Experimental investigation of wind turbine wake dynamics during yaw variation

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Abstract. This work focuses on the analysis of the wake dynamics during yaw manoeuvres. Farm control is becoming always more crucial and voluntary misalignment is one valuable strategy employed to optimize the overall production. Indeed, the appropriate misalignment of a wind turbine can improve the rate of production and the lifetime of the downstream one, and if properly applied, could also improve the overall farm production. The main objective of this work is to analyze the wake deviation dynamics consequent to an imposed yaw manoeuvre strategy. The analysis is performed through wind tunnel experiments and the wake deviation is captured and measured using Particle Imaging Velocimetry. First, the yaw manoeuvre is reproduced in a homogeneous and isotropic turbulent flow and second, in a more realistic atmospheric boundary layer condition. Results show a different behaviour of the wake according to the imposed yaw manoeuvre.

1. Introduction & work objectives

The possibility of reducing wake interaction effects in a wind farm is currently a topic of great interest to improve the overall wind farm power yield. Among different wake control strategies investigated in literature [1–3], voluntary misalignment is supposed to deflect the wake laterally in order to attenuate its impact on the downstream turbine. Indeed, the appropriate misalignment of a wind turbine can improve the rate of production and the lifetime of the downstream one and, if properly applied, could also improve the overall farm production. However, it is still necessary to investigate wake features of yawed wind turbines under static and dynamic operating conditions before applying this strategy. The main objective of this work was to analyze the wake deviation process in case of yaw misalignment scenario via an experimental approach in wind tunnel by the use of Particle Image Velocimetry measurement (Stereo-PIV 2D-3C). The first aim was to study the wake deviation consequent to a static yaw angle variation of a wind turbine in order to characterise the magnitude of this phenomenon. After that, taking into account the possible application of this wake control strategy to increase farm production, the study focuses on the analysis of the transition between the no yaw condition and the maximal yaw condition (in this study 30°). On this purpose, it was chosen to re-scale in wind tunnel the yaw maneuver in order to compare its duration with that of the associated wake displacement. To have a more exhaustive description of this phenomenon, the experiments have been conducted for different scales and incoming flow conditions, from a homogeneous and
isotropic turbulent flow (HIT) to a more realistic flow such as an atmospheric boundary layer (ABL) flow condition. The wind turbine was modelled by actuator discs as broadly done in previous studies performed at such small geometric scales [4–7]. In this work the porous disc models were scaled, taking as a reference a wind turbine of 80 m diameter, at 1:800 and 1:320 respectively for HIT and ABL conditions.

2. Approach & method

As mentioned in the introduction, the wake behavior during yaw variation has been studied under two different incoming flow conditions requiring the use of two different wind tunnels at PRISME laboratory (Orléans University). In this section the two set-ups will be briefly described giving reference to previous works in same conditions, exposed with further details in [8]. Then the metric and the method used to determine the centre of the wake will be fully detailed. As mentioned in the introduction, the wake behaviour during yaw variation has been studied in two different flow conditions and scales taking as a reference a full scale wind speed at hub height of 12 m s\(^{-1}\). Concerning the wind tunnel flow rate, for HIT conditions the reference wind speed was 6 m s\(^{-1}\) while for ABL conditions the reference speed (at hub height) was 5 m s\(^{-1}\), giving a Reynolds number based on the diameter of around 10\(^4\). The purpose of studying the phenomenon in HIT conditions (figure 1) was to isolate the wake deviation with the less possible influence of the flow characteristics, assuming that in this kind of flow the wake deviation would have been easier to detect than in ABL conditions (higher turbulence intensity and larger turbulent eddies).

