Impact of relative spacing of two adjacent vertical axis wind turbines on their aerodynamics

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Abstract. The impact of relative spacing on the individual and overall performance of two adjacent co-rotating Darrieus H-type VAWTs is investigated through high-fidelity URANS simulations, validated with experimental data. The simulations cover relative distances of 1.25d ≤ R ≤ 10d (d: turbine diameter) and relative angles of 0° ≤ Φ ≤ 90°. The relative angles of 30° ≤ Φ ≤ 75° with relative distance range of 1.25d ≤ R ≤ 5d are identified as the optimal regime with the highest overall power performance for the array. In this regime, the downstream turbine has a maximum increase of 5.1% in CP (R = 1.5d and Φ = 45°) with respect to an isolated solo rotor with similar characteristics. Local flow characteristics including wake length, wake expansion, vorticity and velocity fields are also investigated. It is found that for azimuthal angles of 90° ≤ θ ≤ 160° in the optimal regime, regions of accelerated flow are created due to the contraction of the flow between the turbines which benefit the downstream turbine CP and thus the overall power performance of the array. This provides an opportunity for a compact placement of turbines within a vertical-axis wind turbine farm and consequently increasing the farm power density.

Nomenclature

| Symbol | Description |
|--------|-------------|
| Cₘ   | Momentum coefficient [-] |
| Cₚ   | Power coefficient [-] |
| d    | Turbine diameter [m] |
| dθ   | Azimuthal increment [°] |
| R    | Relative distance [-] |
| Reₙ  | Chord-based Reynolds number [-] |
| TI   | Turbulence intensity [%] |
| TurbI | Upstream turbine |
| TurbII | Downstream turbine |
| u    | Streamwise velocity [m/s] |
| Uₙ   | Freestream velocity [m/s] |
| v    | Lateral velocity [m/s] |
| β    | Windward wake expansion [°] |
| γ    | Leeward wake expansion [°] |
| λ    | Tip speed ratio [-] |
| σ    | Solidity [-] |
| Φ    | Relative angle [°] |
| Ω    | Rotational speed [rad/s] |

1. Introduction

Vertical axis wind turbines (VAWTs) are of high interest in offshore [1,2] and onshore wind energy harvesting applications [3,4], especially in locations with frequent changes in wind direction, e.g. urban areas [5,6] and floating offshore wind farms [7]. The escalating appeal of VAWTs is due to their many advantages over horizontal axis wind turbines (HAWTs) including omni-directionality, scalability, and relatively smaller size [8,9]. In addition, earlier studies have reported a high potential for VAWT wind farms for reaching relatively higher power densities (e.g. [10]). This is highly appreciated in dense urban areas, where there is a shortage of available space for wind energy harvesting systems [5].

When wind turbines operate in an array, the relative spacing of the adjacent turbines (i.e. distance and angle between the turbines) influences the individual and overall performance of the turbines [9,11].
While the impact of the relative spacing on the individual and overall performance of adjacent HAWTs has been studied [11], to the best of our knowledge, it has not yet been comprehensively investigated for closely spaced VAWTs. Therefore, the current study systematically investigates the power performance and local flow characteristics of an array of two adjacent co-rotating VAWTs. The findings of this study can provide fundamental insights into the aerodynamic performance of two adjacent VAWTs, as the smallest unit of a wind farm, and support wind farm layout design to reach a higher power density per area of land.

The remainder of the paper is organized as follows: Section 2 details the computational settings and parameters including geometrical and operational characteristics of the turbines, computational domain and grid, computational settings, solution verification and validation. The impact of relative spacing on the power performance of the turbines and the local flow characteristics is investigated in Sections 3 and 4, respectively. Conclusions follow in Section 5.

