Wind tunnel experiments of a pair of interacting vertical-axis wind turbines

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Abstract.
Vertical-axis wind turbines (VAWTs) have received a renewed interest in the wind energy research community, mainly for off-shore applications. One advantage is that installing a pair of counterrotating VAWTs on the same floating platform would result in thrust reduction and potential cancellation of the mooring yaw moment. In addition, such configurations could benefit from increased power output and reduced wake losses.

In this article, we report on wind tunnel experiments to study the mechanical power output of a reference VAWT scale model, tested individually and in a closely-spaced pair of VAWTs. The power output of the individual VAWT configuration is compared with a pair of VAWTs spaced 1.3 diameters apart for two counterrotating directions. A net power increase in the power coefficient for the paired configuration of up to 17.0% compared with two individual rotors has been observed.

1. Introduction
Vertical-axis wind turbines (VAWTs) were first thoroughly studied in the nineteen seventies and eighties under the impulse of Sandia National Laboratories [1]. Today, it is mainly with off-shore applications in mind that VAWTs are being considered as a viable alternative for horizontal-axis wind turbines (HAWTs), see e.g. [2] or [3].

An important driver for the renewed research interest is the work by Dabiri and his co-workers (see i.a. [4, 5, 6]). He pointed out that large farms of VAWTs potentially achieve much higher power densities, defined as the power output per unit ground surface, than classic HAWT wind farms. A key factor is the mutual interaction between VAWTs when placed in close proximity to each other [7]. The positive effects on power output have been confirmed numerically (see i.a. [8] or [9]).

To the authors’ knowledge, only a few experiments have been performed on VAWTs in the form of open field tests or in controlled wind tunnel labs. The seminal studies at Sandia on individual VAWTs are well known (see i.a. [10, 11, 12, 13]). Other, more recent experimental work has been done on aerofoil design for VAWT applications [14], on the difference between the testing of individual VAWTs in confined and unconfined environments [15], on the impact of testing at low Reynolds numbers [16], and on the wake development behind a VAWT [17]. Some experimental work has been done on two- and three-VAWT arrays [18], but these turbines had...
Figure 1. The two turbines were placed 1.3 times their diameter apart on their respective frames in the assembly. A floating floor was mounted on top of the frames.

Figure 2. Top view of the rotors in paired configuration. Left: the paired inner-downwind configuration. Right: the paired inner-upwind configuration.

2. Experimental setup

The rotors are two-bladed H-type Darrieus turbines with NACA0018 blades and two inclined struts per blade. The average Reynolds number based on the chord length and radius is about 100,000. The VAWT rotor is connected via a torque sensor and a drive belt to a brushed-DC motor. This motor is used to drive the VAWT rotor during start-up and as a generator in normal operation. The torque sensor measures mechanical torque and rotational speed (and thus mechanical power) of the VAWTs.

Benchmark values were set by testing the rotors individually, referred to as the isolated configuration. Each rotor has its respective frame to ensure equal performance. The paired configuration consisted of placing the centre of the rotors 1.3 times their diameter apart (referred to as the 1.3D configuration). Figure 1 shows the rotors and the frames in the 1.3D configuration. A floating floor, which consists of large solid plates on slender feet, was installed to separate the flow region around and behind the turbines from the perturbations in the flow created by the supporting structure.

All interaction tests have been performed with the rotors turning in counterrotating direction. Two paired configurations were tested: One with the inner blades moving downwind, referred to as the 1.3D inner-downwind configuration, and one with the inner blades moving upwind, referred to as the 1.3D inner-upwind configuration, as illustrated in Figure 2.
3. Wind-tunnel corrections

All tests were performed in the Politecnico di Milano GVPM wind tunnel, in its large test section (dimensions: \(14 \text{ m} \times 3.8 \text{ m} \times 35 \text{ m}\)). Testing inside a confined environment compared to the outside environment can alter the natural behaviour of the flow. Different elements are typically considered: solid blockage, wake blockage, the effect of the turbine’s thrust, buoyancy and streamline curvature. The buoyancy and streamline curvature are negligible because of the very large dimensions of the wind tunnel test section.