![Figure 1. Set-up of the 2D-3C Stereo PIV system in the square test section (0.5 m height and width, 2 m length) of the “Eiffel type” wind tunnel [8]](image-url)

The flow characteristics, wind turbine models and spacing are summarized in table 1. The measurement settings were exactly those used in [8]: the PIV system consists of a Nd: Yag laser Evergreen 200 (2 × 200 mJ) emitting pulse with wavelength 532 nm, and a 2.5 Hz emission rate for non-synchronized acquisition. The light sheet is oriented in order to cross transversely the test section. Seeding particles are micro-sized olive oil droplets sprayed by a PIVTEC seeding...
system. Images are acquired with two LaVision Imager LX cameras (4032 px × 2688 px) with a 105 mm lens equipped with a 532 nm wavelength filter. The time delay between the images is settled according to flow speeds, at 105 µs and 52 µs for HIT and ABL conditions respectively. The images are processed with a multi pass decreasing size (64 px × 64 px, 32 px × 32 px) interrogation window with an overlap of 50 %. Figure 2 shows the installation in the wind tunnel used for ABL conditions. Experiments were carried out in the return test section as it was done in [4] reproducing a neutrally stratified atmospheric boundary layer. The ABL (scale 1:400) represents a flow above a moderately rough terrain with roughness length of $z_0 = 5 \times 10^{-5} m$ (full scale $z_0=0.02 m$), a power low exponent of $\alpha = 0.14$ and a friction velocity of $u^*=0.29 m s^{-1}$ as in [4]. Concerning the measurement set-up for ABL conditions the Stereo PIV 2D-3C system was installed in an equivalent configuration to the one used in HIT conditions in order to properly compare the results.

![Photo of the PIV set-up in the return test section of the "Lucien Malavard" wind tunnel and vertical profile of the mean stream-wise velocity.](image)

In both experimental conditions, two different disc porosities are tested in order to detect the influence of the induction factor $a = \frac{1}{2}(1 - \frac{U_{wake}}{U_{\infty}})$. The evolution of the wake misalignment due to the yaw manoeuvre is studied at a few diameters (3.5 and 4.2 for HIT and ABL conditions respectively) downstream the yawed disc by the use of stereo PIV. As in [8], the wake deviation has been tested in both static and dynamic conditions with the same two porosities and acquisition methodology (conditional averaging respect to the time delay after the yaw manoeuvre start for dynamic conditions). The maximal statistical uncertainty of the mean wind speed ($\epsilon_u = \frac{ZI_{U_{max}}}{\sqrt{Nb}}$) and its standard deviation ($\epsilon_\sigma = \frac{Z}{\sqrt{2 Nb}}$) are defined according to Benedict and Gould [9], with $Z = 1.96$ (confidence interval of 95%), $Nb$ the number of samples, $I_{U_{max}}$ the maximal turbulence intensity measured in the wake region. The turbulence intensity has been also measured in an empty field (no disc) at the disc location ($I_{U_{up}}$) and at the Stereo PIV measurement plane ($I_{U_{down}}$). These parameters, together with the reference scaled wind speed $U_{ref}$, the model size diameter $D$, the spacing between the model and the measurement plane location $\Delta x$ and the vector resolution ($Vr$), defined as the distance between two vectors in the PIV velocity field normalized by the disc diameters, are summarized for HIT and ABL conditions in table 1.

|        | $D$ [m] | $\Delta x$ [m] | $U_{ref}$ [m s$^{-1}$] | $I_{U_{up}}$ [%] | $I_{U_{down}}$ [%] | $I_{U_{max}}$ [%] | $Nb$ | $\epsilon_u$ [%] | $\epsilon_\sigma$ [%] | $Vr$ |
|--------|---------|----------------|------------------------|-----------------|-----------------|-----------------|------|-----------------|----------------|-------|
| HIT    | 0.1     | $3.5 \times D$| 6                      | 4.8             | 4               | 12              | 300             | 1.6             | 9               | $1.7 \times 10^{-2}$ |
| ABL    | 0.25    | $4.2 \times D$| 5                      | 11              | 11              | 16              | 1000            | 1               | 4               | $10^{-2}$     |
2.1. Wake centre determination method

As exposed in [8], the wake deviation is determined by the estimation of the displacement of the wake center position $Y_c$, then the wake deviation angle $\theta$ can be easily retrieved by simple trigonometric considerations (figure 3).

$$\chi = \gamma + \theta = \gamma + \arctan\left(\frac{\delta}{nD}\right).$$

$Y'_c$ represent the position of the wake center after yaw variation. Figure reproduced from [8].

