A wind-tunnel investigation of wind-turbine wakes in yawed conditions

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Abstract. Wind-tunnel experiments were performed to study the performance of a model wind turbine and its wake characteristics in a boundary layer under different operating conditions, including different yaw angles and tip speed ratios. High-resolution particle image velocimetry (PIV) was used to measure the three velocity components in a horizontal plane at hub height covering a broad streamwise range from upstream of the turbine to the far-wake region. Additionally, thrust and power coefficients of the turbine were measured under different conditions. These power and thrust measurements, together with the highly-resolved flow measurements, enabled us to systematically study different wake properties.

The near-wake region is found to have a highly complex structure influenced by different factors such as tip speed ratio and wake rotation. In particular, for higher tip speed ratios, a noticeable speed-up region is observed in the central part of near wake, which greatly affects the flow distribution in this region. In this regard, the behavior of the near wake for turbines with similar thrust coefficients but different tip speed ratios can vary widely. In contrast, it is shown that the mean streamwise velocity in the far wake of the turbine with zero yaw angle has a self-similar Gaussian distribution, and the strength of wake in this region is consistent with the magnitude of the thrust coefficient.

With increasing yaw angle, as expected, the power and thrust coefficients decrease, and the wake deflection increases. The measurements also reveal that, in addition to turbulent momentum flux, lateral mean momentum flux boosts the flow entrainment in only one side of the wake, which results in a faster wake recovery in that side. It is also found that the induced velocity upstream of a yawed turbine has a non-symmetric distribution, and its distribution is in agreement with the available model in the literature. Moreover, the results suggest that in order to accurately predict the load distribution in yawed conditions, both normal and tangential (with respect to the rotor plane) components of the induced velocity upstream of the turbine should be taken into account.

1. Introduction
Wind-turbine performance and its wake characteristics depend on many factors such as the incoming atmospheric boundary-layer (ABL) and wind-turbine operating conditions [1]. Two important features of turbines’ operation are yaw angle and tip speed ratio (i.e., the ratio between the speed of the tip blade and the velocity of the incoming flow), which both significantly affect the turbine performance and its wake structure.

Turbines working in yawed conditions have recently received considerable attention both as: (i) an unfavorable practical issue in the operation of wind turbines, (ii) and more importantly, as a favorable method to increase the power production of whole wind farm. The former reason is mainly associated with the inaccuracy of wind-direction measurements by the sensor installed on the turbine nacelle [2]. Consequently, it is quite common for turbines to work in yaw misalignments. Apart from this undesirable yaw situation, as mentioned earlier, controlling the
yaw angle of turbines can be potentially used as a control method to improve the performance of the whole wind farm by deflecting the wake away from downwind turbines [3].

Several studies have been performed to investigate the turbine performance under these different operating conditions. Grant et al. [4] and later Grant and Parkin [5] did one of the first wind-tunnel experiments on the near wake (up to one rotor diameter) of a yawed turbine. Using flow visualisation methods, they observed helical vortex tubes downstream of the scaled-down turbine, and they also quantified the skew angle of the near wake for different yaw angles. Later, Medici and Alfredsson [6] characterized the wake of miniature yawed turbine in a few downstream positions. They found that a yaw turbine deflects the wake flow to one side, so it can be used as a potential way to control the turbine wake. Large-eddy simulation (LES) has been used by Jimenez et al. [3] to investigate the deflection of wakes of yawed turbines with different thrust coefficients. They pointed out that, for a given yaw angle, the wake deflects more for turbines with higher thrust coefficients. Recently, Krogstad and Adaramola [7] have controlled both the yaw angle and tip speed ratio of a turbine in their wind-tunnel studies, and examined the performance of the yawed turbine and its near-wake axial velocity. They found that the near wake is strongly affected by both the tip speed ratio and yaw angle.

