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Muyiwa S Adaramola
Norwegian University of Life Sciences (NMBU)

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Experimental investigation of wake effects on wind turbine performance

M.S. Adaramola, P.-Å. Krogstad*

Norwegian University of Science and Technology, N-7491 Trondheim, Norway

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ABSTRACT

The wake interference effect on the performance of a downstream wind turbine was investigated experimentally. Two similar model turbines with the same rotor diameter were used. The effects on the performance of the downstream turbine of the distance of separation between the turbines and the amount of power extracted from the upstream turbine were studied. The effects of these parameters on the total power output from the turbines were also estimated. The reduction in the maximum power coefficient of the downstream turbine is strongly dependent on the distance between the turbines and the operating condition of the upstream turbine. Depending on the distance of separation and blade pitch angle, the loss in power from the downstream turbine varies from about 20 to 46% compared to the power output from an unobstructed single turbine operating at its designed conditions. By operating the upstream turbine slightly outside this optimum setting or yawing the upstream turbine, the power output from the downstream turbine was significantly improved. This study shows that the total power output could be increased by installing an upstream turbine which extracts less power than the following turbines. By operating the upstream turbine in yawed condition, the gain in total power output from the two turbines could be increased by about 12%.

1. Introduction

In a wind farm, space and economic constraints make it impossible to locate turbines sufficiently far apart to prevent interactions between them. The effect of these interactions may have severe implications on the downstream turbines which are located in the wake of the upstream ones. The turbine wake is characterized by streamwise (axial) velocity deficit, which leads to less power available for the downstream turbines. It also causes high turbulence levels which can give rise to high fatigue loads. Depending on the distance between the turbines and the arrangement pattern in a wind farm, the power losses due to wake effects can be up to 23% (see e.g. Barthelmie et al. [1], Dahlberg [2], Beyer et al. [3]) compared to a farm consisting of unobstructed turbines. However, these losses can be significantly higher for the first turbine immediately downstream of the most upstream turbine that is exposed to the undisturbed freestream conditions (see e.g. Barthelmie et al. [1], Dahlberg [2]). Similar effect is experienced on the subsequent downstream turbines but the effect decreases slowly downstream (Dahlberg [2], Beyer et al. [3]). The increase in fatigue loads on the downstream turbine due to wake interference effects can be up to 80% (Sanderse [4]) and this will drastically shorten the life span of the rotor blades.

Turbine wake properties and development depends on many factors which include the wind conditions, site topology and upstream turbine operating conditions (see e.g. Hattori et al. [5], Medici and Alfredsson [6], Adaramola and Krogstad [7], Grant et al. [8]).

Røkenes and Krogstad [9] studied the effect of topology on the wind field. Unlike many previous studies where the mountain is shaped according to simple mathematical expressions, Røkenes and Krogstad designed their model from existing sites which included interacting mountains and deep valleys. They concluded that the interaction with a mountain may increase the wind velocity up to a factor 2 and make the profile more uniform with height, while at the same time reduce the turbulence level. However, the flow quality was very dependent on mountain shape and flow direction.

The terrain effect on the turbine output from a single and two in-line turbines was modelled by Meada et al. [10] by means of variable very coarse surface roughness and large scale grids across the test section inlet. They concluded that the power output is not too sensitive to the actual wind profile. However, when the turbulence intensity in the incoming velocity profile becomes high, the output from the first turbine drops. But the extra diffusion generated makes the wake recover faster, so the output from the second turbine is increased.

* Corresponding author. Tel.: +47 73 59 37 10; fax: +47 73 59 34 91.
E-mail address: per.a.krogstad@ntnu.no (P.-Å. Krogstad).

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Thus, the performance of any turbine operating within the wake of another turbine depends on these parameters as well as the distance between them. In 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 (e.g. Kotb and Soliman [11], Medici and Alfredsson [6]). Currently, a lot of effort has been put into developing numerical models to predict the turbine wake velocity field and to estimate power losses from a wind farm. Some of these studies involve field measurements and are site specific (e.g. Barthelmie et al. [1], Dahlberg [2], Barthelmie et al. [12]).

However, some of the numerical models being developed require detailed experimental data under both variable condition (field) and controlled condition (wind tunnel) to validate them. Despite the practical importance of this flow, the experimental database is in many ways incomplete and scarce (Hattori et al. [5], Barthelmie et al. [12], Vermeer et al. [13]). Detailed experimental information on the performance of a turbine under the influence of wake interference that can be used for prediction verification is quite difficult to find in the open literature. To get sufficiently detailed data wind tunnel studies of the interaction between two turbines are preferred.

Dahlberg and Medici [14] modelled the effect that yawing the upstream turbine effects has on the wind farm power output. They also studied the reduction in power due to the shading effect from the upstream turbine. By traversing one turbine across the wake of another which was operating at various yaw angles, they found that the power output from the downstream turbine was very sensitive to position. For a non-yawed upstream turbine the power reduction was roughly Gaussian with respect to the spanwise distance with a maximum loss of about 80% at a streamwise turbine separation of 3 diameters. The output from the downstream turbine was almost doubled (maximum loss of about 60%) when the upstream turbine was yawed by $\pm 30^{\circ}$. As the wake develops downstream, it widens and the velocity distribution across the wake changes. This affects also the interaction between the turbines. Interestingly, the measurements of Dahlberg and Medici at 9 diameters show that the lowest output from the downstream turbine is no longer when it is located directly behind the non-yawed upstream turbine, but when it is located in the wake of an upstream turbine which is slightly yawed (about 10°).

The effect of reducing the axial induction factor of the most upstream turbine on the total power output from the wind farm has been studied by e.g. Steinbuch et al. [15], Schepers and van der Pijl [16] and Johnson and Thomas [17] (The reduction can be accomplished by changing the blade pitch angle or the tip speed ratio.) Around the peak performance the sensitivity of the power output to the blade pitch angle is lower than the sensitivity of the thrust force. They therefore found that a small change in pitch angle reduces the velocity deficit in the wake so much that the gain in output from a downstream turbine may be higher than the loss in production from the first turbine, thereby increasing the total output.

