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Performance analysis of a cross-axis wind turbine from wind tunnel experiments

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ABSTRACT

Wind energy has been considered as one of the primary renewable energy sources globally. In urban areas, due to the irregular arrangement of buildings, small scale wind turbine plays an important roles for household energy grid. In this study, a newly designed small scale wind turbine namely cross-axis wind turbine (CAWT), which combines the characteristics of horizontal and vertical axis wind turbines (HAWT and VAWT), was examined experimentally on the power performance in a low speed, open-loop circuit wind tunnel at Reynolds numbers of Re = 42900, 57100 and 71400. The results were compared to a traditional straight-bladed VAWT. The performance analyses are evaluated in terms of static performance, dynamic performance, and blade force measurement. The results of static and dynamic performances indicate that CAWT has not only better self-starting characteristics but also higher power coefficients over VAWT. The tangential forces measurement on the horizontal blade of CAWT proves its superior power performance compared to VAWT.

1. Introduction

Wind energy has become one of the primarily renewable energy resources worldwide in the past decade. Wind turbine, which has been the greatest tool of wind energy, helps convert wind power into electricity. It can be classified to horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT) based on rotating orientation. The wind turbines with rated power scaled between 1.5 MW and 5 MW are categorized to be large scale, and for those below 100 kW are small scale ones. According to rotor diameters, wind turbine can also be classified into micro turbine (<1 m), farm windmill (1–15 m), medium-sized turbine (15–55 m), MW turbine (55–80 m) and Multi-MW turbine (>80 m) (Wizelius, 2007). In urban areas, wind condition is complicated because of the irregular arrangement of buildings. As shown in Fig. 1, the boundary layer in urban area includes mixed layer and surface layer. The turbulence intensity, which is proportional to the presence of the building is significantly higher (Toja-Silva et al., 2013). Large scale wind turbines are not favorable in this area; instead, small scale wind turbines become more attractive. In addition, stand-alone small scale wind turbine system offers off grid residential electricity, resulting in 93% reduction of GHG (greenhouse gas) emissions compared to the diesel system for off grid residential electricity (Fleck and Huot, 2009).

Aerodynamic characteristics have been studied intensively on the performance of small scale wind turbines. Tables 1 and 2 list the previous studies on HAWTs and VAWTs. For small scale HAWTs, low speed wind tunnel was applied to test the wind turbines and verify the simulation results using BEM method, which uses the engineering codes to design and analyze the aerodynamic performance of HAWT blades by combining the 2D airfoil data (Bai et al., 2013; Hsiao et al., 2013a). Bai et al (Hsiao et al., 2013a). tested on three different shapes of turbine blade in an open-circuit low speed wind tunnel for verifying the predicted results using improved BEM theory. The results indicated that the optimum twist blade has maximum power coefficient of 0.43. Hirahara et al. (2005). examined the performance of μF500 HAWT through an environmental wind tunnel at the wind speeds of 8–12 m/s and found that the average power coefficient of 0.36 was achieved. Kishore and Priya (2013) tested several HAWTs in the subsonic open jet wind tunnel with the test section sized at 1.47 m × 1.78 m and found that the type of

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Abbreviations: CAWT, Cross Axis Wind Turbine; HAWT, Horizontal Axis Wind Turbine; VAWT, Vertical Axis Wind Turbine; GHG, Greenhouse Gas; BEM, Blade Element Momentum; SWEPT, Small Wind Energy Portable Turbine; LDV, Laser Doppler Velocimeter; TSR, Tip Speed Ratio; ODGV, Omni-Direction-Guide-Vane; SSWT, Small Scale Wind Turbine; MSWT, Medium Scale Wind Turbine; NACA, National Advisory Committee for Aeronautics; NREL, National Renewable Energy Laboratory; ABS, Acrylonitrile Butadiene Styrene; TI, Turbulence Intensity; AOS, Angle of Attack; CNC, Computer Numerical Control; DC, Direct Current.