It is important to note that the experimental studies mentioned above are limited to uniform inflow conditions. In the present work, the interaction between the wake of turbines under different conditions (e.g., yaw angle) and the turbulent boundary layer is studied, to our knowledge, for the first time. The results of this study will help us better understand and more accurately predict this complex interaction. To achieve this goal, detailed wind-tunnel measurements were carried out under different tip speed ratios and yaw angles for a model wind turbine placed in a neutrally stratified boundary layer. Highly spatially-resolved velocity measurements were performed in a broad streamwise range from upstream of the turbine to the far-wake region. Moreover, the main turbine characteristics (power and thrust coefficients) were measured.

In Section 2, the experimental setup is presented. The results are then shown and analyzed for different cases in Section 3. Finally, the summary and future research are presented in Section 4.

2. Experimental Set-up

Experiments were performed in the new closed-loop boundary-layer wind tunnel at the WIRE Laboratory of EPFL. The test section, designed for atmospheric boundary layer studies, is 2 m high, 2.57 m wide, and 28 m long. There is a contraction with a 5:1 area ratio upwind of the test section, and the tunnel is driven by a 130 kW fan. The turbulence intensity in the center of the wind tunnel (free stream) is lower than 0.1%. The turbulent boundary layer is naturally developed over the wind-tunnel floor thanks to the long test section. In the current study, the measurements were performed approximately 22 meters downstream of the test section entrance. The time-averaged incoming velocity at the hub-height of the turbine ($\bar{u}_h$) is kept approximately constant at 4.88 m/s. Figure 1 shows the vertical profiles of the mean velocity and turbulence intensity in the boundary layer in absence of the turbine. The boundary layer thickness is $\delta \approx 0.4m$ at the turbine location. The aerodynamic surface roughness length and the friction velocity were found to be $z_0 = 0.022mm$ and $u_* = 0.19m/s$, respectively, based on fitting a logarithmic velocity profile to the measured velocity profile in the surface layer (approximately lowest 15% of the boundary layer).

Two PIV setups were used to acquire detailed flow information. A high-resolution stereoscopic PIV (S-PIV) system from the LaVision company, called “PIV-setup I” in the following, was used to measure three velocity components downstream of the turbine in the horizontal plane at hub height. Two 29MP 12-bit CCD cameras (6600 × 4400 pixels) together with 105 mm lenses were installed on Scheimpflug mountings to maximize the focused area in the FOV. The FOV and spatial resolution are $4d \times 2.5d$ and 0.015d, respectively, where $d$ is the diameter of the wind turbine.

In addition to the mentioned S-PIV measurements, a high-resolution 2-Dimensional, 2-Components (2D2C) PIV system, called “PIV-setup II” later on in this paper, was used to
measure two velocity components in a horizontal plane at hub height upstream and downstream of the model turbine. A 16-bit sCMOS camera (2560 × 2160 pixels) with a 105 mm lens were used to capture particle images in the horizontal plane. The field of view (FOV) and spatial resolution obtained by this PIV setup are 2d × 1d and 0.013d, respectively.

The model wind turbine used in this experiment was designed and built at the WIRE laboratory of EPFL. This horizontal-axis turbine is 3-bladed, with a diameter of 15 cm. The blade profile is a 5% thick plate with a 5% circular arc camber. The height of the turbine hub above the floor is 12.5 cm. The turbine rotor drives a small DC-generator to extract the energy from the wind.

The tower of the turbine was mounted on a strain gauge sensor to measure the thrust force exerted by the wind on the model turbine. The tip speed ratio was also varied by applying different electrical loads on the generator attached to the turbine rotor.