When computing the wake development, it is essential to predict the initial behaviour correctly, as this influences the entire wake characteristics. This is a time-consuming task, since it requires a fully 3D calculation. However, it is possible to take advantage of the links between the thrust force, the axial induction factor and the pressure drop across the rotor disc. Schepers and van der Pijl [16] devised a fast method to predict the entire wake development where a database for the streamwise pressure development was generated for a number of induction factors (or thrust coefficients). Using this as a look-up table the pressure field is prescribed and a fast parabolic marching method can be used to compute the wake.

In existing wind farms, for example, where it is impossible to change the distance between turbines, it is likely that the overall wind farm efficiency can be improved by strategical control of the power extraction of the individual turbines. This control operation can be achieved by changing the pitch angle, the tip speed ratio (variable speed rotor) as well as the yaw angle of the upstream turbines. These changes can significantly affect the performance of the upstream turbines and hence, their wake properties and therefore, the performance of the turbines further downstream.

This study presents a wind tunnel study of the performance characteristics of a model wind turbine operating in the wake of another turbine operating at various conditions. The effects on the performance of the downstream turbine due to the distance of separation between the turbines and the amount of power extracted from the upstream turbine were studied. This information might be useful for validation of computational studies, and also provide a better understanding of the overall flow structure, helping proper planning and designing of wind farms.

2. Experimental set-up

2.1. Wind tunnel and model turbines

The experiments were performed in the large low-speed, closed-return wind tunnel of Department of Energy and Process Engineering at The Norwegian University of Science and Technology, Trondheim. The tunnel has a test section of 2 m (height) $\times$ 2.7 m (width) $\times$ 12.0 m (length) and equipped with a 6-component force balance (Carl Schenck AG). The accuracy of the force balance is better than 0.5% when operating the turbine at design condition and the total error in the thrust force is always less than 2%. The force balance can be rotated a full 360° with respect to the tunnel axis. The test section height is adjustable to account for wall boundary layer growth and may be increased to 2.3 m. The roof of the test section was carefully adjusted for zero streamwise pressure gradient. Hence, the tests were performed under uniform flow conditions. The air flow is driven by a 220-kW fan that can provide freestream velocities up to $U_{\infty} = 30$ m/s within the test section. The test section is also equipped with a four-axis computer controlled traversing system which enables automated flow measurements at any position. The traversing system is controlled using LabVIEW software. The data was acquired to a PC fitted with a National Instruments NI-cDAQ-9172 16-bit data acquisition board.

For this study, two model turbines with 3-bladed upwind rotors and the same rotor diameter of 900 mm were used. The rotor blade chord length distribution and twist were designed using a standard blade element momentum method. Details of the blade geometry are given in Krogstad and Karlsen [22]. The hub diameter is 90 mm and its height above the ground plane is 820 mm. Both model turbines were fully operational and the power extracted from the wind could be measured directly using torque sensors mounted on the shafts and optical speed-of-rotation measurement devices also fitted to the rotor shaft. The experimental set-up is shown schematically in Fig. 1.

2.2. Scaling and blockage issues

Two problems with wind tunnel tests of a turbine model are scaling effects and wind tunnel wall interference (or blockage effect). Despite these shortcomings, wind tunnel tests are still preferred to field tests where the incoming flow is much more difficult to describe in sufficient detail and simulations are very time-consuming as a result of the characteristics of the wind (De Vries [18]). Full scale tests are therefore much more expensive to carry out and it is rarely possible to get all the information needed

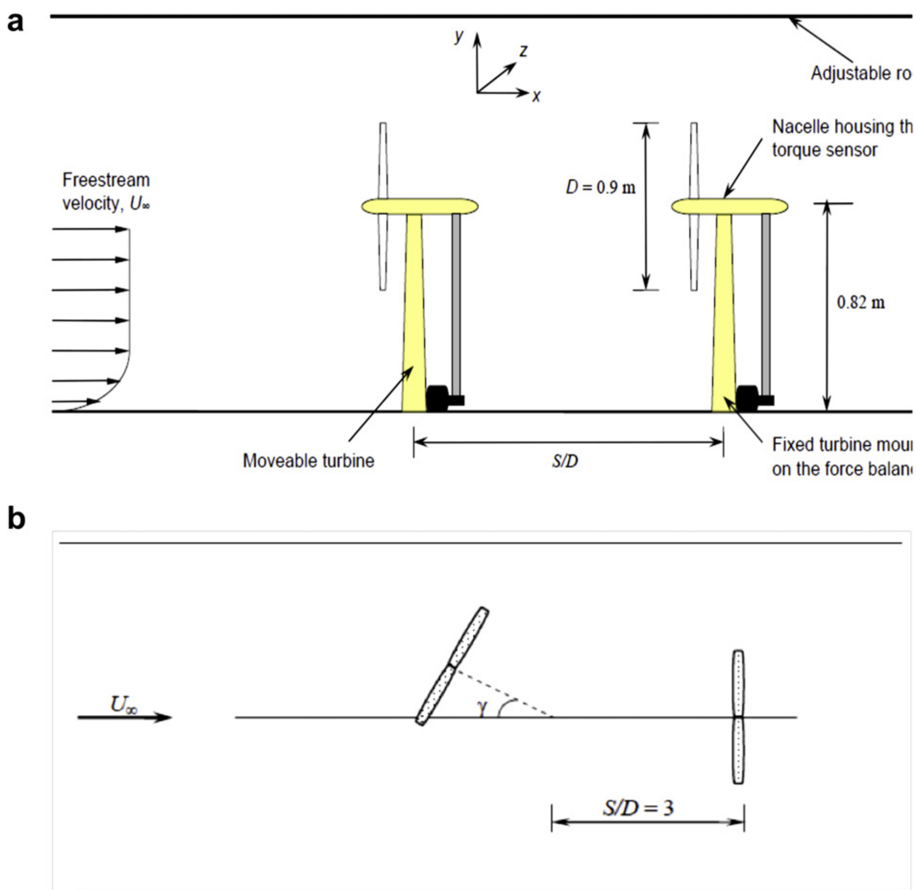

Fig. 1. Sketch of the experimental layout for: (a) turbines in tandem arrangement and (b) top view with the upstream turbine in yawed condition.

to act as a well defined test case for CFD. These problems with field tests are likely to be even more pronounced in floating offshore wind turbine field tests, where the wave induced motion adds to the complexity. Therefore, wind tunnel tests of scaled models are essential because of the controlled test conditions that may be generated (Vermeer et al. [13], De Vries [18]). In addition, changes in variables that influence the performance of the wind turbine and its wake can easily be adjusted and controlled.