Different methods [4, 10, 11] were tested, but finally the wake centre was determined by the “center of mass” method proposed by Howland at al. described in [10]. The wake center position $Y_c$ was retrieved by the calculation of the center of mass weighted by the velocity deficit $(\Delta U = U_\infty - U_{wake})$ of the stream-wise velocity component $U$ over a field perpendicular to the flow direction. Given $X$ the flow direction and $(Y,Z)$ the plane at the velocity field (PIV measurement field), the wake center can be computed as in eq(1):

$$Y_c = \frac{\iint y\Delta Ud\gamma dz}{\iint \Delta Ud\gamma dz} \quad \text{and} \quad Z_c = \frac{\iint z\Delta Ud\gamma dz}{\iint \Delta Ud\gamma dz}$$

With the "center of mass" method, it is possible to analyze both crosswise coordinates of the wake center. Due to the negligible variation detected over the vertical coordinate, the horizontal displacement of the wake will be only treated. Taking into account the uncertainties on the wind speed, the PIV vector resolution (see table 1) and the methods used to estimate the center of the wake, it was possible to estimate the measurement uncertainty for both set-ups applying usual error propagation methods. The estimated measurement uncertainty is $\theta = \pm 0.14^\circ$ and $\theta = \pm 0.07^\circ$ for HIT and ABL conditions respectively.

3. Static Results

The static misalignment has been discussed in detail in [8], comparing different wind speeds and porosities to exclude Reynolds and porosity effect. The same HIT set-up and disc porosities (induction factor) were used in the present work. As results are similar, for the sake of the brevity, the influence of the atmospheric boundary layer will be only discussed. As mentioned before the measurements were performed varying statically the yaw angle $\gamma$ between 0$^\circ$ and 30$^\circ$ by step of 10$^\circ$. The analyzed cases are summarized in table 2.

Figure 4 shows the static results. Taking into account of the measurement uncertainty, the first three cases seem to have the same trends highlighting no significant influence of porosity and flow conditions on the wake behaviour. Nevertheless, looking at case 4, it is noticed a discrepancy between its trend and the other three, which can be explained by the more complex nature of the
Table 2. Static case measurements.

| Case | set-up | \( U_{\text{ref}} \) [ms\(^{-1}\)] | Porosity [%] | a |
|------|--------|-----------------|--------------|---|
| 1    | HIT    | 6               | 57           | 0.16 |
| 2    | HIT    | 6               | 67           | 0.11 |
| 3    | ABL    | 5               | 57           | 0.16 |
| 4    | ABL    | 5               | 67           | 0.11 |

ABL flow. Indeed, the flow in-homogeneity together with the higher level of turbulence make the velocity deficit generated by the higher porosity disc too low and unsuitable to properly track the wake center. For this reason the higher porosity will be not discussed for ABL conditions. It is interesting to notice that, as already remarked by other works and models ([10–12]), the wake deviation angle is one order of magnitude lower than the imposed yaw manoeuvre. Indeed for a 30° yaw angle it has been retrieved a maximal wake deviation around 1.6° depending on the considered case.

![Graph showing deviation angle \( \theta \) as a function of the yaw angle \( \gamma \): • case 1, • case 2, ■ case 3, ★ case 4.](image)

**Figure 4.** Deviation angle \( \theta \) as a function of the yaw angle \( \gamma \): • case 1, • case 2, ■ case 3, ★ case 4.