3. Results

3.1. Turbine characteristics

One of the key factors in turbine performance is the power coefficient (\(C_p\)) defined as:
\[C_p = \frac{Q\Omega}{(0.5\rho \left(\frac{\pi d^2}{4}\right) \bar{u}_h^3)},\]
where \(Q\) is the torque generated by the rotor, \(\Omega\) is the rotational velocity of turbine, \(\rho\) is the density of air and \(\bar{u}_h\) is the mean incoming velocity at hub height. The graph of power coefficient versus tip speed ratio (\(\lambda\)) for different yaw angles (\(\gamma\)) is shown in Fig 2.a. For \(\gamma = 0\), the maximum power coefficient is approximately 0.35 and occurs at \(\lambda \approx 4\). The figure shows that a small yaw angle (e.g., \(\gamma = 10\)) slightly decreases the power production of the turbine. However, higher yaw angles (e.g., \(\gamma = 30\)) cause a dramatic drop in the power production. This is due to the reduction in the effective incoming velocity as well as the rotor frontal area for a yawed turbine [7]. To better compare the highest achievable power production in different yaw angles, Fig. 3 shows the maximum \(C_p\) for each yaw angle normalized with the maximum \(C_p\) at \(\gamma = 0\). The figure includes, for comparison, the graphs of \(\cos^2(\gamma)\) and \(\cos^3(\gamma)\). One cannot find a unanimous statement on \(C_p - \gamma\) curve in the literature. Based on the momentum theory [8] and some experimental studies (e.g., [7]), the maximum \(C_p\) versus \(\gamma\) has a shape similar to \(\cos^3(\gamma)\). On the other hand, other studies (e.g., [9]) proposed \(\cos^2(\gamma)\) shape for \(C_p - \gamma\) curve. Fig. 3 shows that the maximum power production approximately varies as \(\cos^3(\gamma)\) in our wind-tunnel measurements.

Another key factor which is important to characterize the turbine performance is the thrust coefficient (\(C_T\)) defined as:
\[C_T = \frac{T}{(0.5\rho \left(\frac{\pi d^2}{4}\right) \bar{u}_h^2)},\]
where \(T\) is the perpendicular force exerted on a turbine by the incoming wind. The variation of the thrust coefficient versus tip speed ratio for different yaw angles is shown in Fig. 2.b. The force measurements reveal that the thrust force decreases as the yaw angle increases, like the trend earlier seen for power production, which is in agreement with previous studies [7]. In general, it also shows that the value of thrust coefficient
Figure 2. Turbine performance versus tip speed ratio for different yaw angles: (a) power coefficient ($C_p$), and (b) thrust coefficient ($C_T$). For red-colored points, PIV measurements were performed.

gradually increases by increasing the tip speed ratio.

3.2. Mean flow characteristics

The effect of tip speed ratio on turbine wake properties will be first presented, and then the effect of yawing the turbine on the flow both upstream and downstream of the model turbine will be shown. For each yaw angle, the flow measurements were performed for two different tip speed ratios: (i) The tip speed ratio of the turbine when the electrical circuit connected to the generator is open, so the turbine rotates freely. This tip speed ratio is called $\lambda_f$ later on in this paper. (ii) The tip speed ratio at which the turbine has the maximum power production, and it is called the optimal tip speed ratio ($\lambda_o$) in the following. $\lambda_f$ and $\lambda_o$ for each yaw angle are indicated in Fig. 2 with red-colored points. As mentioned in section 2, two PIV systems were employed in this experiment. The PIV-setup I was used in three FOVs with some overlapping to capture the wake flow in a broad streamwise range from the near-wake ($0.4d$) to the far-wake region ($12d$). Note that in all the contour plots showing the results of PIV-setup I, overlapped locations are indicated by dashed lines. Additionally, the PIV-setup II was employed to quantify the wind flow in a smaller area around the turbine including upstream and very near wake of the turbine (from $-2d$ to $2d$). All the PIV measurements presented in this paper were carried out in the horizontal plane at hub height.