For a realistic simulation of the full-scale condition to be obtained both the tip speed ratio and Reynolds number ideally ought to be the same for the full scale and the wind-tunnel turbines. The tip speed ratio condition can easily be met, while Reynolds number criteria are impossible to achieve in model scale studies. For this study the Reynolds number based on the tip speed and chord length is $Re = 1.2 \times 10^5$ at the design tip speed ratio. This Re is low when compared to that of a full-scale wind turbine which is typically in the range of 0.7×10^6 to 10×10^6 (Wilson [19]). A suggested minimum Reynolds number required for reliable comparison of the model test results with full scale data is of the order of $Re = 3 \times 10^5$ (De Vries [18]). However, as a test case for numerical analysis, lower Re is acceptable if the characteristics of the airfoil used for the model are known (Grant et al. [8] Vermeer et al. [13], Haans et al. [20]). The purpose of the present tests was not to model the performance of a particular full scale turbine, but to provide data at controlled operating conditions to be used to predictions by high resolution CFD and blade element momentum method. We therefore do not consider Reynolds number effects to be important as long as the simulations are performed at the model scale Re.

The two models used for this study have the same rotor diameter and thus, the same blockage ratio of about 11.8%, defined as the rotor swept area divided by the wind tunnel cross-sectional area. This is close to the suggested upper limit of about 10% suggested in order to avoid wind tunnel wall interference on the measurements (De Vries [18]). The blockage effect can be neglected if the wake can expand freely (Fuglsang and Bak [21]). Using the WAsP wake model Barthelmie et al. [12] suggested that the wake diameter expands as $D_W = D + 2kS$ (where D_W is the wake diameter, D = rotor diameter, S = downstream distance from the turbine and k is a wake decay coefficient, with values between 0.04 and 0.05). The wake diameter at $S = 9D$ (maximum distance considered in this study) is estimated to be 1.9D which is less than the equivalent diameter of the wind tunnel test section (≈2.8D). Some blockage effects will still exist. The tower to rotor height ratio is the same as a typical full-scale turbine, so the interference from the ground should be roughly as found for a full-scale turbine. Sideways the tunnel walls represent symmetry planes, so the interference here is not very different from an infinite array of turbines with a separation of 3D. The main concern therefore relates to the blockage from the roof which is located only 1.3D above the hub centre. In the mapping of the wake development presented in Adaramola and Krogstad [7] it was observed that the wake was not entirely circular, with a vertical growth rate near the top that was about 85% of the rate in the horizontal direction. Unfortunately no method is available to correct for this asymmetry.

2.3. Instrumentation and procedures

The freestream reference velocity was measured using a Pitot-static pressure probe which was mounted on a stand upstream of, and slightly to the side, of the turbine. The rotor speed of the model turbines were controlled separately and set by MICROMASTER 440 frequency inverters which were connected to 0.37 kW AC electric motors. The downstream model turbine was mounted on the six-component force balance, which allowed the thrust force of the turbine to be measured.

In order to study the wake effect on the downstream turbine, three different scenarios were considered. The effect of distance of separation (S/D, where S is the separation distance between the two model turbines) on the performance of the downstream turbine was investigated with the upstream turbine operating at its design tip speed ratio ($\lambda = \omega R/U_\infty$ where ω is the speed of rotation, R is the rotor radius and U_∞ is the freestream velocity). The downstream turbine performance measurements were taken at $S/D = 3$, 6 and 9 with blade pitch angle set at $\beta = -2$, 0 and 2°, respectively. With the downstream turbine located at $S/D = 3$, its performance was also investigated with the upstream turbine operating at two additional tip speed ratios that correspond to a tip speed ratio close to where the deep stall region starts (denoted as *low* in the plots) and at λ mid-way between the optimum and run-away point (denoted as *high* in the figures). The selected low and high tip speed ratios were set at about ±42% from the optimum λ, respectively. For these values of λ the power extracted by the upstream turbine was $C_p = 0.25$ for the low λ and $C_p = 0.35$ for the high setting.

In addition, at $S/D = 3$, the downstream turbine performance was investigated when the upstream turbine was operating at a number of yawed conditions. The upstream turbine yaw angle (γ) was varied from 0 to 40° and the turbine was rotated around a vertical axis close to the rotor plane in order to always keep the rotor as close as possible to the tunnel centre line. When the turbine is yawed, the blockage effect based on the projected cross-section of the rotor will be reduced, but due to the offset of the wake towards to the yaw direction as it develops downstream, possible interference on the expansion of the wake from the wall only affects the outer part on the side which is furthest away from the centre line and therefore giving the smallest effect on the downstream turbine. From our previous studies on wake development (see e.g. Adaramola and Krogstad [7]), the shift of the wake was found to be less than 0.2D for the range of operating conditions and streamwise distances used in the present study. Since the wake expansion increases with downstream distance from the turbine, the wall effects are most significant at larger distances and in order to reduce this effect, a separation of $S/D = 3$ between the turbines was chosen for the yaw experiments. The experimental arrangement for this set-up is shown in Fig. 1(b).

For each case, the power coefficient $C_p = 8E/\pi\rho U_\infty^3 D^2$ and thrust coefficient $C_T = 8T/\pi\rho U_\infty^2 D^2$ of the downstream turbine were estimated using the reference velocity seen by the upstream turbine, which was the same for all tests at about $U_\infty \approx 11.5$ m/s (E and T are the extracted power and the thrust force on the turbine, respectively, and ρ is the air density). The maximum power coefficient of the downstream turbine relative to that of the unobstructed single turbine was estimated using the optimum power coefficient of the upstream turbine. This was $C_p \approx 0.45$, measured at the design condition ($\lambda = 6$).

