Influence of the direction of rotation on the wake characteristics of closely spaced counter-rotating vertical-axis wind turbines

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Abstract. Closely spaced counter-rotating vertical-axis wind turbines (VAWTs) exhibit a considerable power improvement compared to the same turbines in isolation. It thus makes sense to study their potential for wind farm production optimisation. With this objective in mind, the wake of an isolated VAWT is compared experimentally to the wake of counter-rotating VAWTs. Because of the unsteady aerodynamics, the wake of an isolated VAWT deflects towards the region behind its upwind moving blade. The direction of rotation thus directly influences the deflection of the wake. For paired configurations, it is possible to use this wake deflection as an advantage. A pair of counter-rotating VAWTs where the upwind moving blades are at the centre of the pair, exhibits a particularly narrow wake. With the benefit of a power improvement and a narrow wake, closely spaced counter-rotating VAWTs exhibit promising characteristics to improve the power density in a wind farm.

1. Introduction
Vertical-axis wind turbines (VAWTs) exhibit potential for specific niche applications [1, 2]. Although VAWTs are nowadays not able to challenge the individual efficiency of horizontal-axis wind turbines [3], they are being considered for their unique advantages, e.g. position of the drive train, insensitivity to wind direction, lower centre of gravity. One recurring proposed application is, for example, the use of VAWTs on offshore floating platforms [4, 5].

Another important driver for the increasing popularity of VAWT research has been the study of closely spaced counter-rotating VAWTs. Paired VAWTs benefit from a substantial power increase [6]. Driven by this motivation, paired VAWTs have been studied through open-field tests [7] and numerical simulations [8, 9]. Several wind tunnel studies also focus on the study of paired VAWTs, e.g. [10], but such experimental studies remain relatively scarce.

A novel concept proposes the combination of paired VAWTs and floating platforms for offshore wind farms [11]. Undeniably, when considering wind farm applications, the wake becomes an influential characteristic to optimize wind farm power production. The present study focusses on the wake of closely spaced counter-rotating VAWTs. More specifically, it focusses on the effect that the direction of rotation of the paired VAWTs has on the propagation of the wake.
2. Methodology

2.1. Experimental setup

This work contributes to the understanding of paired VAWTs, thanks to its novel perspective on the subject, i.e. an experimental approach. For this study, a dedicated experimental setup is designed to position two vertical-axis wind turbine rotors with respective drive trains in proximity of each other. A floating floor is installed below the rotors to simulate the proximity of ground or water.

The rotors are straight-bladed H-type Darrieus rotors, Figure 1. The height $H$ is 0.800 m, the diameter $D$ is 0.500 m and the blade chord $c$ is 0.050 m. The rotors have a solidity of $\sigma = bc/D = 0.20$ with $b$ the number of blades ($b = 2$). They operate at tip-speed ratio $\lambda = \omega (D/2)/U_0 = 3$ ($\omega$ = rotational speed, $U_0$ = unperturbed wind velocity). Their design and operation is more extensively described in [12].

In paired configuration, the inter-turbine spacing between the rotors corresponds to 1.3D shaft-to-shaft (expressed in diameters). Two paired configurations are considered:

(i) The inner-downwind configuration, where the blades at the middle of the pair move along with the wind (Figure 2, top);

(ii) The inner-upwind configuration, where the blades at the middle of the pair move against the wind (Figure 2, bottom).

The GVPM wind tunnel of PoliMi is used in this study because of its large test section (width × height × length = 13.84 m × 3.84 m × 35 m). The blockage induced by the setup is 2% and is considered negligible. Based on $U_0 = 10.7$ m/s, the average chord based Reynolds number, defined as:

$$Re_c = \frac{c\lambda U_0}{\nu},$$

is 110 000 ($\nu$ = kinematic viscosity). The turbulence intensity in the wind tunnel is 2%. 
2.2. Characterised wake domain and measuring equipment

The wake of the paired VAWTs is characterised at three downwind distances. Downwind positions are normalised by $D$ (an equivalent diameter is also defined, see Section 2.3). Measurements have been carried out at downwind distances ($x$-direction) of 4D, 6D and 12D. Each downwind position was characterised at 34 lateral positions ($y$-direction) and at 5 different heights ($z$-direction).