For the analysis of the blockage and thrust, we define a total blockage correction, \(\epsilon_t\), similar to [19], as the sum of the solid blockage correction, \(\epsilon_{sb}\), the wake blockage correction, \(\epsilon_{wb}\), and the correction for thrust, \(\epsilon_{\text{thrust}}\):

\[
\epsilon_t = \epsilon_{sb} + \epsilon_{wb} + \epsilon_{\text{thrust}}
\]

In [19], they formulate different, often simplified expressions to calculate these correction factors. More recently, Dossena et al. [15] have experimentally studied the aerodynamic performance of a VAWT in confined and unconfined environment. They present experimental blockage corrections both as a function of the tip-speed ratio and as a function of the thrust coefficient.

As their setup is quite similar to ours (low solidity straight bladed VAWT), we have based our blockage correction on their experimentally obtained values. However, their solid blockage ratio, \(\alpha\), defined as the ratio between the frontal swept surface of the rotor(s) and the wind tunnel surface, was 0.10, which is larger than ours. Our solid blockage ratio is 0.9% when testing the turbines in the isolated configuration or 1.8% when testing the turbines in a paired configuration. To apply their blockage correction to our setup, we have assumed that a linear rescaling can be applied. In fact, according to Glauert’s correction formula [20, 21],

\[
\frac{U'_0}{U_0} = 1 + \alpha \frac{C_T}{\sqrt{1 - C_T}}
\]

the blockage correction, is indeed a linear function of \(\alpha\). Although certainly not uniformly valid, this formula seemed to capture the correct trend for a range of thrust coefficients below unity (see Figure 9 of [15]). In the formula, \(U'_0\) and \(U_0\) are the corrected and uncorrected wind speeds respectively, \(C_T\) is the thrust coefficient.

Our blockage correction approach can thus be summarised as follows. Based on the corrected speed suggested in Figure 8 of [15], we found a blockage correction of 9% to be necessary at a tip-speed ratio of 3 and for a solid blockage ratio of 10%. Considering our \(\alpha\) is 11.1 and 5.6 times smaller, we estimate our blockage correction coefficients to be 0.8% and 1.6% for the isolated configuration and the paired configuration respectively. These factors are applied to \(U_0\) to obtain blockage corrected power coefficient and tip-speed ratio values.

4. Performance measurement technique

The mechanical power output of every turbine is individually measured and logged (through the rotating torque sensor). The power coefficient, \(C_P\), is calculated based on the mechanical torque, \(\tau\), and the rotational speed, \(\omega\):

\[
C_P = \frac{P_{\text{mech}}}{P_{\text{wind}}} = \frac{\tau \omega}{\frac{1}{2} \rho D H U_0'^{3/2}},
\]

where the power in the wind is calculated from the corrected wind tunnel speed, \(U'_0\), the air density, \(\rho\), and the frontal swept area of the rotor defined by the diameter, \(D\), and the height of the rotor, \(H\). The wind tunnel speed was measured using Prandtl tubes in front of the VAWT rotors. The tip speed ratio, \(\lambda\), is defined as:
\[
\lambda = \frac{\omega (D/2)}{U_0^2}.
\]  

To study the power output of a pair of VAWTs, the power coefficient is redefined as the simple average of the two individual power coefficients:

\[
\overline{C}_P = \frac{P_1 + P_2}{\frac{1}{2} \rho U_0^3 (2DH)} = \frac{1}{2} (C_{P,1} + C_{P,2}).
\]  

where the index refers to the power (coefficient) of the individual rotors.