3.2.1. Effect of tip speed ratio on turbine wakes: Fig. 4 shows contours of normalized mean streamwise velocity ($\bar{u}/\bar{u}_h$) downwind of the turbine with zero yaw for the two aforementioned tip speed ratios. As seen in the figure, the center of the near wake region for the optimal tip speed ratio ($\lambda_o$) has higher velocity deficit compared to the one for the higher tip speed ratio
In other words, the near wake is surprisingly less pronounced for the case of higher tip speed ratio $\lambda_f$ (i.e. higher blockage ratio and slightly higher $C_T$ (see Fig. 2.b)). Consideration of the flow just behind the turbine might help us to explain the reason of this apparent paradox between the wake and force measurements. To do this, Fig. 5 shows contours of the normalized mean streamwise velocity ($\bar{u}/\bar{u}_h$) in the vicinity of the turbine for both tip speed ratios. From the figure, a speed-up region is found just downstream of the inner part of the rotor for both cases, although it is considerably stronger for the higher tip speed ratio ($\lambda_f$). Firstly, this is due to the fact that the wind velocity around the turbine hub increases based on conservation of mass. Secondly and more importantly, the angle of attack for the inner part of the blade in the case of higher tip speed ratio ($\lambda_f$) is very low or even negative [7]; this substantially intensifies the speed-up region in this case as shown in the figure. Further downstream, this high velocity region lessens the wake of the nacelle. As a result, the central part of the near wake region seems weaker for the higher tip speed ratio ($\lambda_f$) (Figs. 4 and 5) although $C_T$ of the turbine is slightly higher in this case. It is also important to note that the central part of the rotor does
not make a significant contribution to the overall thrust force compared to outer part due to the large difference in their swept areas.

Despite the near-wake region, as seen in Fig. 4, the wake of the turbine in the far-wake region ($x/d > 4$), which is less sensitive to the rotor dynamics, is similar for the two considered tip speed ratios. To facilitate the quantitative comparison of the results, lateral profiles of the normalized mean streamwise velocity ($\bar{u}/\bar{u}_h$) in different positions downstream of the turbine ($x/d = 1, 2, 4, 6$ and $8$) are shown in Fig. 6 for both $\lambda_f$ and $\lambda_o$. As expected, the figure shows that the velocity profiles in the far-wake region ($x/d \geq 4$), unlike the near wake, have a Gaussian distribution. Furthermore, it can be seen in this figure that the minimum velocity in the far-wake region is slightly lower for the higher tip speed ratio ($\lambda_f$) despite having higher velocities in the center of near wake. This is consistent with our force measurements as $C_T$ is found to be slightly higher in this case. Note that for the higher tip speed ratio ($\lambda_f$), the wake is slightly deflected to one side. This might be due to the interaction between the rotating wake of turbine and the incoming turbulent boundary layer.

In general, these wind-tunnel measurements confirm the well-known fact that although the overall thrust coefficient, along with the incoming ABL conditions, can represent the general characteristics of far-wake regions [10], it is not sufficient for near-wake predictions. In fact, our results show that relying only on the thrust coefficient can even yield completely untrue near-wake predictions. Detailed information regarding the rotor characteristics such as the operating tip speed ratio, blade geometry and twist distribution is indeed needed to systematically analyze and predict this very complex region [11].

One important feature of the near-wake region of wind turbines is the wake rotation. In a horizontal plane, the vertical component of velocity ($\bar{w}$) shows rotation of the wake. Fig. 7 shows contours of normalized mean vertical velocity ($\bar{w}/\bar{u}_h$) in the same horizontal plane for two different tip speed ratios. As expected, the wake rotates in the opposite direction to that of the

![Figure 6](image-url)

**Figure 6.** Lateral profiles of the normalized mean streamwise velocity ($\bar{u}/\bar{u}_h$) in the wake of zero-yawed turbine: solid lines correspond to the free-rotating turbine $\lambda_f = 6.34$, and dashed lines correspond to the optimal tip speed ratio $\lambda_o = 3.9$.

![Figure 7](image-url)

**Figure 7.** Contours of the normalized mean vertical velocity ($\bar{w}/\bar{u}_h$) in the horizontal plane at hub height downwind of a zero-yawed turbine at: tip speed ratio of free-rotating turbine $\lambda_f = 6.34$ (top), the optimal tip speed ratio $\lambda_o = 3.9$ (bottom).
blades due to conservation of angular momentum [12]. Note that the turbine blades rotate in the counterclockwise direction, viewed from upwind of the turbine. This strong wake rotation, along with the presence of the turbulent boundary layer, makes the near wake region deviate considerably from axisymmetric behavior (see Fig. 6). With increasing downwind distance, however, the vertical velocity decreases due to wake recovery as shown in Fig. 7. In addition, it can be seen that the wake rotation is noticeably stronger for the optimal tip speed ratio ($\lambda_o$). This is due to the fact that the torque generated from the turbine is definitely higher in this case, so the turbine induces stronger rotation in the wake compared to the other case.