3. Results and discussion

3.1. Single model turbine

The effect of blade pitch angle setting on the performance of an unobstructed single model turbine is presented in Fig. 2. Both the power and thrust coefficients are strongly dependent on the pitch angle, but the graphs show that C_T is the most sensitive. For each pitch angle C_P follows the expected power curve characteristics for a wind turbine. The power coefficient increases with the tip speed

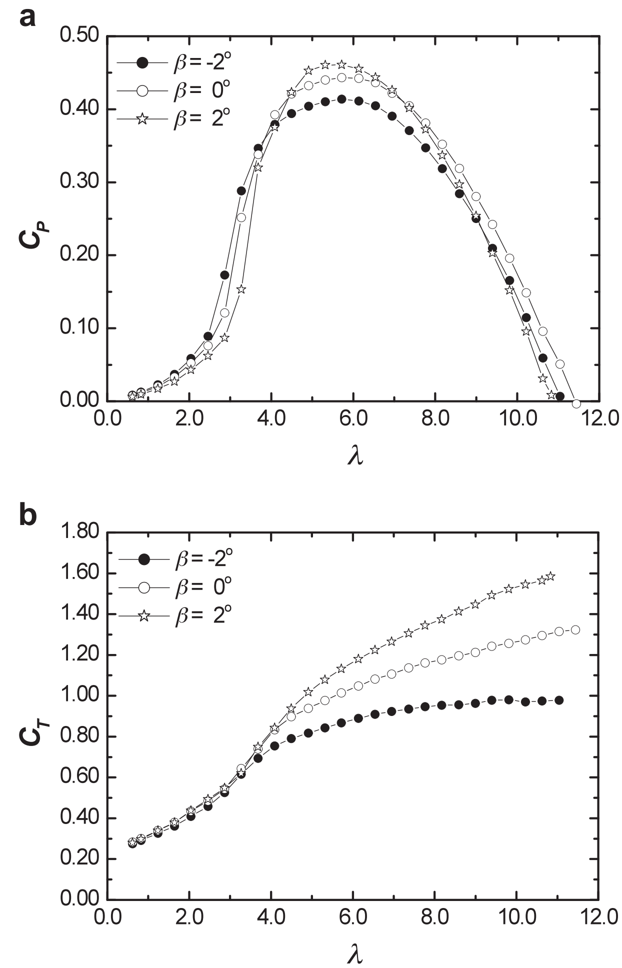

Fig. 2. Effect of pitch angle on the turbine performance (a) power coefficient and (b) thrust coefficient.

ratio, attains a maximum value at the design point ($\lambda = 6$) and then decreases with further increase in λ. In a numerical study of the turbine performance (Krogstad and Karlsen [22]) the first indications of stall were found near the root of the blade at $\lambda = 4$ and for $\lambda < 3$ the blade operates in a deep stall mode over the entire span of the blade. As stall develops at low λ, a corresponding loss in lift and power production is observed (Fig. 2(a)). In the partly stalled region between $\lambda \approx 2.5$ to 3.5 the development in power generation as λ increases depends slightly on the pitch angle, but in the fully stalled region at $\lambda < 2.5$, changes in pitch angle has little effect, as expected. At very high λ the inner section of the blade operates at a negative angle of attack, leading to negative power production over this part of the blade. The increase in lift with pitch angle for the outer part of the blade strongly affects the thrust coefficient (Fig. 2(b)), which increases significantly with increasing pitch angle at high λ. As could be expected, the run-away point, where the turbine no longer extracts energy from the flow, is seen to depend on the pitch angle.

Yawing the turbine also has a significant effect on both the power and thrust coefficients, as shown in Fig. 3. With the changes in the yaw angle of the wind turbine, the angle of attack on rotor blades also change and this leads to changes in the aerodynamic behaviour of the blade. In addition, when the turbine is in a yawed position, both the effective wind velocity and the rotor swept area are affected. At very low tip speed ratios the blades operate in a deep stall mode and therefore the power curves are not

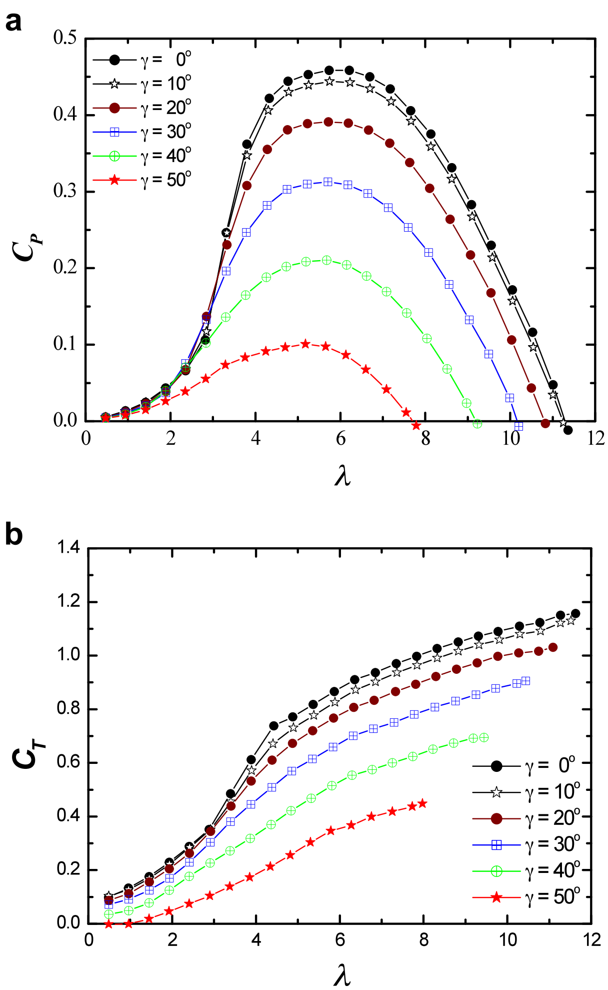

Fig. 3. Effect of yaw angle on the turbine performance (a) power coefficient and (b) thrust coefficient.

significantly affected by the yaw angle. For all other λ, yawing the turbine implies a reduction in C_P and C_T.

It was verified that the peak power output closely follows the theoretical curve. $C_P(\gamma) = C_P(\gamma = 0)\cos^3(\gamma)$. In Section 3.2.3 it will be shown that this may be used as a control parameter to increase the total output of a wind farm compared to when all turbines are operating in a non-yawed mode. Despite the loss in power, yawing may be used to reduce the interaction between the turbines and thereby increase the total output.