4. Dynamic Results
In this section the results of the yaw variation influence on the wake dynamics are discussed. A preliminary investigation of the wake dynamics was already conducted in [8] although with a lower number of measurements and a different wake center determination method. Given the interesting results, it has been chosen to increase the number of measurements and to improve the protocol used to investigate the phenomenon together with the use of a more accurate wake center detection method. A particular attention has been given to the yaw variation scaling in order to properly represent the displacement in wind tunnel. Taking as reference a full scale yaw variation nominal speed of 0.5 \( \frac{\text{°}}{\text{s}} \), it is possible to retrieve the reference duration for a 0° - 30° and a 30° - 0° rotation. The yaw motion was re-scaled according to this estimation. Indeed, applying similarity analysis with the full scale condition, the yaw variation takes 10\( \tau_0 \), where \( \tau_0 \) is the aerodynamic time scale based on the inflow velocity \( V_0 \) and disc diameter \( D \) (\( \tau_0 = \frac{D}{V_0} \)). So wind tunnel experiments have been performed taking into account this similarity law. The yaw motion was carried out using a Kollmorgen AKM24D-ANBNC-00 rotational servomotor and
measured by a Kübler type 8.5872.3832.G141 circular encoder. All the system was controlled via LabView providing a continuous measurement of the angular position. A crucial point is the determination of the wake deviation duration, because this task is complicated by the nature of the measurements. Indeed, due to the PIV instrumentation (no time-solved), it was only possible to apply a conditional averaging of the PIV fields retrieving though a discrete measurement of the wake position history. The PIV system was triggered with delays from the start of the manoeuvre selected as multiples of $\tau_0$. Acquisition has been done up to a few $\tau_0$ further to $10\tau_0$ in order to take into account the advection delay. Thus, it was necessary to develop a protocol to estimate this duration starting from discrete measurements. The number of measurements acquired in this work was sufficient to fit a 3rd order polynomial to the wake deviation path and to estimate the slope $\frac{d\theta}{d\tau}$ as the value corresponding to the point of the maximal gradient of this curve. The start ($\tau_{\text{start}}$) and the end ($\tau_{\text{end}}$) of the deviation were retrieved crossing the line of slope $\frac{d\theta}{d\tau}$ passing to the point of maximal gradient respectively with the static values of $\theta$ for $\gamma = 0^\circ$ ($\tau_{\text{start}}$) and $\gamma = 30^\circ$ ($\tau_{\text{end}}$). To compare the results of different flow conditions, the parameters were normalized with the aerodynamic time scale $\tau_0$, giving $\tau_{\text{start}}^*$ and $\tau_{\text{end}}^*$, and consequently the wake deviation duration $\tau_w^* = \tau_{\text{end}}^* - \tau_{\text{start}}^*$. The same methodology was applied to estimate the duration of the yaw manoeuvre ($\tau_m^*$) to avoid any bias due to the duration measurement methods (figure 5).

In this way, it was possible to retrieve the ratio between the wake deviation duration and the yaw manoeuvre duration $\tau_{\text{ratio}} = \frac{\tau_w^*}{\tau_m^*}$. The proper estimation of $\tau_{\text{start}}^*$ is fundamental to assess the advection velocity, noted $U_{\text{adv}}$, as the ratio between the spacing and the delay between the start of the manoeuvre and the start of the deviation: $U_{\text{adv}} = \frac{\Delta X}{\tau_{\text{start}} - \tau_{\text{mstart}}}$. The analysed dynamic cases are summarized in table 3 in which “+” yaw stands for yaw increment and vice versa.

Figure 6 shows the results for the dynamic yaw variation in HIT conditions. The results are normalized by the corresponding value of $\theta(\gamma = 30^\circ)$ to be properly compared. Looking at the trends, a strong similarity between cases 5&6 and 7&8 can be observed. This suggests a negligible impact of the induction factor on the wake dynamics. Despite the similarity in trends between yaw increase and yaw decrease, there are some substantial differences concerning the time-related parameters. Indeed, looking at the advection speed $U_{\text{adv}}$, it is influenced by the manoeuvre type. In fact, for a yaw increase manoeuvre this parameter is consistently higher than
Table 3. Dynamic case measurements.

| Case | set-up | Porosity [%] | Yaw | $\frac{d\theta}{d\tau} [s]$ | $\tau_\text{start}^*$ | $\tau_\text{end}^*$ | $\tau_\text{ratio}^*$ | $U_{\text{adv}} [m/s]$ | $\frac{U_{\text{adv}}}{U_{\text{ref}}}^*$ |
|------|--------|--------------|-----|-------------------|------------------|-----------------|------------------|----------------|-----------------|
| 5    | HIT    | 57           | +   | 0.23              | 5                | 12.8            | 0.92             | 4.7            | 0.78            |
| 6    | HIT    | 67           | +   | 0.20              | 4.8              | 12.8            | 0.93             | 5              | 0.82            |
| 7    | HIT    | 57           | -   | -0.25             | 6.7              | 13.9            | 0.85             | 3.4            | 0.57            |
| 8    | HIT    | 67           | -   | -0.24             | 6                | 12.6            | 0.77             | 3.9            | 0.64            |
| 9    | ABL    | 57           | +   | 0.16              | 4.9              | 14              | 0.91             | 4.3            | 0.86            |
| 10   | ABL    | 57           | -   | -0.19             | 7.5              | 15.3            | 0.77             | 2.8            | 0.56            |