3.2.2. Effect of yaw angle on the flow upstream and downstream of the turbine: For each yaw angle, only the flow measurements for the optimal tip speed ratio ($\lambda_o$) are presented in this section. Figure 8 shows contours of normalized mean streamwise velocity ($\bar{u}/\bar{u}_h$) for different yaw angles ($\gamma = 0, 10, 20$ and $30\degree$) in the same horizontal plane. Based on momentum conservation, the wake deflection is caused by the lateral component of the force that turbine exerts on the air flow. As expected, it is clear that the wake deflection increases with increasing the yaw angle. In

![Figure 8](image)

**Figure 8.** Contours of the normalized mean streamwise velocity ($\bar{u}/\bar{u}_h$) in the horizontal plane at hub height downwind of a turbine for different yaw angles ($\gamma = 0, 10, 20$ and $30\degree$).

![Figure 9](image)

**Figure 9.** Lateral profiles of the normalized mean streamwise velocity ($\bar{u}/\bar{u}_h$) in the wake of a turbine with the yaw angle of $30\degree$ ($\gamma = 30\degree$).
addition, the figure shows that the wake is less pronounced as the yaw angle increases because of the reduction in thrust force of the turbine (Fig. 2.b).

To quantitatively investigate the wake of the yawed turbine, lateral profiles of normalized mean streamwise velocity ($\bar{u}/\bar{u}_h$) at different positions ($x/d = 2, 4, 6, 8$ and $10$) downstream of a turbine with the yaw angle of $30^\circ$ are shown in Fig. 9. As seen in the figure, one side of the wake (lower side in Fig. 9) is wider than the other side, and this difference is more obvious with increasing the downwind distance. This means that the wake recovery in one side is faster than the other side. Generally, the wake recovery for a turbine with zero yaw angle is associated with the turbulent momentum flux ($u'v'$ in the horizontal plane) that transfers the energy from the outer flow into the wake region [13, 14]. For a yawed turbine, however, the mean components of velocity can also play a significant role as the wake is not parallel to the incoming flow. Thus, in addition to the turbulent momentum flux, the lateral mean momentum flux ($\bar{u}\bar{v}$) should be considered as an effective mechanism for the flow entrainment.

Figs. 10 and 11 show contours of normalized lateral turbulent ($u'v'/\bar{u}_h^2$) and mean ($\bar{u}\bar{v}/\bar{u}_h^2$) momentum fluxes, respectively, for a turbine with yaw angles of $0^\circ$ and $30^\circ$. For both yaw angles, as expected, Fig. 10 shows a strong enhancement in the magnitude of $u'v'$ on both sides of the wake owing to the strong shear between the wake and the outer flow. Apart from the turbulent momentum flux, Fig. 11 shows that substantial entrainment flux caused by mean values of velocity ($\bar{u}\bar{v}$) exists only in one side of the wake of the turbine with the yaw angle of $30^\circ$. This can explain the non-axisymmetry of turbine wakes in yawed conditions shown in Fig. 9.

To illustrate the flow field in the vicinity of a yawed turbine, Fig. 12 shows the contours of normalized mean streamwise velocity ($\bar{u}/\bar{u}_h$) around the turbine with the yaw angle of $30^\circ$. Downstream of the turbine, the figure shows that the presence of the nacelle profoundly affects the central part of the wake. This can be explained by the increase in the frontal area of the

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**Figure 11.** Contours of the normalized lateral mean momentum flux ($\bar{u}\bar{v}/\bar{u}_h^2$) in the horizontal plane at hub height downwind of a turbine with: zero yaw angle (top), and $30^\circ$ yaw angle (bottom).
nacelle for a yawed turbine compared with the case of zero yaw. Additionally, it can be seen that yawing the turbine induces a non-symmetric flow distribution upstream of the turbine. Glauert [15] addressed this non-symmetric distribution for the first time by studying the performance of an autogyro. Based on his model, the magnitude of induced velocity normal to the rotor plane is higher in front of the downwind side of a yawed rotor (in this paper, the side in the positive spanwise region) compared to the upwind one. Fig. 13 shows the vectors of the velocities induced by the turbine both in the normal and tangential directions (with respect to the rotor plane) for the turbine with the yaw angle of 0° (Fig. 13.a) and 30° (Fig. 13.b). The normalized mean streamwise velocity ($\bar{u}/\bar{u}_h$) is also shown as a contour plot. From the figure, the induced velocity in both normal and tangential directions for a turbine with zero yaw angle is approximately symmetric. For a yawed turbine, on the other hand, the induced velocities clearly have a non-symmetric distribution.