2. Computational settings and parameters
Sixty three high-fidelity 2D URANS simulations, validated with experimental data, are carried out on two adjacent co-rotating Darrieus H-type VAWTs in seven center-to-center relative distances (R) and nine relative angles (Φ) (Table 1).

| Center-to-center distance (R) [d] | 1.25d, 1.5d, 1.75d, 2.25d, 3d, 4d, 5d, 10d |
|----------------------------------|--------------------------------------------|
| Relative angle (Φ) [°]           | 0°, 5°, 10°, 15°, 30°, 45°, 60°, 75°, 90° |

The results of a detailed sensitivity analysis show that for R ≥ 10d the turbines have negligible effects on one another. Therefore, relative distances larger than 10d are not included in the test matrix and the simulations. Further information on the sensitivity analysis will be presented in Sections 3 and 4.

2.1. Geometrical and operational characteristics of the turbines
The simulated turbines are single-straight-bladed Darrieus H-type VAWTs, schematically depicted in Figure 1. The geometrical and operational parameters of the turbines (Table 2) are selected with respect to the wind-tunnel measurements by Tescione et al. [12], which is also employed for the validation study (see Section 2.4).

![Figure 1. Schematic depiction of the turbines.](image)
Table 2. Geometrical and operational characteristics of the studied turbines.

| Parameter                | Value | Parameter                   | Value |
|--------------------------|-------|-----------------------------|-------|
| Number of blades, n [-]  | 1     | Tip speed ratio, λ [-]      | 4     |
| Diameter, d [m]          | 1     | Rotational speed, Ω [rad/s] | 74.4  |
| Height, H [m]            | 1     | Free-stream velocity, U_∞ [m/s] | 9.3   |
| Swept area, A [m²]       | 1     | Turbulent intensity, TI [%] | 5     |
| Solidity, σ [-]          | 0.06  | Chord-based Reynolds number, Re_c [×10⁵] | 1.57  |

2.2. Computational domain and grid

The computational domain consists of two co-rotating cores for the two rotors and a fixed surrounding domain. The relative distance of the two turbines (R) is defined as the length of the turbines’ center to center line. The relative angle (Φ) is defined as the angle between the turbines’ center to center line and the X-axis. Relative spacing is, therefore, the combination of R and Φ. The size of the computational domain is 35d × 40d, which is based on the best practice guidelines for CFD simulations of VAWTs [15,16] (Figure 2a).

The number of cells ranges from 0.7 to 1.2 million cells based on a systematic grid sensitivity analysis. The maximum y’ is below 4.4. Figures 2b-e illustrate a sample computational grid for one of the arrangements, consisting of ≃0.85 million quadrilateral cells.

![Figure 2. (a) Computational domain, (b, c, d and e) sample computational grid.](image)

2.3. Computational settings

The computational settings that are used in the simulations are based on the best practice guidelines for accurate CFD simulation of VAWTs [3,4,15–17] (Table 3). The boundary conditions are detailed in Table 4. The sliding grid interface technique [18] is used for the interface between the rotating cores of the two rotors and the fixed domain.
| Table 3. Computational settings. |
|----------------------------------|
| CFD approach                     | Incompressible unsteady Reynolds-averaged Navier-Stokes (URANS) |
| Solver                           | ANSYS Fluent v19.1 [19] |
| Turbulence model                 | 4-equation transition SST with curvature correction (γ-Reθ model) [20] |
| Pressure-velocity coupling scheme | SIMPLE |
| Discretization order (time and space) | 2nd order |
| Transient formulation            | Second-order implicit |
| Azimuthal increment, d0 [°]       | 0.1 |
| Number of turbine revolutions to reach statistical convergence [-] | 20 (presented results are sampled at 21st revolution) |

| Table 4. Boundary conditions. |
|--------------------------------|
| Inlet                          | uniform mean velocity; total turbulence intensity = 5% (the incident TI is 3.65% due to turbulence decay in the domain [4]) turbulence length scale = 1 m (= d); Intermittency = 1 |
| Outlet                         | zero static gauge pressure |
| Side boundaries                | symmetry |
| Blades                         | no-slip wall |