in case of a yaw decrease one. According to the related higher value of $\tau_\text{start}^*$ in the case of yaw decrease, this suggests that the wake reacts later in case of yaw decrease manoeuvre. Looking at the duration, in case of yaw increase, $\tau_\text{ratio}^*$ is generally consistently above 0.9 suggesting a quasi-static behaviour of the wake dynamics, while in case of yaw decrease, $\tau_\text{ratio}^*$ is below 0.9 suggesting an accelerated wake deviation. Analogous considerations can be done looking at $\frac{U_{\text{adv}}}{U_{\text{ref}}}^*$.

Figure 6. Time evolution of $\theta$ (dots) and $\gamma$ (lines) during a dynamic yaw variation in HIT conditions. Yaw increase and decrease are represented on the left and on the right respectively. Symbols: • cases 5&7, ◆ cases 6&8.

Figure 7 shows a comparison between the HIT and ABL conditions, only cases 5&7 of HIT conditions are depicted. Concerning cases 9&10 for ABL conditions, their trends show a general good accordance with the respective HIT conditions. However, in spite of an average of 1000 image pairs for the velocity field, a more noisy time evolution is retrieved from measurements under ABL conditions, due to the more in-homogeneous flow and the higher level of turbulence.

From these results, it is possible to estimate the characteristic time parameters for ABL conditions. It can be deduced that the ABL presence does not seem to affect significantly the wake behaviour. Indeed, for ABL conditions, the advection speed $U_{\text{adv}}$ also seems influenced by the kind of manoeuvre such as $\tau_\text{ratio}^*$ and the other parameters. Nevertheless some considerations regarding the yaw manoeuvre should be done. As it can be observed in figure 7, although the yaw manoeuvre curves have substantially the same start and end times, they show a slight difference regarding their slope. This difference is due to the scaling of the yaw manoeuvre motion. Indeed in HIT conditions, the model is at a lower scale and consequently, the aerodynamic time scale $\tau_0$
is lower. This implies a different path caused by the higher acceleration imposed to compensate the transitory of the system. This discrepancy in the yaw motions does not seem to particularly affect the wake behaviour, but unfortunately, may create a bias in the duration estimation, especially if it is estimated with the same method used for the estimation of the wake deviation duration. Practically, according to the protocol applied to estimate the yaw manoeuvre duration, this causes a difference in the estimation of the order of 0.5τ0 in the case of HIT set-up. Despite this difference, it was chosen to maintain this protocol because there is no risk to underestimate the yaw motion time which would overestimate the dynamic behaviour of the wake deviation.

5. Conclusion
The aerodynamic response of a modelled wind turbine wake has been analyzed in two different set-ups and experimental conditions reproducing opposite misalignment scenarios. In both cases, static and dynamic yaw variations were performed. First, the phenomenon was studied in a homogeneous isotropic turbulent flow in order to isolate the effect of the yaw variation on the wake behaviour. Second, the same analysis was performed in a more realistic flow environment such as the atmospheric boundary layer. The results enable to observe different behaviours depending on the type of yaw manoeuvres. In the case of yaw increase, the wake seems to have a faster response to the wind turbine manoeuvre than in the case of yaw decrease. This can be noticed looking at the advection speed, that is slowed down by the yaw decrease manoeuvre with a consequent delay on the effect of the yaw control strategy on the wake. Although the yaw decreasing manoeuvre slows down the advection velocity and consequently the wake reaction to the yaw, it seems that once started, the wake displacement is slightly faster in case of yaw decreasing than in case of yaw increasing. Finally, the presence of the ABL does not seem to affect significantly the wake dynamics giving relevance to the use of the results obtained in a less realistic flow such as HIT conditions as the reference case for the study of the wake dynamics. In conclusion, the results obtained in this work confirm and go further than the preliminary study done in [8]. Indeed it has been possible to better quantify the effect of the yaw manoeuvre on the wake deviation and to assess the influence of ABL conditions.

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