Next, these velocity measurements upstream of the turbine are used to assess the validity of Glauert’s model [15]. Note that, however, the flow upstream of the central part of the rotor cannot be considered for this purpose as the flow is influenced by the presence of nacelle in this region. By considering the outer half of the rotor, it can be seen that the magnitude of the normal induced velocity is higher in front of the downwind side of the turbine, which is consistent with Glauert’s theory. On the other hand, the contour plot in the figure shows that the streamwise velocity is lower in front of the upwind side of rotor (i.e., bigger projected induced velocity in the streamwise direction). This can be explained by the fact that the tangential induced velocity in front of turbine’s upwind side decelerates the incoming flow, whereas it accelerates the incoming flow in front of the downwind side. This causes the higher induced velocity projected in the streamwise direction in front of the upstream side of rotor, although the normal induced velocity is lower there. This finding suggests that, in addition to the normal induced velocity, the induced velocity in the tangential direction must be taken into account in models that try to simulate turbines in yawed conditions (e.g., blade element-momentum (BEM) models).

4. Summary and future research

Wind-tunnel measurements were carried out to study the performance of a wind turbine and its wake characteristics under different yaw angles and tip speed ratios. In these experiments, a three-bladed horizontal-axis turbine was placed in the turbulent boundary-layer generated in the recirculating wind tunnel at the WIRE Laboratory of EPFL. High-resolution PIV was used to quantify the wind flow in the horizontal plane at hub height from 2 rotor diameters upstream of the turbine to 12 rotor diameters downstream. In addition to flow measurements, the thrust and power coefficients of the model turbine were measured under different conditions.

It is found that the near wake region is considerably influenced by different factors such as the tip speed ratio of turbine and the wake rotation. For higher tip speed ratios, as previously reported for bigger turbines in free-stream flows [7], a speed-up region exists downwind of the inner part of rotor. Due to the presence of this high-velocity region, the near wake of the turbine working at higher tip speed ratios seems weaker, although the thrust coefficient is higher in this case. This finding indicates that the overall characteristics of turbines such as thrust coefficient are not sufficient for near-wake predictions. The mean streamwise velocity in the far wake of the turbine with zero yaw angle, in contrast to the near wake, has a self-similar Gaussian distribution.
in the horizontal plane. The wake rotation is also found to be stronger when the turbine rotates at the optimal tip speed ratio with respect to the case without any electrical loads (i.e., freely spinning).

For a yawed turbine, as expected, both power production and thrust force of the model turbine decrease with increasing yaw angle. In particular, the maximum power production versus tip speed ratio varies approximately as \( \cos^3(\gamma) \), where \( \gamma \) is the yaw angle. As expected, the wake deflection increases with increasing yaw angle. Moreover, it is found that, in addition to turbulent momentum flux, lateral mean momentum flux greatly increases the wake entrainment only on one side of the wake of the yawed turbine. As a result, the wake recovers faster on that side.

Upstream of the yawed turbine, the induced velocities are non-symmetrically distributed in both normal and tangential directions (with respect to the rotor plane). Qualitative comparison between the measurements and the model proposed by Glauert [15], which addresses this non-symmetric distribution, shows an agreement.

In our future research, hot-wire anemometry will be used to obtain highly time-resolved measurements. That will enable us to study dynamic characteristics of turbine wakes such as tip vortices and wake meandering in different operating conditions. In addition, we will extend the analytical model proposed by Bastankhah and Porté-Agel [10] to include the effect of yaw angle on turbine-wake predictions.

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