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Nomenclature

A_{gauge}	The area of tri-axial strain gauge [m^2]
A_s	Swept area (m^2)
A_{test}	Test section area (m^2)
A_{front}	Model frontal area (m^2)
c	Chord length (mm)
c_h	chord length of the horizontal blade (mm)
c_v	chord length of the vertical blade (mm)
C_D	three dimensional drag coefficient
C_d	drag coefficient
C_l	lift coefficient
C_p	Power Coefficient
C_n	Radial force coefficient
C_t	Tangential force coefficient
dR	Individual uncertainty
E	Young's modulus [GPa]
F_t	Tangential force [N]
h_v	The span of vertical blade [m]
h_h	The span of horizontal blade [m]
N	Sample size
N_B	Number of blades
P	Power (W)
P_{atm}	Atmosphere pressure (Pa)
$P_{dynamic}$	Dynamic pressure (Pa)
P_{static}	Static pressure (Pa)
P_{total}	Stagnation pressure (Pa)
Q(θ)	Reaction torque which is function of θ
R	Rotor radius (mm)
$\frac{\partial R}{\partial X_i}$	Sensitivity coefficient
T_{temp}	Temperature ($^\circ C$)
T	Torque (N-m)
U_0	Free-stream velocity (m/s)
$U_{\infty,u}$	The correction stream-wise free stream velocity (m/s)
$\bar{u}$	Mean value of each average velocity (m/s)
u_j	Each point average velocity in the measured section (m/s)
u_{rms}	Axial Root-Mean-Square Velocity (m/s)
$(\overline{u'^2})^{\frac{1}{2}}$	Magnitude of fluctuation in the flow
V	Free stream velocity (m/s)
W	width of deflector
$\overline{X_i}$	Mean value of the sample data
$X_{i,k}$	Each data measured by experiment
$\overline{X_i}$	The average of data base
$s(\overline{X_i})$	Standard uncertainty
$q_{\infty,u}$	The stream-wise dynamic pressure (Pa)

Greek symbols

ε_{sb}(blade)	Blade blockage correction factor
ε_{sb}(stand)	Support strut blockage correction factor
ε_t	Total blockage correction factor
α	Angle of Attack (degree)
β	Pitch angle (degree)
λ	Tip Speed Ratio (TSR)
ρ	Density (kg/m^3)
σ_{WT}	Solidity of CAWT and VAWT
σ_Y	Tangential stress [GPa]
ω	Rotational speed (rad/s)
ε_X	Radial strain
ε_Y	Tangential strain
γ_{XY}	Shear strain
γ	Poisson ratio

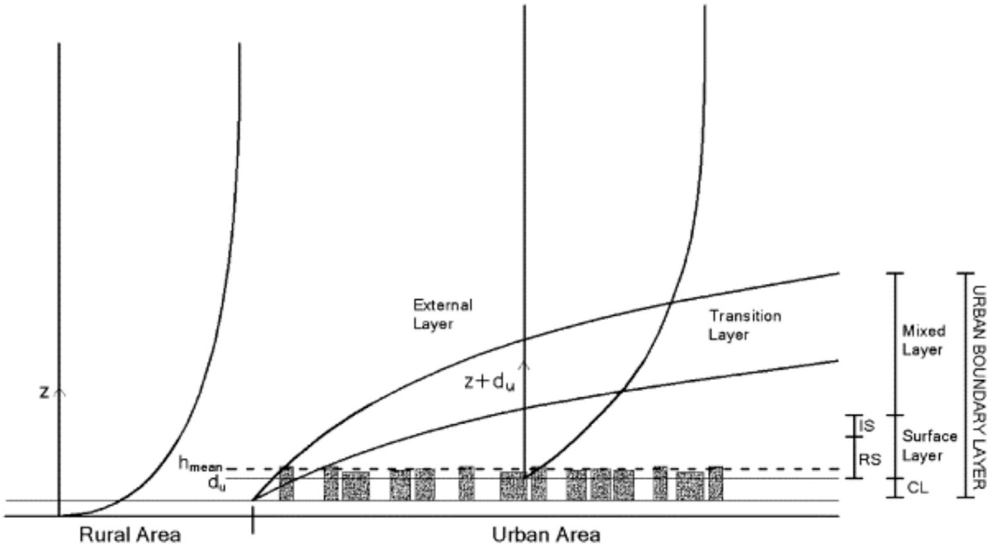

Fig. 1. Boundary layer of wind flow in urban areas (Toja-Silva et al., 2013).

SWEPT (small wind energy portable turbine) has a good power performance ranging from 0.31 to 0.34 at the wind speeds of 3 m/s ~ 5.5 m/s.

For VAWT, wind tunnel experiment is also a favorable method for examing the aerofynamic behaviors on blade and around the rotor. Roy and Saha (2015) tested the newly invented Sanvonius type VAWT (SSWT) in an open jet wind tunnel and the results showed that maximum power coefficient was 0.31, relatively higher than conventional semi-circular, semi-elliptic, and Benesh type VAWTs. Through installing the deflectors at various locations before the wind turbine, the power output of SSWT was additionally improved under concentrated and oriented jets (Roy and Saha, 2014a; Roy et al., 2014). The blockage effects increased with increasing TSR and blockage ratio but can be neglected as the TSR is below 0.5 (Roy and Saha, 2014b). Li et al. has published a series of articles mentioning the examination of straight blade VAWT in