The reference value of $z = 0$ m corresponds to the mid-span height of the rotors. An upwind Pitot-static tube measures $U_0$. A vertical arm equipped with 5 sensors at different heights (4 Cobra probes and 1 omniprobe) is moved laterally to measure the wake. Three-dimensional velocity components are measured, defined by $u$, $v$ and $w$ in the direction of $x$, $y$ and $z$ respectively.

The lateral range of the measurements spans 2 m. In between this specified range, measurements are carried out with lateral intervals of $6.25 \times 10^{-3}$ m ($0.125D$ when normalised).

Table 1 summarizes some important characteristics of the measurements.

| Probe type       | $x/D$ [-] | $y/D$ [-] | $z$ [m] | $f_s$ [Hz] |
|------------------|-----------|-----------|---------|-----------|
| Pitot-static tube| $-7.5^*$  | 0         | 0.00    | 2000      |
| Cobra probe      | 4, 6, 12  | $-2 < y/D < 2$ | $\pm0.25$, $\pm0.50$ | 2000      |
|                  |           | $\Delta y = 0.125$         |         |
| Omniprobe        | 4, 6, 12  | $-2 < y/D < 2$ | 0.00    | 500       |
|                  |           | $\Delta y = 0.125$         |         |

* $f_s$ = sampling frequency

** negative value refers to upwind distance.

2.3. Post-processing

The results presented in this study are based on discrete measurements in the wake of various VAWT configurations. In order to create a spatial representation of the wake, contour plots are presented using a linear interpolation, Figures 4 to 6.

An equivalent diameter $D_{eq}$ is defined for the paired configuration by taking into account the spacing between the turbines $s$ which is $0.3D$:

$$D_{eq} = 2D + s.$$  \hspace{1cm} (2)

The further presented figures all depict downwind distances as $x/D$ in order to maintain clarity. However, to compare turbines of equal size and power, $D_{eq}$ is introduced. Table 2 compares downwind distances normalised by $D$ and $D_{eq}$.

Table 2: Comparison of downwind distances normalised by $D$ and $D_{eq}$

| $x/D$ | $x/D_{eq}$ |
|-------|------------|
| 4     | 1.74       |
| 6     | 2.61       |
| 12    | 5.22       |

3. Results

3.1. Wake of an isolated vertical-axis wind turbine

Measurements in the wake at mid-span of an isolated VAWT are used as a baseline to compare afterwards with the paired configurations. The blue curves in Figure 3a correspond to velocity
measurements at three downwind distances (4D, 6D and 12D). The blue vertical lines on the figure correspond to the outer dimensions of the area swept by the VAWT in isolation. On Figure 3a, each left blue line corresponds to the location of the upwind moving blade and each right blue line corresponds to the location of the downwind moving blade.

The asymmetric wake of the VAWT is retrieved in these measurements, i.e. the lowest velocity retrieved in each velocity profile is located behind the upwind moving blade. VAWTs typically exhibit this asymmetric wake induced (amongst other parameters) by the aerodynamic variation along the azimuthal position. A blade moving against the wind is exposed to higher wind speeds and different angles of attack than a blade moving along with the wind. The lateral asymmetry of the wake thus depends on the direction of rotation of the rotor.

In Figure 3b, the velocity profiles of the isolated VAWT have been shifted along $y/D$ to allow comparison with a paired rotor turning the same direction (discussed in Section 3.2). In this figure, the left and right vertical blue lines still correspond to the location of the upwind moving blade and downwind moving blade.

### 3.2. Mid-span velocity profiles

The wake of the paired configurations is compared to the wake of the isolated configuration by means of their corresponding mid-span velocity profiles (Figure 3). The outer dimensions of the area swept by the second rotor are indicated with grey vertical lines. Two wake characteristics are compared: the lowest normalised velocity and the width of the wake. We define the width here as the distance between the points where the velocity reaches 80% of the freestream value. The choice for 80% (as opposed to the customary 99%) was required to guarantee that end points were found within the spatial range for all downstream positions.