3.2. Wake interference effect

3.2.1. Separation distance and pitch angle

The effect of the wake due to the presence of an upstream turbine operating at its optimum λ on the performance of the downstream turbine is shown in Fig. 4. The coefficients for the downstream turbine were estimated using the freestream velocity measured upstream of the first turbine since this is constant. Compared to Fig. 2, there is a general reduction in both the power and thrust coefficients when the turbine is operating in the wake. This reduction is due to the fact that the downstream turbine is exposed to a considerably lower velocity than the upstream turbine.

With increasing distance between the turbines, S/D, the velocity in the wake gradually recovers and this leads to the increase in power produced, but at $S/D = 9$ it is still lower than that of the unobstructed turbine. The thrust coefficient (Fig. 4(b)) increases slowly as S/D increases but remains considerably smaller than for the unobstructed turbine (Fig. 2(b)). The run-away tip speed ratio (based on the upstream reference velocity) is also affected by the wake and increases with distance. Hence, for a constant rotor speed, it can be deduced that the cut-in wind speed at which the downstream turbine can begin to produce power depends on the distance of separation between the turbines. Therefore, in addition to the loss in power caused by the wake of the upstream turbine, the range of the operating tip speed ratio is also reduced due to the wake.

The maximum power coefficient of the downstream turbine normalized by that of the unobstructed single turbine operating at designed conditions (tip speed ratio $\lambda \approx 6$ and pitch angle $\beta = 0°$) is shown in Fig. 5 for different blade pitch angles and turbine separation distances. At $S/D = 3$ and $\beta = -2°$, the loss in maximum C_P of the downstream turbine is about 46%. The figure shows that as the distance between the turbines increases, there is a gradual recovery of power production. The power losses are about 38% and 29% at $S/D = 6$ and 9, respectively. This is similar to the results reported by Dahlberg [2] and Barthelmie et al. [12] when the turbines were operating below rated power. They reported significant drops in power output from the turbine immediately downstream of the first turbine, but the power recovers gradually with increasing S/D in agreement with the present observations.

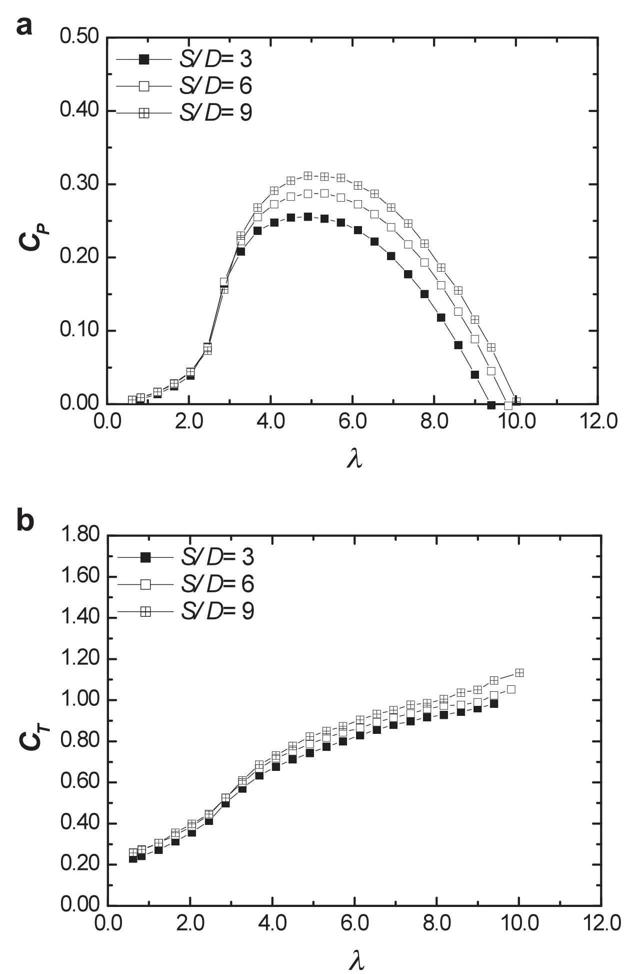

Fig. 4. Wake effect of the first (upstream) turbine on the second (downstream) turbine performance at various S/D locations: (a) Power coefficient and (b) thrust coefficient.

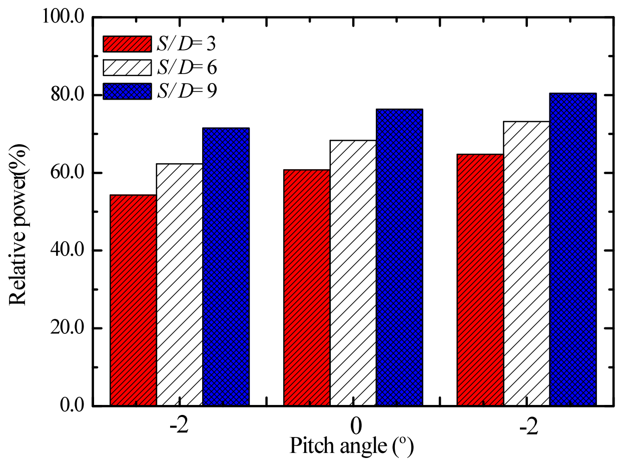

Fig. 5. The relative maximum power coefficient of the second (downstream) turbine as a function of the turbine separation and pitch angle of the first (upstream) turbine.

As shown in Section 3.1, the pitch angle of the blade affects the power extracted from the air flow by the wind turbine and therefore its wake development. Therefore, by operating the turbines at different pitch angle, it is possible to extract more power from those downstream. The effect of operating the upstream turbine at different pitch angles on the performance of the downstream turbine, when this is operating at a fixed pitch angle is presented in Fig. 5. This figure shows that at a given distance, the loss in maximum C_P of the downstream turbine depends strongly on the pitch angle. For example at $S/D = 3$, when the pitch angle of the upstream turbine is changed from $-2°$ to $+2°$, the loss is observed to be reduced from 46% to 35%. Similar trends are observed at $S/D = 6$ and $S/D = 9$ and agrees with the results of the study reported by Schepers and van der Pijl [16]. They concluded that by changing the pitch angle of the upstream turbine, its axial induction factor is affected and hence modifying the wake velocity deficit.

