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Experimental and numerical investigation on aerodynamic performance of a novel disc-shaped wind rotor for the small-scale wind turbine

Zhang Xu[a], Yan-Hao Feng[a], Chuang-Yao Zhao[a,*], Yu-Lei Huo[a], Sha Li[a], Xiao-Jian Hu[b], Ying-Jie Zhong[a]

[a] *College of Mechanical Engineering, Zhejiang University of Technology, Hangzhou 310014, PR China*
[b] *HydroChina Huadong Engineering Corporation, Hangzhou 310014, PR China*

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ABSTRACT

A series of novel disc-shaped wind rotors used in the small-scale wind turbine are redesigned with the inspiration from the eco whisper turbine. The aerodynamic parameters such as power coefficient and torque coefficient are obtained by numerical simulation and wind tunnel test. The tip speed ratio, pitch angle and opening angle are taken into consideration to account for the influences on the power coefficient. The specific case with pitch angle of 30° and opening angle of 45° is tested in a wind tunnel and simulated with different turbulence models for Reynolds number in the range of 6.8×10^4–1.70×10^5, respectively. The results indicated that: (1) the numerical results based on the standard *k*-*ω* model agree well with the experimental results; (2) the orthogonal method shows the rank of influencing factors is pitch angle, opening angle and tip speed ratio, whose contributions to the power coefficient are about 66.36%, 18.53% and 11.43%, respectively; (3) the effects of both pitch angle and opening angle on power coefficient may be positive or negative, depending on the level of tip speed ratio; (4) as tip speed ratio increases, peak power coefficient can be achieved for an individual pitch angle or opening angle; (5) the value of tip speed ratio correspondent to the peak power coefficient decreases with decreasing pitch angle or opening angle; (6) the rotor with pitch angle of 20° and opening angle of 30° at a tip speed ratio of 1.4 provides the highest power coefficient of 0.47. The maximum power coefficient in the present paper is higher than most of the rotors in literature according to the comparison.

1. Introduction

Energy is the lifeblood of national economy, but the traditional fossil energy is facing shortage and environmental deterioration and thus is not able to meet the growing number of human demands [1]. Many countries have developed renewable energy to reduce their dependences on the fossil fuels [2]. Wind power is a clean, inexhaustible, low cost operation and abundant resource [3], has attracted great attention from the researchers and governments.

The wind power is commonly utilized for electricity generation with wind system. The traditional wind power industry generally adopts centralized wind system and equipped with large-scale wind turbines, while also brings in problems of voltage deviation, resistive loss, and interruptions, etc. [4]. Instead, the distributed wind system, installed with small-scale wind turbines, which provides electricity on the retail part of the electric meter without the additional transmission facilities [5], has behaved superiorities in smart grid and energy cascade utilization [6] and become an important development direction for wind energy. Hence the distributed wind system by, i.e. using small-scale wind turbines is a sustainable option to replace the large ones.

With increasing utilization of small-scale wind turbines, there arises the need of understanding the performance of small-scale wind turbines over the past few years. The small-scale wind turbine has little negative effect on the stability of the power network distribution and does not need large power storage capabilities. A typical small-scale wind turbine has a rotor with a diameter ranging from 3 to 10 m and a power capacity of 1.4–20 kW. The small-scale wind turbines can be classified into horizontal and vertical axis wind turbines (HAWT and VAWT), depending on the orientation of their rotational axes [7]. In general, the HAWTs are widely used today in large-scale turbines due to being more efficient than VAWT and the abilities of self-starting and yawing, while are less competitive in distributed energy due to the uncertain directions, efficiency loss, land use and acceptability in human [8]. The VAWTs are more suitable for small-scale and rooftop applications [6] based on advantages in low noise, and easier operation and maintenance because their locations are near the ground, but are difficultly

* Corresponding author.
E-mail address: cyzhao@zjut.edu.cn (C.-Y. Zhao).

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Nomenclature

A	swept area of the rotor, m^2
A_t	cross-section area of wind tunnel, m^2
b	chord length, m
C_t	static torque coefficient
C_l	lift coefficient
C_d	drag coefficient
C_p	power coefficient
D	rotor diameter, m
d	equivalent diameter of rotor, m
K_{ij}	sum of ANORA result in the same level, i, j = 1, 2, 3,…
M	torque of rotor, N·m
m	number of level in ANOVA
N	number of tests in ANOVA
n	rotor angular velocity, rpm
P	power of rotor, kW
R	rotor radius, m
r	radius of the blade to the axis of the rotor, m
Re	Reynolds number
rp	repetition number in ANOVA, $rp = N/m$
SS_j	sum of squares in ANOVA, j = 1, 2, 3,…
T	size of sample
TSR	tip speed ratio
u	mainstream wind velocity, m/s
u_0	relative wind velocity, m/s
V_j	variance of ANOVA
X_i	C_p result of ANOVA test, I = 1, 2, 3, …
y^+	non-dimensional distance of the first grid point off the wall

Greek letters

α	pitch angle, °
β	attack angle, °
ε	blockage ratio
φ	relative wind direction angle, °
θ	opening angle, °
ρ	air density, kg/m^3
σ	population standard deviation
ω	rotor angular velocity, 1/s
ν	air kinematic viscosity, m^2/s

popularized because of weak wind gathering capability due to near ground installation [9]. Additionally, the hybrid turbines combining the advantages of HAWT and VAWT were also studied in aerodynamics and noise control [9,10]. In recent years, the optimal techniques and strategies for both HAWT and VAWT applied to wind turbine performance optimization are also studied comprehensively [11].