2.4. Solution verification and validation

To investigate the dependency of the results on the computational grids, three uniformly refined grids with a linear refinement factor of $\sqrt{2}$ are simulated for a sample case (Table 5 and Figure 3).

| Table 5. Grid-sensitivity analysis specifications. |
|-----------------------------------------------|
| R [m] | $\Phi$ [°] | Number of cells [-] | Number of segments on the airfoil [-] |
|       |            | Coarse grid | Medium grid | Fine grid | Coarse grid | Medium grid | Fine grid |
| 1.25  | 0°         | 414,096    | 745,422    | 1,381,353 | 565        | 800        | 1,130     |

Instantaneous momentum coefficient ($C_m$), streamwise velocity ($u$) and lateral velocity ($v$) are compared for the three grids (Figure 4). Negligible differences are observed in $C_m$ and velocity components among the three grids for both of the upstream and downstream turbines. Therefore, the medium grid is selected for the rest of the study.

Figure 3. Computational domain for the grid sensitivity analysis.
Figure 4. Grid-sensitivity analysis, (a) Instantaneous moment coefficient ($C_m$) for TurbI, (b) $C_m$ for TurbII, (c) normalized mean lateral velocity and (d) normalized mean streamwise velocity in a downstream distance of $x/d = 0.625$, 2 and 4 of the upstream turbines.

CFD simulations are validated through three separate validation studies previously performed for Darrius H-type VAWTs [16,17]. These validation studies compare the CFD results against the following experiments:

a. The experiment by Ferreira et al [21] where the vorticity field and characteristics of the separated/shed leading-edge vortex for the turbine blade in dynamic stall are reported;

b. The experiment by Tescione et al [22] where the time-averaged normalized streamwise and lateral velocity components along the lateral direction at different streamwise positions in turbine wake are reported;

c. The experiment by Castelli et al [23] where turbine power coefficient at different tip speed ratios are reported.

3. Power performance

Figure 6 shows the power coefficient ($C_p$) values of the turbines at different $\Phi$ for $R = 1.25d$, 1.5d, 2.25d, 3d, 5d and 10d. In this figure, the individual and overall $C_p$ of each arrangement is normalized by the $C_p$ of a solo turbine in an isolated setting with similar geometrical and operational characteristics ($C_p$Solo). The results show that for all the relative distances ($R$), at the relative angle range of $30^\circ \leq \Phi \leq 75^\circ$, TurbII experiences an increased $C_p$ compared to the $C_p$Solo, with a maximum increase of 5.1% in $R = 1.5d$ and $\Phi = 45^\circ$ (Figure 6b). The results also indicate that in all the cases, within the aforementioned range of $\Phi$, the mean overall $C_p$ value of the arrangement is very close to or slightly greater than $C_p$Solo ($C_{p\text{overall}}/C_{p\text{Solo}} \geq 1$), indicating that even though the two VAWTs are in close proximity, they do not have a negative impact on one another. In some cases, they even improve the power performance of one another and consequently the overall performance of the array.

Figure 5. Instantaneous moment coefficient ($C_m$) for (a) TurbI and (b) TurbII in the selected arrangements.
In order to explain the power performance enhancement in the downstream turbine (TurbII) and values of \( C_{p,\text{TurbII}}/ C_{p,\text{Solo}} \gtrsim 1 \), instantaneous momentum coefficient (\( C_m \)) for three selected cases (\( R = 1.5d, \Phi = 0^\circ, 45^\circ \) and \( 90^\circ \)) in comparison to that of an isolated solo turbine are presented in Figure 5. These three selected cases represent the whole test matrix and different regimes identified in the arrangements (see Section 5). Whilst the instantaneous \( C_m \) values of the TurbI are very close (Figure 5a), there are significant differences in the \( C_m \) values of the TurbII between the selected cases (Figure 5b).

