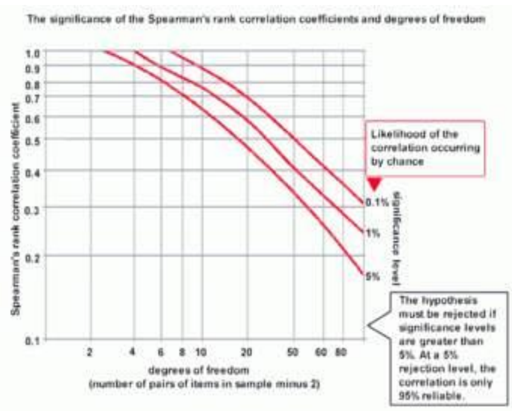

FIG: CORRELATION FOR HUB AXIS IN X DIRECTION

It location downstream of the blade tip (Y = □0.5D, Z = 0, see Figure 5), while the other position was placed at different locations along the same horizontal line from one side to the other side of the blade tip. Measurements were made at different values of X/D ranging from 0 to 4 within which the changes in wake characteristics were more significant. As shown in Figure 8, the correlation curves in all cases dropped almost monotonically with the increasing separation between the two points. In the turbine wake, the correlation coefficients became lower than that in the free stream flow, especially at small separation distances. Near the turbine (X/D = 1), it was observed that the faster the turbine rotation, the smaller the correlation coefficient became, as explained above. With the increase in X/D, this phenomenon gradually disappears. Among the three cases, the decreasing range of the correlation coefficient was the maximum for _ = 3.5, while the recovery for this case was also the fastest. In addition, at the other side of the reference position, small negative correlation coefficients may occur (e.g., X = 3, 4D and Y = 0.1~0.5D). The negative correlation implies that wind velocity fluctuations at the two positions were out of phase, and this may be due to the three-blade geometry and the strong tip vortex when the turbine rotational speed was large enough.

WAKE EFFECTS ON A DOWNSTREAM HAWT

After understanding the performance and the wake characteristics of a single HAWT, two
HAWTs in a tandem arrangement (see Figure 1b) were taken as examples to study how the wake of
a turbine affects the performance of another. The two HAWTs had the same parameters, as shown in Section 2.1. The location of the upstream turbine was fixed at $x = 0$, while the downstream turbine
was located at different downstream locations so as to achieve varying separation distance L. Their root pitch angles were named □ανδ □, respectively. Three root pitch angles, i.e., 7.5°, 15°, and 22.5°, were used in the wind tunnel tests _down was first set equal to _up. Compared with the output power of a single turbine with the same pitch angle, the percentage change in power generation DP of both the two turbines are shown in
(see solid points connected by dashed lines). Due to the aerodynamic interference between the two turbines in tandem arrangement, their output powers both decreased when compared with a single isolated turbine, especially for the downstream turbine. The aerodynamic interference became weaker with the increase in L/D, so the output powers recovered gradually. No matter how fast the downstream turbine rotates, the effect on the performance of the upstream one is limited, for its output power loss is very small and can almost be ignored when L/D is larger than 2. For the downstream turbine, however, the output power may drop a lot as it is located in the wake of the upstream one. Apparently, this power loss largely depends on _up. The faster the rotational speed of the upstream turbine is, the smaller the output power of the downstream turbine becomes. For _up = 7.5_, the output power loss of the downstream turbine exceeded 60% when L/D was 1 or 2, and was still up to about 20% even when L/D increased to 12. With the increasing _up, the rotational speed of the upstream turbine decreased, so its wake had less adverse effects on the downstream turbine’s performance. For _up = 22.5_, the range of the output power loss of the downstream turbine decreased to about 10% and remained stable within the range of L/D from 1 to 10. _down was then changed to the other two on β. The faster the rotational speed of the upstream turbine is, the smaller the output power of the downstream turbine becomes. For β□□ = 7.5°, the output power loss of the downstream turbine exceeded 60% when L/D was 1 or 2, and was still up to about 20% even when L/D increased to 12. With the increasing β□□, the rotational speed of the upstream turbine decreased, so its wake had less adverse effects on

the downstream turbine's performance. For β = 22.5°, the range of the output power loss of the downstream turbine decreased to about 10% and remained stable within the range of L/D from 1 to 10. β was then changed to the other two values not equal to β. The resulting changes in ΔP for these two cases are also shown in Figure 9 in the form of an "error" bar.

Once β was fixed, ΔP of the downstream turbine at a given location fluctuated within a small range with the change in its own pitch angle, i.e.β.

In summary, the downstream turbine's performance was mainly determined by the wake characteristics of the upstream one, which were associated with its pitch angle, while adjusting the pitch angle of the downstream wind turbine itself could not help much to mitigate the loss in power generation.

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CONCLUSION

In this study, the wake characteristics of a three-blade horizontal axis wind turbine model at different TSRs were measured and analyzed. The effect of the turbine wake on the performance of a downstream turbine was also studied using wind tunnel tests. The main conclusions of this study are summarized as follows:

(1) At a fixed velocity of incoming flow, the rotational speed of the wind turbine decreased with the increase in blade pitch angle, especially when the pitch angle was between 7.5_ and 22.5_. This led to a reduction of the power coefficient. With the increase in velocity of incoming flow, the rotational speed of the wind turbine increased stably but the power coefficient first increased to a peak value and then decreased again.

(2) After passing through the wind turbine, the velocity of incoming flow decreased but the turbulence intensity increased significantly. These wake effects were strong within the blade swept area and decreased progressively from the hub center to the blade tip. A small pitch angle provided smaller disturbance to the flow, but the blades turned faster, leading to larger changes in the wind velocity and turbulence intensity due to the more frequent passage of the turbine blades. Compared with the region above the hub axis, the wake characteristics below the hub axis were more difficult to recover due to the presence of the ground surface and disruption of the flow from the supporting pole.

(3) The turbine captured energy from the incoming flow and disturbed it, changing the correlation of the wake flow. Around the hub axis, the wake correlation decreased significantly from the free stream case, but this effect could be slightly weakened by the rotation of the turbine. The faster the rotational speed of the turbine was, the more this decreased correlation coefficient recovered. Overall, the decreased correlation within the blade swept area gradually recovered to the free stream values increased at increasing downstream locations. Moreover, an anti-correlated region can be observed at the two lateral sides of the turbine blade swept area.

(4) Due to the aerodynamic interference between the two turbines in the tandem arrangement, their output powers both decreased when compared with a single isolated turbine, especially for the downstream one. The interference became weaker with the increase in their separation distance, so the output powers recovered gradually. As the performance of the downstream turbine was mainly determined by the wake of the upstream one, the output power of the downstream turbine decreased with the increase in rotational speed of the upstream turbine, but was less related to its own pitch angle. In the wake of the upstream turbine, the reduced mean wind velocity was the most dominant factor in determining the loss of power generation of the downstream
turbine. Although higher turbulence intensities make the rotational speed of the turbine less stable, the effect was limited. The wake correlation was another important factor governing the performance of the downstream turbine. The decrease in the correlation of the stream wise velocity within the blade swept area was accompanied with the increased correlation of the tangential velocity, which may be favorable to the downstream turbine performance.

(5) This paper mainly focused on the wake characteristics of the wind turbine whose performance was evaluated based on its power generation only, while the changes in thrust force and power quality should be further investigated. Meanwhile, the Reynolds number in the present wind tunnel experiments was much smaller than those in most commercial wind turbine installations. Although previous studies have shown that the primary wake characteristics behind a turbine can be reproduced at relatively low Reynolds numbers, the Reynolds number effect on the results should be be further studied by numerical simulations or field experiments.

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