At downwind distance 4D and 6D, the magnitude of the minimum normalised velocity in the wake of the paired configurations is similar to the isolated configuration. For the three configurations, the minimum velocity is reduced to below 10% of its unperturbed condition at $x/D = 4$ and recovers to about 40% at $x/D = 6$. The position of the minimum normalised velocity, however, differs for the inner-upwind configuration and the isolated configuration (e.g. Figure 3b at 6D). The wake of the closely spaced second VAWT thus obstructs the normal deflection.

Further downwind ($x/D = 12$), the minimum retrieved velocity in the wake is about 75% for both the isolated configuration and the inner-downwind paired configuration, Figure 3a. For the inner-upwind paired configuration the minimum velocity is recovered to 65% of $U_0$, Figure 3b.

The inner-downwind pair exhibits a relatively wide wake influenced by the location of the large velocity deficits which are near the outer edges of the pair. For the inner-upwind paired configuration, the large velocity deficits are located around the centre of the wake. Thus, at 12D, the wake width of the inner-downwind configuration has increased to $1.7D_{eq}$ (similar to the expansion of the isolated wake with respect to $D$), while the inner-upwind pair only expands up to $1.1D_{eq}$.

### 3.3. Streamwise velocity

A VAWT pair with inner-downwind moving blades exhibits two individual wakes deflecting outwards, Figures 4a to 4e. The result is a relatively large wake. This is not the case for the wake of an inner-upwind pair, Figures 4f to 4j. Here, the two originally-independent wakes deflect towards each other resulting in a narrower wake. At mid-span ($z = 0$ m, Figure 4h), normalised velocities of $u/U_0 = 1$ are retrieved almost immediately outside the downwind-projected boundaries of the rotors (indicated with the solid black lines on the figures).

Layers in the wake below $z = 0$ exhibit similar flow velocities in both configurations, independent of the direction of rotation. In both configurations the flow is reduced to 0.5$U_0$ at $x/D = 4$. The location of this reduced flow is at the outside of the pair for the inner-downwind
configuration and at the middle of the pair for the inner-upwind configuration. However, the inner-upwind configuration also induces a region where the flow is reduced to $0.5U_0$ under the VAWTs, Figure 4f. Vertical induced velocities are responsible for the vertical expansion of the wake. This feature remains absent in the inner-downwind configuration, Figure 4a.

Above mid-span, the vertical expansion of the wake of the inner-upwind pair also induces a narrow channel of normalised flow around $0.5U_0$, figures 4i and 4j. Outside of the centrally reduced flow velocity, magnitudes of the flow range around $u/U_0 = 1$. Even above the VAWT rotors, the inner-upwind configuration still exhibits this narrow channel, Figure 4j, which is not present for the inner-downwind configuration. Here, reduced flow velocities are located at the outside of the pair. Above the VAWTs, this reduced flow is mostly dissipated where minimal flow velocities range around $0.8U_0$, Figure 4e.

3.4. Streamwise turbulence intensity
In this study, the turbulence intensity is defined as:

$$I_u = \frac{\sigma_u}{U_0}$$

(3)

where $\sigma_u$ corresponds to the local standard deviation of the streamwise velocity. The property gives insights on the occurrence of unsteady aerodynamics and sheared flow inducing higher turbulence, Figure 5. A region of high turbulence intensity deflects outwards for the inner-downwind rotating pair (Figure 5a) and contracts for the inner-upwind rotating pair (Figure 5b).
Figure 4: Streamwise normalised velocities in xy-planes at different heights for the inner-downwind configuration (left) and the inner-upwind configuration (right).
Figure 5: Turbulence intensity, defined as $I_u$, in $xy$-plane for the inner-downwind configuration (left) and the inner-upwind configuration (right).