**Figure 6.** Effect of relative angle (\( \Phi \)) on turbines’ individual and overall performance for different relative distances (R).
As expected, $C_{m,\text{TurbII}}$ for the selected case with $\Phi = 0^\circ$ is constantly lower than that of the other arrangements as the TurbII is located in the wake of the TurbI and experiences much lower velocities (see Section 4.3 and Figure 8b). For $\Phi = 45^\circ$, $C_{m,\text{TurbII}}$ is slightly higher than that of the solo turbine and the selected case with $\Phi = 90^\circ$. Further discussion of the flow field is presented in Section 4.

4. Flow field

To identify the mechanisms that lead to the power performance enhancement/reduction of the double-rotor arrays, local flow characteristics of the turbines is compared against that of an isolated solo turbine for three selected cases: (i) $R = 1.5d$, $\Phi = 0^\circ$; (ii) $R = 1.5d$, $\Phi = 45^\circ$; and (iii) $R = 1.5d$, $\Phi = 90^\circ$.

4.1. Wake characteristics

The wake characteristics (e.g. wake length, width and expansion rate) of upstream turbines within a wind farm are important factors in the layout design of the farm [11]. In general, for HAWTs, to have a high power performance in the farm, corresponding to an ideal aerodynamic case, the turbines should not be placed in the wake of one another. However, this is not cost effective considering the cost of land and thus not practical [24]. Therefore, in practice, downstream turbines within a HAWT wind farm are typically placed fully/partially in the wake of the upstream ones. However, this is not the case for the VAWT wind farms and they can be placed in much closer distances, not having a negative impact on one another and even in some cases, enhancing the power performance/density of the wind farm [10].

Table 6 details the wake length of the three sample arrangements in comparison to a solo turbine. The wake length is defined as the streamwise distance between the upstream turbine (TurbI) center and the point in the wake where $u/U_\infty = 0.97$. According to the table, the impact of the relative angle on the wake length of the array is 9.3% for $\Phi = 0^\circ$. Increasing the relative angle of the turbines from $0^\circ$ to $90^\circ$ is found to decrease the wake length increase to 3.1% higher than the solo turbine.

Table 6. Wake length of the selected cases compared to the solo turbine.

| Sample arrangement ($R = 1.5d$) | $\Phi = 0^\circ$ | $\Phi = 45^\circ$ | $\Phi = 90^\circ$ |
|-------------------------------|-----------------|-----------------|-----------------|
| Overall Wake length increase of the farm compared to solo case [%] | 9.3 | 8.9 | 3.1 |

Table 7 details the wake expansion/contraction of the selected sample arrangements compared to the solo turbine. It can be seen that when the turbines are placed in the direct wake of one another, the wake region expands both in length (Table 6) and width. The highest wake expansion occurs for $\Phi = 0^\circ$. At $\Phi = 45^\circ$, however, a significant wake contraction is evident where the flow is contracted between the two turbines, leading to a high-velocity region. Formation of this high-velocity region explains the higher power performance of the TurbII and consequently the overall array for $30^\circ \leq \Phi \leq 75^\circ$.

Table 7. Wake expansion/contraction of the selected Sample arrangements.

| selected cases | TurbI | TurbII |
|----------------|-------|--------|
|                | Windward ($\beta$) | Leeward ($\gamma$) | Windward ($\beta$) | Leeward ($\gamma$) |
| Solo           | 2.7°  | 2.3°   | -      | -     |
| $\Phi = 0^\circ$ | 6.3°  | 5.8°   | 6.3°   | 5.8°   |
| $\Phi = 45^\circ$ | -2.7° | 2.2°   | 3°     | -2.2°  |
| $\Phi = 90^\circ$ | 3.5°  | -0.4°  | 0.4°   | 2.9°   |

