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Original Research Article

Performance of a vertical axis wind turbine in grid generated turbulence

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ABSTRACT

The effect of external free-stream turbulence on the aerodynamic performance of a vertical axis wind turbine was studied via wind tunnel testing under controlled levels of wind turbulence. Three levels of turbulence intensity of 5%, 7.5%, and 10% were generated upstream of the vertical axis wind turbine using a grid turbulence generator. Turbulent flows generated downstream of the grid had uniform mean flow profiles, free of any wind shear effects. Turbulence characteristics were reported in terms of turbulence velocity fluctuations, probability density function, and power spectral density. It is demonstrated that the turbulence generated downstream of the current grid is quasi-isotropic. Results show that the turbine power output was substantially increased in the presence of the grid turbulence, even though the increase in turbine power coefficient due to the effect of grid turbulence was small at the same tip speed ratios. Among grid generated turbulent flows, the increase in power output with increasing turbulence intensity was marginal. Moreover, the self-starting behavior of the vertical axis wind turbine is improved under the influence of external free-stream turbulence.

Introduction

Aerodynamic performance of a wind turbine can be significantly affected by wind turbulence [1]. In addition, turbulence intensity can increase mechanical stresses on turbine components [2] and reduce the fatigue life of the turbine structure [3]. The impact of wind turbulence is especially crucial for small wind turbines since they are typically installed near to ground where obstacles such as buildings, trees, etc. can result in high levels of free-stream turbulence [4]. Moreover, wind turbulence approaching small wind turbines in urban areas can be many times greater than that of a rural wind farm [5].

Vertical axis wind turbines (VAWT); which play an important role in the small wind turbine market are the topic of current study. These machines offer several benefits over their horizontal design counterparts including insensitivity to yaw, lower noise emission, and better integration in architectural projects [6]. Despite the importance of the wind turbulence in VAWTs' power generation, the available literature on the topic is relatively scarce.

A commonly used approach for reporting the turbine power curves is to determine the output power as statistical averages of power measurements binned by wind speed, whereby the variance of the data is lost [1,7]. Thus the effect of free-stream turbulence is not captured by this method. There are, nonetheless, a few studies that attempted to characterize the effect of wind turbulence on the turbine's performance. These works by Kooiman and Tullis [8], Lubitz [9], and Smith [10] were all performed in atmospheric environment with no control on the level of free-stream turbulence. The unique distinction of these studies by other typical atmospheric performance testing works was the output data in these studies [8–10] were split into smaller segments and the variance of the data was used to determine the turbulence intensity of each segment. Also, the turbine aerodynamic characteristics of each data segment were compared to quantify the effect of wind turbulence. Such an approach is heavily dependent on the sample size of the output data; which may be correlated to time scales present in the atmospheric wind [8,9].

Kooiman and Tullis [8] studied the effects of wind velocity and direction fluctuations on the energy production of a VAWT by urban environment testing on a rooftop. The turbine's output power was found to vary with wind velocity fluctuations, but roughly independent of direction fluctuations [8]. Kooiman and Tullis [8] compared their urban performance testing with an earlier work on the same wind turbine in a low turbulence wind tunnel ($Tu < 2\%$) as their "smooth" flow performance benchmark. They [8] reported a marginal reduction in the turbine's performance

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Nomenclature

A_r	rotor frontal area, $A_r = DH$
AEP	annual energy production
AR	blade aspect ratio, $AR = H/c$
B	blockage ratio
C_P	power coefficient, $C_P = P/(0.5\rho A_r U_\infty^3)$
c	blade chord length
D	diameter of the rotor
d	diameter of holes in OPP
F	flatness
f	frequency
H	blade height
HAWT	horizontal axis wind turbine
I	electrical current
N	number of the blades
n	sample number in velocity signals
OPP	orificed perforated plate
P	power
PDF	probability density function
PSD	power spectral density
R	radius of the rotor
RPM	rotation per minute
S	skewness
s	rotor solidity factor, $s = Nc/R$
t	time
SBVAWT	straight bladed vertical axis wind turbine
Tu	turbulence intensity, $\mathrm{Tu}(\%) = u_{rms}/\overline{U} \times 100$
u	streamwise velocity fluctuation
U	streamwise velocity component
$\overline{U}$	time-averaged streamwise velocity
U_∞	free-stream wind velocity
V	electrical voltage
VAWT	vertical axis wind turbine
X	streamwise distance between OPP and VAWT