Wind rotor for gathering and capturing wind energy is one of the most important parts in a wind turbine, whose design methods have been paid great attention. With a closed-type wind tunnel with a cross-section of 2.7 × 2 m, Krogstad and Lund [12] measured the aerodynamic parameters of mechanical torque, mechanical power, and power coefficient. These experimental results were also used to validate the CFD simulations. Singh and Ahmed [13] designed a 2-blade rotor used in an Air-X marine's 400 W wind turbine and tested it in an open ocean field. They obtained power coefficient (C_p) of the rotor as 0.1, 0.217 and 0.255 at wind velocity of 4, 5 and 6 m/s, respectively, and found that the optimum pitch angle (α) is 18°.

Researchers have focused on optimization of the rotor's aerodynamic performance in blade design [7]. Hirahara et al. [14] built a 4-blade small HAWT, whose blades have the similar cross section to the airfoil of NACA 2404. Their results indicated that the C_p reaches 0.4 and 0.36 at a tip speed ratio of 2.7 and rated running condition, respectively. Duquette and Visser [15] numerically studied the influences of rotor solidity and blade number on the C_p with the SG6043 airfoil, and found that the C_p increases as the solidity changes from 5–7% to 15–25% and blade number varies from 3 to 12. Kishore et al. [16] developed a small-scale wind energy portable turbine with a diffuser, and it produced 1.4–1.6 times more power than a normal small-scale wind energy portable turbine, even obtained a peak C_p of 0.14 at a tip speed ratio of 2.9. To suppress the flow separation, Wang et al. [17] proposed a flow control method by setting micro-cylinder in the front of the blade leading edge. Their results indicated that the blade torque can be maximally increased by 27.3% by using the micro-cylinder with proper diameter and position. In their another work [18], the effects of the thicknesses and cambers of airfoils on the aerodynamic performance of vertical axis wind turbine are investigated numerically.

Recently, some novel rotors are proposed for distributed wind systems. Roy and SAHA [19] proposed a novel Savonius-style wind turbine, and found its C_p is 34.8% more than the conventional Savonius-style wind turbine. Ying et al. [20] investigated the performance of an omni-flow wind turbine with the wind tunnel test and CFD simulation, and found that it can start at wind velocity of 1.6 m/s and its maximum C_p is around 0.17. Chong et al. [9] designed a cross axis wind turbine (CAWT) with a 45° deflector, 3 vertical blades and 6 horizontal blades. They found that the rotor rotation speed is increased by around 70% and the C_p is 2.8 times more than the VAWT. In order to improve the starting performance of straight-bladed vertical axis wind turbine, Li et al. [21] designed a truncated-cone-shaped wind gathering device installed up and down of the rotor to gather more incoming air and to increase wind velocity. The new rotor behaved 24.2% more maximum averaged static torque coefficient than the original one at the same work condition.

Some studies are conducted to evaluate the turbulence models with respect to their performance in simulating the flow field of the wind rotors. Wang [22] concluded that the standard k–ε turbulence model is inappropriate for the aerodynamic analysis of HAWT blades. Rocha et al. [23] found that k–ω series turbulence models, which viewed as two-equation eddy viscosity models, are popularly used to simulate the aerodynamic forces in HAWT blades. Wang et al. [24] reported that the SST k–ω model is better than the standard k-ω model in calculating the low Reynolds number flows around the oscillating airfoils. Rezaeiha et al. [25] compared the SST k-ω, LES and RNG k-ε models to the experiment result in simulating the urban vertical axis wind turbines, and found that the deviations of the SST k-ω model and RNG k-ε model are −3.2% and −20.3%, respectively. To investigate the wake characteristics of the wind turbine, different turbulence models are examined to study the effect of turbulence models on wake shape by Naderi and Torabi [26].

From the above brief review, it can be seen that the small-scale wind turbine has many advantages and is widely used in distributed wind systems, while it cannot provide as high aerodynamic performance as the conventional large-scale one. Moreover, the researchers mainly focused on the small-scale VAWTs, although the HAWTs possessing many advantages. The disc-shaped wind rotor is a product of an Australian company [27], which behaves higher aerodynamic performance even at a low tip speed ratio and characteristics of low noise and portability, while its mechanisms of aerodynamic performance enhancements are not well understood and are barely reported in publications. In this work, the comprehensive performance of the re-designed disc-shaped wind rotors are investigated by wind tunnel tests and numerical simulations, in order to illuminate the enhancement mechanisms in aerodynamic performance, to provide the base data for the optimization of geometry parameters at various tip speed ratios, and to obtain the parameter combination for a higher power coefficient.