4.2. Vorticity field

Figure 7 illustrates the normalized Z-vorticity for the relative distance of $R = 1.5d$ and the relative angles of $\Phi = 0^\circ$, 15°, 30°, 45° and 90°. For $0 \leq \Phi \leq 30^\circ$, significant interaction occurs between the wake of the upstream turbine and the blade of the downstream turbine. In this regime, the aerodynamics of the downstream turbine is largely influenced by the presence of the upstream rotor. For $\Phi = 45^\circ$, the blade of the downstream turbine hardly passes through the wake of the upstream turbine. However, the wakes...
of the two turbines are adjacent and not completely independent yet, which, as explained in Section 4.1, leads to the contraction of the two wakes in comparison to a solo turbine. For $\Phi > 45^\circ$, the wake interactions of the two turbines fade away. The observed trend is in line with the trends observed for the $C_p$ values in Figure 6 in which for the relative angles of $45^\circ < \Phi$, an increase in the $C_p$TurbII values and consequently the $C_p$Overall is found.

![Figure 7. Instantaneous normalized Z vorticity in $\theta = 0^\circ$ for](a) isolated solo turbine and dual rotor arrays with a relative distance of $R = 1.5d$ and a relative angle of (b) $\Phi = 0^\circ$, (c) $\Phi = 15^\circ$, (d) $\Phi = 30^\circ$, (e) $\Phi = 45^\circ$, and (f) $\Phi = 90^\circ$.]

4.3. Velocity field
Figure 8 depicts the instantaneous normalized streamwise velocity field of the selected cases with blades positioned at $\theta = 130^\circ$. The figure shows that at an azimuthal angle of $\theta = 130^\circ$, the blade of the TurbII for the selected case of $\Phi = 45^\circ$, passes through a high-velocity region created due to the contraction of the flow between the two turbines’ wakes (as explained in Section 4.1 and 4.2). This is in line with the higher $C_m$TurbII for this selected case within the range of $90^\circ \leq \theta \leq 160^\circ$ (Figure 5b) and the higher value of $C_p$TurbII (Figure 6b).

5. Conclusions
In this study, 63 high-fidelity URANS simulations, validated with experimental data, are carried out to systematically investigate the effect of relative spacing of the rotors, (i.e. relative distance and relative angle), on the individual and overall power performance and the flow field of two co-rotating, same-phase Darrieus H-type VAWTs in a dual rotor array.

The main conclusions are as follows:
- Three regimes are identified for the dual rotor array:
  - (i) Wake interaction ($0^\circ \leq \Phi \leq 30^\circ$ with $R/d < 5d$): wake regime in which the downstream turbine operates in the direct wake of the upstream turbine and the overall performance of the array is comparatively low;
  - (ii) Synergic interaction ($30^\circ \leq \Phi \leq 75^\circ$ with $R/d \leq 3$): the optimal regime in which the power performance of the downstream turbine and consequently the overall power performance of the array is the highest due to the positive interaction between the rotors;
(iii) Minimal interaction \((75^\circ < \Phi \leq 90^\circ)\): in which the two turbines have little interaction and operate fairly similar to when isolated.

- The optimal relative spacing for the dual rotor array corresponds to \(1.25d \leq R \leq 5d\) and \(30^\circ \leq \Phi \leq 75^\circ\).
- Analysis of the wake shows that the reason for the improved performance of the array in the optimal regime is the creation of high-velocity regions due to the concentration of the flow between the two turbines’ wakes. Further discussion on this can be found at [25].
- The average power performance of the studied dual-rotor VAWT array over all wind directions varies between 87\% and 95\% of that of an isolated solo turbine with the same characteristics (i.e. \(0.87 \leq C_{p,\text{Overall}}/C_{p,\text{Solo}} \leq 0.95\)).

These findings support the high potential for compact arrays of VAWTs with higher power density. This potential higher power density is especially of great value in dense urban areas where there is a shortage of available space for the installation of wind energy harvesting systems.

Figure 8. Normalized streamwise velocity of the selected arrangements in \(\theta = 130^\circ\) for the (a) isolated solo turbine and sample arrangements of (b) \(\Phi = 0^\circ\), (c) \(\Phi = 45^\circ\), and (d) \(\Phi = 90^\circ\).

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