The configurations differ from each other with regards to the streamwise distance that the turbulence intensity propagates. There appears to be a cancellation mechanism enhancing the dissipation of the turbulence for the inner-upwind configuration, Figure 5b. Flow regions where $I_u$ exhibits magnitudes around 0.15 are almost completely dissipated at $x/D = 6$. On the other hand, for the inner-downwind configuration, such magnitudes persist until $x/D = 8$.

The turbulence intensity also differs around the middle of the pair. While almost no increase in $I_u$ is observable between the rotors of the inner-downwind configuration, some increase is observed between the rotors of the inner-upwind configuration. The inner-upwind configuration exhibits centrally located levels of turbulence intensity around $I_u = 0.15$. The analysis of vertical influx contributes to the understanding of this as this is a location of highly sheared flow.

3.5. Vertical velocity

The vertical velocity component $w$ indicates vertical influx of high velocity flow into the wake. Figure 6 illustrates this vertical velocity component normalised by $U_0$, i.e. $w/U_0$. The direction of rotation of the VAWT pair widely influences the vertical influx, mostly with respect to the location where vertical influx occurs. The planes at $z = 0.25$ m indicate a downward influx with a magnitude around $0.1U_0$ (figures 6c and 6f, blue zones). The inner-upwind configuration differs however, from the inner-downwind configuration with a central region of upwards moving flow (central red zone in Figure 6f). This upwards moving flow induces locally sheared flow resulting in turbulence near the middle of the pair (observed in Section 3.4).

At mid-span ($z = 0.00$ m), the vertical flow exhibits a substantially different image from the previously-described higher planes. In the near wake, both the inner-downwind and inner-upwind configurations indicate upwards moving flow. Further downstream, between $x/D = 4$ and 6, the former one exhibits two independent regions of downwards moving flow. At mid-span, the downwards vertical influx thus remains the dominant influx promoting the recovery of the wake.

The wake of the inner-upwind configuration at mid-span is characterised by similar vertical
movements. A major difference consists of the fact that the flow moves downwards at the centre of the pair. Upwards moving flow replenishes the wake from the outer sides of the pair. The vertically sheared flow regions (white regions), correspond well with the images created based on the streamwise turbulence intensity.

Vertical influx in the wake also occurs at lower heights, figures 6a and 6d. The flow escapes the wake vertically behind upwind moving blades. The regions behind downwind moving blades are regions of high velocity flows entering the wake. The result is one central region of upward moving flow behind the centre of the inner-downwind configuration. This similar region is divided into two regions of vertically upwards moving flow for the inner-upwind configuration, where the downwind moving blades are at the outside of the pair, Figure 6d.

3.6. Spectral content

The spectral content of the wake measurements reveals the presence of periodic disruptions in the flow. This spectral analysis focuses on \( x/D = 4 \) at two different heights, \( z = 0.00 \) m and \( z = 0.50 \) m. A power spectral density (PSD) is calculated for each lateral position. These PSDs are graphically represented alongside each other to create a three-dimensional view of the PSD in the wake, Figure 7. The x-axis corresponds to the frequency scale, \( f \). The y-axis corresponds to the normalised lateral position, \( y/D \) (the different PSDs are plotted side-by-side along this
The vertical z-axis (logarithmic) shows the magnitude of the PSD which also corresponds to the colour scale. By means of indication, the centre position of each VAWTs is projected on the vertical plane with a solid line (at $f = 0$). The dashed lines on either side of the solid lines indicate the outside boundaries of the swept area of the respective VAWT.

A common observation of the four spectra is that the PSDs are high behind the upwind moving blades. Depending on the direction of the wake deflection, these high levels of unsteadiness occur at the outside of the pair (inner-downwind configuration) or at the middle of the pair (inner-upwind configuration).