3.2.2. Effect of the upstream turbine tip speed ratio

Fig. 6 shows the performance of the downstream turbine when the upstream turbine was operating at the three selected tip speed ratios. The data presented are for the downstream turbine located at $S/D = 3$ and its blade pitch angle set at $\beta = 2°$. This figure shows that the performance of the downstream turbine depends strongly on the operating conditions of the upstream turbine, or more specifically on its tip speed ratio, λ. As expected, the lowest C_P of the downstream turbine was obtained when the upstream turbine was operated at its peak efficiency. At low or high λ settings for the upstream turbine, less energy is extracted from the air compared to when it is operating at its design λ. This leads to relatively higher wind speeds in the wake as reported by e.g. Adaramola and Krogstad [7], Steinbuch et al. [15] and Johnson and Thomas [17], and therefore, higher power production for the downstream turbine.

The maximum power coefficient of the downstream turbine normalized by that of the unobstructed single turbine operating at design conditions is shown in Fig. 7. The loss in power is about 21% and 26% when the upstream turbine is operating at low and high λ, respectively. This is significantly lower than the power deficit of 35% for the downstream turbine when the upstream turbine was operated at optimum λ. Hence, by adjusting the operating condition of the upstream turbine the wake effect on the downstream turbine can be significantly reduced. Therefore, it is possible that the overall wind farm power output may be increased by operating the upstream turbine away from its optimum tip speed ratio.

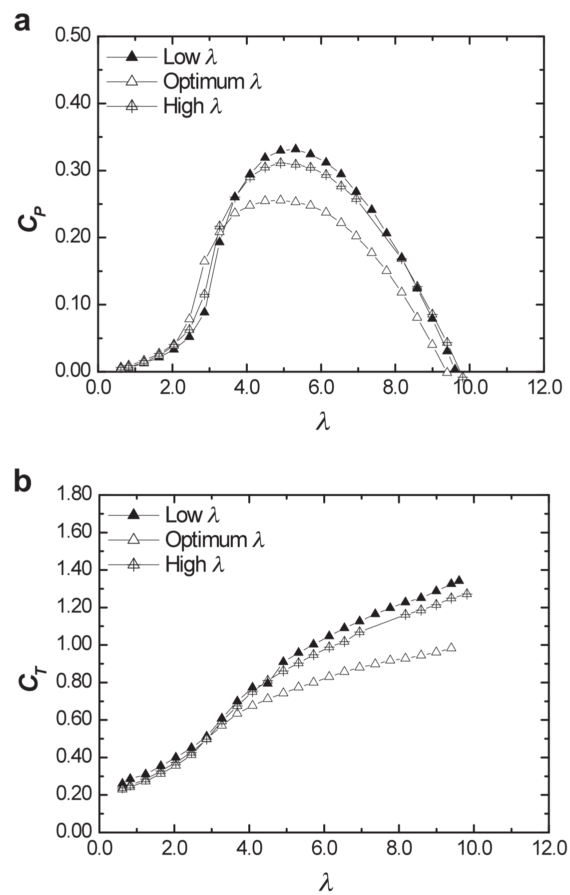

Fig. 6. Wake effect of the first (upstream) turbine on the second (downstream) turbine performance as function of the first (upstream) turbine operating condition at $S/D = 3$: (a) power coefficient and (b) thrust coefficient.

3.2.3. Effect of upstream turbine yaw angle

Fig. 8 shows how the performance of the downstream turbine is affected by operating the upstream turbine under various yaw angles. The downstream turbine is again located at $S/D = 3$ and its pitch angle is $\beta = 0°$. As the upstream turbine yaw angle increases there is a gradual increase in the power coefficient of the downstream turbine

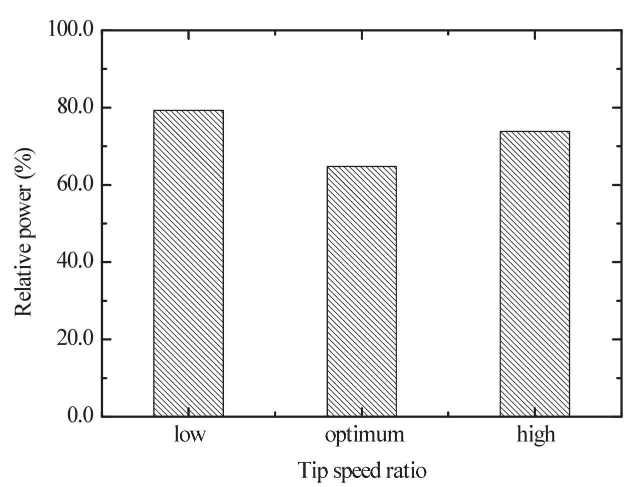

Fig. 7. The relative maximum power coefficient of the second (downstream) turbine as function of the first (upstream) turbine operating condition at $S/D = 3$ when the blade pitch angle is 2°.

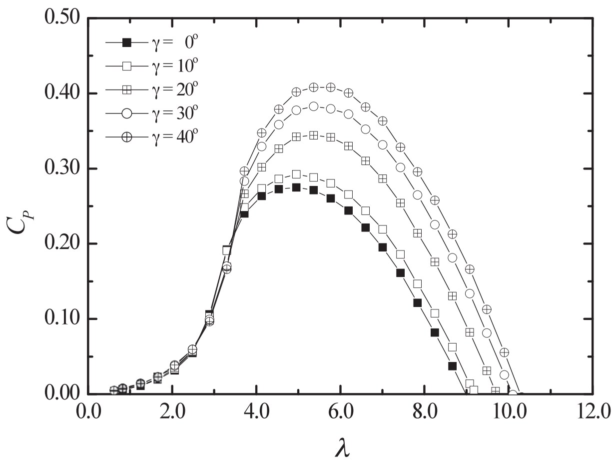

Fig. 8. Wake effect of the first (upstream) turbine on the second (downstream) turbine performance at $S/D = 3$ with the first (upstream) turbine operating at various yaw angles.

at a given tip speed ratio except within the stalled region, where the power is lost irrespective of the nature of the incoming flow. By operating the upstream turbine in yaw, the effective wind speed component that interacts with the rotor blades and the effective rotor swept area with respect to the wind direction are reduced. Hence, less power may be extracted from the air flow by the upstream turbine. The second effect this has on the downstream turbine is that by yawing the upstream turbine the wake is deflected sideways. Hence the rotor sweeps a smaller part of the wake area. (Unfortunately this also leads to the adverse effect of increased dynamic loads on the blades.) The downstream turbine is therefore exposed to higher wind speed compared to when the turbines are in an in-line arrangement. This results in the improved performance of the downstream turbine observed in the figure. Another benefit is that for a constant rotor speed, the figure shows that with increasing yaw angle of the upstream turbine, the cut-in wind speed at which the downstream turbine can start producing power is reduced (higher λ).

