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A wind tunnel study on the aerodynamic interaction of vertical axis wind turbines in array configurations

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ABSTRACT

The aerodynamic interaction of vertical axis wind turbines in several array configurations was studied by conducting a series of wind tunnel measurements. Four configurations of two- and three-turbine arrays were tested and their results were compared with that of the isolated reference case. Two pairs of counter-rotating and co-rotating vertical axis wind turbines were tested where the free-stream wind was perpendicular to the two side-by-side turbines. The counter-rotating configuration resulted in a slight improvement in the aerodynamic performance of each turbine compared to the isolated case, while the co-rotating installation caused a slight performance reduction of turbines at some free-stream velocities. Several measurements were also performed for three-turbine arrays with different spacing where a vertical axis wind turbine was operating downstream of a counter-rotating pair, perpendicular to the free-stream wind. An enhancement in the aerodynamic performance of the downstream turbine was observed in almost all arrays and at most tested wind speeds. For the array spacing studied, the optimum range of the streamwise distance of the downstream turbine from the counter-rotating pair and the spacing between the pair was determined to be about three and one rotor diameters, respectively.

1. Introduction

Optimal positioning of wind turbines in a wind farm is crucial in today's wind market [1,2]. Wind turbines in a wind farm modify the structure of the wind flow by creating turbulence structures and reducing the wind velocity [3,4]. Therefore, the wind stream in a wind farm is partly undisturbed and partly varied by the wake of the upstream turbines. This modified wind flow will typically result in lower power output for the wind turbines located downstream, as compared to an isolated turbine [5,6]. To avoid these wind and power fluctuations and to reduce structural vibrations and fatigue loads, wind turbines are typically spaced far apart, occupying large areas of land [7–9].

The turbine spacing constraint for horizontal axis wind turbines (HAWTs) dictates that these turbines must be spaced 3–5 turbine diameters apart in the crossflow direction and 6–10 diameters apart in the streamwise direction to maintain 90% of the performance of an isolated turbine [10]. While HAWTs shed wakes and wind trails that negatively affect the neighboring turbines in both crossflow and downstream directions, the wake of vertical axis wind turbines (VAWTs) can potentially provide constructive aerodynamic interactions for a group of turbines. The literature suggests that when two counter-rotating VAWTs are placed close together, the flow induced by each turbine is oriented in the same direction, resulting in reduced turbulence and vortex shedding [6,11]. The mutual coupling effect existing between rotors can result in positive interactions, improving the power performance of VAWTs while reducing the footprint of turbines. Considering the fact that VAWTs can harness wind energy from any direction [12], this lack of directional sensitivity can enable turbines to extract energy from adjacent wakes; something seemingly less attainable for HAWTs. This potential benefit of VAWTs in group installations, combined with relatively lower manufacturing and maintenance costs, and less aerodynamic noise makes them a promising alternative to HAWTs [13]. While there are many studies on the optimal positioning of HAWTs in a wind farm, the aerodynamic interaction of VAWTs, particularly counter-rotating machines, has been

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Nomenclature

A_r	rotor frontal area, $A_r = DH$
AR	blade aspect ratio, $AR = H/c$
B	blockage ratio
b	streamwise distance from a pair of turbines
C_P	power coefficient, $C_P = P/(0.5\rho A_r U_\infty^3)$
c	blade chord length
D	diameter of the rotor
H	blade height
$HAWT$	horizontal axis wind turbine
I	electrical current
N	number of the blades
P	power
R	radius of the rotor
R_l	electrical resistance of the load
rms	root mean squared
RPM	rotation per minute
s	spacing between two turbines
SB	straight bladed
Tu	turbulence intensity, $Tu(\%) = u_{rms}/\overline{U} \times 100$
U	streamwise velocity
$\overline{U}$	time-averaged streamwise velocity
U_∞	free-stream wind velocity
u	streamwise velocity fluctuation
$VAWT$	vertical axis wind turbine
w	turbine distance from wind tunnel wall
x	streamwise coordinate
y	spanwise coordinate
Greek letters	
λ	blade tip speed ratio, $\lambda = R\omega/U_\infty$
ρ	density
σ	rotor solidity factor, $\sigma = Nc/R$
ω	rotational speed of rotor

investigated only in a handful of studies [6,11,14–16].