At mid-span of the inner-downwind configuration, the broadband unsteadiness (between 0 Hz and 20 Hz) are retrieved over the complete span of the paired configuration, including the spacing between the turbines (Figure 7a). However, the energy of the PSD between the turbines is slightly lower than directly behind the turbines. In Section 3.3, a high velocity channel was observed between the two turbines. This high velocity locally enhances the dissipation of vortices. On the other hand, $y/D = 0$ corresponds to the most energetic frequencies retrieved in the mid-span wake of the inner-upwind configuration, Figure 7c. However, for both configurations, the spacing between the turbines is a region characterised by a rapid decay towards the level of unsteadiness in the free stream (blue PSDs at the outside of the pairs).

The spectral content at $z = 0.50 \text{ m}$ is more sensitive to tip-vortices as the rotor dimensions are exceeded at $z = 0.40 \text{ m}$. Three regions where the PSD is high are observed in Figure 7b: two behind the upwind moving blades ($y/D = \pm 1.1$) and one between the two turbines ($y/D = 0$). At 20 Hz, the rotational frequency, energetic peaks are retrieved behind the upwind moving blades and in between the two turbines. More peaks are also observed between the two turbines at 40 Hz, corresponding to the blade passing frequency.

In contrast, Figure 7d does not exhibit as many energetic peaks. The high energy frequencies are again located behind the upwind moving blades (between $y/D = \pm 0.5$). Furthermore, some energetic peaks are observed at $f = 20 \text{ Hz}$ but none are observable at the blade passing frequency of 40 Hz.

In general, the PSDs are high behind the upwind-moving blades. Thus, especially in this azimuthal range, the rotors are a source of unsteadiness in the form of e.g. vortical structures and sheared flow leading to turbulence.

4. Discussion and conclusion

The wake of closely spaced counter-rotating paired VAWTs exhibits a sensitivity to the direction of rotation. The wake of a pair where the inner blades move downwind deflects outwards, while the opposite is true for the wake of a pair where the inner blades move upwind.

In the streamwise direction, the two configurations exhibit similar velocity magnitudes. However, the wake differs just above and below the VAWT pair. In the inner-upwind configuration, the wake of the VAWTs expands vertically inducing velocity deficient flow regions above and below the VAWT dimensions. This vertical expansion is induced by the lateral deflection of the wakes towards each other, leaving the flow no other escape than vertically.

The vertical influx is comparable for the two pairs, i.e. vertical influx from above or below the wake occurs mostly behind the downwind moving blades. The region behind the upwind moving blades is a region where velocity deficient flow leaves the wake vertically.

The mid-span wake is characterised by unsteadiness even though the rotation frequency and blade passing frequency can be identified. Disruptions propagate mostly behind the upwind moving part of the rotation. Around the middle of the pair, interaction between the two VAWTs is responsible for locally higher unsteadiness.

At higher positions, the disruptions (amongst which tip-vortices), are concentrated behind the upwind moving part of the rotation. This mechanism induces large differences between the inner-downwind and inner-upwind moving blades. The high velocity channel between the VAWTs
is also a region of increased unsteadiness.

The wakes presented in this study have been characterised for VAWTs in neutrally buoyant flows, i.e. the effects of stratified flows or convectively unstable flows have not been considered. Such phenomena will, however, influence the wake propagation in the atmospheric boundary layer, where characteristics such as vertical flow movement, turbulent kinetic energy production and dissipation rates will be influenced (see, e.g. [13]).

To conclude, the wake of a VAWT migrates behind the upwind-moving blades. These are located at the outside of the pair for the inner-downwind configuration. The result is a relatively large wake deflecting outwards. Because the upwind moving blades are located at the middle of the pair for the inner-upwind configuration, this configuration induces a narrower wake. In terms of their wake, the inner-upwind configuration is thus the most promising configuration for wind farm power production optimization.

All streamwise distances have been expressed in terms of the diameter, $D$. For the paired configuration an equivalent diameter, $D_{eq}$ indicates that the wake is relatively shorter than for isolated rotors. Furthermore, a previous study has demonstrated experimentally that paired VAWT configurations produce up to 16% more energy than two isolated VAWTs [6]. Paired VAWTs thus allow for higher power densities in wind farms than isolated VAWTs.
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