5. Reliability of the measurements

Our experimental work is confronted with two types of uncertainties: uncertainties originating from the precision of the data acquisition instruments and uncertainties linked to the processing of the data. In this case it is the latter which predominates. During a test, the turbines are kept at a constant rotational speed for at least sixty seconds. These subsets of constant speed, and thus constant tip-speed ratio, are referred to as a plateau. Every identified plateau is then averaged to obtain one datapoint on a \(C_P(\lambda)\)-curve. A datapoint for the turbine gets accepted when all the following conditions are satisfied:

(i) The voltage generated by the turbines individually is above 20 V;
(ii) The voltage generated by the turbines individually is below 70 V;
(iii) The power generated by the turbines individually is above 30 W;
(iv) The rotational speed of the rotors is above 850 rpm;
(v) The standard deviation of the rotational speed for a plateau is lower than \(\sqrt{10}\) rpm;
(vi) The duration of a plateau is longer than 10 s;
(vii) The slope of a plateau is less than 0.05 rpm/s to assure that the rotational speed remains constant;
(viii) The relative rpm difference for paired configurations is smaller than 10%.

A plateau must thus satisfy to these conditions for at least 10 s, however most plateaus are larger than 2000 s. For each plateau the standard deviation on \(\tau\), \(\omega\) and \(U_0\) are then converted into a standard deviation on \(C_P\) and \(\lambda\) using classic error propagation techniques.

6. Performance of a pair of VAWTs

A positive interaction between paired counterrotating vertical-axis wind turbines was confirmed experimentally. The amplitude of this interaction depends on the tip-speed ratio, the direction of rotation and whether the turbines are synchronised or not.

6.1. Performance of isolated VAWTs

Several identical rotors were manufactured but the small scale of the dimensions make the rotors very vulnerable for deficiencies. A small deficiency can easily result in a different aerodynamic performance. The two rotors that presented the best aerodynamic similarity have been used for the interaction tests. Their performance is illustrated in Figure 3. At low tip-speed ratio they exhibit small differences but at optimal and higher tip-speed ratio their performance agrees well. Both rotors reach their optimal \(C_P\) around a tip-speed ratio of 3.
Figure 3. The $C_P(\lambda)$-curves of one rotor (blue) and the other (red) exhibit the similar performances of the rotors when placed in isolated configuration. The confidence bounds were determined as described in Section 5.

6.2. Synchronisation
Before every test, the rotors are homed to a fixed position with the struts perpendicular to the incoming wind as shown in Figure 2. Then, the rotors are spun up individually to the desired rotational speed and brought to within about 20 rpm (1–2% of the average rotational speed). In paired configuration the rotors tend to synchronise spontaneously: the rotational speeds equalise, and the phase difference between both rotors converges consistently to a mean value. We observed that the instantaneous phase difference oscillates slowly around a small mean value with a period of a few seconds. The precise mean value of the phase difference varies from test to test, depending on the configuration and on the tip-speed ratio. This synchronisation is quite strong and repeatable. Once synchronised, the rotors remained in this state seemingly forever (Figure 4, last 1800 s and Figure 5, last 2000 s). It is remarkable that the synchronisation for the 1.3D inner-upwind configuration appears to be more stable than the synchronisation for the 1.3D inner-downwind one. For the 1.3D inner-upwind configuration the relative phase difference remained mainly between 0.1 and -0.1 radians. For the 1.3D inner-downwind configuration the relative phase difference exhibits stronger oscillations but remained mainly between 0.05 and -0.25 radians, suggesting a favoured position for one turbine passing the home position before the other. It is even possible to drag one turbine along in synchronisation when the rotational speed of the other turbine is varied up to about 100 rpm (more than 10%). This was attempted in the tests for which the data is shown in Figures 4 and 5. The rotors de-synchronised around 1000 s and were re-synchronised manually. When both rotational speeds are varied simultaneously, a complete $C_P(\lambda)$ curve can be measured in one go without the turbines desynchronising.