The idea of employing counter-rotating VAWTs was first patented by Thomas in 2004 [11]. He claimed that putting a pair of VAWTs in a counter-rotating configuration can result in aerodynamic efficiency enhancement of the pair through vortex interaction between the two adjacent rotors [11]. According to him, the high solidity rotors are a good choice for this scenario as they can be more efficient in the coupled vortex interaction phenomenon. He further explained that the separation distance between two turbines should be as small as safely possible for maximum effectiveness [11]. The other important outcome from this patent is that the counter-rotating configuration has the highest efficiency when the pair of turbines is perpendicular to the prevailing wind direction [11]. Two series of full-scale field measurement of counter-rotating VAWTs in a wind farm was reported in two separate studies by Dabiri [6] and Kinzel et al. [14]. Dabiri [6] measured the aerodynamic performance of counter-rotating VAWTs in two-, three- and six-turbine configurations under natural wind conditions. In the two-VAWT configuration testing, Dabiri [6] found an increase, though small, in the counter-rotating turbines' performance compared to that of isolated installation. In the array testing, he reported the performance of the turbine located downstream of a counter-rotating pair recovered to within 5% of the isolated turbine performance when the streamwise distance increased to four turbine diameters [6]. This outcome was significantly emphasized by Dabiri [6] in comparison to the recovery distance of HAWTs which is up to 15–20 D for a similar level of wake recovery. Dabiri's [6] results are comparable to those of Kinzel et al. [14] who found the flow velocities return to 95% of the undisturbed wind within 6 D downstream of a counter-rotating pair. Kinzel et al. [14] studied the flowfield of an array of nine counter-rotating pairs of the same VAWTs and in the same wind farm as in Dabiri's study [6] with an emphasis on the fluxes of mean and turbulence kinetic energy. Kinzel et al. [14] showed that the planform kinetic energy flux can be the dominant source of energy in wind farms. They also measured a high planform kinetic energy flux for the counter-rotating VAWT array which facilitates rapid flow recovery in the wake region behind the turbine pairs [14].

There have also been a few numerical simulations on counter-rotating VAWTs due to a recent interest in distributed small wind applications. Korobenko et al. [15] conducted a series of full-scale, three dimensional, time-dependent numerical simulations on a pair of counter-rotating VAWTs. They reported a slight drop in the predicted aerodynamic torque of the pair compared to the single turbine. Korobenko et al. [15] attributed this reduction to the small separation distance between the turbines (0.32 D) that caused the turbines' blades to encounter the wake of the blade from other neighboring turbine. This resulted in higher drag on a particular blade, and consequently less aerodynamic torque [15]. The aerodynamic performance of pairs of counter-rotating and co-rotating VAWTs was also analyzed numerically by Duraisamy and Lakshminarayan [16] in their two dimensional flow modeling. They found that pairs of counter-rotating or co-rotating VAWTs can generate more power than an isolated turbine by taking advantage of the beneficial induced velocity field [16]. They also reported that the majority of the wake deficit behind a single VAWT is confined to a few diameters downstream of the turbine and its spatial extent is seen to diminish with increased tip speed ratio [16].

As briefly reviewed, all recent works on counter-rotating VAWTs are either field measurements, analytical, or numerical simulations. Although these studies provide valuable information regarding the aerodynamic interaction of a group of wind turbines, they have some limitations. Field measurements are subject to various terrain effects, the stochastic nature of wind and meteorological conditions; making the repetition of the observation improbable if not impossible [4,10]. Numerical simulations still suffer from the lack of accuracy in turbulence modeling especially in separated flow regions [17], and analytical solutions use many simplifications which make them suitable mostly for engineering applications [18]. Wind tunnel testing, on the other hand, provides controlled conditions to systematically study this subject. Therefore, the objective of this study was to analyze the aerodynamic interaction of counter-rotating VAWT arrays using a series of wind tunnel measurements under controlled flows with uniform and steady wind conditions. The broader goal of the current research is to determine the optimal conditions for positioning turbines in a wind farm to achieve improved performance based on the constructive aerodynamic interaction among the turbines.

2. Experimental apparatus

2.1. Wind tunnel and VAWT model

Experiments were conducted in the atmospheric boundary