The maximum power coefficient of the downstream turbine normalized by that of the unobstructed single turbine operating at designed conditions is shown in Fig. 9. The graph clearly shows that by increasing the yaw angle of the upstream turbine, there is a corresponding increase in the maximum C_P of the downstream turbine. At a yaw angle of $\gamma = 10°$ the gain is only about 4% compared to when the upstream turbine is operating in a non-yawed position, but this increases to about 29% at $\gamma = 40°$ (the largest yaw angle considered in this study). Since the power output from the upstream turbine decreases with increasing yaw angle, the gain in power output from the downstream may not necessarily (especially at low yaw angle) increase the overall power output from these two turbines. However, in a wind park with more rows of turbines the strategy used for the first row will affect all downstream rows. Hence by suitably setting the operating point of each turbine a net gain appears to be possible.

3.2.4. Wind farm efficiency

In this section, the sum of power output from the two turbines is compared with the power output obtained if they were both in an unobstructed environment. The wind farm efficiency, defined as $\eta = 100\% \times P_{wake}/P_{freestream}$, is shown in Fig. 10. (Here P_{wake} = power produced by the upstream turbine + power produced by the downstream turbine operating in the wake, $P_{freestream}$ = sum of the turbine powers when exposed to the freestream and operating at design conditions.). The error bars on all the figures are included to indicate ±2% uncertainty in the data (This corresponds to the uncertainty estimated from all the data sets available at $\lambda = 6$ for zero yaw and pitch angles.) As expected, the efficiency of the wind farm increases with increasing distance between the two turbines. For a blade pitch angle setting of $\beta = -2°$ for the upstream turbine, the wind farm efficiency increases from 65% to 76% when the distance between the turbines is increased from $S/D = 3$ to $S/D = 9$ (Fig. 10(a)). An additional increase is possible by changing the pitch angle of the upstream turbine. For instance, when the pitch angle is increased from $\beta = -2°$ to $\beta = +2°$, the wind farm efficiency increases from about 65% to 72% at $S/D = 3$. Similar improvements are observed at $S/D = 6$ and $S/D = 9$ when the pitch angle is increased.

Similarly, with the downstream turbine located at $S/D = 3$, the efficiency of the wind farm is seen to depend strongly on the tip speed ratio of the upstream turbine (Fig. 10(b)). The farm efficiency value of 61% observed for the low tip speed ratio region is significantly smaller than 69% when the upstream turbine is operating at its design condition. This is because of the reduction in power produced by the upstream turbine when it is operating at this tip speed ratio region is larger than the gain achieved by the second turbine. However, there is slight increase (of about 3%) in the wind farm performance when the upstream turbine was operated at slightly higher tip speed ratio than the optimum value. As the tip speed ratio of the upstream turbine is increased even further, its power output will eventually be reduced faster than the gain achieved from the downstream turbine and thus, the wind farm efficiency will again be reduced. The optimum tip speed ratios for the two turbines will need to be carefully selected to maximize the output of a given wind farm configuration.

With the upstream turbine operating in yawed condition and the downstream turbine located at $S/D = 3$ with the pitch angle set to $\beta = 0°$, it is observed that the wind farm efficiency increases gradually with increasing upstream turbine yaw angle. When $\gamma = 10°$ the increase is only about 2.5% (above the non-yawed upstream turbine configuration), increasing to a peak wind farm efficiency of about 77% at $\gamma = 30°$. A further increase in γ causes a reduction in the total power output (Fig. 10(c)), primarily due to the strong drop in power produced by the upstream turbine. The highest wind farm efficiency recorded was 79%, observed when the turbine separation was 9D and the upstream turbine was operating at non-yawed condition. This is only marginally higher than the 77% observed with $S/D = 3$ when the upstream turbine is operated

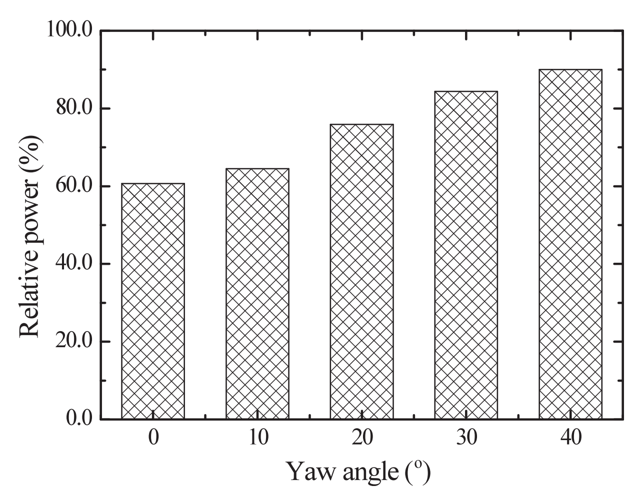

Fig. 9. The relative maximum power coefficient of the second (downstream) turbine at $S/D = 3$ with the first (upstream) turbine operating at various yaw angles.