Subscripts

l	load
r	rectifier
rms	root mean squared
w	winding
opt	optimum

Greek letters

Λ	turbulence integral length scale
μ	statistical mean of a sample data
λ	blade tip speed ratio, $\lambda = R\omega/U_\infty$
ρ	density
σ	standard deviation
ω	rotational speed of rotor

from the smooth flow values for Tu < 15%, and almost a linear reduction with increasing turbulence intensity for Tu > 15%. Using the similar methodology of Kooiman and Tullis [8], Lubitz [9] conducted a series of performance testing of a HAWT in an open farm to investigate the effect of ambient turbulence on the turbine output power. According to Lubitz [9], the turbine energy production was altered by ambient turbulent level, but the impact was different at various wind speeds. Wind turbulence levels lower than 14% resulted in increased output power, while no consistent trend was reported for higher turbulence levels. Smith [10] reported performance curves and annual energy productions (AEP) for seven small wind turbines at varying levels of wind turbulence. There was 9–32% variation in turbines AEP over the studied turbulence intensity range [10]. Most of the turbines had lower AEP in both the extreme low and high turbulence levels; except one, whose AEP was increased with increasing turbulence intensity [10].

As mentioned earlier, all of the works cited above used the same methodology to quantify the effect of wind turbulence; which is highly dependent on the sample size. It can be argued that using a different sample size may lead to different conclusions. Besides, there is no consensus on the effect of free-stream turbulence on the wind turbine's operation as different trends have been reported in the literature. This may be partially due to the different turbulent flow types studied by different researchers, complicated by varying amounts of wind shear and unsteady wind.

This highlights the need for systematic performance testing under controlled turbulent flows with uniform and steady wind conditions. To achieve better experimental control, it would be advantageous to start with the simplest form of inflow turbulence, isotropic turbulence. To this end a grid in wind tunnel testing has been employed to generate isotropic turbulence. The current study attempts to investigate the influence of free-stream turbulence intensity on the aerodynamic performance of a Darrieus-type VAWT by creating steady quasi-isotropic turbulent winds using a grid in a wind tunnel.

Experimental Setup

Model description

Experiments were conducted in a closed-loop wind tunnel whose 1.8 m long test section has a 0.76 m by 0.76 m cross section. The maximum achievable velocity is about 34 m/s in the empty working section with a background turbulence intensity of less than 0.5%. In the presence of a grid turbulence generator however, the maximum achievable velocity is approximately 21 m/s. The mean velocity and turbulence intensity were nearly uniform in the core of the wind tunnel in absence of the VAWT. A schematic of the wind tunnel test section including the wind turbine and the grid turbulence generator is shown in Fig. 1.

The VAWT used in the current study is a commercial mini wind turbine, P-10 model, manufactured by Shanghai Aeolus Windpower Technology Co., Ltd. [11]. This wind turbine has five straight blades made from aluminum with hollow section as depicted in Fig. 1. The blades of this wind turbine have a custom-made asymmetric airfoil profile. The coordinates of this airfoil profile have been digitized and plotted in Fig. 2. Blade chord length and height were 45 mm and 0.3 m, respectively. This results in a blade aspect ratio of 6.6 which is close to the optimum range of this parameter for straight bladed VAWTs (SB-VAWT); $10 < AR_{opt} < 20$, as determined in Ref. [12]. The rotor diameter of the turbine was 0.3 m which corresponds to a rotor aspect ratio of unity, which is in the desirable range for SB-VAWTs; $0.5 < (H/D)_{opt} < 2$ [12]. The solidity ratio of this wind turbine, however, is far from the optimum values. The current SB-VAWT is categorized under high-solidity turbines ($s > 1$) with a solidity ratio of 1.5, while many works have reported the optimum range of this variable to be $0.2 < s_{opt} < 0.6$ as explained in Ref. [12]. Each blade was connected to the central shaft via two supporting arms at intermediate locations of 0.33 and 0.66 of the blade height. The supporting arms were Aluminum bars with rectangle cross-section of 2 mm by 25 mm.

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