6.3. Performance of the 1.3D configuration
To compare the performance of individual VAWTs with a pair of counterrotating VAWTs, two different types of tests were carried out: variable TSR-tests and constant TSR-tests. The performance was originally analysed with the variable TSR-tests to create a complete $C_P(\lambda)$-curve for each case. The optimal tip speed ratio for each configuration was found and for every configuration, long constant TSR data measurements were performed. The wind tunnel experiments of a pair of counterrotating VAWTs all resulted in a statistically significant improvement of the performance. The turbines consistently perform better as a pair compared to the same turbines in isolation. The comparison of the $C_P(\lambda)$-curves for the
Figure 4. Phase difference between the 1P-signals with the rotors stabilised (and synchronised) at 1250 rpm during one test of the 1.3D inner-upwind-rotating configuration.

Figure 5. Phase difference between the 1P-signals with the rotors stabilised (and synchronised) at 1250 rpm during one test of the 1.3D inner-downwind-rotating configuration.

Figure 6. The positive interaction between paired counterrotating vertical-axis wind turbines was confirmed during wind tunnel tests. The paired 1.3D inner-downwind configuration (red) performs better than the isolated turbines (blue). The 1.3D inner-upwind configuration (green) exhibits an even higher performance compared to the inner-downwind equivalent. The confidence bounds were determined as described in Section 5.

different configurations is illustrated in Figure 6. The data of a turbine is always represented with confidence intervals as explained in Section 5. The solid curves represent an average over both turbines per configuration to exemplify the variation with tip-speed ratio. The calculation of this average is straightforward for those configurations in which the turbines were closely-spaced, as then the turbine rotational speeds (and thus the tip-speed ratios) were kept equal. However, for the turbines in isolation (the blue curve in Figure 6), no such average can be made as the turbines were tested independently. Therefore, the data of these independent tests in isolation were first interpolated over the tip-speed ratio and only then averaged.
The performance clearly improves for paired configuration (red and green) compared to the isolated configuration (blue), especially around the optimal tip-speed ratio. But this increase persists even before and after the optimal tip-speed ratio. However, the shape of the experimental $C_P(\lambda)$-curves appears to be flatter for the isolated configuration while the optimal tip-speed ratio is more pronounced for the 1.3D configuration.

During the constant TSR-tests, the rotational speed of the rotors were set such that the rotors were performing optimally for the respective configuration. Each configuration was tested for at least 120 minutes without modifying the tip-speed ratio. The results are illustrated in Figure 7. The average of each dataset is represented with a horizontal marker and its value. The conclusion of these tests is an average increase of 14.0% for the 1.3D downwind-inner configuration and an increase of 17.0% for the 1.3D upwind-inner configuration compared to the isolated configuration. The spreading of the data for the 1.3D downwind-inner configuration is larger than the 1.3D upwind-inner, which we believe can be attributed to the less stable synchronisation.

7. Discussion and Conclusion

Compared with the results of Ahmadi-Baloutaki et al. [18], who tested at larger inter-turbine distances, we find a much larger increase in power. We believe that this difference can be attributed to the differences in solidity and interturbine distances.

The magnitude of the increase corresponds quite well to the numerical simulations of Zanforlin and Nishino [8], where it is stated that the improved efficiency comes from an extension of the azimuthal range in which torque is generated. A tangential component to the flow is created by the blockage of the neighbouring turbine which is not present for an isolated turbine. In their numerical simulations, interferences of the shaft and struts were not included, nor the blade tip losses. Their interturbine distance was set to 1.5 times the rotor diameter. With this setup, they find an increase of 8.6% for the inner-upwind configuration and an increase of 14.8% for the inner-downwind configuration.

The wind tunnel experiments of pairs of counterrotating vertical-axis wind turbines resulted in an increase of 14.0% for the inner-downwind configuration and an increase of 17.0% for the inner-upwind configuration. When the VAWTs are placed as a pair they synchronise spontaneously and remain synchronised. The power improvement depends on the tip-speed ratio, the direction of rotation and whether or not the turbines are synchronised.
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