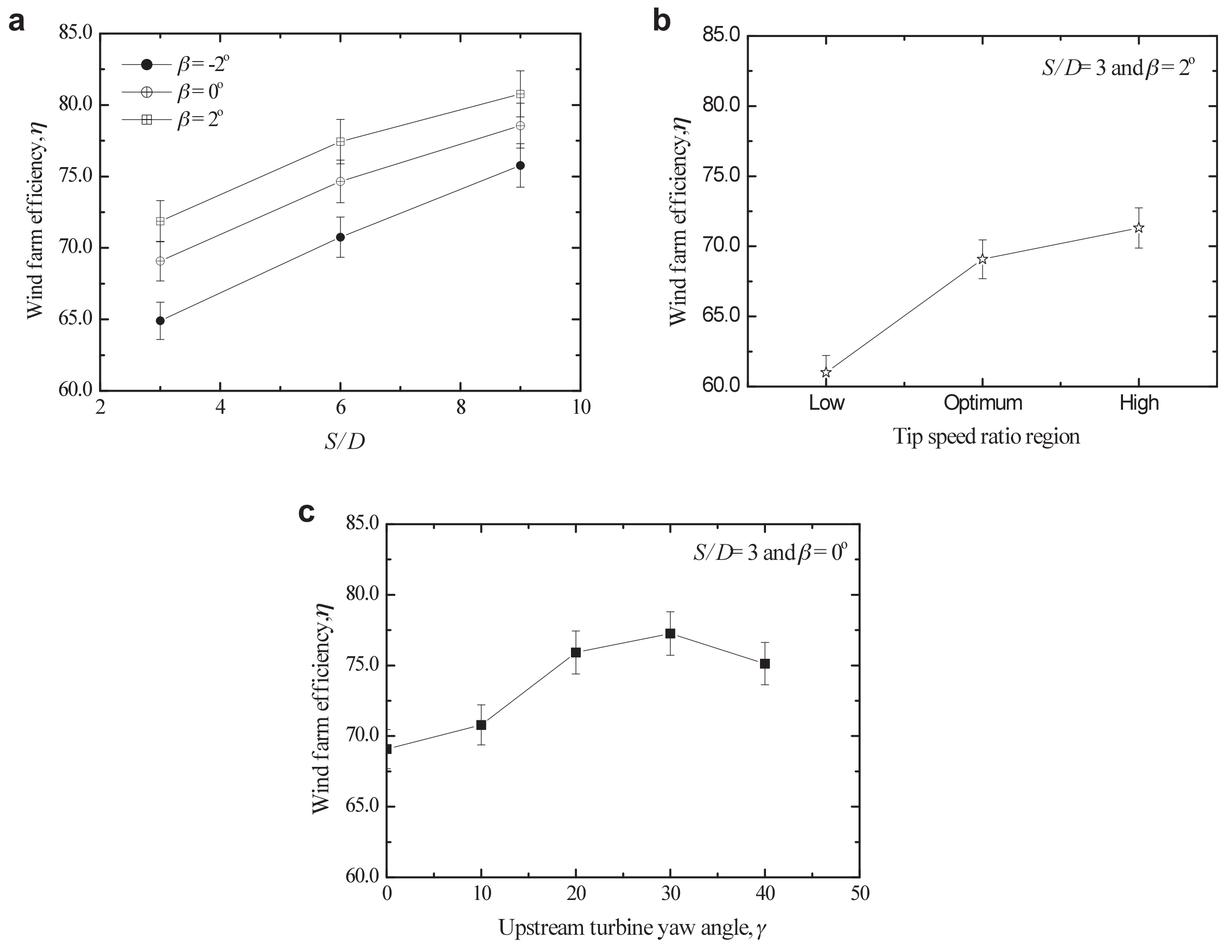

Fig. 10. Wind farm efficiency due to: (a) Distance of separation effect; (b) Upstream tip speed ratio effect; and (c) Upstream yaw angle effect.

at a yaw angle of $\gamma = 30°$. The benefit this has on wind farm planning is obvious.

Using the total power output from the two turbines when the upstream turbine is in non-yawed position and the downstream turbine is located at $S/D = 3$ and with a pitch setting of $\beta = 0°$ as a reference, the increases in the wind farm power output by yawing the upstream turbine are 8% and 13% when the downstream turbine is at $S/D = 6$ and 9, respectively. Further increase was possible by pitching the blades of the downstream turbine. The efficiency also depends on the operating point of the upstream turbine. When operating at the low tip speed ratio setting, the farm efficiency was reduced by about 12%, while a gain of about 3% was obtained for the high λ.

With the upstream turbine operating at yawed conditions, the wind farm performance clearly improved and attained a maximum increase of about 12% for $\gamma = 30°$. Dahlberg and Medici [14] reported similar gains in wind farm power output when the upstream turbine is yawed. For a yaw angle of 20° and turbines separated by $S/D = 3$, they observed a 10% gain compared to when the upstream turbine was not yawed. When the upstream turbine was operating at a yaw angle of $\gamma = 20°$, it was found that the efficiency of the wind farm is higher when the downstream turbine is located at $S/D = 3$ compared to when the upstream turbine is operating in a non-yawed condition and the downstream turbine was located at $S/D = 6$. Therefore, operating the upstream turbine at an appropriate yaw angle will not only improve the wind farm power output but will also reduce the space requirement for the wind farm.

4. Conclusions

The wake interference effects on the performance characteristics of a model wind turbine were investigated experimentally. Two similar model turbines with the same rotor diameter were used.

The results presented in this paper show that the power losses for a turbine operating in the wake of another are significant. In this study, it was found that the loss in maximum power coefficient of the downstream turbine varies between about 20 and 45% depending on the distance between the turbines and their operating conditions. Compared with the unobstructed turbine, the thrust of the downstream turbine is significantly lower. The reduction in power and thrust coefficients for the downstream turbine is a result of the velocity deficit in the wake so that the downstream turbine sees a considerably lower freestream velocity than the upstream turbine and thus, less energy is available in the flow. However, by adjusting the tip speed ratio of the upstream turbine, the power output from the downstream turbine can be substantially increased.

It was also observed that yawing the upstream turbine has a positive impact on the power output from the downstream turbine. In this study, the gain in relative maximum power coefficient of the downstream turbine increased steadily with increasing yaw angle up to about 90% of an unobstructed turbine at a yaw angle of 40°, which is about 29% higher than for the non-yawed upstream turbine.

The overall efficiency of the wind farm (two model wind turbines) was found to be strongly dependent on the distance between the turbines and their operating conditions. By operating the upstream turbine at an appropriate yaw angle (e.g. 20°) and using a relatively small distance of separation between the turbines, the efficiency of the wind farm is comparable to when the distance between them is high and the upstream turbine is not yawed. Therefore, operating the upstream turbine at a suitable yaw angle will not only improve the total wind farm power output, but will also reduce the space required for a given wind farm. However, when the distance between the turbines is small, operating the downstream turbine below its designed conditions could have negative effects on the wind farm performance. Therefore, by systematically controlling the operating conditions of the upstream wind turbine, the overall performance of a wind farm can be improved significantly.

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